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African rainforest moisture contribution to continental agricultural water consumption

Maganizo Kruger Nyasulu [a,b,c,*], Ingo Fetzer [a,b], Lan Wang-Erlandsson [a,b,c], Fabian Stenzel [c], Dieter Gerten [c,d,e], Johan Rockström [a,c], Malin Falkenmark [a,1]

[a] Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
[b] Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
[c] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany
[d] Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany
[e] Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Berlin, Germany

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ABSTRACT

Precipitation is essential for food production in Sub-Saharan Africa, where more than 80 % of agriculture is rainfed. Although ~40 % of precipitation in certain regions is recycled moisture from Africa's tropical rainforest, there needs to be more knowledge about how this moisture supports the continent's agriculture. In this study, we quantify all moisture sources for agrarian precipitation (African agricultural *precipitationshed*), the estimates of African rainforest's moisture contribution to agricultural precipitation, and the evaporation from agricultural land across the continent. Applying a moisture tracking model (UTRACK) and a dynamic global vegetation model (LPJmL), we find that the Congo rainforest (>60 % tree cover) is a crucial moisture source for many agricultural regions. Although most of the rainforest acreage is in the DRC, many neighboring nations rely significantly on rainforest moisture for their rainfed agriculture, and even in remote places, rainforest moisture accounts for ~10–20 % of agricultural water use. Given continuous deforestation and climate change, which impact rainforest areas and resilience, more robust governance for conserving the Congo rainforest is necessary to ensure future food production across multiple Sub-Saharan African countries.

1. Introduction

Sub-Saharan Africa has to tackle high food insecurity due to the region's crop and livestock production's sensitivity to climatic changes and extremes (Campbell et al., 2018; Dawson et al., 2016; FAO et al., 2020; Holleman et al., 2020). In response to production failures, large areas of rainforest have been converted to agricultural land in recent decades, resulting in approximately 39 million hectares of tree cover loss between 2001 and 2015, largely attributed to agricultural-related causes (Curtis et al., 2018; Malhi et al., 2013). These conversions are projected to intensify further to meet the growing population's demands for food and fuel (FAO, 2019; FAO et al., 2020; Foley et al., 2011).

African agricultural land like other global terrestrial land are sink regions of precipitation that originated as evaporation locally or elsewhere (van der Ent and Savenije, 2013). The downwind areas of precipitation, receiving evaporation from regions of interest are called *evaporationsheds* (van der Ent and Savenije, 2013). The upwind areas of evaporation contributing to precipitation in regions of interest are referred to as *precipitationsheds* (Keys et al., 2012). Tropical rainforests are an essential regulator in the global water cycle (Duku and Hein, 2021; Lawrence and Vandecar, 2015; Savenije, 1995; van der Ent et al., 2010). Through evapotranspiration, herein referred to simply as evaporation (*E*) (Miralles et al., 2020), rainforests supply a considerable amount of water to the atmosphere, which travels as atmospheric moisture to provide downwind land areas with precipitation, through the process called moisture recycling (Keys et al., 2012; O'Connor et al., 2021). In Africa, the major moisture sources (precipitationshed) of continental precipitation are situated in the east and central areas of the continent, while the major sinks (evaporationshed) are located in the west (van der Ent et al., 2010).

Tropical rainforests are known to supply moisture for precipitation over agricultural-land (Alkama and Cescatti, 2016; Mahmood et al.,

* Corresponding author at: Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
E-mail address: kruger.nyasulu@su.se (M.K. Nyasulu).
[1] Deceased.

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2014; Spracklen et al., 2018). Modeling and empirical studies for the tropics show that future agricultural productivity is highly sensitive to tropical rainforest deforestation-driven water and climate variability (D'Almeida et al., 2007; Davidson et al., 2012; Lawrence and Vandecar, 2015). Experiments in the Amazon rainforest show that deforestation caused by agricultural expansion cancels out seasonal rainfall, lowering agricultural output, particularly in the heavily dependent regions of eastern Para and northern Maranhao (Oliveira et al., 2013).

Traditional water assessment studies that are linked to agriculture have mainly focused on visible water that is present as runoff, in water bodies (streams, rivers and lakes) or as groundwater (Pastor et al., 2014; Schlosser et al., 2014; Vörösmarty, 2002; Vörösmarty et al., 2000). This type of water is characterized as ``*blue*'' water, mostly used in irrigation systems (Falkenmark, 1986). Since several decades ago, the invisible part of the water that is available for plants, as soil and atmospheric moisture, has been included in water assessment as "*green*" water (Falkenmark, 1986; Falkenmark and Rockström, 2006). Green water is infiltrated water from precipitation that is available as soil moisture for plant consumption water (Falkenmark, 1986; Falkenmark and Rockström, 2006). It is essential for global agricultural production, contributing to >60 % of all agricultural outputs (Falkenmark and Rockström, 2004), with sub-Saharan Africa regions almost entirely depending on green water (>95 %) (Alexandratos, 1995; Rost et al., 2008). This makes green water an essential element in attaining Africa's United Nations (UN) Sustainable Development Goals (SDGs) on food.

Land Use Change (LUC) affects the amount of moisture that is available for agriculture and can result in a 7–17 % reduction in crop yields in major food baskets, such as the Sahel region (Bagley et al., 2012). Using a convolutional long short-term memory neural network (ConvLSTM), a machine learning method, Duku and Hein (2021) predicted a decrease in precipitation due to deforestation in regions north of the African equator, while some regions of southern Africa would see an increase in precipitation under various climatic futures. The authors emphasized limitations in this approach because it depends on extrapolating the current (2000–2015) correlations between deforestation and rainfall to the future with a much lower forest cover than the baseline period. In addition, the model lacked some key atmospheric characteristics namely, different pressure levels, water vapor fluxes, atmospheric column moisture contents, and specific humidity. This, therefore, demands a spatially more detailed grid-to-grid analysis of moisture fluxes and transport coupled to key atmospheric parameters.

Since moisture in rainforests is often recycled several times, every broken link in this chain will lead to reductions in downwind moisture provision. Thus, regions fed by precipitation generated in the forest region demand reliable onset of seasonal precipitation for the sowing period (critical for plant germination) (Butt et al., 2011). Any precipitation perturbations, such as delayed onset or early cessation, will threaten smallholder farmers because they expect precipitation to start and stop in specific months (Benhin, 2006; Bennett et al., 2012; Castellazzi et al., 2008), even though in cases where farmers have adequate weather and precipitation information, they adjust their cropping system depending on the perceived risk of failure (Waha et al., 2013). Therefore, understanding the intra-continental water flows is vital to inform smallholder farmers of the future implications of land-use change in the Congo rainforest on local precipitation availability for their agricultural system.

Knowledge of African agricultural regions' dependence on rainforests as major moisture sources is essential in the face of massive ongoing rainforest conversions to agricultural land and/or the inherently increased risk of losing their water provisioning capacity due to unintended habitat tipping (Singh et al., 2022; Staal et al., 2018). Studies show that climatic (long-term drying) trends, artisanal forestry, and short-term agriculture using cleared land over only one or a few seasons are the primary causes of Congo rainforest deforestation (Curtis et al., 2018; Kadoya et al., 2022; Shapiro et al., 2022). For the latter, a study estimates that only 50 % of global deforested land is later used as productive cropland (Pendrill et al., 2022). Recent estimates of Congo rainforest deforestation suggest a significant net decrease post-2000 (Shapiro et al., 2022). In a comparative analysis, Mayaux et al. (2013) observed decreasing annual rates in major African tropical rainforest regions from 590,000 ha yr^{-1} between 1990 and 2000 to 290,000 million ha yr^{-1} between 2000 and 2010. Future projections, however, suggest that the deforestation rate will rise by 0.5 % annually to 2030 due to increasing improvements in the road network as well as planned mining and timber (Nayar, 2009).

These scenarios may imply significant changes to atmospheric moisture recycling and transport with potential effects on Sub-Saharan Africa's predominantly rainfed agriculture (Dunkelman et al., 2018; Keys and Falkenmark, 2018; Portmann et al., 2010). There is still a lack of understanding about the moisture rainforests currently contribute to precipitation in both local and remote agricultural sink regions. Understanding these cross-boundary atmospheric water interactions can influence rainforest management as a common good. This is because most of these remote sink regions located outside of the rainforest jurisdiction do not have political and policy influence on rainforest land use decision, that is primarily influenced by Cameroon and Democratic Republic of Congo (DRC) (Somorin et al., 2012). Therefore, remote regions might face a high risk if their dependence on rainforest moisture is compromised by changes in precipitation. Further, there are gaps in mapping which rainforest regions are critical to moisture provision. We, provide an analysis of the present situation, underscoring the value of conserving the African rainforest for sustaining the continent's agriculture. Specifically, we quantify (in a spatially detailed manner) African agricultural-land's *precipitationsheds* and where and how much African tropical rainforest evaporation contributes to crop precipitation in agricultural systems across the continent.

