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Review

Land use and land cover changes and their impacts on surface-atmosphere interactions in Brazil: A systematic review

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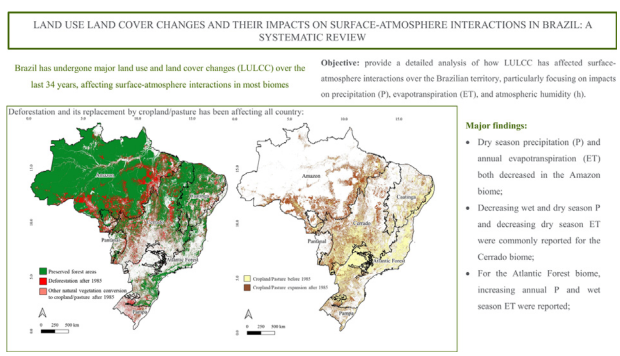
HIGHLIGHTS

- Brazil has undergone land cover changes over the last 34 years, affecting surface-atmosphere interactions in most biomes;
- Dry season precipitation (P) and annual evapotranspiration (ET) both decreased in the Amazon biome;
- Decreasing wet and dry season P and decreasing dry season ET were commonly reported for the Cerrado biome;
- For the Atlantic Forest biome, increasing annual P and wet season ET were reported;
- Gaps remain in documenting LULCC impacts on surface-atmosphere interactions over Caatinga, Pantanal, Pampa.

GRAPHICAL ABSTRACT



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ABSTRACT

Major land use and land cover changes (LULCC) have taken place in Brazil, including large scale conversion of forest to agriculture. LULCC alters surface-atmosphere interactions, changing the timing and magnitude of energy fluxes, impacting the partitioning of available energy, and therefore the climate and water balance. The objective of this work was to provide a detailed analysis of how LULCC has affected surface-atmosphere interactions over the Brazilian territory, particularly focusing on impacts on precipitation (P), evapotranspiration (ET), and atmospheric humidity (h). Our systematic review yielded 61 studies, with the Amazon being the most studied biome followed by the Cerrado. P was the most analyzed variable, followed by ET. Few papers analyzed LULCC impacts on h. For the Amazon biome, decreasing dry season P and in annual ET were reported. In the Cerrado biome, decreasing P in the wet and dry seasons and decreasing dry season ET were the most common result. For the Atlantic Forest biome, increasing annual P and increasing wet season ET, likely due to reforestation, were reported. Few studies documented LULCC impacts on surface-atmosphere interactions over the Brazilian biomes Caatinga, Pantanal and Pampa. Therefore, new research is needed to assess impacts of LULCC on these biomes, including assessments of atmospheric moisture recycling, and interactions of LULCC with global climate and climate extremes including droughts.

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1. Introduction

More than 70% of the Earth's land surface has undergone some type of anthropogenic change (Luyssaert et al., 2014), altering the planet's biophysical and biogeochemical processes (Keys and McConnell, 2005). Land use and land cover changes (LULCC) alter surface-atmosphere interactions, changing the timing and magnitude of energy fluxes, impacting the partitioning of available energy and therefore the water balance. Case studies from different regions of the globe have shown that LULCC and climate variability have significant impacts on several environmental variables, such as precipitation (P) (Hasler et al., 2009; Perugini et al., 2017; Spracklen et al., 2012), evapotranspiration (ET) (Baker and Spracklen, 2019; Nosetto et al., 2012) and energy fluxes (Bastable et al., 1993; Ferreira et al., 2020; H. de C. Teixeira et al., 2013). Brazil has experienced major LULCC, with significant impacts in all its biomes. The Brazilian Institute of Geography and Statistics (IBGE) defines six biomes in Brazil based on climate, vegetation, fauna and soil (IBGE, 2019; Pigatto and Lopes, 2019): the Atlantic Forest; Amazon rainforest; mixed savanna, grassland and forest (Cerrado); woody and deciduous dry forest (Caatinga); wetlands (Pantanal); and grasslands (Pampa) (Souza et al., 2020). The corresponding terrestrial ecoregions from Olson et al. (2001) are tropical and subtropical moist broadleaf forests (Amazon and Atlantic Forest); tropical and subtropical grasslands, savannas and shrublands (Cerrado and Pampa); tropical and subtropical dry broadleaf forests (Caatinga); and flooded grasslands and savannas (Pantanal). Time series of Landsat imagery show that Brazil lost 71 Mha of natural vegetation from 1985 to 2017, mostly to cattle ranching and cropland expansion, while pasture expanded by 46% and agriculture by 172% (Souza et al., 2020).

