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## Biophysical effects of land cover changes in West Africa: a systematic review

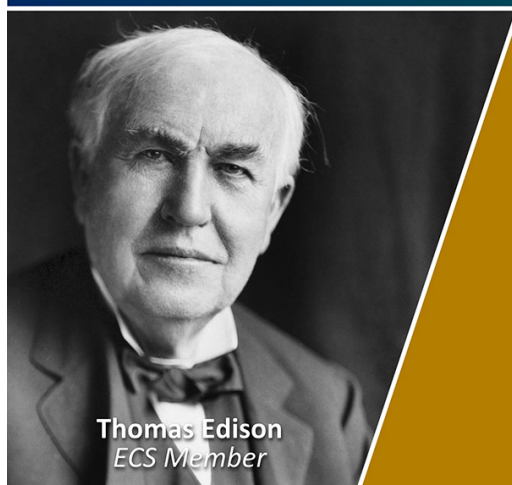
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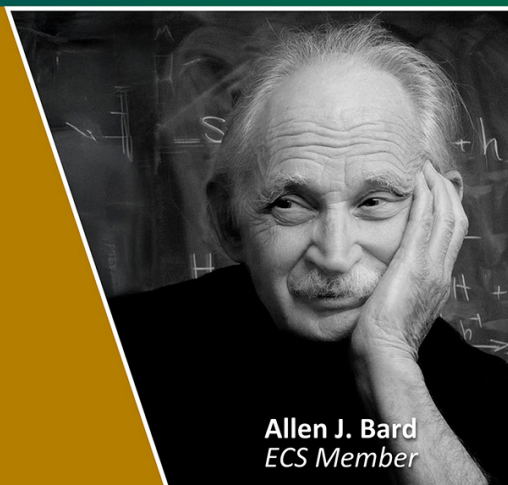
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## TOPICAL REVIEW

Biophysical effects of land cover changes in West Africa:  
a systematic review

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**Keywords:** land use, land cover change, deforestation, afforestation, climate modeling, PRISMA, West Africa

Supplementary material for this article is available [online](#)

**Abstract**

West Africa is undergoing rapid agricultural intensification driven by population growth, leading to significant anthropogenic land use and land cover change (LCC), including both deforestation and afforestation. These changes can profoundly affect the regional climate system by altering the surface energy balance, moisture fluxes, and atmospheric circulation, potentially exacerbating the vulnerability of human, ecological, and economic systems. Despite the ability of climate models to simulate LCC impacts, considerable uncertainties remain, particularly in simulations of precipitation and temperature responses. This study provides the first multidisciplinary systematic review of LCC impacts in West Africa. Data from 26 selected publications were eventually synthesized from an initial pool of nearly 6000 studies. Results indicate that deforestation generally contributes to regional warming, with significant historical temperature increases of  $+0.26 \pm 0.12$  °C and projected increases of  $+0.88 \pm 0.25$  °C under the future scenarios. Conversely, afforestation could have significantly cooled the climate, lowering temperatures by  $-0.24 \pm 0.14$  °C historically and  $-0.22 \pm 0.14$  °C in future scenarios, without even accounting for carbon sequestration. Deforestation decreases regional precipitation by  $80 \pm 58$  mm yr<sup>-1</sup> historically and  $-55 \pm 102$  mm yr<sup>-1</sup> in future scenarios, while large-scale afforestation could substantially reduce droughts with increased precipitation, averaging  $+40 \pm 67$  mm yr<sup>-1</sup> historically and  $80 \pm 58$  mm yr<sup>-1</sup> in future scenarios. These results emphasize the need to integrate LCC-induced climate effects into land-based mitigation strategies, climate policy, and assessment frameworks.

## 1. Introduction

West Africa is experiencing rapid population growth associated with significant agricultural intensification (Van Bavel 2013, Bliefernicht *et al* 2018, Iyakaremye *et al* 2021a, Potapov *et al* 2022). Those anthropogenic land use and land-cover change (LCC) can have a significant impact on local, regional, and global climates by mainly altering atmospheric dynamics through two distinct processes: modifications in the net flux of greenhouse gases, such as CO<sub>2</sub>, resulting from changes in vegetation and soil carbon (biogeochemical effects); and variations in the surface energy budget mediated by albedo, evapotranspiration, and surface roughness (biophysical effects) (Bonan 2008, Bathiany *et al* 2010, Mahmood *et al* 2014, Perugini *et al* 2017, Guug *et al* 2025).

LCC can also influence hydrology to an extent comparable to climate change at the regional scale (e.g. Araza *et al* 2021, Kayitesi *et al* 2022). However, its quantification remains limited, with potentially large uncertainties. Understanding LCC impacts and land-atmosphere interactions is crucial to assessing future climate changes (Wulfmeyer *et al* 2014, Harper *et al* 2018, Duveiller *et al* 2020, Roe *et al* 2021). In other words, enhanced representation of both the spatial and temporal dimensions of LCC is essential for a deeper understanding of human impact on the natural environment and climate (Roy *et al* 2015). To address these issues, Earth System Models (ESMs) and their land modeling components, such as dynamic global vegetation models, are used tools for global/regional scale analyses of LCC effects on climate (De Noblet-Ducoudré *et al* 2012, Sy *et al* 2017). These assessments are typically based on comparing simulations with and without LCC (Bonan 2008, Pitman *et al* 2009, Boisier *et al* 2012, De Noblet-Ducoudré *et al* 2012, Sy *et al* 2017, Sy and Quesada 2020). However, large uncertainties typically hinder this modeling approach in the numerical results due to the simplified process description (De Noblet-Ducoudré *et al* 2012, Rounsevell *et al* 2014, Lejeune *et al* 2017, Sy *et al* 2017, Davin *et al* 2020, Glotfelty *et al* 2021). For instance, the influence of LCC on precipitation in these numerical experiments remains highly uncertain due to the presence of low signal-to-noise ratios (Laux *et al* 2017).

For regions with extensive LCC, many studies have reported biophysical decreases in annual mean temperature of a magnitude similar to the concomitant increase in GHGs (Boisier *et al* 2012, De Noblet-Ducoudré *et al* 2012, Sy *et al* 2017). However, considerable disagreement remains in model results when simulating precipitation and temperature responses to LCC (Pitman *et al* 2009, De Noblet-Ducoudré *et al* 2012, Sy *et al* 2017, Sy and Quesada 2020, Glotfelty *et al* 2021). This is particularly true in West Africa,

where research is often based on simulations with coarse resolution (e.g. Boone *et al* 2016, Sy *et al* 2017, Glotfelty *et al* 2021, Smiatek and Kunstmann 2023) and/or limited to a single climate model (e.g. Diba *et al* 2018, Camara *et al* 2022). Model uncertainties could be partly alleviated by improving the realism of the physically interconnected processes at the surface-atmosphere interface and a better description of these processes in state-of-the-art land surface models (De Noblet-Ducoudré *et al* 2012, Boone *et al* 2016, Sy *et al* 2017, Glotfelty *et al* 2021). The debates on the uncertainties related to the sign and the magnitude of the net effects of LCC on local/regional climate in model responses are ongoing and have been addressed in several papers (Pitman *et al* 2009, 2012, Avila *et al* 2012, Christidis *et al* 2013, Mahmood *et al* 2014, Findell *et al* 2017, Perugini *et al* 2017, Quesada *et al* 2017, Sy *et al* 2017, Lejeune *et al* 2018, Li Qiuping *et al* 2018, Chen and Dirmeyer 2019, Sy and Quesada 2020, Glotfelty *et al* 2021). Furthermore, the net effects of LCC on local/regional climate mainly depend on the type of LCC, its intensity, and local climate conditions (Mahmood *et al* 2014, Perugini *et al* 2017).

For instance, deforestation in tropical regions leads to a net global warming effect due to reduced evapotranspiration, which outweighs the cooling effect caused by a higher albedo (Perugini *et al* 2017). Conversely, at higher latitudes, the impact of deforestation is reversed, resulting in a net cooling effect due to the increased presence of high-albedo snow resulting from the conversion of tall vegetation to cropland/grassland or rapid urbanization (Mahmood *et al* 2014, Perugini *et al* 2017). The magnitude of the impact of deforestation depends on the spatial scale of the change. It also depends on the type of removed natural vegetation (Sy *et al* 2017). Consequently, numerous studies have recommended caution when attributing and assessing the effects of historical and future LCC due to the lack of a comprehensive, systematic assessment and limited agreement among model results (Pitman *et al* 2009, Pielke *et al* 2011, IPCC-SREX 2012, Mahmood *et al* 2014, Perugini *et al* 2017, Quesada *et al* 2017, Spracklen *et al* 2018, IPCC-SRCL 2019, Sy and Quesada 2020).

Moreover, West Africa is a region particularly vulnerable to socio-economic, climatic and land use threats: (i) since the decade of the 80s, regional heatwaves have become hotter, longer and more widespread, and increasing trends in extreme heavy precipitation and droughts have been observed (Trisos *et al* 2022); (ii) West Africa is considered as a worldwide hotspot of land-atmosphere interactions (Koster *et al* 2004), with increasing population density (Iyakaremye *et al* 2021b), high water stress and land degradation (Sylla *et al* 2015); (iii) land cover dynamics are huge: the area of human-dominated

land cover categories more than doubled in 40 years (Herrmann *et al* 2020), (iv) rain-fed agriculture is the main source of employment and income, but maize and wheat yields as well as agricultural productivity growth have decreased in the last decades mainly in response to climate change (Trisos *et al* 2022, Arfasa *et al* 2024, Waongo *et al* 2024); (v) irrigation demand in West Africa is expected to triple by 2050, a matter largely modulated by climate and LCC (Arfasa *et al* 2024), (vi) under the SSP2-4.5 and SSP5-8.5 future scenarios, Iyakaremye *et al* (2021a) indicate that temperature extremes are expected to intensify in Africa, with projected increases ranging from 0.25 °C to 1.8 °C under SSP2-4.5 and from 0.6 °C to 4 °C under SSP5-8.5. West Africa is identified as one of the regions projected to warm faster than the other regions, with large precipitation uncertainties driven in particular by different land-atmosphere interaction representations (Sylla *et al* 2016b, Sy *et al* 2017, Sy and Quesada 2020, Trisos *et al* 2022). Moreover, several studies have also already advocated for a more comprehensive assessment of the impact of LCC in the West Africa (Abiodun *et al* 2008, Sy *et al* 2017, 2024, Achugbu *et al* 2023, Mwanthi *et al* 2023, Smiatek and Kunstmann 2023, Ingrosso and Pausata 2024). These studies agree that the full scope of regional/local climate impacts of anthropogenic LCC remains challenging due to the high level of uncertainties surrounding quantifying these impacts, making it difficult to provide a clear message that can be effectively utilized in developing regional/local climate mitigation and adaptation strategies.