2. Method and data

We tracked moisture from the rainforest-covered areas to connect a source to its sink regions for agricultural-land and natural vegetation. Further on, we estimate the contribution of the precipitation originating from the rainforest to the crop water consumption in the sink region (for a methodological overview, see Fig. 1) using a moisture tracking model (UTRACK) (Tuinenburg and Staal, 2020) in combination with a dynamic vegetation model (LPJmL) (Schaphoff et al., 2018b, 2018a). By backtracking received moisture in agricultural-lands through estimated precipitation, the analysis determines connected source and sink regions and their quantitative significance for each water-receiving region. Forward tracking is used to specifically determine forest region's contribution to agriculture, and backward tracking is used to determine the agricultural-land's precipitationshed. All data has been scaled to 50 km by 50 km (0.5 degree) resolution at the equator, and analysed for a time period 2008 to 2017.

2.1. Forest cover data

African rainforest cover extent is based on the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 data product at 500-meter spatial resolution (Friedl et al., 2010). The area considered the median tree cover classification of evergreen and deciduous broadleaved forests with >60 % tree coverage during the period 2008–2017 (Sulla-Menashe and Friedl, 2018). Subsequently, the product was resampled to 0.5-degree (50 by 50 km) resolution by nearest neighbor aggregation to harmonize with the LPJmL and UTRACK input data resolutions (see Fig. B.1(a), in supplementary).

2.2. LPJmL

The global vegetation and water balance model LPJmL was used to dynamically determine crop and natural vegetation growth and

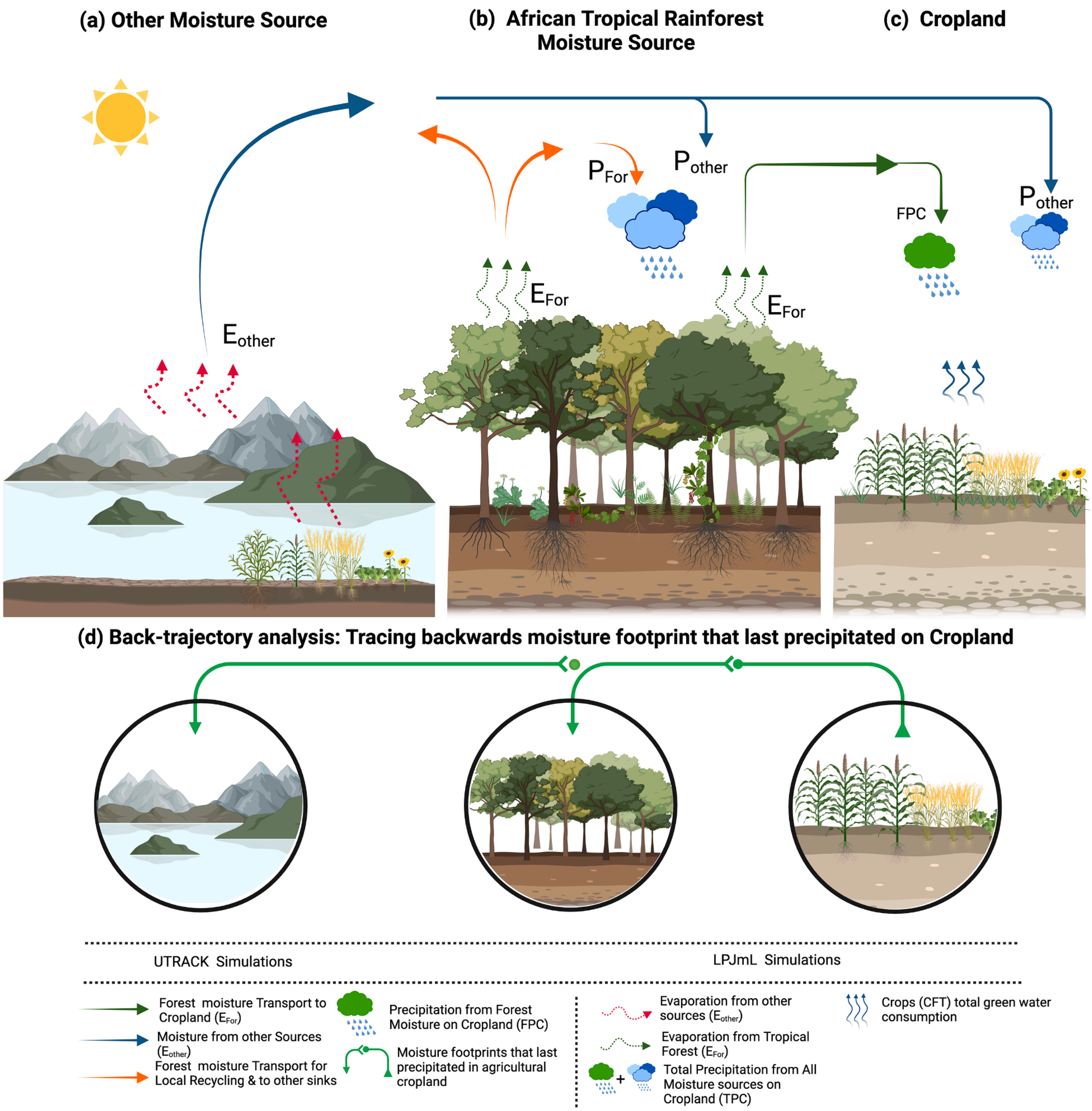

Fig. 1. Schematic overview of the study design (a) different moisture sources (E_{other}) supply moisture that later falls as precipitation (P_{other}) either onto (b) rainforests or (c) agricultural-land (cropland) (here distinguishing different crop functional types, CFTs represented in the LPJmL model). Within the African tropical forest, there is local moisture recycling, with rainforest evaporation (E_{For}) generating local precipitation (P_{For}). Some of which E_{For} supplies moisture to distant agricultural-land areas (FPC). (d) Total precipitation on agricultural-land can be traced backwards to its respective moisture source; either an oceanic or terrestrial region with the UTRACK model (green arrows) through a process called back-trajectory.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

production and the aggregation of evaporation, interception, and transpiration (E) at a monthly time scale (Schaphoff et al., 2018a). The derived E is then used in the UTRACK simulation (Section 2.3). We use the same climate input data for the UTRACK (see Section 2.3 below) version used here (Tuinenburg et al., 2020; Tuinenburg and Staal, 2020) and LPJmL simulations. This involved a combination of daily Global Soil Wetness Project Phase 3 (GSWP3) data from 1901 to 1978 (Kim and Oki, 2015) and fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis for the global climate and weather (ERA5) data from 1979 to 2018 (ECMWF, 2017; Hersbach et al., 2019) to avoid a break between the datasets (ISIMIP3BASD, Lange and Büchner, 2021). GSWP3 was bias-adjusted to ERA5, following the general procedure of Lange et al. (2022), but with different climate input. As land-use input, a new hybrid dataset is used (Ostberg et al., 2023). Country-specific time series of total harvested area per crop from FAOSTAT (2020) are combined with country-specific irrigated harvested area per crop or crop group from Aquastat (2020) and MIRCA2000 (Portmann et al., 2010) to derive country-scale time series of crop-specific rainfed and irrigated harvested areas. These country-scale harvested areas are disaggregated into grid cells using rainfed and irrigated agricultural-land extent information from HYDE version 3.2.1 (Klein Goldewijk et al., 2017), spatial crop patterns in 2000 (Monfreda et al., 2008), and rainfed and irrigated multiple-cropping suitability from GAEZ version 3 (Fischer et al., 2012).

Fallow land has been added to the *"other crop classes"*, and irrigated areas are based on Jägermeyr et al. (2015). Crop functional types (CFT) specific sowing dates are dynamically calculated but fixed after 1970 (Waha et al., 2012).

We generated the monthly E, the monthly CFT-specific "green" water consumption (GWC), from both irrigated and rainfed simulations across Africa at 0.5-degree resolution, and the amount of precipitation in each fraction of grid cell covered by a given CFT from the simulations. The GWC calculation in LPJmL is based on the methods proposed by Fader et al. (2011) and Rost et al. (2008), and is calculated as a function of productive (transpired) water from soil water supply and atmospheric demand (see Rost et al., 2008).

2.3. Moisture recycling

Moisture flow with precipitationsheds and evaporationsheds was derived from the model run outputs of the UTRACK model (Tuinenburg and Staal, 2020). UTRACK is a Lagrangian-type atmospheric moisture tracking model that tracks budgets of moisture footprints from their evaporative origin, through the atmosphere, and to their downwind precipitation area, and backwards by follow the precipitated moisture to its evaporative region of origin (for more model description, see Tuinenburg et al., 2020; Tuinenburg and Staal, 2020). UTRACK is the first model to use high resolution ERA5 reanalysis data for atmospheric tracking that has multiple vertical resolutions, a key element for resolving any vertical shear in atmospheric moisture transport (Wunderling et al., 2022). The model tracks each moisture parcel for 30 days along its trajectory until 99 % of its moisture content has rained out. The interpolated three-dimensional scale of ERA5 comprising of wind speed, wind direction, 25 pressure layers in atmospheric columns, allows the high resolution for tracking the parcel's trajectories in UTRACK. Thus, for every evaporation (1 mm) 100 parcels are released at 50 hpa above the surface to the ground in random spatial location of 0.25° grid cell of evaporation input, which are later scaled to 0.5° resolution for our analysis. For comprehensive model description, see Tuinenburg et al. (2020) and Tuinenburg and Staal (2020). To track the moisture transport, we fed the LPJmL's *E* output as input to UTRACK at 0.5-degree resolution for the period 2008 to 2017 following Tuinenburg et al. (2020) approach.