LULCC, both globally and in Brazil, can affect local biodiversity but also carbon emissions, regional and local climate, and the hydrological cycle (Davidson et al., 2012). LULCC affects land surface budgets, altering the exchange of moisture and energy (Bonan, 2008). Converting forest to pasture tends to reduce ET locally and P regionally by weakening both atmospheric moisture recycling (Keys et al., 2012) and deep convection in the atmosphere (Costa and Foley, 2000), which reduces convective clouds and P (Salazar et al., 2015). Vergopolan and Fisher (2016) assessed a decade of patterns in P and ET over deforested and forest areas using remote sensing products, finding lower absolute annual values in P and ET over deforested than over intact forest areas. Air masses that have passed over extensive pan-tropical forests produce more rain than air that had passed over less vegetated areas (Spracklen et al., 2012). Webb et al. (2005) found a significant positive relationship between tree cover and the number of rainy days in the Atlantic forest of Brazil. Those studies demonstrate the importance of intact forests, which maintain ET and atmospheric moisture that can return to land as rainfall.

LULCC and its effects on surface-atmosphere interactions and hydroclimate are usually documented in case studies (van Vliet et al., 2016), which are important to understand the impacts of LULCC in detail, but the results are limited to a specific type of LULCC and site (Flyvbjerg, 2006). Summaries of the understanding of LULCC and its impacts (Chen et al., 2020; Keys and McConnell, 2005; Magliocca et al., 2015; Perugini et al., 2017; Spracklen and Garcia-Carreras, 2015) are often conducted to develop or advance theories, determine further research needs, and evaluate or provide information for decision-making (Magliocca et al., 2014, 2015). Unlike meta-analysis, meta-studies of LULCC may not analyze case study data statistically due to the large variety of study design and inclusion of qualitative data (van Vliet et al., 2016).

We conducted a systematic review and detailed analysis of how LULCC has affected the surface-atmosphere interactions over the Brazilian territory, focusing on impacts on precipitation, evapotranspiration, and atmospheric humidity. The literature reviewed includes observational and model-based research. The study supports present and future research by reviewing what has been done and gaps and limitations to be addressed. Section 2 briefly summarizes LULCC in Brazil and its effects on biomes. Section 3 presents an overview of surface-atmosphere interactions and how LULCC impacts them. In section 4 we describe the methods used in this systematic review. Section 5 presents the results, subdivided by variable analyzed (P, ET and atmospheric humidity) and by biome, and discusses limitations of previous work and opportunities for further research. Section 6 summarizes the conclusions.

2. Land use and land cover change in Brazil

Brazil has experienced extensive LULCC in all of its biomes (Fig. 1). The expansion of pasture and agriculture activities has been the main driver for deforestation in Brazil (Gibbs et al., 2010), contributing to greenhouse gas (GHG) emissions and impacting biodiversity, water resources, soil, and local and regional climate (Davidson et al., 2012; Dias et al., 2016; Gibbs et al., 2010; Souza et al., 2020).

Widespread clearing of forest for farming (pasture and agriculture, Fig. 2 and Table 1) from 1985 to 2020 occurred mainly in the Amazon (11% of the biome area), Cerrado (13%) and Caatinga (12%) biomes. In the Pampa biome, farming increased at the expense of natural non-forest cover (16%), which includes grassland and wetlands. For the Atlantic