In the context of global warming mitigation, afforestation has been widely proposed as a key land-based strategy (Cook-Patton *et al* 2020, Doelman *et al* 2020, Duveiller *et al* 2020, Palmer 2021). In West Africa, large-scale initiatives such as the Great Green Wall have been launched to address climate change and land degradation (Smiatek and Kunstmann 2023, Ingrosso and Pausata 2024). This ambitious project aims to restore approximately 100 million hectares of forest by 2030 (UNCCD 2024). However, climate change mitigation policies, including reducing emissions from deforestation and forest degradation (REDD+), primarily focus on biogeochemical mechanisms like carbon sequestration, often overlooking the biophysical effects of afforestation. While biogeochemical processes are well integrated into global climate policies such as the Paris Agreement, biophysical effects—such as changes in surface albedo, evapotranspiration, and energy fluxes—are frequently neglected despite their significant regional impacts (Mahmood *et al* 2014, Perugini *et al* 2017, Sy *et al* 2017, Spracklen *et al* 2018, Duveiller *et al* 2020, Sy and Quesada 2020). Although climate models have significantly advanced

our understanding of the potential impacts of afforestation on local and regional climates (Bonan 2008, Perugini *et al* 2017), debates persist regarding the net climatic effects of afforestation (Perugini *et al* 2017, Duveiller *et al* 2018a, Breil *et al* 2021, Arnault *et al* 2023, Ingrosso and Pausata 2024). The biophysical effects of afforestation, for instance, can either enhance or counteract the cooling effects associated with carbon sequestration (Bala *et al* 2007, Pongratz *et al* 2010, Arora and Montenegro 2011, Windisch *et al* 2021). Specifically, afforestation may induce radiative surface warming due to the lower albedo of forested areas, while non-radiative cooling effects could arise from increased heat dissipation and enhanced evapotranspiration (Bonan 2008, Duveiller *et al* 2018b).

Here, using a multidisciplinary systematic review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol (Moher *et al* 2009) (see methods), this study provides a comprehensive analysis of the global literature on the regional biophysical impacts of LCC in West Africa to establish robust messages and associated uncertainties. This review stands apart from previous studies (Mahmood *et al* 2014, Perugini *et al* 2017) by strictly adhering to PRISMA eligibility criteria (Enu *et al* 2023), encompassing peer-reviewed scientific articles, books, and book chapters published from 1975 to 2023. Notably, this review examines historical and future model-based simulation results on the effects of LCC in West Africa. It also aims to provide policymakers with the critical evidence needed to assess the importance of the biophysical impacts of LCC, which are frequently overlooked despite their substantial regional/local effects (Mahmood *et al* 2014, Perugini *et al* 2017, Spracklen *et al* 2018, Duveiller *et al* 2020).

## 2. Data and methods

### 2.1. Search and selection strategy

The eligibility criteria outlined in the PRISMA guidelines were employed to systematically review the peer-reviewed literature on LCC biophysical impacts over West Africa. It is worth noting that West Africa was chosen due to its tropical location and ongoing agricultural intensification (Bliefernicht *et al* 2018, Potapov *et al* 2022), highlighting the potential benefits of afforestation policies within climate-smart agriculture (Rosenstock *et al* 2016). PRISMA was primarily designed for systematic reviews of studies evaluating the effects of health interventions (Moher *et al* 2009). Nevertheless, it remains widely utilized as a systematic review method in climate impact studies (e.g. Harper *et al* 2021, Carr *et al* 2022, Mensah *et al* 2022, Fiorenza *et al* 2023, Petersson-Bloom *et al* 2023).

As a preliminary step, the systematic review was conducted to select peer-reviewed scientific articles, books, and book chapters that specifically examine changes in surface air temperature and precipitation resulting from explicit LCC transition scenarios in West Africa and were published between 1 January 1975, and 30 April 2023. To achieve this, a variety of specific keywords, synonyms, search phrases, and strategies are employed tailored to each database/portal (e.g. Web of Science, Scopus, Google Scholar, and the WASCAL library; see table S3) to identify relevant studies focusing on biophysical LCC (deforestation and afforestation) impact on regional climate in West Africa. Due to the sensitivity of search engines and portals to the order of search keywords, a range of keywords for each database source was also utilized (see table S3).

## 2.2. Selection criteria and data extraction

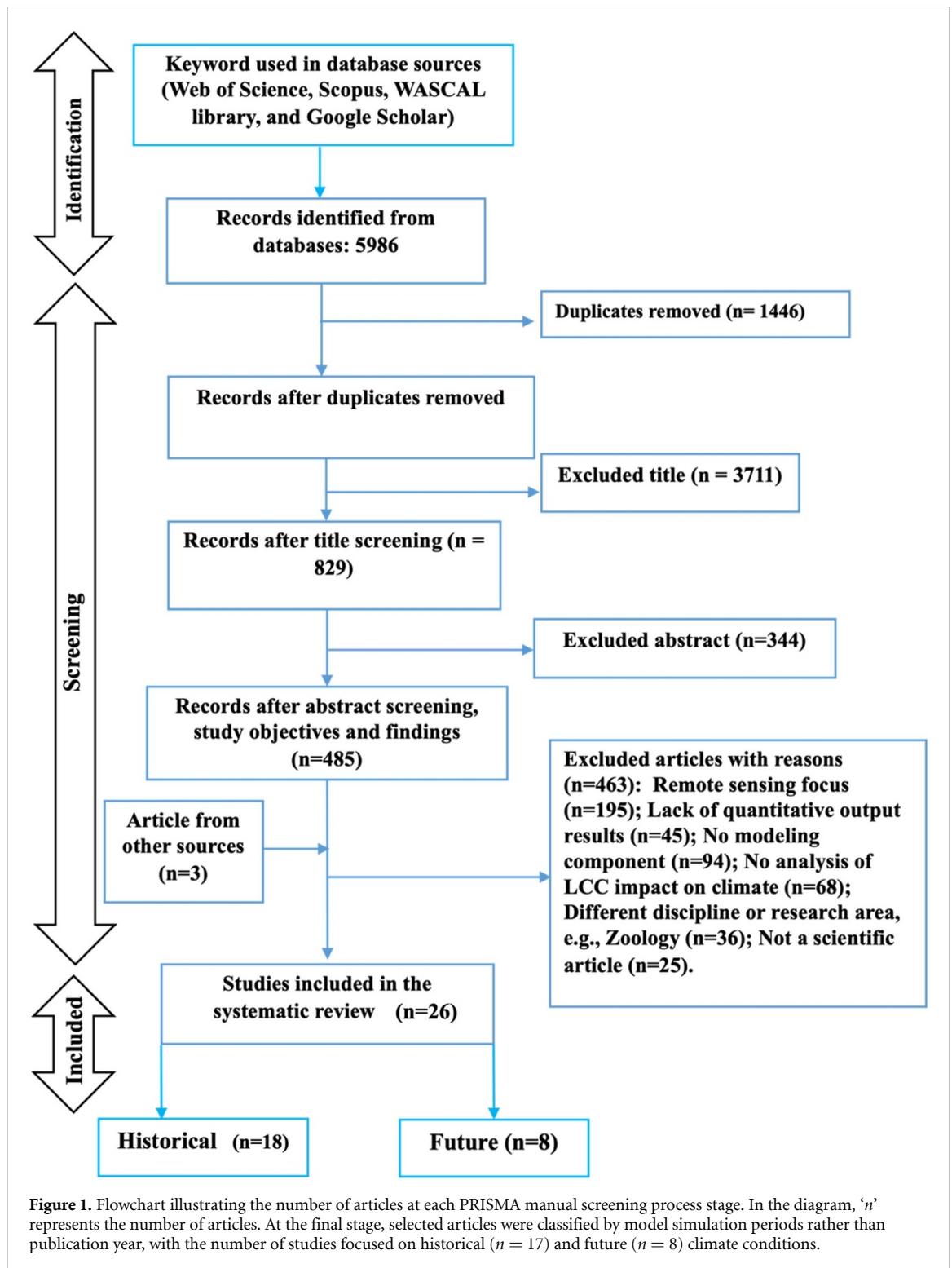
This study focuses on evidence from studies utilizing LCC model-based outputs at regional or country scales in West Africa. However, we have included the values provided for each region in the overall average for studies such as Smiatek and Kunstmann (2023), which cover the entire Sahel divided into three distinct regions. This approach ensures a comprehensive representation of data relevant to West Africa. Nevertheless, we acknowledge certain limitations arising from the lack of standardized definitions for the West African region in ESMs, as highlighted in previous studies (Boone *et al* 2016, Sy *et al* 2017, Sy and Quesada 2020, Glotfelty *et al* 2021, Achugbu *et al* 2023, Mwanthi *et al* 2023). While eddy-covariance flux towers and field experiments can provide local-scale insights into LCC effects (Bliefernicht *et al* 2018), they were excluded from this study due to their limited representativeness at the regional scale. Additionally, the reviewed literature includes only LCC-modeling-based articles because of data scarcity, limited *in-situ* measurements, and regional observation/satellite-driven assessments in this area. Moreover, this systematic review focused its primary emphasis on surface air temperature and precipitation variables for two significant reasons: (i) they constitute the primary variables of interest for policymakers at both local and regional levels, and (ii) they result as comprehensive indicators of biophysical influences on climate due to their responses to both biophysical radiative and non-radiative effects (Duveiller *et al* 2020, Sy *et al* 2024). We also focused on modifications of the main biophysical characteristics of the land surface, such as changes in leaf area index (LAI) and surface albedo, which ultimately result in changes in energy, moisture, and momentum fluxes (Davin and Noblet-Ducoudre', 2010, De Noblet-Ducoudré *et al* 2012, Sy *et al* 2017). An overview of all inclusion and exclusion criteria used for each study is provided in

table S1 and figure 1. The selection criteria primarily emphasize studies published in English and cited papers specifically within West Africa. The title and abstract were assessed to determine their relevance to our objectives. Subsequently, we thoroughly reviewed the full papers to extract all quantitative model output results, model types, considered study area, simulation period, published year, and LCC scenarios (see tables 1 and S2 for more details).