Like most models, UTRACK is built on multiple assumptions for simulating the path of moisture flow from *E* source through the atmosphere to sink region. Two of such uncertainty sources are in the atmospheric forcing data and accompanied model assumptions. UTRACK has documented these underlaying sources of uncertainty (Tuinenburg et al., 2020 and Tuinenburg and Staal, 2020). To compensate for the uncertainties in the vertical atmospheric shear the UTRACK model uses multiple vertical resolution pressure layers available in the three-dimensional forcing data, ERA5. Uncertainties arising from parameterized processes including convective up- and downdrafts, re-evaporation, and microphysics in the vertical redistribution have been resolved using a probabilistic analysis in which moisture parcels are randomly distributed along the local vertical moisture profile once every 24 h (for details see Tuinenburg and Staal, 2020). Despite the known ERA5 biases in the tropics, UTRACK's terrestrial moisture recycling simulations have been validated by comparing the seasonal tropical stable-isotope quantity sensitivity (deuterium excess) to recycling effects which has a statistical significance between 0.52 and 0.70 at seasonal levels, climate subzones, and in different tropical vegetational variations, making such biases minimal (Cropper et al., 2021).

2.4. Back-trajectory and forward tracking

To estimate the precipitationsheds for agricultural-lands we used a backward tracking method where we traced back all moisture that precipitated on agricultural-land, targeting only the fraction of total precipitation on managed land, not that on natural vegetation. Further, to estimate where the moisture from the Congo rainforest goes (the evaporationshed), we used a forward tracking analysis to calculate the moisture originating from the rainforest that contributes to precipitation in all landscapes (FP) and agricultural land (FPC). FPC was computed at monthly time resolution as a product of precipitation in each fraction of grid-cell allotted to CFT.

2.5. Analysis

2.5.1. Rainforest precipitation contribution ratio to agricultural-land (CFT ratio)

Agricultural-land was disaggregated into all the CFTs (see Schaphoff et al., 2018b) except the bio-energy grass and bio-energy tree. The forest's significance in providing moisture to agricultural-land was analyzed in two ways. First, as FPC-ratio (ρ = FPC/TPC) - (1), i.e., the ratio of FPC to total precipitation in agricultural-land (TPC). Secondly, we analyze if forest evaporation can provide water to agriculture during periods of high precipitation variability, i.e., whether forest *E* has buffering properties for agriculture. We use the coefficient of variation (CV) of total precipitation on agricultural-land and compute a trendline against the fraction of precipitation from rainforest (for more details, see Supplementary section E). A low CV indicates less variability and high stability. Such methods have been applied in similar moisture feedback research (O'Connor et al., 2021).

2.5.2. Seasonal and monthly forest-moisture contributions

We spatially explicitly analyze seasonal differences in both the origins of moisture that precipitates onto African agricultural-land and the FPC ratio. This is to account for the fact that the inner-tropical regions where the rainforest is located have no distinct dry-wet season (rather being dominated by a hot and humid climate). The dry season in regions north of the equator occurs in December–February and June–September for the southern part, with the wet season occurring in the opposite seasons. In this study, we selected the Congo Rainforest's seasons (dry: December, January, and February [DJF]; wet: June, July, and August [JJA]).

Further, a monthly assessment of water sources, total precipitation, and forest moisture alongside the GWC was used to estimate water availability and consumption throughout the farming calendars of each of the 13 CFTs occurring on the African continent (temperate cereals, rice, maize, tropical cereals, pulses, temperate roots, tropical roots, oil crops sunflower, oil crops soybean, oil crops groundnut, oil crops rapeseed, sugarcane, and all other crops). We averaged the area-weighted CFT-specific GWC for each month and grid cell over the study period of 2008–2017. The LPJmL simulations use sowing and harvest periods based on a set of rules described in Waha et al. (2012) that are based on climate- and crop-specific thresholds. However, for visualization we used the FAO cropping calendar disaggregated by major sowing and harvest period, available at https://cropcalendar.apps.fao.org/#/home(FAO, 2022). Finally, we exemplarily illustrate in more detail the continental-scale spatial variations of FPC dependencies in three selected countries with high, medium, and low FPC ratios.

3. Results

3.1. Origins of agriculture-supporting rain in Africa

The backward tracking analysis established that >30 % of precipitation on agricultural-land has evaporated from conterminous African regions, which are predominantly forest regions, including the Congo rainforest, and water bodies (Fig. 2(a)). Furthermore, a high percentage (~40 %) of the evaporation from the freshwater bodies of Lake Malawi, Lake Tanganyika, and Lake Victoria (Fig. 2(a)) contributes to the rainfall over agricultural-land. Despite these findings, on average, some of the major moisture sources for agriculture in Africa reside in the Indian

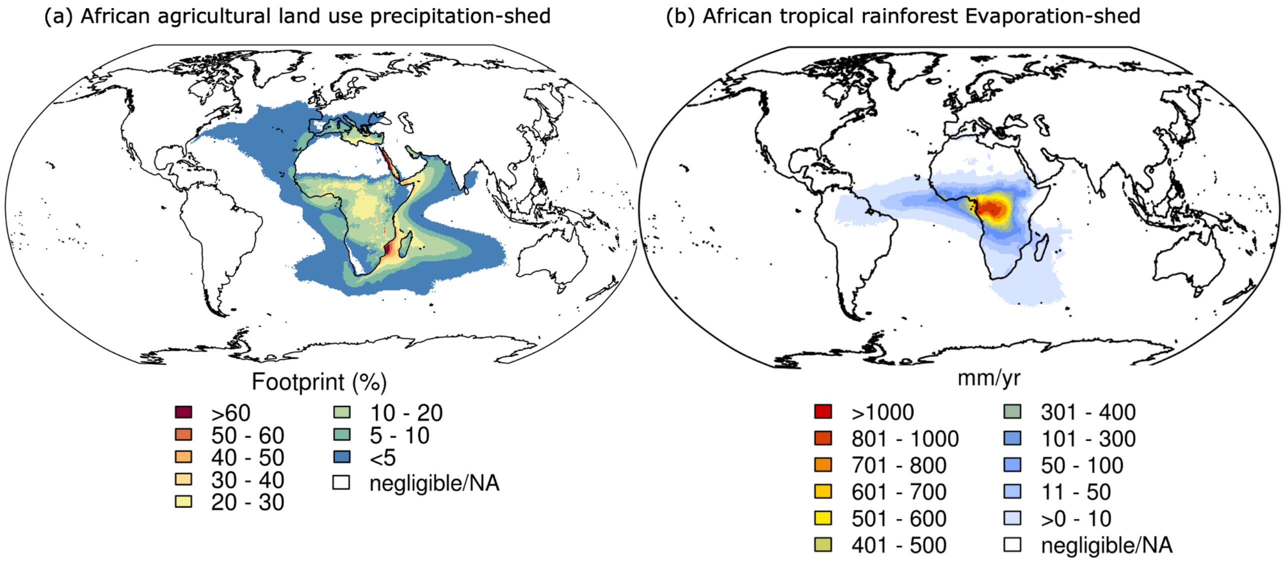

Fig. 2. (a) Annual African agricultural precipitationshed expressed as a percent of the moisture footprint that precipitates over agricultural areas; (b) the annual tropical rainforest evaporationshed in mm/year.

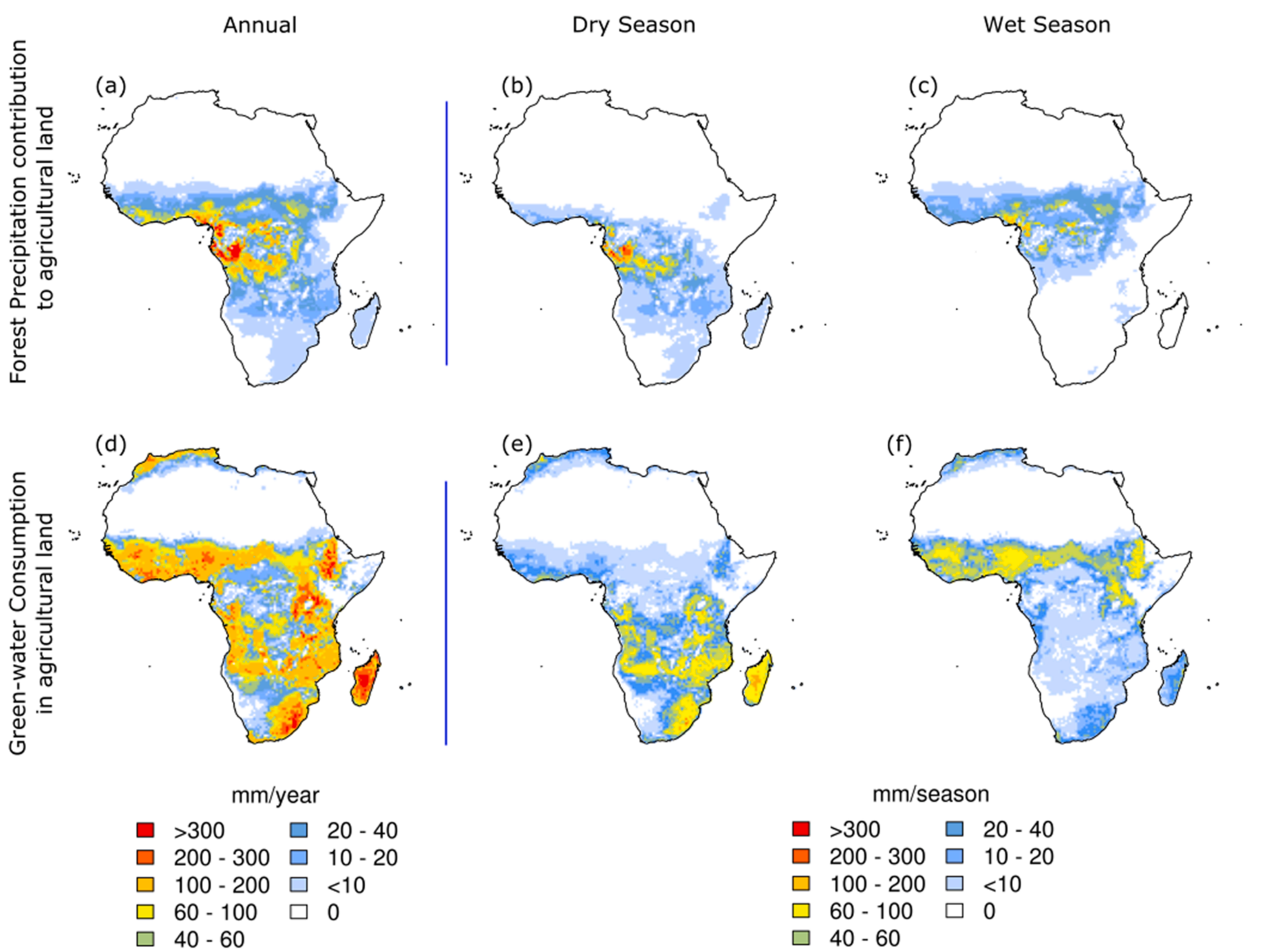

Fig. 3. The top row is the forest precipitation contribution to agricultural land expressed at annual (a) and monthly averages for dry (b) and wet (c) seasons. The bottom row is the total green water consumption in agricultural land at annual (d), dry season (e), and wet season (f). Annual in mm/year and seasonal at mm/month for the 2008–2017 average.

Ocean and the Red Sea (Fig. 2(a)) with footprints of >40 % per annum. The Gulf of Aden and Red Sea sources intensify during dry seasons (December–February) to >40 %, whereas the wet season is dominated by E from the Indian Ocean along the coasts of Mozambique of >60 % (see supplementary Fig. C.1). Tracking only E from the rainforest that falls as precipitation over land and ocean, we found that the hotspot regions reside in the central part of the Congo rainforest of >40 % (Fig. 2 (b)). The rainforest-sourced precipitation is highly seasonal, with the regions around and north of the equator having a high moisture distribution in wet season for >10 mm/month while the southern region having values <5 mm/month and some regions not even receiving any FP. The opposite trends occur during the dry season where FP intensifies towards the south from around >10 to >100 mm/month (Fig. C.2 in supplementary).

3.2. Rainforest-agriculture interrelationship, an atmospheric moisture transport perspective

The annual E mean in tropical rainforests was > 900 mm/year (Fig. B.1(c) in supplementary), but varied across the year. E in regions north of the equator peaked more during the wet season than the dry season (Fig. B.1(d)–(e)). These rainforest E variations affect the moisture volume and contribution (FPC) that is later transported to agriculture elsewhere (Figs. 1 and 2(b)). We found that FPC contributes >200 mm/year in some regions (Fig. 3(a)) and varies across seasons with sums >20 mm/season (Fig. 3(b), (c)). Fig. 3(d)–(f), shows the African agricultural land average CFTs GWC in which southern region cropping current occurs during the dry season, and the northern region during the wet season. Overall, the CFT GWC is on average >60 mm/season compared to the FPC of approximately 10 to 60 mm/season across the seasons (Fig. 3). This spatial variation means that regions where FPC is less than the GWC, the FPC only complements to the sum total of precipitations from other moisture source falling in the region. For instance, oceanic sources in the southern and eastern part of the continent. However, some regions within and in the western part of the rainforest have high FPC of >100 mm/season compared to GWC of 60 to 100 mm/season. In such regions GWC can be met entirely by FPC.

3.3. Country-scale analysis

The rainforest's moisture contribution to agriculture increases in the dry season in comparison to the wet season, when there is less contribution from other moisture sources (Figs. 3(a)–(c) and 4(a)). For instance, during the dry season, agricultural areas situated within the DRC and to the northwest (Cameroon) of the Congo rainforest have the highest FPC on average with some regions receiving >100 mm/season. As the season gradually moves from dry to wet, FPC hotspots tends to move southward from regions west of the Congo rainforest (Gabon, Equatorial Guinea) towards southern DRC, the north and north-western provinces of Zambia, and northern Angola.

Fig. 3(a)–(c) shows spatially these distributions. However, to best represent them at a country and seasonal scale, Fig. 4(a) provide a more detailed illustration. Countries that represent highest seasonal dependence on FPC are Cameroon (Dry:42 %, Wet:66 %), Chad (Dry:22 %, Wet:42 %), Central African Republic (Dry: 30 %, Wet: 47 %), Equatorial Guinea (Dry: 33 %, Wet: 28 %), DRC (Dry: 41 %, Wet: 46 %), Republic of Congo(Dry: 26 %, Wet: 37 %), and Gabon. Since the FPC ratio is calculated based on agricultural land in the country, and not for all grid cells of the country, it implies that even FPC ratio values >10 % are important GWC for they supplement to the TPC in the target agricultural sink region. Therefore, countries like Nigeria, Liberia Rwanda and others with about >10 % FPC ratio, benefit from the FPC. For a more country level analysis of rainforest relevance to agriculture, three exemplary countries were selected that presented cases with *high* (Gabon), *medium* (Angola), and *low* (Uganda) FPC ratios (ρ).

In Angola, annual FPC ratio is >10 % in the northern agricultural zone (Fig. 4(b)), which is one of the key food baskets of the country. While our monthly analysis in Fig. 4(b) is averaged across the whole country's agricultural land, the FPC ratio is high between May and October. This FPC is vital, as it supplements to total precipitation from other sources that feeds into wheat sowing period in May, and early maize sowing in October (shown in cropping calendar Fig. 4(b)–(d)). For Gabon, the average FPC ratio during important sowing periods was ~40 % (Fig. 4(c)). Both Angola and Gabon had monthly averages of GWC between May and August approximately equivalent to TPC, a phenomenon that can be attributed to perennial and dry-season CFT transpiration.

Contrarily, in Uganda (Fig. 4(d)), the FPC seasonal contribution is <4 % in the wet and dry seasons, respectively. Thus, rainforest buffering properties are less compared to Gabon and Angola. Instead, agricultural-land depends on other terrestrial and oceanic moisture sources (Fig. 2 (a)).

In summary, four key results emerge from our analysis. First, the African agricultural-land's dependence on continental and oceanic moisture sources is spatially explicit. The eastern African agricultural land benefits most from oceanic moisture sources, while the western part is land-dominated, with the Congo Rainforest playing a significant role (Fig. 2(a)).

Secondly, the inner-tropical rainforest contributes significant volumes of moisture to agricultural areas across much of Central Africa and tends to increase in most regions during the dry season when other moisture sources and absolute volumes of moisture in the affected areas are low (Fig. 3(b), (c)). For example, Gabon's moisture footprint increases from ~30 % to ~40 % nationally in the wet and dry season respectively, with some parts of the country near the rainforest region reaching up to >60 % (Fig. 4(a)).