## 2.3. Data screening

Different combinations of search keywords relevant to LCC model-based studies (refer to table S3) were utilized in the search process. Duplicate articles were removed, and only peer-reviewed and cited English-language articles were included. The systematic review process followed a structured approach for both inclusion and exclusion of articles, as illustrated in figure 1. The initial database search yielded nearly 6000 articles ( $n = 5986$ ). After conducting eligibility screening based on title, research area, and abstract, the number of articles was reduced to 485. Subsequently, some papers were excluded for reasons of unscientific articles or reviews or lack of quantitative data on LCC impact and/or not a model-based study in West Africa. In the final step, a total of 26 articles remained, from which the values presented in this paper were systematically extracted. These values were obtained through a careful, step-by-step review of the selected studies directly from the main text, tables, or supplementary materials. This rigorous approach ensured the accuracy and reliability of the data used in our analysis. To ensure impartiality, these processes were repeated three times (see figure 1, tables S1 and S3). Additionally, as shown in table S2, out of the initial 26 articles that passed the data screening and selection criteria, 22 provided model results on changes in surface air temperature, 25 on precipitation, 12 on surface albedo, and 4 on LAI. It is worth noting that among the selected articles, some have investigated the biophysical effects of LCC using a single model (e.g. Wang *et al* 2015, Achugbu *et al* 2023), while others employed multi-model ensemble simulations (e.g. 5 global climate models (GCMs) for Boone *et al* 2016; 4 RCMs for Glotfelty *et al* 2021; and 7 GCMs for, Sy *et al* 2017), which allow us further to discuss the uncertainties and the various mechanisms at play.

Furthermore, modeling studies were categorized under different explicit LCC scenarios. Specifically, model results were classified into two primary LCC categories: (i) deforestation scenarios (referred to as 'Deforestation'), where total or partial fractions of forest cover are removed or replaced with another land cover type (see Charney 1975, Zheng and Eltahir 1997, Abiodun *et al* 2008, Wang *et al* 2015, Boone *et al* 2016, Sy *et al* 2017, Ji *et al* 2015, Chilukoti and Xue 2020, Sy and Quesada 2020, Glotfelty *et al* 2021, Duku and Hein 2021, Obahoundje *et al* 2021,



Idrissou *et al* 2022, Achugbu *et al* 2023, Crook *et al* 2023, Mortey *et al* 2023); (ii) afforestation scenarios (referred to as 'Afforestation'), where grassland and/or cropland areas are partially or fully replaced by forest (see Abiodun *et al* 2012a, Sylla *et al* 2015, Diba *et al* 2016, Diasso and Abiodun 2017, Noulèkoun *et al* 2018, Odoulami *et al* 2018, Achugbu *et al* 2021, Smiatek and Kunstmann 2023), as detailed in table 1.

In terms of seasonal variation, most studies conducted in West Africa have predominantly focused on the West African Monsoon (WAM) season, with limited attention given to other seasons (see table 1). However, there is a notable lack of standardized definitions of seasonal periods across studies (see table 1). For example, the WAM season has been variably defined as June–July–August (JJA), June–July–August–September (JJAS),

**Table 1.** Summary of the characteristics of the papers included in this study.  $\Delta T$ ,  $\Delta P$ ,  $\Delta$ Albedo, and  $\Delta$ LAI represent changes in surface air temperature, precipitation, surface albedo, and leaf area index, respectively, in response to different LCC scenarios. The selected studies are systematically categorized based on key model parameterization configurations: (i) models with dynamic vegetation representation versus those without, (ii) models employing parameterized convection schemes versus convection-permitting approaches, and (iii) models using idealized versus realistic LCC scenarios.

Papers	Variables	Impact scale	Climate models	Vegetation models	Simulation periods and scenarios	Seasonal/annual	Dynamic Vegetation	Parametrized convection (PC) or convection-permitting (CP)	Idealized (ID) or realistic (RE)	LCC scenarios: Deforestation (DEF), Afforestation (AFF)
Glotfelty <i>et al</i> (2021)	$\Delta T$ , $\Delta P$ , $\Delta$ Alb	West Africa	WRF	Noah, Noah-MP, CLM-D, CLM-AF	2010–2015	Annual	No	PC	RE	DEF, AFF
Abiodun <i>et al</i> (2008)	$\Delta T$ , $\Delta P$ , $\Delta$ Alb	West Africa	RegCM3	BATS	1981–1990	Annual	No	PC	ID	DEF
Wang <i>et al</i> (2015)	$\Delta T$ , $\Delta P$ , $\Delta$ Alb, $\Delta$ LAI	West Africa	RegCM4.1, UCLA, CAM5	CLM4	2001–2006	AM, JJAS	No	PC	ID	DEF
Achugbu <i>et al</i> (2021)	$\Delta T$ , $\Delta P$	West Africa	WRF3.9.1.1	Noah-MP	2012	Annual	No	PC	ID	DEF, AFF
Boone <i>et al</i> (2016)	$\Delta T$ , $\Delta P$ , $\Delta$ Alb, $\Delta$ LAI	West Africa	UCLA-AGCM, UCLA-GFS, UCONN CAM5, GSFC GOES-5, UKMO HadGEM 2-A	SSIB-1, CLM 3.5, CLSM, MOSES	1952–1957	JAS	No	PC	ID	DEF
Achugbu <i>et al</i> (2023)	$\Delta T$ , $\Delta P$ , $\Delta$ Alb	West Africa	WRF3.9.1.1	Noah-MP	2011–2012	DJF, JAS	No	PC	ID	DEF

(Continued.)

Table 1. (Continued.)

Papers	Variables	Impact scale	Climate models	Vegetation models	Simulation periods and scenarios	Seasonal/annual	Dynamic Vegetation	Parametrized convection (PC) or convection-permitting (CP)	Idealized (ID) or realistic (RE)	LCC scenarios: Deforestation (DEF), Afforestation (AFF)
Sy et al (2017)	$\Delta T, \Delta P, \Delta \text{Alb}, \Delta \text{LAI}$	West Africa	ARPEGE, CCAM, CCSM, ECEARTH-, ECHAM5, IPSL, SPEEDY	ISBA, CABLE, CLM, TESSEL, JSBACH, ORCHIDEE, LPJmL	1970–1999	Annual	No	PC	RE	DEF
Abiodun et al (2012a)	$\Delta T, \Delta P, \Delta \text{Alb}$	West Africa	RegCM3	BATS	2030–2050 based on A1B scenario	MAM, JJA	No	PC	ID	AFF
Odoulami et al (2018)	$\Delta P, \Delta \text{Alb}$	West Africa	RegCM 4.3 and WRF	BATS and Noah LSM	2031–2060 under RCP4.5 scenario	Annual	No	PC	ID	AFF
(Abiodun et al (2012b)	$\Delta T, \Delta P$	Nigeria	RegCM3	BATS	2031–2050 under A1B scenario	MJJ, JAS	No	PC	ID	AFF
Zheng and Eltahir (1997)	$\Delta T, \Delta P$	West Africa	Zonally-symmetric model		1950–1969	Annual	No	PC	ID	DEF
Diasso and Abiodun (2017)	$\Delta T, \Delta P$	West Africa	RegCM4 and WRF3.5.1	BATS1E and MPI-ESM-LR	2031–2060 under RCP4.5 scenario	JAS	No	PC	ID	AFF
Diba et al (2018)	$\Delta T, \Delta P$	West Africa	RegCM4.5	BATS1E	1990–2009	JJAS	No	PC	ID	AFF
Oguntunde et al (2012)	$\Delta T, \Delta P$	West Africa	RegCM3	BATS	2031–2050 under A1B scenario	JFM, AMJ, JAS, OND	No	PC	ID	AFF
Diba et al (2016)	$\Delta T, \Delta P$	West Africa	RegCM4	BATS1E	2003–2009	JJAS	No	PC	ID	AFF

(Continued.)

Table 1. (Continued.)

Papers	Variables	Impact scale	Climate models	Vegetation models	Simulation periods and scenarios	Seasonal/annual	Dynamic Vegetation	Parametrized convection (PC) or convection-permitting (CP)	Idealized (ID) or realistic (RE)	LCC scenarios: Deforestation (DEF), Afforestation (AFF)
Ji <i>et al</i> (2015)	$\Delta T, \Delta P$	West Africa	RegCM4.3.4	CLM4.5	2081–2099 Under RCP8.5 scenario	Annual	No	PC	ID	DEF
Bamba <i>et al</i> (2019)	$\Delta T, \Delta P$	West Africa	RegCM4.7	BATS	2000–2011	JJAS	No	PC	ID	AFF
Charney (1975)	$\Delta P, \Delta \text{Alb}$	West Africa	Hadley circulation		1973	JA	No	PC	ID	DEF
Sylla <i>et al</i> (2015)	$\Delta T, \Delta P$	West Africa	RegCM4.3	CLM3.5	1998–2010	DJE, JJA	No	PC	RE	DEF
Chilukoti and Xue (2020)	$\Delta T, \Delta P, \Delta \text{Alb}, \Delta \text{LAI}$	West Africa	GFS	SSiB2	1948–2010	JJA, DJF	No	PC	RE	DEF
Mortey <i>et al</i> (2023)	$\Delta T, \Delta P$	West Africa	GLEAM	ESA CCI LC	1992–2019	Annual	No	PC	RE	DEF
Sy and Quesada (2020)	$\Delta T, \Delta P$	West Africa	CanESM2, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM-LR, MIROC-ESM	CTEM, JULES, ORCHIDEE, SEIB-DGVM, JSBACH	2071–2100 under RCP8.5 and RCP2.6 scenarios	Annual	Yes/No	PC	RE	DEF
(Smiatek and Kunstmann (2023)	$\Delta T, \Delta P$	West Africa	MPAS7	Noah LSM	1997–2012	JJAS	No	PC	ID	AFF
Crook <i>et al</i> (2023)	$\Delta T, \Delta P, \Delta \text{Alb}$	West Africa	MetUM	JULES	2014	June	No	CP	RE	DEF
Duku and Hein (2021)	$\Delta P$	West Africa		ConvLSTM	2000–2012	JJA	No	PC	ID	DEF
Saley <i>et al</i> (2019)	$\Delta T$	West Africa	RegCM4	BAST	1988–2012	JJA	No	PC	ID	AFF

or July–August–September (JAS) (see table 1). These discrepancies in seasonal delineation can lead to variations in the estimated magnitude of LCC-induced climate signals. In other words, such inconsistencies may affect the accuracy and comparability of findings related to the seasonal biophysical effects of LCC and may contribute to divergent reports of temperature and precipitation responses.