Thirdly, the monthly average GWC (Fig. 4(b)–(d)) is mostly above the FPC throughout the seasons across the three exemplary countries. In Gabon GWC peaks from ~87 mm/month in January to ~89 mm/month in March, while FPC ranges from ~43 mm/month to ~50 mm/month for January and March respectively signifying a high FPC dependence. In Angola, January was the highest month with GWC of ~134 mm/month compared to an FPC of ~10 mm/month (see table D.1 in supplement). This exemplifies that FPC on average contributes to TPC required for crop uptake. Spatially, countries located from Central toward the west of Equatorial region, are well positioned to benefit the most from FPC in their agricultural land. For instance, Cameroon, Central African Republic, Chad, the DRC, Equatorial Guinea, and the Republic of Congo (circle plot in Fig. 4(a)) located within the western Congo rainforest region were other countries within the evaporationshed with equally high annual FPC averages of approximately 252, 66, 37, 253, 202, and 391 mm/year, respectively. This is attributed to the regions' positionality in the tropics with easterly jet transporting moisture from the rainforest eastwards (see for more details Hua et al., 2019).

Fourth, while annual continental FPC (>40 %) is not as high as that of oceanic moisture sources of up to >60 % (Fig. 2(a), (b)), we observed a strong and negative relationship between the FPC ratio and overall variation in total precipitation within the agricultural land residing in the Congo rainforest evaporationshed (Fig. E1(b) in supplementary). This is evident in the fact that the buffering mechanism, as measured by the coefficient of monthly precipitation variation on agricultural land, tends to increase as we move away from the Congo rainforest's evaporationshed to ~2.4 (Fig. E.1 in the supplementary). This can suggest a greater degree of unpredictability or variability in monthly precipitation patterns which might have implications to drought risk, flooding, and agricultural planning. Such FP properties in the evaporationshed can buffer water shortfalls in agricultural-land during times of precipitation variability.

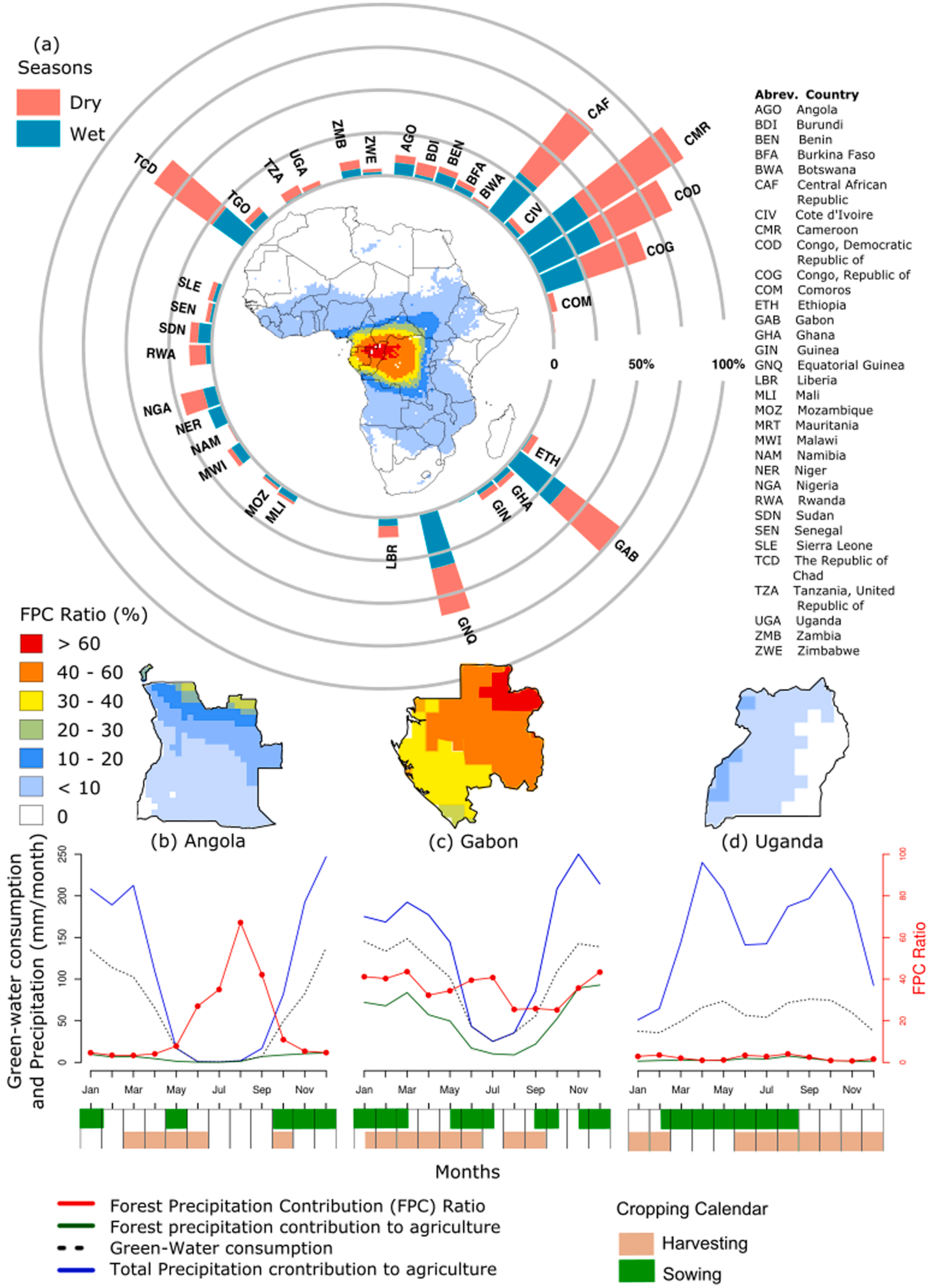

Fig. 4. (a) Modeled seasonal averages (period 2008–2017) of forest moisture contribution to agricultural areas in all countries within the Congo rainforest evaporationshed. The map inside the circle plot represents the annual average of FPC ratio. The country abbreviations are based on three sets of ISO 3166–1 country codes. Below (a), are three exemplary countries, showing average water fluxes across the country's agricultural area and representing cases with medium (b. Angola), high (c. Gabon), and low (d. Uganda) rainforest moisture dependance. The linear plots are monthly average values of total precipitation (blue), green crop water consumption (dotted black), FPC (green), and forest moisture precipitation contribution ratio (red line with dots). The *x*-axis indicates the generalized monthly cropping calendar from FAO (2022) for the most important crops. green: the sowing season; brown: the harvest period.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

More than 80 % of African food production is rainfed and depends on atmospheric moisture and its transport, which induces local cloud formation responsible for precipitation locally or in remote places (Keys and Falkenmark, 2018). In this study, at the seasonal level (Fig. 2(a), (b)), both the Congo rainforest and the inland Great Rift Valley water bodies show to be important moisture sources for agricultural water consumption, providing precipitation to rainfed agriculture during the critical sowing periods. Especially in the Congo rainforest, climate change, poses an increasing risks of changes to seasonal dynamics and moisture transport capacities, which can have an impact on water availability (Abiodun et al., 2008; Ellison et al., 2017; Gerten, 2013; Hassan and Tularam, 2017; Lunyolo et al., 2020). Moreover, most of the forest region responsible for local and remote moisture recycling (Fig. 2) resides in an area vulnerable to deforestation (Hansen et al., 2013). Even patchy deforestation strongly undermines the Congo rainforest's resilience, which can affect its ability to resist short-term perturbations (climatic extremes, wildfires), long-term adaptation to climate change, or increasing human pressures (deforestation), risking an abrupt shift permanently into a savanna-like state (Staal et al., 2020). Other equally important moisture source regions like the Great Rift Valley are also under-threat from climate change and land use change which is anticipated to exacerbate climatic extremes by altering the hydrological cycle resulting in modification of moisture recycling capability (Herrnegger et al., 2021; Odada et al., 2003; Wamucii et al., 2021). However, this is beyond the scope of this research. As a consequence, the absence of these rainforest properties, will compound to future risk of food production loss and fluctuations in economic returns for local farmers, which can potentially spill over into social and political instabilities.

The buffering properties of the tropical rainforest guarantee the amount and timely onset of precipitation in the receiving regions (Fig. 4). This is essential for local farmers, as they, based on traditional regional structures and knowledge passed down through generations, rely on the seeding and cropping of specific crops in their region based on known seasonal precipitation and temperature dynamics (Tarchiani et al., 2017). Within the Congo rainforest, there is evidence of an increased length of the dry season by 6.4–10.4 days between 1988 and 2013, which resulted from decreased rainfall between April and June, which induced a negative feedback loop to moisture provision for rainfall (Jiang et al., 2019). Our analysis shows that the dry season atmospheric moisture budget does not fully coincide with the established cropping calendar (Fig. 4), but it remains critical for maintaining the local water cycle, particularly drought recovery and soil moisture provision during the dry period (Atallah et al., 2007; Konrad and Perry, 2010; Li et al., 2013). Moreover, the supply of moisture across the planting period supports periods of moisture gaps (dry spells) in the crucial planting season (Fig. E.1 in the supplementary). As noted, forest-precipitation availability amplifies in the dry season when other sources of precipitation decline. Such rainforest buffering mechanisms support De Kock et al. (2021) observation that moisture recycling from rainforests buffers climatic warming scenarios that may trigger droughts.

Drought-prone southern Angola has its northern food basket heavily dependent on FPC. However, projected drought and dry period intensification that hinders food production in the southern part of the country makes the northern food baskets more significant (Serrat-Capdevila et al., 2022). Likewise, the majority of the countries with high FPC ratios on average have total precipitation greater than GWC during the cropping seasons (Fig. 4). This implies a lower risk of food production deficits and potentially less risk of socioeconomic instabilities beyond climatic conditions (Sasson, 2012). Maintaining the African rainforest is thus critical for sub-Saharan African agriculture, not only directly as a moisture source essential for food production but also indirectly by stabilizing social and political conditions. Poor management of local tropical rainforests may thus lead to social and political instabilities in many regions. There is evidence that current precipitation fluctuations are driving rural and urban migration in sub-Saharan Africa (Hassan and Tularam, 2017) which both displaces people and encourages further shifting farming towards the water-sufficient region, which, as alluded to earlier, drives deforestation. A rise in the price of agricultural products has also been linked to precipitation fluctuations and conflicts (Raleigh et al., 2015).

For mitigating local water risks in high FPC-dependent countries, regionally adapted water management strategies such as rainwater harvesting and soil moisture management like mulching can be advocated, even for those with lower FPC buffering capacity (Piemontese et al., 2020). Nonetheless, the cross-border consequences of rampant deforestation in the Congo rainforest, driven by local needs, will continue to impede precipitation availability both locally and in distant countries reliant on rainforest E, such as Angola, Liberia, and the Central African Republic (Fig. 4(a)). The transnational precipitation linkages observed here are not represented in any policy or regional agreements (Keys et al., 2017; Keys and Wang-Erlandsson, 2018). Knowledge of these teleconnections and linkages is vital to initiating policy and rainforest management movements that target the entire forest evaporationshed and beyond.

5. Outlook and conclusion

Our results are model-based and produced at a 0.5° spatial resolution (50 × 50 km grid) with no smaller-scale variation in climatic and hydrologic processes. As a result, we provide an overview of the relationships between continental rainforest moisture and agricultural water consumption. Future analyses will require online coupled modeling that accounts for how much of each water parcel (precipitable water) available is actually translated to root moisture (water directly available for plants) and later transpired by the different vegetation (productive water) – based on which an assessment can be performed on how much FPC actually contributes to food and calorie production per area (and how this may change under scenarios of climate and land use change). Further studies should also investigate all equally important moisture source regions' capabilities and exposure to stressors, namely the Great Rift Valley.

Nonetheless, our findings corroborate the hypothesis that moisture from rainforests plays an important role in increasing water resilience for local water cycles and agricultural production. This makes it a valuable resource for transboundary regional management and policing. Policy and strategic actions on the rainforest should go beyond climate action (SDG 13) and emission reduction actions advocated by the UN Deforestation, Forest Degradation, and Enhancement of Carbon Stocks (REDD+) (UNFCCC, 2016), rather, they should provide a governance foundation for the moisture recycling linkages between rainforest and agriculture production within the SDG on food (goal 2). Land tenure and rights reforms and power redistribution through women's empowerment have proven to be key attributes to supplement existing and much-recommended "*integrated landscape approaches*" (Reed et al., 2015) in curbing agricultural-driven deforestation and degradation. Community land tenure can influence the management and type of afforestation processes (either tree varieties or adopting nature-based solutions). The current African Union Continental Green Recovery Plan (2021–2027) (AU, 2020), the Continental Africa Water Investment Program (AIP, 2023), and the financial pool from climate adaptation and mitigation (Savvidou et al., 2021) can serve as financial backing for such measures. However, managing the Congo rainforest transcends beyond the regions that benefit from forest moisture to a global scale due to its complex dynamical properties in climate modification and biodiversity integrity that affect the entire planet.

In conclusion, there are many facets to the forest-agriculture interrelationship; here we draw from three linkages. Firstly, anthropogenic climate change will intensify forest cover changes and thereby affect moisture recycling, which can lead to extreme climatic conditions such as droughts and extreme rainfall. Secondly, future population growth will continue to pose pressure on rainforest moisture recycling due to projected pressure on rainforest resources and encourage expansion of land use change into the rainforest region. As a consequence, changes in moisture recycling will be detrimental to crop production.

Declaration of generative artificial intelligence (AI) and AI-assisted technologies in the writing process

No AI-assisted technology was used in the process of writing this paper.

CRediT authorship contribution statement

Maganizo Kruger Nyasulu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ingo Fetzer:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing – review & editing, Project administration. **Lan Wang-Erlandsson:** Conceptualization, Supervision, Writing – review & editing. **Fabian Stenzel:** Software, Supervision, Writing – review & editing. **Dieter Gerten:** Conceptualization, Supervision, Writing – review & editing. **Johan Rockström:** Conceptualization, Investigation, Project administration, Supervision, Writing – review & editing. **Malin Falkenmark:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

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

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2023.109867.

References

Abiodun, B.J., Pal, J.S., Afiesimama, E.A., Gutowski, W.J., Adedoyin, A., 2008. Simulation of West African monsoon using RegCM3 Part II: impacts of deforestation and desertification. Theor. Appl. Climatol. 93, 245–261. https://doi.org/10.1007/s00704-007-0333-1.

AIP, 2023. Africa's Rising Investment Tide: how to Mobilise US$30 Billion Annually to Chieve Water Security and Sustainable Sanitation in Africa.

Alexandratos, N., 1995. World agriculture: towards 2010: an FAO study.

Alkama, R., Cescatti, A., 2016. Biophysical climate impacts of recent changes in global forest cover. Science 351, 600–604.

Aquastat, F., 2020. FAO's Global Information System on water and agriculture.

Atallah, E., Bosart, L.F., Aiyyer, A.R., 2007. Precipitation distribution associated with landfalling tropical cyclones over the eastern United States. Mon. Weather Rev. 135, 2185–2206.

AU, 2020. African Union Green Recovery Action Plan.

Bagley, J.E., Desai, A.R., Dirmeyer, P.A., Foley, J.A., 2012. Effects of land cover change on moisture availability and potential crop yield in the world's breadbaskets. Environ. Res. Lett. 7, 014009 https://doi.org/10.1088/1748-9326/7/1/014009.

Benhin, J.K., 2006. Climate change and South African agriculture: impacts and adaptation options. CEEPA discussion paper.

Bennett, A.J., Bending, G.D., Chandler, D., Hilton, S., Mills, P., 2012. Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. Biol. Rev. 87, 52–71.

Butt, N., de Oliveira, P.A., Costa, M.H., 2011. Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. J. Geophys. Res. 116, D11120. https://doi.org/10.1029/2010JD015174.

Campbell, B.M., Hansen, J., Rioux, J., Stirling, C.M., Twomlow, S., (Lini) Wollenberg, E., 2018. Urgent action to combat climate change and its impacts (SDG 13): transforming agriculture and food systems. Curr. Opin. Environ. Sustain. 34, 13–20. https://doi.org/10.1016/j.cosust.2018.06.005.

Castellazzi, M., Wood, G., Burgess, P.J., Morris, J., Conrad, K., Perry, J., 2008. A systematic representation of crop rotations. Agric. Syst. 97, 26–33.

Cropper, S., Solander, K., Newman, B.D., Tuinenburg, O.A., Staal, A., Theeuwen, J.J.E., Xu, C., 2021. Comparing deuterium excess to large-scale precipitation recycling models in the tropics. Npj Clim. Atmos. Sci. 4 (60) https://doi.org/10.1038/s41612-021-00217-3.

Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A., Hansen, M.C., 2018. Classifying drivers of global forest loss. Science 361, 1108–1111. https://doi.org/10.1126/science.aau3445.

D'Almeida, C., Vörösmarty, C.J., Hurtt, G.C., Marengo, J.A., Dingman, S.L., Keim, B.D., 2007. The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. Int. J. Climatol. 27, 633–647.

Davidson, E.A., de Araújo, A.C., Artaxo, P., Balch, J.K., Brown, I.F., C., Bustamante, M. M., Coe, M.T., DeFries, R.S., Keller, M., Longo, M., 2012. The Amazon basin in transition. Nature 481, 321–328.

Dawson, T.P., Perryman, A.H., Osborne, T.M., 2016. Modelling impacts of climate change on global food security. Clim. Change 134, 429–440. https://doi.org/10.1007/s10584-014-1277-y.

De Kock, W., Blamey, R., Reason, C., 2021. Large summer rainfall events and their importance in mitigating droughts over the South Western Cape, South Africa. J. Hydrometeorol. 22, 587–599.

Duku, C., Hein, L., 2021. The impact of deforestation on rainfall in Africa: a data-driven assessment. Environ. Res. Lett. 16, 064044 https://doi.org/10.1088/1748-9326/abfcfb.