In table 1, modeling studies have been systematically categorized based on different explicit parameterization configurations. The classification was structured according to the following key criteria: (i) dynamic vegetation representation, distinguishing models that incorporate dynamic vegetation processes from those that do not; (ii) convection schemes, contrasting models that use parameterized convection (PC) schemes with those that use convection-permitting (CP) approaches; and (iii) LCC scenarios, grouping studies based on whether they used idealized (e.g. where the total or partial fractions of the forest cover are removed or replaced with another land-cover category) or ‘realistic’ LCC scenarios. This categorization provides a clear framework for comparing methodological approaches and their implications in the modeling studies.

Furthermore, among the 26 selected papers, most studies conducted in West Africa do not include vegetation as a dynamic component (table 1). Instead, the seasonal evolution of the LAI is generally prescribed using remote sensing products, with monthly LAI values typically held constant across years (Boone *et al* 2016, Sy *et al* 2017, Glotfelty *et al* 2021). Notably, only one study (see, Sy and Quesada 2020) included models with dynamic vegetation capabilities (table 2), showing that the deforestation signal is generally more pronounced when dynamic vegetation processes are enabled. This limited representation is largely due to the relatively recent development of dynamic vegetation models, which are more commonly integrated into GCMs (Quillet *et al* 2010, Sy and Quesada 2020). Dynamic vegetation models improve the representation of land–atmosphere interactions by allowing vegetation to respond dynamically to climatic changes, thereby improving the accuracy of LCC impact estimates (Westermann *et al* 2024).

Regarding convection schemes, table 1 shows that most studies used PC schemes, with only one study using a CP approach (see, Crook *et al* 2023) to assess deforestation impacts. Regarding the LCC scenarios, most studies were based on idealized scenarios, typically involving more drastic deforestation or afforestation, while six of the 26 studies used ‘realistic’ scenarios (table 1). Concerning the future scenarios, among the seven studies focusing on projected climate changes, three considered the A1B scenario from the Fourth Assessment Report (AR4) (Abiodun *et al* 2012a, 2012b, Oguntunde *et al* 2012), while four studies employed Representative Concentration

Pathways (one study used RCP2.6, two used RCP4.5, and one used RCP8.5) to assess the effects of future LCC (Ji *et al* 2015, Diasso and Abiodun 2017, Odoulami *et al* 2018, Sy and Quesada 2020), although with different simulation periods.

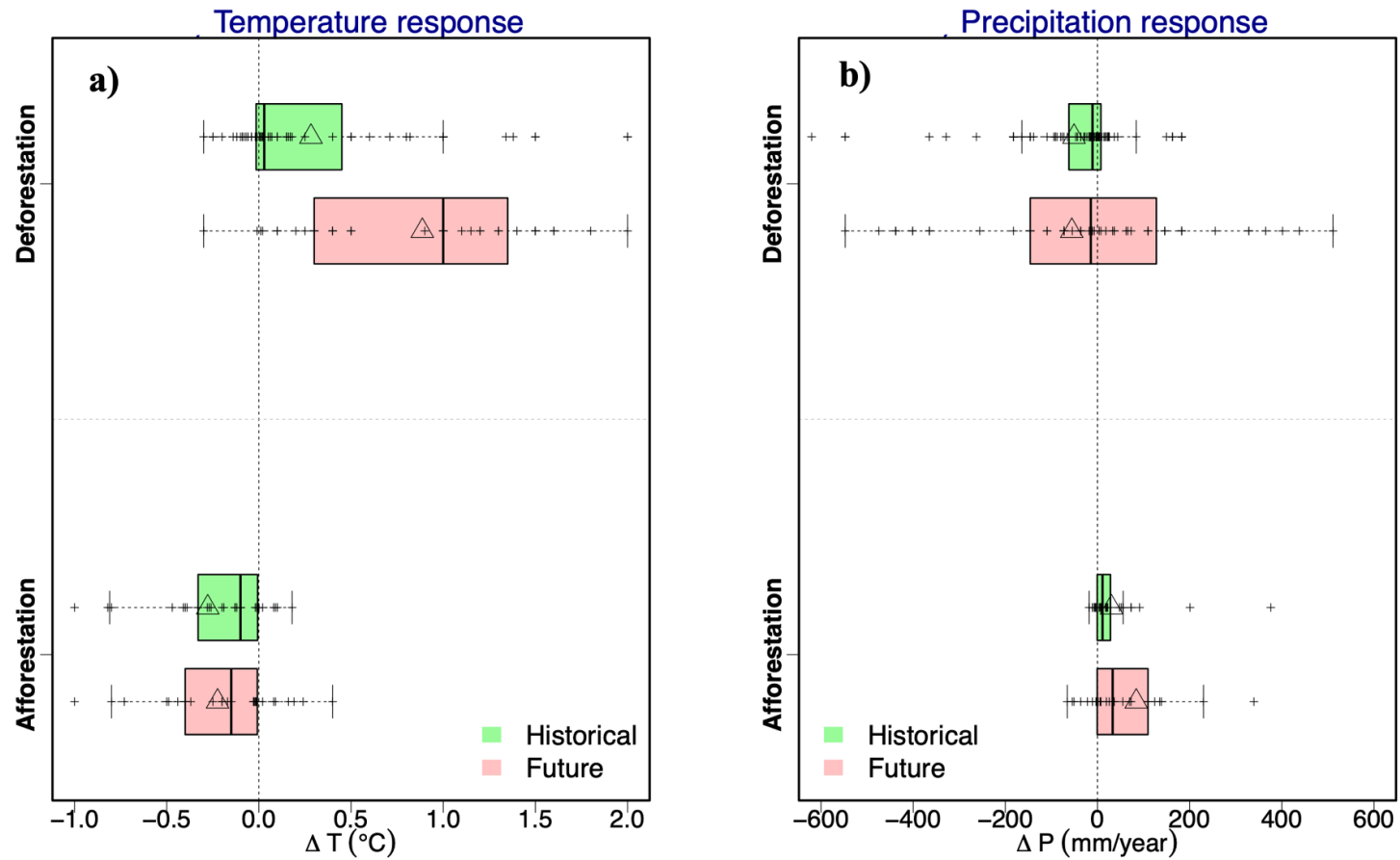
### 3. Review results and discussion

#### 3.1. Model-based LCC studies in West Africa

Among the 26 papers considered, the majority were published after 2017, with the earliest study identified being Charney (1975) (see table 1 and figure S2). Approximately 60% of these publications were published in the last six years, indicating a growing focus on LCC’s regional and local biophysical impacts in West Africa. Several factors likely contribute to this increased interest: (i) West Africa is particularly vulnerable to climate impacts due to its high exposure and limited adaptive capacity (Barros *et al* 2014), and has experienced significant multidecadal rainfall variability and severe droughts, particularly in the 1970s and 1980s (Nicholson 2013, Masih *et al* 2014). Additionally, since the mid-1970s, mean annual and seasonal temperatures have increased by 1 °C–3 °C, with the largest increases observed in the Sahara and Sahel regions (Cook and Vizy 2015, Lelieveld *et al* 2016, Trisos *et al* 2022); (ii) the region also faces critical land-use challenges, such as deforestation, overgrazing, and land degradation due to agricultural expansion and urbanization, which have significantly altered the landscape (Boone *et al* 2016, Sy *et al* 2017, Bliefernicht *et al* 2018, Potapov *et al* 2022). These changes strongly influence land–atmosphere interactions, intensifying climate extremes and altering local and regional climate systems (Russo *et al* 2016, Barry *et al* 2018, Sy and Quesada 2020); (iii) since Charney’s (1975) seminal work on the link between desertification and drought in the Sahel, West Africa has been at the center of discussions on the biophysical impacts of deforestation and desertification (Zheng and Eltahir 1997, Fuller and Ottke 2002); (iv) the population of the region has almost doubled in the last 50 years and is expected to double again by mid-century, leading to increasing pressure on land resources and accelerating land-use change (Van Bavel 2013, Sy *et al* 2017).

#### 3.2. Simulated temperature responses

Surface air temperature responses to LCC scenarios of afforestation and deforestation over the simulation periods are summarized in figure 2(a) and table 2. Boxplots display the temperature responses from individual models (represented by different cross symbols), while the triangle represents the multi-model ensemble mean (i.e. the average result from all models). On average, deforestation scenarios lead to regional warming, with simulated values of  $+0.26 \pm 0.12$  °C during the historical period and  $+0.88 \pm 0.25$  °C in future scenarios (95% confidence interval). In contrast, afforestation produces a cooling



**Figure 2.** Biophysical effects of LCC (deforestation and afforestation scenarios) on surface air temperature ( $^{\circ}\text{C}$ ) (a) and precipitation ( $\text{mm yr}^{-1}$ ) (b). The boxplots show the distribution of individual model temperature and precipitation responses to LCC scenarios. The triangle indicates the multi-model ensemble mean (i.e. the average of results from different individual model), while each cross represents the response of a single model. The median of the multi-model ensemble is marked with a black line; the lower hinge of each box represents the first quartile (Q1, 25th percentile), and the upper hinge represents the third quartile (Q3). The bars indicate the maximum and minimum values, with individual model responses beyond the whiskers plotted as black circles. Green and red boxplots represent model responses over different simulation periods (historical and future).

**Table 2.** Regional averages of surface air temperature ( $^{\circ}\text{C}$ ) and precipitation ( $\text{mm yr}^{-1}$ ) responses under different land cover change (LCC) scenarios based on model outputs. The table shows the regional average, 95% Confidence Interval (95% CI), and maximum and minimum responses calculated from different individual model simulations. The regional mean significance at the 0.05 level was calculated using the rank-based non-parametric Mann–Whitney–Wilcoxon (MWW) test.

Temperature response ( $^{\circ}\text{C}$ )							
Period	LCC scenarios	Mean	(95% CI)	<i>p</i> -value	Max	Min	Entries
Historical	Deforestation	0.26	0.12	<0.05	2	−0.3	14 <sup>1,3–7,11,18,19,20,23,25</sup>
	Afforestation	−0.24	0.14	<0.05	0.18	−3	6 <sup>1,4,13,14,16,22</sup>
Future	Deforestation	0.88	0.25	<0.05	3.4	−0.3	4 <sup>2,15,21</sup>
	Afforestation	−0.22	0.14	<0.05	0.4	−1.48	3 <sup>8,10,12</sup>
Precipitation response ( $\text{mm d}^{-1}$ )							
Historical	Deforestation	−0.13	0.08	<0.05	0.5	−2.5	16 <sup>1,3–7,11,17–20,23,24</sup>
	Afforestation	0.10	0.18	<0.05	4.1	−0.05	6 <sup>1,4,13,14,16,22</sup>
Future	Deforestation	−0.15	0.28	>0.05	2.1	−5	4 <sup>2,15,21</sup>
	Afforestation	0.22	0.16	<0.05	1.8	−0.18	4 <sup>8,9,10,12</sup>

<sup>1</sup>Glotfelty *et al* (2021); <sup>2</sup>Abiodun *et al* (2008); <sup>3</sup>Wang *et al* (2015); <sup>4</sup>Achugbu *et al* (2021); <sup>5</sup>Boone *et al* (2016); <sup>6</sup>Achugbu *et al* (2023); <sup>7</sup>Sy *et al* (2017); <sup>8</sup>Oguntunde *et al* (2012); <sup>9</sup>Odoulami *et al* (2018); <sup>10</sup>Abiodun *et al* (2012a); <sup>11</sup>Zheng and Eltahir (1997); <sup>12</sup>Diaso and Abiodun (2017); <sup>13</sup>(Diba *et al* (2018); <sup>14</sup>Diba *et al* (2016); <sup>15</sup>Ji *et al* (2015); <sup>16</sup>Bamba *et al* (2019); <sup>17</sup>Charney (1975); <sup>18</sup>Sylla *et al* (2015); <sup>19</sup>Chilukoti and Xue (2020); <sup>20</sup>Mortey *et al* (2023); <sup>21</sup>Sy and Quesada (2020); <sup>22</sup>Smiatek and Kunstmann (2023); <sup>23</sup>Crook *et al* (2023); <sup>24</sup>Duku and Hein (2021); <sup>25</sup>Saley *et al* (2019).

effect, with values of  $-0.24 \pm 0.14$   $^{\circ}\text{C}$  in the historical period and  $-0.22 \pm 0.14$   $^{\circ}\text{C}$  in future projections (see table 2 and figure 2(a)). As expected, the warming due to deforestation is more pronounced in the future, although the range of temperature change is large and could include negative values ( $-0.3$   $^{\circ}\text{C}$  to  $+2.0$   $^{\circ}\text{C}$ ). For afforestation, the largest cooling effect occurs during the historical period, with temperature changes ranging from  $-0.2$   $^{\circ}\text{C}$  to  $+1.0$   $^{\circ}\text{C}$ . This suggests that afforestation had a more significant cooling impact historically, likely due to greater vegetation cover. By contrast, in future scenarios, elevated levels of atmospheric  $\text{CO}_2$  and altered radiation balances may diminish the cooling effects of afforestation.

Regarding the emission scenarios, on average, projections of temperature changes under the RCP8.5 scenario are more pronounced than under RCP2.6 (see table 3), mainly because tropical deforestation is projected to be more extensive under RCP8.5 than under RCP2.6 (Ward *et al* 2014). In other words, under the RCP2.6 scenario, the impact of deforestation on regional climate is weaker and statistically less significant compared to RCP8.5 (see table 3). This can be attributed to the lower greenhouse gas (GHG) concentrations and reduced radiative forcing associated with RCP2.6, which result in a more stabilized climate system with diminished model sensitivity to deforestation (Sy and Quesada 2020). Concerning afforestation, our findings indicate that the climate signal—particularly under the RCP4.5 scenario—is approximately twice as pronounced as that observed under the A1B scenario for temperature changes (see table 3). This stronger climate response under RCP4.5 compared to A1B can be attributed to several key factors: (i) the differences in radiative forcing and

emission pathways between the two scenarios. The A1B scenario (Nakicenovic and Swart 2000) assumes a balanced energy mix with moderate GHG emissions, representing a future world characterized by rapid economic and low population growth. In addition, under A1B, radiative forcing is projected to reach approximately  $6.0 \text{ W m}^{-2}$  by 2100. In contrast, RCP4.5 is a stabilization scenario in which emissions peak around mid-century and then decline, leading to a lower radiative forcing of  $4.5 \text{ W m}^{-2}$  by 2100 (Thomson *et al* 2011). While RCP4.5 has lower overall radiative forcing than A1B, the climate system remains sensitive enough for afforestation to induce distinct biophysical effects, including alterations in surface energy balance and regional precipitation patterns; (ii) unlike A1B, RCP scenarios explicitly integrate land-use change assumptions, including afforestation, as part of climate mitigation strategies (Thomson *et al* 2011). In other words, RCP4.5 incorporates larger afforestation efforts compared to A1B, leading to stronger land-cover-induced climate feedback. In contrast, A1B does not explicitly prioritize afforestation, meaning its land-use effects are less emphasized in climate models (Falloon *et al* 2012). In summary, the explicit inclusion of afforestation as a mitigation strategy in RCP4.5, combined with its goal of stabilizing radiative forcing at a lower level, may enhance the afforestation's climate impacts compared to A1B. It is worth noting that the difference in the simulation and model configurations may influence the model responses; for instance, the models used in RCP scenarios tend to incorporate updated land surface schemes, which may enhance the representation of afforestation effects compared to the older A1B-based simulations (Monerie *et al* 2012).

**Table 3.** Annual and seasonal changes in temperature and precipitation under different model parameterization configurations. The table compares the effects of convection schemes, land cover change scenarios (both idealized vs realistic), and future emission scenarios on climate responses.

Variables	Future scenarios				Seasonal changes					Idealized (ID) or realistic (RE) scenarios		Parametrized convection (PC)/convection-permitting (CP)	
	A1B	RCP2.6	RCP4.5	RCP8.5	Annual	MAM	DJF	JJA	SON	ID	RE	PC	CP
Afforestation													
Tmean (°C)	<b>-0.33</b> <sup>8,10,14</sup>	NA	<b>-0.6</b> <sup>12</sup>	NA	<b>-0.13</b> <sup>1,4,9</sup>	<b>-0.28</b> <sup>8,14</sup>	<b>-0.15</b> <sup>14</sup>	<b>-0.27</b> <sup>8,10,12-15,17,23,26</sup>	<b>-0.4</b> <sup>14</sup>	<b>-0.28</b> <sup>4,8,10,12-15,17,23,26</sup>	<b>-0.2</b> <sup>1</sup>	<b>-0.28</b> <sup>1,4,8,10,12-15,17,23,26</sup>	NA
Pmean (mm d <sup>-1</sup> )	<b>0.41</b> <sup>8,10,14</sup>	NA	<b>1.24</b> <sup>9,12</sup>	NA	<b>0.07</b> <sup>1,4,9</sup>	<b>0.10</b> <sup>8,14</sup>	<b>3</b> <sup>14</sup>	<b>1.04</b> <sup>8,10,12-15,17,23,26</sup>	NA	<b>0.72</b> <sup>4,8,9,10,12-14,17,23</sup>	<b>0.02</b> <sup>1</sup>	<b>0.55</b> <sup>1,4,8,9,10,12-15,17,23</sup>	NA
Deforestation													
Tmean (°C)	NA	<b>0.02</b> <sup>22</sup>	NA	<b>0.76</b> <sup>16,22</sup>	<b>0.27</b> <sup>1,2,4,7,11,16,21,22</sup>	<b>0.01</b> <sup>3,22</sup>	<b>0.12</b> <sup>6,19,22</sup>	<b>0.38</b> <sup>3,5,6,19,20,22,24</sup>	<b>0.1</b> <sup>22</sup>	<b>0.31</b> <sup>2,4,6,11,14,16</sup>	<b>0.25</b> <sup>1,3,5,7,19,20,21,22,24</sup>	<b>0.29</b> <sup>1-7,11,16,19,20,21,22,24</sup>	<b>0.0</b> <sup>24</sup>
Pmean (mm d <sup>-1</sup> )	NA	<b>-0.01</b> <sup>22</sup>	NA	<b>-0.02</b> <sup>16,22</sup>	<b>-0.08</b> <sup>1,2,4,11,16,21,22</sup>	<b>-0.40</b> <sup>3,22</sup>	<b>-0.1</b> <sup>6,19,22</sup>	<b>-0.43</b> <sup>3,5,6,7,19,20,22,24,25</sup>	<b>-0.01</b> <sup>22</sup>	<b>-0.43</b> <sup>2,3,4,5,6,11,16,18,25</sup>	<b>-0.03</b> <sup>1,7,19,20,21,22,24</sup>	<b>-0.15</b> <sup>1-7,11,16,18,19,20,21,22,24,25</sup>	<b>+0.64</b> <sup>24</sup>

<sup>1</sup>Glotfelty *et al* (2021); <sup>2</sup>Abiodun *et al* (2008); <sup>3</sup>Wang *et al* (2015); <sup>4</sup>Achugbu *et al* (2021); <sup>5</sup>Boone *et al* (2016); <sup>6</sup>Achugbu *et al* (2023); <sup>7</sup>Sy *et al* (2017); <sup>8</sup>Abiodun *et al* (2012a); <sup>9</sup>Odoulami *et al* (2018); <sup>10</sup>Abiodun *et al* (2012b); <sup>11</sup>Zheng and Eltahir (1997); <sup>12</sup>Diasso and Abiodun (2017); <sup>13</sup>Diba *et al* (2018); <sup>14</sup>Oguntunde *et al* (2012); <sup>15</sup>Diba *et al* (2016); <sup>16</sup>Ji *et al* (2015); <sup>17</sup>Bamba *et al* (2019); <sup>18</sup>Charney (1975); <sup>19</sup>Sylla *et al* (2015); <sup>20</sup>Chilukoti and Xue (2020); <sup>21</sup>Mortey *et al* (2023); <sup>22</sup>Sy and Quesada (2020); <sup>23</sup>Smiatek and Kunstmann (2023); <sup>24</sup>Crook *et al* (2023); <sup>25</sup>Duku and Hein (2021); <sup>26</sup>Saley *et al* (2019); NA means the study did not examine the variable.