Dunkelman, A., Kerr, M., Swatuk, L.A., 2018. The new green revolution: enhancing rainfed agriculture for food and nutrition security in Eastern Africa 305–324. https://doi.org/10.1007/978-3-319-64024-2_12.

ECMWF, 2017. Copernicus Climate Change Service (C3S): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access.

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M.van, Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D.V., Tobella, A. B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C.A., 2017. Trees, forests and water: cool insights for a hot world. Glob. Environ. Change 43, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002.

Fader, M., Gerten, D., Thammer, M., Heinke, J., Lotze-Campen, H., Lucht, W., Cramer, W., 2011. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol. Earth Syst. Sci. 15, 1641–1660. https://doi.org/10.5194/hess-15-1641-2011.

Falkenmark, M., 1986. Fresh water - time for a modified approach. Ambio 15, 192–200.

Falkenmark, M., Rockström, J., 2006. The new blue and green water paradigm: breaking new ground for water resources planning and management. J. Water Resour. Plan. Manag. 132, 129–132. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129).

Falkenmark, M., Rockström, J., 2004. Balancing Water for Humans and Nature: The New Approach in Ecohydrology. Earthscan.

FAO, 2022. Global Cropping Calendar. FAO.

FAO, 2019. Safeguarding Against Economic Slowdowns and Downturns, The state of Food Security and Nutrition in the World. FAO, Rome.

FAO, IFAD, UNICEF, WFP, WHO, 2020. The State of Food Security and Nutrition in the World 2020. FAO, IFAD, UNICEF, WFP and WHO. https://doi.org/10.4060/ca9692en.

FAOSTAT, F., 2020. Statistics Division of Food and Agriculture Organization of the United Nations (2018).

Fischer, G., Nachtergaele, F.O., Prieler, S., Teixeira, E., Tóth, G., van Velthuizen, H., Verelst, L., Wiberg, D., 2012. Global agro-ecological zones (GAEZ v3. 0).

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. https://doi.org/10.1038/nature10452.

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X., 2010. MODIS collection 5 global land cover: algorithm refinements and characterization of new datasets. Remote Sens. Environ. 114, 168–182. https://doi.org/10.1016/j.rse.2009.08.016.

Gerten, D., 2013. A vital link: water and vegetation in the Anthropocene. Hydrol. Earth Syst. Sci. 17, 3841–3852. https://doi.org/10.5194/hess-17-3841-2013.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.
Hassan, O.M., Tularam, G.A., 2017. Impact of rainfall fluctuations and temperature variations on people movement in Sub-Saharan Africa: a Time Series Analysis of data from Somalia and Ethiopia. Presented at the 22nd International Congress on Modelling and Simulation. https://doi.org/10.36334/MODSIM.2017.A5.Hassan.
Herrnegger, M., Stecher, G., Schwatke, C., Olang, L., 2021. Hydroclimatic analysis of rising water levels in the great rift valley lakes of Kenya. J. Hydrol. Reg. Stud. 36, 100857.
Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., 2019. ERA5 monthly averaged data on pressure levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Accessed On.
Holleman, C., Rembold, F., Crespo, O., Conti, V., 2020. The Impact of Climate Variability and Extremes On Agriculture and Food Security-An Analysis of the Evidence and Case Studies (Report). FAO, Rome.
Hua, W., Zhou, L., Nicholson, S.E., Chen, H., Qin, M., 2019. Assessing reanalysis data for understanding rainfall climatology and variability over Central Equatorial Africa. Clim. Dyn. 53, 651–669. https://doi.org/10.1007/s00382-018-04604-0.
Jägermeyr, J., Gerten, D., Heinke, J., Schaphoff, S., Kummu, M., Lucht, W., 2015. Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrol. Earth Syst. Sci. 19, 3073–3091.
Jiang, Y., Zhou, L., Tucker, C.J., Raghavendra, A., Hua, W., Liu, Y.Y., Joiner, J., 2019. Widespread increase of boreal summer dry season length over the Congo rainforest. Nat. Clim. Change 9, 617–622. https://doi.org/10.1038/s41558-019-0512-y.
Kadoya, T., Takeuchi, Y., Shinoda, Y., Nansai, K., 2022. Shifting agriculture is the dominant driver of forest disturbance in threatened forest species' ranges. Commun. Earth Environ. 3, 108. https://doi.org/10.1038/s43247-022-00434-5.
Keys, P.W., Falkenmark, M., 2018. Green water and African sustainability. Food Secur. 10, 537–548. https://doi.org/10.1007/s12571-018-0790-7.
Keys, P.W., van der Ent, R.J., Gordon, L.J., Hoff, H., Nikoli, R., Savenije, H.H.G., 2012. Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. Biogeosciences 9, 733–746. https://doi.org/10.5194/bg-9-733-2012.
Keys, P.W., Wang-Erlandsson, L., 2018. On the social dynamics of moisture recycling. Earth Syst. Dyn. 9, 829–847. https://doi.org/10.5194/esd-9-829-2018.
Keys, P.W., Wang-Erlandsson, L., Gordon, L.J., Galaz, V., Ebbesson, J., 2017. Approaching moisture recycling governance. Glob. Environ. Change 45, 15–23. https://doi.org/10.1016/j.gloenvcha.2017.04.007.
Kim, H., Oki, T., 2015. The pilot phase of the global soil wetness project phase 3. In: Presented at the AGU Fall Meeting Abstracts, pp. GC24B–GC205.
Klein Goldewijk, K., Beusen, A., Doelman, J., Stehfest, E., 2017. Anthropogenic land use estimates for the Holocene–HYDE 3.2. Earth Syst. Sci. Data 9, 927–953.
Konrad, C.E., Perry, L.B., 2010. Relationships between tropical cyclones and heavy rainfall in the Carolina region of the USA. Int. J. Climatol. 30, 522–534.
Lange, S., Büchner, M., 2021. ISIMIP3b bias-adjusted atmospheric climate input data (v1. 1).
Lange, S., Mengel, M., Treu, S., Büchner, M., 2022. ISIMIP3a atmospheric climate input data (v1.0). ISIMIP Repository. https://doi.org/10.48364/ISIMIP.982724.
Lawrence, D., Vandecar, K., 2015. Effects of tropical deforestation on climate and agriculture. Nat. Clim. Change 5, 27–36. https://doi.org/10.1038/nclimate2430.
Li, L., Li, W., Barros, A.P., 2013. Atmospheric moisture budget and its regulation of the summer precipitation variability over the Southeastern United States. Clim. Dyn. 41, 613–631.
Lunyolo, L.D., Khalifa, M., Ribbe, L., 2020. Assessing the interaction of land cover/land use dynamics, climate extremes and food systems in Uganda. Sci. Total Environ., 142549 https://doi.org/10.1016/j.scitotenv.2020.142549.
Mahmood, R., Pielke, R.A., Hubbard, K.G., Niyogi, D., Dirmeyer, P.A., McAlpine, C., Carleton, A.M., Hale, R., Gameda, S., Beltrán-Przekurat, A., Baker, B., McNider, R., Legates, D.R., Shepherd, M., Du, J., Blanken, P.D., Frauenfeld, O.W., Nair, U.S., Fall, S., 2014. Land cover changes and their biogeophysical effects on climate: land cover changes and their biogeophysical effects on climate. Int. J. Climatol. 34, 929–953. https://doi.org/10.1002/joc.3736.
Malhi, Y., Adu-Bredu, S., Asare, R.A., Lewis, S.L., Mayaux, P., 2013. African rainforests: past, present and future. Philos. Trans. R. Soc. B 368, 20120312. https://doi.org/10.1098/rstb.2012.0312.
Mayaux, P., Pekel, J.-F., Desclée, B., Donnay, F., Lupi, A., Achard, F., Clerici, M., Bodart, C., Brink, A., Nasi, R., 2013. State and evolution of the African rainforests between 1990 and 2010. Philos. Trans. R. Soc. B 368, 20120300.
Miralles, D.G., Brutsaert, W., Dolman, A., Gash, J.H., 2020. On the use of the term "evapotranspiration''. Water Resour. Res. 56, e2020WR028055.
Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob. Biogeochem. Cycles 22, 1–19.
Nayar, A., 2009. Model predicts future deforestation. Nature. https://doi.org/10.1038/news.2009.1100.
O'Connor, J.C., Dekker, S.C., Staal, A., Tuinenburg, O.A., Rebel, K.T., Santos, M.J., 2021. Forests buffer against variations in precipitation. Glob. Change Biol. 27, 4686–4696. https://doi.org/10.1111/gcb.15763.
Odada, E.O., Olago, D.O., Bugenyi, F., Kulindwa, K., Karimumuryango, J., West, K., Ntiba, M., Wandiga, S., Aloo-Obudho, P., Achola, P., 2003. Environmental assessment of the East African Rift Valley lakes. Aquat. Sci. - Res. Bound. 65, 254–271. https://doi.org/10.1007/s00027-003-0638-9.
Oliveira, L.J.C., Costa, M.H., Soares-Filho, B.S., Coe, M.T., 2013. Large-scale expansion of agriculture in Amazonia may be a no-win scenario. Environ. Res. Lett. 8, 024021 https://doi.org/10.1088/1748-9326/8/2/024021.
Ostberg, S., Müller, C., Heinke, J., Schaphoff, S., 2023. LandInG 1.0: a toolbox to derive input datasets for terrestrial ecosystem modelling at variable resolutions from heterogeneous sources. Geosci. Model Dev. Discuss. 2023, 1–46. https://doi.org/10.5194/gmd-2022-291.
Pastor, A.V., Ludwig, F., Biemans, H., Hoff, H., Kabat, P., 2014. Accounting for environmental flow requirements in global water assessments. Hydrol. Earth Syst. Sci. 18, 5041–5059. https://doi.org/10.5194/hess-18-5041-2014.
Pendrill, F., Gardner, T.A., Meyfroidt, P., Persson, U.M., Adams, J., Azevedo, T., Bastos Lima, M.G., Baumann, M., Curtis, P.G., De Sy, V., Garrett, R., Godar, J., Goldman, E. D., Hansen, M.C., Heilmayr, R., Herold, M., Kuemmerle, T., Lathuillière, M.J., Ribeiro, V., Tyukavina, A., Weisse, M.J., West, C., 2022. Disentangling the numbers behind agriculture-driven tropical deforestation. Science 377, eabm9267. https://doi.org/10.1126/science.abm9267.
Piemontese, L., Castelli, G., Fetzer, I., Barron, J., Liniger, H., Harari, N., Bresci, E., Jaramillo, F., 2020. Estimating the global potential of water harvesting from successful case studies. Glob. Environ. Change 63, 102121. https://doi.org/10.1016/j.gloenvcha.2020.102121.
Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. Glob. Biogeochem. Cycles 24. https://doi.org/10.1029/2008GB003435.
Raleigh, C., Choi, H.J., Kniveton, D., 2015. The devil is in the details: an investigation of the relationships between conflict, food price and climate across Africa. Glob. Environ. Change 32, 187–199.
Reed, J., Deakin, L., Sunderland, T., 2015. What are 'integrated landscape approaches' and how effectively have they been implemented in the tropics: a systematic map protocol. Environ. Evid. 4, 1–7.
Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system: global water use in agriculture. Water Resour. Res. 44 https://doi.org/10.1029/2007WR006331.
Sasson, A., 2012. Food security for Africa: an urgent global challenge. Agric. Food Secur. 1 (2) https://doi.org/10.1186/2048-7010-1-2.
Savenije, H.H.G., 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. J. Hydrol. 167, 57–78. https://doi.org/10.1016/0022-1694(94)02632-L.
Savvidou, G., Atteridge, A., Omari-Motsumi, K., Trisos, C.H., 2021. Quantifying international public finance for climate change adaptation in Africa. Clim. Policy 21, 1020–1036.
Schaphoff, S., Forkel, M., Müller, C., Knauer, J., von Bloh, W., Gerten, D., Jägermeyr, J., Lucht, W., Rammig, A., Thonicke, K., Waha, K., 2018a. LPJmL4—A dynamic global vegetation model with managed land—Part 2: model evaluation. Geosci. Model Dev. 11, 1377–1403. https://doi.org/10.5194/gmd-11-1377-2018.
Schaphoff, S., von Bloh, W., Rammig, A., Thonicke, K., Biemans, H., Forkel, M., Gerten, D., Heinke, J., Jägermeyr, J., Knauer, J., Langerwisch, F., Lucht, W., Müller, C., Rolinski, S., Waha, K., 2018b. LPJmL4—A dynamic global vegetation model with managed land—Part 1: model description. Geosci. Model Dev. 11, 1343–1375. https://doi.org/10.5194/gmd-11-1343-2018.
Schlosser, C.A., Strzepek, K., Gao, X., Fant, C., Blanc, É., Paltsev, S., Jacoby, H., Reilly, J., Gueneau, A., 2014. The future of global water stress: an integrated assessment. Earths Future 2, 341–361.
Serrat-Capdevila, A., Limones, N., Marzo-Artigas, J., Marcus, W., Petrucci, B., 2022. Water Security and Drought Resilience in the South of Angola. World Bank. https://doi.org/10.1596/37189.
Shapiro, A., d'Annunzio, R., Jungers, Q., Desclée, B., Kondjo, H., Iyanga, J.M., Gangyo, F., Rambaud, P., Sonwa, D., Mertens, B., 2022. Are deforestation and degradation in the Congo Basin on the rise? An Analysis of recent trends and associated direct drivers.
Singh, C., van der Ent, R., Wang-Erlandsson, L., Fetzer, I., 2022. Hydroclimatic adaptation critical to the resilience of tropical forests. Glob. Change Biol. 28, 2930–2939.
Somorin, O.A., Brown, H.C.P., Visseren-Hamakers, I.J., Sonwa, D.J., Arts, B., Nkem, J., 2012. The Congo Basin forests in a changing climate: policy discourses on adaptation and mitigation (REDD+). Glob. Environ. Change 22, 288–298.
Spracklen, D.V., Baker, J.C.A., Garcia-Carreras, L., Marsham, J.H., 2018. The effects of tropical vegetation on rainfall. Annu. Rev. Environ. Resour. 43, 193–218. https://doi.org/10.1146/annurev-environ-102017-030136.
Staal, A., Fetzer, I., Wang-Erlandsson, L., Bosmans, J.H.C., Dekker, S.C., van Nes, E.H., Rockström, J., Tuinenburg, O.A., 2020. Hysteresis of tropical forests in the 21st century. Nat. Commun. 11, 4978. https://doi.org/10.1038/s41467-020-18728-7.
Staal, A., Tuinenburg, O.A., Bosmans, J.H.C., Holmgren, M., van Nes, E.H., Scheffer, M., Zemp, D.C., Dekker, S.C., 2018. Forest-rainfall cascades buffer against drought across the Amazon. Nat. Clim. Change 8, 539–543. https://doi.org/10.1038/s41558-018-0177-y.
Sulla-Menashe, D., Friedl, M., 2018. The Terra and Aqua Combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 Data Product. NASA EOSDIS Process DAAC.
Tarchiani, V., Rossi, F., Camacho, J., Stefanski, R., Mian, K.A., Pokperlaar, D.S., Coulibaly, H., Sitta Adamou, A., 2017. Smallholder farmers facing climate change in West Africa: decision-making between innovation and tradition. J. Innov. Econ. 24, 151. https://doi.org/10.3917/jie.pr1.0013.