At the seasonal scale, for deforestation, the most pronounced warming is observed during the WAM season (JJA), with average temperature increases of up to 0.38 °C (see table 3). This warming is also consistent during the year-round, likely due to a reduction in evapotranspiration. Wang *et al* (2015) show that, in the context of regional climate responses to deforestation in West Africa, changes driven by evapotranspiration play a more important role than changes in albedo during the monsoon season. Specifically, decreases in evapotranspiration dominate over increases in albedo, resulting in net warming across the Sahel (Boone *et al* 2016, Chilukoti and Xue 2020, Sy and Quesada 2020, Achugbu *et al* 2023). Abiodun *et al* (2008) further illustrate that deforestation can induce a warming effect of 0.1 °C–0.5 °C over the northern Sahel while reducing temperatures by 0.15 °C–0.5 °C in southern West Africa during spring and summer. Similarly, Chilukoti and Xue (2020) found a comparable warming effect over degraded areas in West Africa, with deforestation causing a significant surface warming of 0.82 K during the summer season (JJA). Finally, in their analysis of the diurnal cycle of deforestation effects in June, Crook *et al* (2019) found warmer near-surface temperatures during the day (up to 1 K) and cooler near-surface temperatures at night (about –0.5 K) in deforested areas, resulting in a net warming effect over the entire day.

For afforestation, the cooling effect is most pronounced during the post-monsoon autumn season (SON), with temperatures decreasing by up to –0.4 °C on average (Oguntunde *et al* 2012, Sy *et al* 2024). This cooling is also consistent throughout all seasons and is likely to be driven primarily by increased forest transpiration as a result of increased leaf density. In contrast, during the monsoon season (JJAS), the cooling effect is less pronounced, with temperature reductions reaching up to –0.27 °C on average (see table 3). However, during the pre-monsoon season (MAM), Ingrosso and Pausata (2024) identified a net warming effect associated with afforestation. This warming is mainly driven by a reduction in surface albedo, which leads to increased absorption of solar radiation. The concurrent increases in evapotranspiration and cloud cover during this period are too weak to effectively compensate for the albedo-induced radiative forcing, resulting in a net temperature rise.

Regarding the potential impact of LCC scenarios, table 3 shows that simulations using idealized deforestation scenarios have more pronounced climate impacts than those based on ‘realistic’ scenarios. Specifically, idealized deforestation scenarios lead to a temperature increase of about 0.31 °C, while realistic scenarios show a smaller increase of about 0.25 °C. Similarly, idealized scenarios show a cooling effect of –0.28 °C for afforestation, while realistic scenarios show a more moderate cooling of –0.2 °C. These

differences are probably because idealized scenarios typically prescribe more drastic and uniform LCCs, such as replacing existing vegetation with a single forest type or vice-versa, which amplifies the simulated climate impacts. In contrast, realistic scenarios incorporate more nuanced and gradual changes in land cover, which better reflect real-world conditions and result in less temperature responses. This highlights the importance of scenario design in accurately assessing the climate impacts of LCC, as idealized scenarios may overestimate the magnitude of changes compared to more realistic representations.

### 3.3. Simulated precipitation responses

Figure 2(b) shows the responses of precipitation (mm yr<sup>–1</sup>) to deforestation and afforestation scenarios, comparable to the temperature patterns observed in figure 2(a). Deforestation consistently led to regional decreases in precipitation in both the historical and future periods. Specifically, historical deforestation reduced precipitation by  $-0.13 \pm 0.08$  mm d<sup>–1</sup> ( $-47 \pm 29$  mm yr<sup>–1</sup>), while future projections show a slightly larger reduction of  $-0.15 \pm 0.28$  mm d<sup>–1</sup> ( $-54 \pm 102$  mm yr<sup>–1</sup>) (see table 2 and figure 2(b)). Conversely, afforestation led to regional increases in precipitation of  $+0.10 \pm 0.18$  mm d<sup>–1</sup> ( $+40 \pm 67$  mm yr<sup>–1</sup>) in the historical period and  $0.22 \pm 0.16$  mm d<sup>–1</sup> ( $80 \pm 58$  mm yr<sup>–1</sup>) in the future scenarios. As expected, both deforestation and afforestation impacts increased in the future projections, but with considerable variability between model results. Deforestation projections included potential wetting effects, albeit with a large range in precipitation changes from –450 to +500 mm yr<sup>–1</sup>, while afforestation results included potential drying effects, again with a large model response’s spread from –75 to +250 mm yr<sup>–1</sup> (figure 2(b)).

Regarding deforestation, as also observed with temperature, projections of precipitation changes under the RCP8.5 scenario are approximately twice as pronounced as those under RCP2.6 (see table 3). This is primarily because tropical deforestation is projected to be more extensive under RCP8.5 compared to RCP2.6 (Ward *et al* 2014). In contrast, for afforestation, the climate signal—particularly under the RCP4.5 scenario—is, on average, about three times more pronounced than that observed under the A1B scenario for precipitation changes (see table 3). This difference is likely driven by several key mechanisms, as previously discussed, including (i) the differences in radiative forcing and emission pathways between the two scenarios and (ii) the explicit integration of land-use changes assumptions, such as afforestation, as part of climate mitigation strategies in RCP4.5. These factors collectively contribute to the stronger climate signal observed under RCP4.5 compared to A1B.

At the seasonal scale, the most pronounced effect of deforestation is also observed during the WAM season in JJAS, leading to a significant reduction in precipitation, with an average decrease of up to  $-0.43 \text{ mm d}^{-1}$  (see table 3). These results are consistent with studies showing that both historical and future deforestation over West Africa can lead to simulated decreases in precipitation (Ji *et al* 2015, Wang *et al* 2015, Boone *et al* 2016, Sy *et al* 2017, Sy and Quesada 2020). The reduction in rainfall is observed throughout the year, with a significant decrease also simulated during the pre-monsoon season (MAM), with an average decrease of up to  $-0.4 \text{ mm d}^{-1}$ . Wang *et al* (2015) found that the decline in precipitation during the pre-monsoon season is spatially coherent across West Africa, with more pronounced declines near the coast, where the magnitude of the decline can exceed  $2 \text{ mm d}^{-1}$  in certain areas. During the WAM season, the strongest reduction in precipitation is centered around  $12^\circ\text{N}$ , where deforestation causes a weakening of the monsoon circulation (Wang *et al* 2015). This leads to a southward shift of the rain belt, creating a dipole pattern in the precipitation response during JJAS. Specifically, rainfall decreases over the Sahel region while increasing over the Guinea Coast. The mechanisms through which deforestation may lead to increased rainfall in certain areas can be attributed to several factors. For instance, tropical grasslands in the tropics are sometimes erroneously parameterized as more evaporative in climate models, leading to an overestimation of precipitation when the forest is replaced by grassland. Additionally, when deforestation occurs on a smaller scale, a phenomenon known as the ‘vegetation breeze’ can occur (Cochrane and Laurance 2008, Garcia-Carreras and Parker 2011). This process involves the creation of a low-pressure zone over the deforested area, which draws in locally heated, moist air masses from surrounding vegetated regions. As these air masses ascend, cloud formation and precipitation over the deforested area is enhanced. Although based on 5 d simulations, under the CP model, Crook *et al* (2023) also observed enhanced rainfall over deforested areas in West Africa. They reported an average increase of 6% ( $0.64 \text{ mm d}^{-1}$ ) in rainfall over deforested pixels throughout the day, primarily driven by more frequent and larger storms, with a lesser contribution from more intense storms between 18:00 and 06:00 UTC, with rainfall changes being more pronounced during the night than during the day. Furthermore, the magnitude and spatial distribution of these rainfall changes are strongly influenced by soil moisture conditions and the proximity of deforestation to the coast due to interactions with sea breeze dynamics.

For afforestation, most studies simulate a significant increase in precipitation during the rainy season, with an average increase of  $1.04 \text{ mm d}^{-1}$  (see table 3). However, Oguntunde *et al* (2012) reported a higher

increase during the winter season, with changes of up to  $3.0 \text{ mm d}^{-1}$  observed in the Niger Delta in a future afforestation experiment involving the conversion of grassland to tropical forest. The increase in rainfall following afforestation is consistent throughout the year and is mainly driven by increased transpiration and the release of recycled moisture through forest evapotranspiration (Abiodun *et al* 2012a, Oguntunde *et al* 2012, Sy *et al* 2017, Ingrosso and Pausata 2024). These processes may also contribute to the northward extension of the monsoon (Pausata *et al* 2020, Ingrosso and Pausata 2024). Such effects are particularly pronounced during the rainy season when water availability is at its peak, and hydrological changes can significantly influence precipitation patterns and processes (Malhi *et al* 2008, Phillips *et al* 2009, Kumagai and Porporato 2012), thereby modulating atmospheric feedback mechanisms (Meir *et al* 2006, Bonan 2008).

Similar to temperature, idealized scenarios for both deforestation and afforestation show stronger climate impacts on precipitation than those based on realistic LCC scenarios (table 3). On average, idealized deforestation scenarios lead to a larger decrease in precipitation, with an estimated decrease of about  $-0.43 \text{ mm d}^{-1}$ , while realistic deforestation scenarios show a much smaller decrease of about  $-0.03 \text{ mm d}^{-1}$ . Similarly, afforestation in idealized scenarios produces a significant wetting effect, with increases in precipitation of up to  $0.72 \text{ mm d}^{-1}$ . In contrast, realistic afforestation scenarios show only a marginal effect, with an increase of about  $0.02 \text{ mm d}^{-1}$ , on average, with a high effect, particularly for afforestation in experiments where the savanna is converted to a woody savanna (Glotfelty *et al* 2021). These discrepancies are likely due to the more abrupt and extensive LCCs in idealized scenarios compared to realistic scenarios, which incorporate gradual and spatially heterogeneous changes that better represent real-world conditions.

### 3.4. Comparison with other tropical studies

According to the Special Report on Climate Change and Land (IPCC-SRCL 2019), there is a *high confidence* that large-scale tropical deforested areas are warmer than surrounding non-deforested zones. After a pantropical deforestation experiment, a significant mean biophysical warming of  $+0.61 \pm 0.48 \text{ }^\circ\text{C}$  is found when averaged over the entire tropics ( $n = 18$  simulations across 15 studies). Perugini *et al* (2017), integrating more tropical subregional studies, found a very similar significant biophysical warming of  $0.60 \pm 0.26 \text{ }^\circ\text{C}$  over the tropical zones ( $n = 34$  simulations across 12 studies). In West Africa, our quantitative review indicates a smaller warming response of  $+0.26 \pm 0.12 \text{ }^\circ\text{C}$ , likely due to the relatively small extent of deforestation simulated in this region, as discussed by Sy *et al* (2017). However, projected future deforestation shows a much larger warming response

of  $+0.88 \pm 0.25$  °C, probably due to more drastic LCCs and more sensitive models. We found that the evapotranspiration reduction is the leading driver (see figure S3), largely outdoing the albedo-cooling effect in response to tropical deforestation, as commonly reported in the literature both for models and observation-based outputs (Perugini *et al* 2017, Jia *et al* 2019).

Moreover, large-scale tropical deforestation results in a significant mean rainfall decrease, as confirmed by the overwhelming majority of studies, both observational and modeling results (Lawrence and Vandecar 2015, Perugini *et al* 2017, Spracklen *et al* 2018, Sy and Quesada 2020). This is consistent with our West African study: West African deforestation results in a rainfall decrease on average (table 2 and figure 2(b)). Perugini *et al* (2017) reported a mean simulated decrease of  $-288 \pm 110$  mm yr<sup>-1</sup> (95% confidence interval) for tropical studies ( $n = 42$  simulations), while our results indicate a  $-47$  to  $-55$  mm yr<sup>-1</sup>, a much lower number than most tropical modeling studies. Furthermore, based on observational satellite-based methodology, local reductions in precipitation ranged from  $-115 \pm 86$  mm yr<sup>-1</sup> in South East Asia to  $-55 \pm 28$  mm yr<sup>-1</sup> in the Amazon and  $-50 \pm 45$  mm yr<sup>-1</sup> in the Congo for a comparable 20% historical deforestation (Smith *et al* 2023). This last value in Africa is coherent with the modeling studies found in West Africa (figure 2(c)). Given a 2200 mm yr<sup>-1</sup> annual mean rainfall over the Amazon basin, across all simulations ( $n = 96$ ), the average change in annual mean Amazon basin rainfall induced by historical deforestation was  $-264 \pm 242$  mm yr<sup>-1</sup> (Spracklen and Garcia-Carreras 2015), a much higher estimate than the observational-based estimates. However, it is worth noting that observation-based estimates account for fewer deforestation impacts than model-based ones: the space-for-time assumption does not consider remote impacts of deforested pixels, trends in global climate change partly induced by LCCs, or slight hydroclimatic dynamic differences between neighboring pixels (though the assumption of a common background climate is made for distance) (Quesada *et al* 2017, Chen and Dirmeyer 2020, Sy and Quesada 2020).

Although the Sahel has shown signs of recovery from the severe droughts of the 1970s and 1980s, rainfall levels have not fully returned to pre-drought conditions (Sylla *et al* 2016a, Biasutti 2019, Nouaceur and Murarescu 2020). While multiple datasets confirm this trend, there remains variability in magnitude due to observational limitations in West Africa (e.g. Sanogo *et al* 2015, Nicholson *et al* 2018). Recently, Tano *et al* (2023) reported a decrease in precipitation in most West African countries, with the most significant decrease observed in Liberia. Part of this decreasing trend has been forced by global warming

through a reduction of the land-sea thermal gradient, which in turn led to a weakened monsoon circulation and a northward shift of monsoon rainfall, inducing less rainfall in West Africa (Tano *et al* 2023). Another large driver of this trend is tropical West African deforestation (Quesada *et al* 2017, Sy *et al* 2017), which reduced the evapotranspiration flux with shallower vegetation but also the available energy for thermal fluxes in general in response to a higher albedo. Indeed, to highlight the potential importance of this driver in this region of the globe, Quesada *et al* (2017), using 5 global coupled models with and without future plausible LCC scenarios found that deforestation decreases by 41% future WAM boost simulated under future climate change because of a decrease in evapotranspiration, cloud amount along with more anticyclonic conditions. However, due to the lack of other attribution studies in the region with the best regional and GCMs available associated with plausible LCC scenarios in West Africa, we still lack key information on the relative contribution of both drivers on climate. Under future global warming scenarios, precipitation changes in West Africa are not consensual and are non-significant for the multi-model means, as simulated by the climate models (Hartley *et al* 2015, Almazroui *et al* 2020). For all those reasons, given the temperature and precipitation responses to LCC, we infer a lower land-atmosphere interaction tropical hotspot in West Africa simulated by the models.

### 3.5. Planting trees as key helpers to help mitigate regional warming and drying

Simulation results due to large-scale afforestation, albeit few (less or equal to 6 outputs per scenario, see figures 2(b) and (c)), indicate substantial and significant cooling and wetting. The biophysical cooling found of approx.  $-0.2$  °C in response to large-scale afforestation can moderately mitigate the regional West African warming of 0.2 °C per decade approximately (1970–2014, Iyakaremye *et al* 2021a), without even accounting for the biogeochemical effect (Bonan 2008). Moreover, our results indicate that the regional rainfall increase by 40–80 mm yr<sup>-1</sup> in response to large-scale reforestation or afforestation may compensate for the rainfall amount loss from significant recent drying trends in countries of West Africa like Guinea, Liberia, Ghana, or Ivory (Tano *et al* 2023).

Afforestation also presents significant socio-economic and environmental implications, necessitating careful consideration for sustainable development and policy implementation. While it can improve local microclimates by increasing humidity and reducing temperatures, thereby benefiting rain-fed agriculture in some regions (Waongo *et al* 2024), it may also compete with agricultural land, threatening food security, particularly in semi-arid areas where farming is a primary livelihood (Mwanthi *et al* 2023, Waongo *et al* 2024).

Economically, afforestation creates opportunities in forestry and carbon markets (Nkonya *et al* 2016), but it risks reducing farmland and exacerbating food insecurity (Chia *et al* 2020). Although initiatives like REDD+ and carbon markets provide financial incentives (FAO 2022), their effectiveness depends on governance structures and equitable benefit distribution (Angelsen *et al* 2012). Socially, afforestation can lead to land tenure conflicts and disrupt local livelihoods (Ribot and Peluso 2003), underscoring the need for policies that integrate agricultural needs and ensure fair benefit-sharing (Lambin and Meyfroidt 2011, Leach *et al* 2012). Environmentally, afforestation can enhance rainfall patterns and mitigate extreme heat (Lawrence and Vandecar 2015), though its effects vary with vegetation type and density (Ingrosso and Pausata 2024, Sy *et al* 2024). However, large-scale plantations may deplete groundwater resources, while native species can restore ecosystems (Brancalion *et al* 2019). Conversely, monoculture plantations often degrade soil health and biodiversity (Barlow *et al* 2007). Although afforestation contributes to carbon sequestration (Bastin *et al* 2019), its success depends on species selection and management practices (Sy *et al* 2024). A balanced approach, integrating ecological and socio-economic considerations, is essential to maximize benefits while minimizing risks.

### 3.6. Uncertainties in simulated temperature responses

Various LCC-induced compensating phenomena, simulated differently in different model simulations, can influence the magnitude and direction of temperature responses (see figure 2(b)). These include: (i) local/regional physical mechanisms, such as changes driven by albedo-induced cooling effects versus evapotranspiration-induced warming effects (see figure S3) (Sy and Quesada 2020, Sy *et al* 2024). (ii) Variability in how models treat non-local effects (Hirsch *et al* 2014, Chen and Dirmeyer 2016, Winckler *et al* 2017, Chen *et al* 2022). For example, deforestation in one region can influence climate patterns in another, but the magnitude and nature of these influences can differ significantly between models; (iii) model resolution can also affect the simulation of temperature changes, especially in orographic regions (Iles *et al* 2020). The difference may be due to the ability of RCMs to capture finer-scale biophysical effects of LCC that GCMs may miss. However, this increased resolution may also introduce additional uncertainties related to local processes that are less critical at the global scale (Sy *et al* 2023). In addition, each model incorporates its own set of assumptions, parameterizations and simplifications (Rounsevell *et al* 2014, Glotfelty *et al* 2021). These include how LCC information and crop phenology are represented in LSMs (Pitman *et al* 2009,

Boisier *et al* 2012, Sy *et al* 2017, Sy and Quesada 2020), the methods used to integrate LCC into background land cover, and the datasets used to characterize current or potential natural vegetation (De Noblet-Ducoudré *et al* 2012). These factors can influence both the magnitude and effectiveness of the energy fluxes exchanged between the surface and the atmosphere (Rounsevell *et al* 2014, Boone *et al* 2016, Sy *et al* 2017). Finally, recent simulations from studies published after 2018 generally show lower climate sensitivity than those from studies published before 2017 (figure S1). Differences in experimental design, particularly the spatial scale and extent of reforestation and afforestation, play a crucial role in shaping model responses (Ingrosso and Pausata 2024, Sy *et al* 2024). For instance, large-scale afforestation efforts tend to have more pronounced impacts due to their stronger influence on land–atmosphere interactions, whereas smaller-scale afforestation projects are more localized and may have less significant effects on temperature. These factors should be carefully considered when interpreting model discrepancies.