Tuinenburg, O.A., Staal, A., 2020. Tracking the global flows of atmospheric moisture and associated uncertainties. Hydrol. Earth Syst. Sci. 24, 2419–2435. https://doi.org/10.5194/hess-24-2419-2020.

Tuinenburg, O.A., Theeuwen, J.J.E., Staal, A., 2020. High-resolution global atmospheric moisture connections from evaporation to precipitation. Earth Syst. Sci. Data 12, 3177–3188. https://doi.org/10.5194/essd-12-3177-2020.

van der Ent, R.J., Savenije, H.H., 2013. Oceanic sources of continental precipitation and the correlation with sea surface temperature. Water Resour. Res. 49, 3993–4004.

van der Ent, R.J., Savenije, H.H.G., Schaefli, B., Steele-Dunne, S.C., 2010. Origin and fate of atmospheric moisture over continents. Water Resour. Res. 46 https://doi.org/10.1029/2010WR009127.

Vörösmarty, C.J., 2002. Global water assessment and potential contributions from Earth systems science. Aquat. Sci. 64, 328–351.

Vörösmarty, C.J., Green, P.J., Green, P.A., Green, P.A., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288. https://doi.org/10.1126/science.289.5477.284.

Waha, K., Müller, C., Bondeau, A., Dietrich, J.P., Kurukulasuriya, P., Heinke, J., Lotze-Campen, H., 2013. Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. Glob. Environ. Change 23, 130–143. https://doi.org/10.1016/j.gloenvcha.2012.11.001.

Waha, K., van Bussel, L.G.J., Müller, C., Bondeau, A., 2012. Climate-driven simulation of global crop sowing dates: simulation of global sowing dates. Glob. Ecol. Biogeogr. 21, 247–259. https://doi.org/10.1111/j.1466-8238.2011.00678.x.

Wamucii, C.N., Van Oel, P.R., Ligtenberg, A., Gathenya, J.M., Teuling, A.J., 2021. Land use and climate change effects on water yield from East African forested water towers. Hydrol. Earth Syst. Sci. 25, 5641–5665. https://doi.org/10.5194/hess-25-5641-2021.

Wunderling, N., Wolf, F., Tuinenburg, O.A., Staal, A., 2022. Network motifs shape distinct functioning of Earth's moisture recycling hubs. Nat. Commun. 13, 6574. https://doi.org/10.1038/s41467-022-34229-1.