### 3.7. Uncertainties in simulated precipitation responses

Uncertainties in simulated precipitation responses to LCC can be attributed to various mechanisms, primarily those related to changes in evapotranspiration and moisture availability (Seneviratne *et al* 2010, Boone *et al* 2016, Perugini *et al* 2017, Quesada *et al* 2017, IPCC-SRCCL 2019, Ingrosso and Pausata 2024). These mechanisms are typically simulated differently across models, leading to significant discrepancies. For example, different climate models use different parameterization schemes for key processes affecting precipitation, such as convection, cloud formation, and precipitation dynamics (Boone *et al* 2016). Glotfelty *et al* (2021) attribute differences in precipitation response to LCC to a possible underrepresentation of moisture recycling in atmospheric model configurations. This underrepresentation can result in insufficient moisture convergence or inadequate activation of the cumulus parameterization, leading to excess water vapor forming cloud cover instead of precipitation (Wang *et al* 2016). Discrepancies in precipitation response can also be linked to how the African easterly jet is represented, including different meridional shifts and variations in the strength of these shifts among models (Boone *et al* 2016). The interaction between land surface properties and the atmosphere is complex, and its representation varies widely across different models (Sy *et al* 2017). Differences in how land–atmosphere exchanges, such as heat and moisture fluxes, are modeled can lead to discrepancies in simulated precipitation responses (Pitman *et al* 2009, De Noblet-Ducoudré *et al* 2012). For example, the net effect on total evaporation due to LCC is uncertain because

different models balance evaporative responses with net radiation changes in various ways (Pitman *et al* 2009). This uncertainty may depend on how models represent complex vegetation–atmosphere interactions, the strength of land–atmosphere coupling, and vegetation parameterization (Koster *et al* 2006, Pitman *et al* 2009, Rounsevell *et al* 2014, Sy *et al* 2017). Moreover, feedback processes between LCC and climate, such as changes in surface albedo, evapotranspiration, and heat fluxes, can amplify or moderate precipitation changes. Models vary in their representation and sensitivity to these feedback mechanisms, leading to different magnitudes and directions in simulated precipitation responses (Pitman *et al* 2009). In addition, large-scale afforestation plays a crucial role in improving regional moisture recycling and cloud formation, while smaller-scale projects tend to have more localized and less pronounced effects. In particular, large-scale afforestation can induce significant changes in local microclimates, increasing humidity and altering precipitation patterns, whereas smaller-scale interventions may have more limited climatic impacts. These differences in scale contribute to variations in model responses and should be considered when interpreting discrepancies in simulation results. In addition, most studies in West Africa have relied on prescribed vegetation models (see table 2), which may not fully capture the dynamic feedback between vegetation and climate. In contrast, dynamic vegetation models allow for interactive vegetation–climate processes, providing a more comprehensive representation of feedback mechanisms (e.g. Sy *et al* 2017).

While modeling approaches can produce similar broad-scale trends, the choice of model configuration can significantly influence results, particularly in regions such as West Africa, where the vegetation–climate coupling is strong (Koster *et al* 2004, 2006). Moreover, most of the experiments analyzed in this study rely on PC models (see table 1), which simplify convective processes and may underestimate the intensity and spatial variability of precipitation. In contrast, CP models, although often limited to smaller spatial domains or shorter simulation periods due to computational constraints, explicitly resolve convection and can provide more accurate precipitation simulations, especially in convective-dominated regions such as West Africa (Kendon *et al* 2012, Marsham *et al* 2013, Stein *et al* 2015, Stratton *et al* 2018, Lucas-Picher *et al* 2021, Crook *et al* 2023). CP also improves the diurnal cycle and spatial distribution of convection (Birch *et al* 2014b) and yields more accurate timing and intensity of monsoonal rainfall (Birch *et al* 2014a). Additionally, turning off convection parameterization improves cloud and precipitation representation by reducing excessive daytime convection (Stein *et al* 2015). However,

studies using CP models suggest that their response to soil moisture–precipitation interactions may be different from, or even opposite to, that of PC models (Hohenegger *et al* 2009, Taylor *et al* 2013, Crook *et al* 2023). Recent evidence suggests that while CP and PC models produce qualitatively similar responses of the monsoon circulation to increased vegetation cover over West Africa, CP models tend to show a more pronounced effect (Jungandreas *et al* 2023). These differences in model parameterization may contribute to variations in simulation results and should be carefully considered in future studies.

#### 4. Limitations and future research

A significant limitation in this review is the lack of standardized definitions for the West African region across ESMs (Boone *et al* 2016, Sy *et al* 2017, Sy and Quesada 2020, Glotfelty *et al* 2021, Achugbu *et al* 2023, Mwanthi *et al* 2023). This inconsistency in regional delineation likely contributes to discrepancies in findings across studies, as differences in geographic boundaries, spatial scales, and criteria used to define regions can significantly affect the comparison of LCC effects. Additionally, methodological differences, dataset inconsistencies, and variability in observed signals further complicate cross-study comparisons. Furthermore, variations in simulation periods, the extent of LCC scenarios—whether idealized or realistic—and differences in future emission scenarios may also influence results, as the strength of LCC effects can evolve over time. Addressing these discrepancies is essential to enhance the robustness and comparability of future research. For example, one study might use political boundaries, while another uses ecological zones, leading to variations in LCC's extent and spatial distribution. These inconsistencies may affect the accuracy and comparability of estimates regarding the regional biophysical effects of LCC, resulting in discrepancies in reported impacts on temperature and precipitation. Assessing the scale-dependence of LCC impacts is also complex, as localized effects may be more pronounced at smaller scales, while larger scales might average out these impacts. This lack of standardization complicates efforts to generalize conclusions about LCC effects on regional climates. To address these limitations, it is crucial to establish standardized definitions and criteria for regional boundaries in climate model experiments. This involves developing agreed-upon geographic, ecological, or climatic parameters that can be uniformly applied across studies. Additionally, incorporating methods to assess the scale-dependence of LCC effects could provide more nuanced insights into how these impacts vary with different spatial extents. Improving standardization and methodological approaches will

enable future research to quantify better and compare the biophysical effects of LCC, leading to more robust and actionable findings. Furthermore, the limited selection of keywords (see table S3) and poorly written abstracts may have excluded important papers from the review. Additionally, the exclusion of papers published in languages other than English, such as French—which is widely spoken in West Africa—could also restrict the scope of this study

While our study provides valuable insights into the impacts of LCC on mean temperature and precipitation, it has certain limitations. Specifically, our analysis is constrained by the limited number of studies examining changes in climate extremes in response to LCC, most of which focus on afforestation. This gap highlights a critical area for future research, as understanding the effects of LCC on climate extremes—such as heatwaves, floods, droughts, and heavy rainfall is essential for comprehensive climate risk assessment and adaptation planning. For instance, while afforestation may reduce aridity and enhance rainfall extremes in West Africa (Ingrosso and Pausata 2024), it can also lower surface albedo, leading to localized warming and increased heat extremes, particularly during the pre-monsoon season (Saley *et al* 2019, Ingrosso and Pausata 2024, Sy *et al* 2024). These competing effects underscore the need for further research to refine afforestation strategies, ensuring maximum climate benefits while minimizing unintended consequences in West Africa.

## 5. Concluding remarks

This study presents the first comprehensive synthesis of the global literature on the regional biophysical impacts of LCC in West Africa, focusing on simulated changes in surface air temperature and precipitation. It also addresses key uncertainties in the quantification of these impacts on regional climate. Using the PRISMA protocol, nearly 6000 articles were reviewed, and information from 26 selected publications was synthesized. The results indicate that deforestation generally leads to regional warming, with an increase of  $+0.26 \pm 0.12$  °C for historical period and  $+0.88 \pm 0.25$  °C for future deforestation scenarios. In contrast, afforestation tends to lead to regional cooling, with temperature decreases of  $-0.24 \pm 0.14$  °C in the historical period and  $-0.22 \pm 0.14$  °C in the future. In terms of precipitation, deforestation is associated with a regional decrease in rainfall, averaging  $-47 \pm 29$  mm yr<sup>-1</sup> in the historical period and a more pronounced decrease of  $-55 \pm 102$  mm yr<sup>-1</sup> projected for the future. Conversely, afforestation is associated with increased precipitation, with increases of up to  $+40 \pm 67$  mm yr<sup>-1</sup> historically and  $80 \pm 58$  mm yr<sup>-1</sup> in the future.

The study also highlights significant uncertainties in the simulated impacts of LCC on regional climate in West Africa. These uncertainties might arise from various sources, such as model assumptions, parameterizations, simplifications, resolution, and representations of local and non-local processes, as well as direct and indirect effects, resulting in a wide range of model simulation results (Boone *et al* 2016 Perugini *et al* 2017, Quesada *et al* 2017, Sy *et al* 2017, Sy and Quesada 2020, Glotfelty *et al* 2021). The inter-model spread underscores the complexity of accurately simulating the biophysical impacts of LCC. It also highlights the need for careful interpretation of model results, posing challenges for policymakers relying on model projections to make informed decisions about land use, climate adaptation, and mitigation strategies.

Overall, the results of the study are critical for policy assessment and highlight the importance of incorporating LCC-related climate change metrics into comprehensive climate assessments. To improve the accuracy of climate projections, it is essential to address the mechanisms that drive uncertainties in LCC impacts. Achieving this goal will require a concerted effort within the climate modeling communities. This effort should begin with a coordinated assessment of the representation of LCCs and how well climate models capture their effects in offline and coupled climate models. This, in turn, will inform more effective climate adaptation and mitigation strategies and ultimately support sustainable land management in West Africa.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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## Contributions

Abdel Nassirou Yahaya Seydou and Souleymane Sy designed the study. Abdel Nassirou Yahaya Seydou and Souleymane Sy carried out data screening, collection, and analysis. Souleymane Sy wrote the manuscript. All authors contributed their expertise and made substantial improvements to the manuscript through discussions and revisions.

## Conflict of interest

The authors declare no competing financial interests.

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