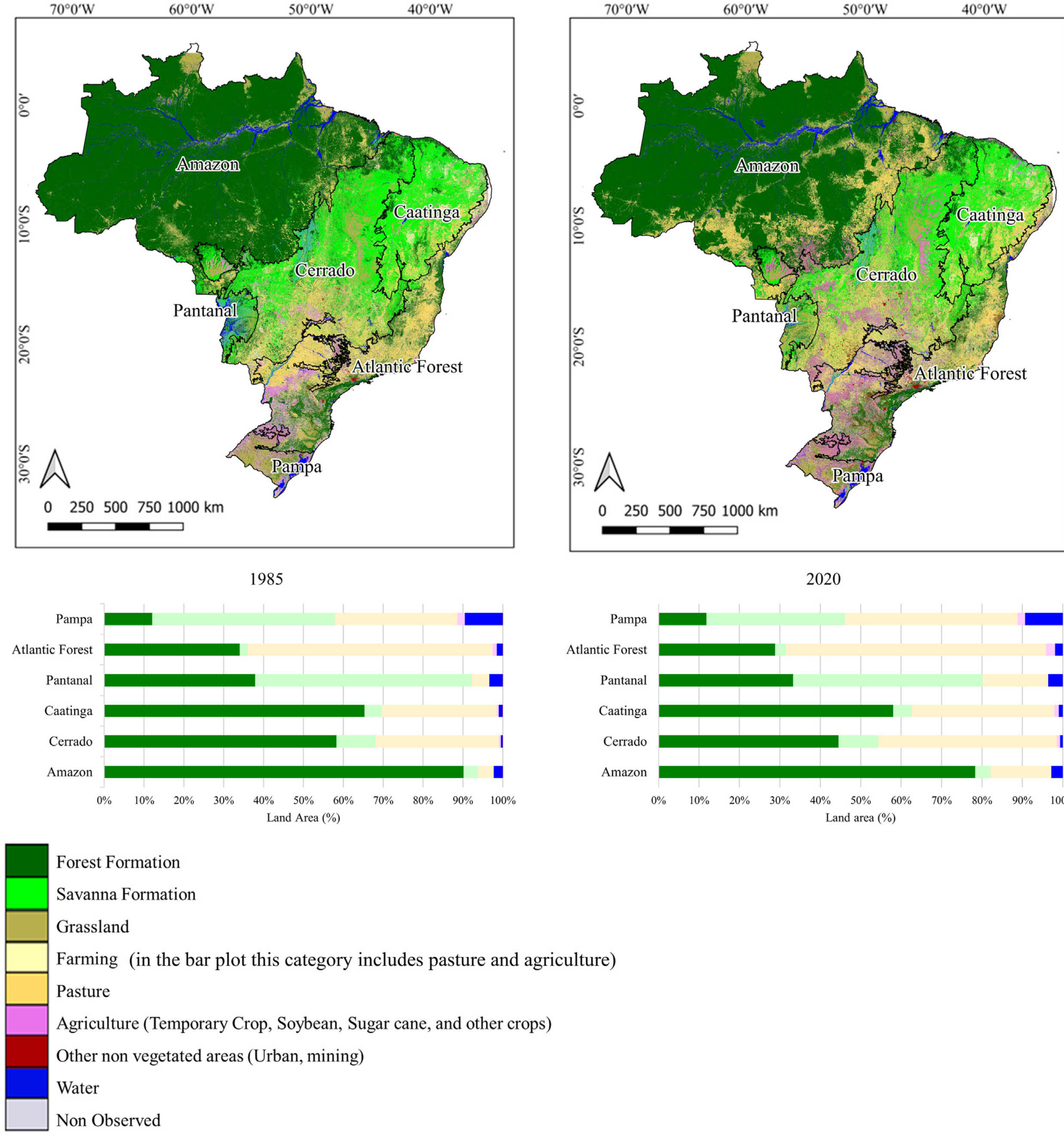

Fig. 1. Land cover in Brazilian biomes in years 1985 and 2020. Bar plots show the percentage of each category of land cover in each biome (data source: MapBiomas, 2021).

Forest biome, not much change occurred during this period, since the main changes happened prior to 1985 (Brannstrom and Oliveira, 2000). Most of the farmland in 2020 was natural vegetation in 1985 in the Amazon (79%) and Pantanal (81%), while around one third of farmland was natural vegetation in 1985 in the Cerrado (36%), Caatinga (38%) and Pampa (40%), and just 7% of farmland in 2020 was forest in 1985 in the Atlantic Forest.

LULCC is a threat for Brazilian Amazon ecosystems (Davidson et al., 2012; Fearnside, 1993; Scott, 2020). To 2020, about 814,000 km^2 of the Legal Amazon has been deforested, which corresponds to approximately 19% of its original cover (PRODES, 2021), with 14% in farmland (Table 1). While deforestation rates in the Amazon fell steadily from 2004 to 2015 (Aragão et al., 2018), they increased after 2015 and, in the year 2020, deforestation in the Amazon had its highest percentage increase in the last 10 years (Barbosa et al., 2021). The Amazon basin represents 40% of the global tropical forest area (Marengo et al., 2018), and provides numerous ecosystem services (Sampaio et al., 2019).

More than 54% of the natural vegetation of the Cerrado biome was converted to other land covers (MMA/IBAMA, 2011) with 44% of the total biome area in farming (Table 1). The Brazilian Caatinga is the third most degraded and destroyed biome in Brazil after the Atlantic Forest and the Cerrado (Leal et al., 2005), where 30–52% of the original land cover has been altered by human activities (Antongiovanni et al., 2020; Leal et al., 2005; Salazar et al., 2015), and 34% is in farming. The Brazilian Pantanal, one of the most important wetlands on the planet, is also under high land change pressure. In the first eight months of 2020 alone (Jan-Aug), around 12% of the biome was destroyed by fires, consequence of a mix of factors, including severe high temperatures, little precipitation, and lack of government action (Barbosa et al., 2021).

The Brazilian Atlantic forest has historically experienced the most extensive LULCC, and is one of the most threatened ecosystems on Earth, with less than 10% of its original forest remaining intact in several fragments and 65% of the biome area in farming. Finally, the conversion of

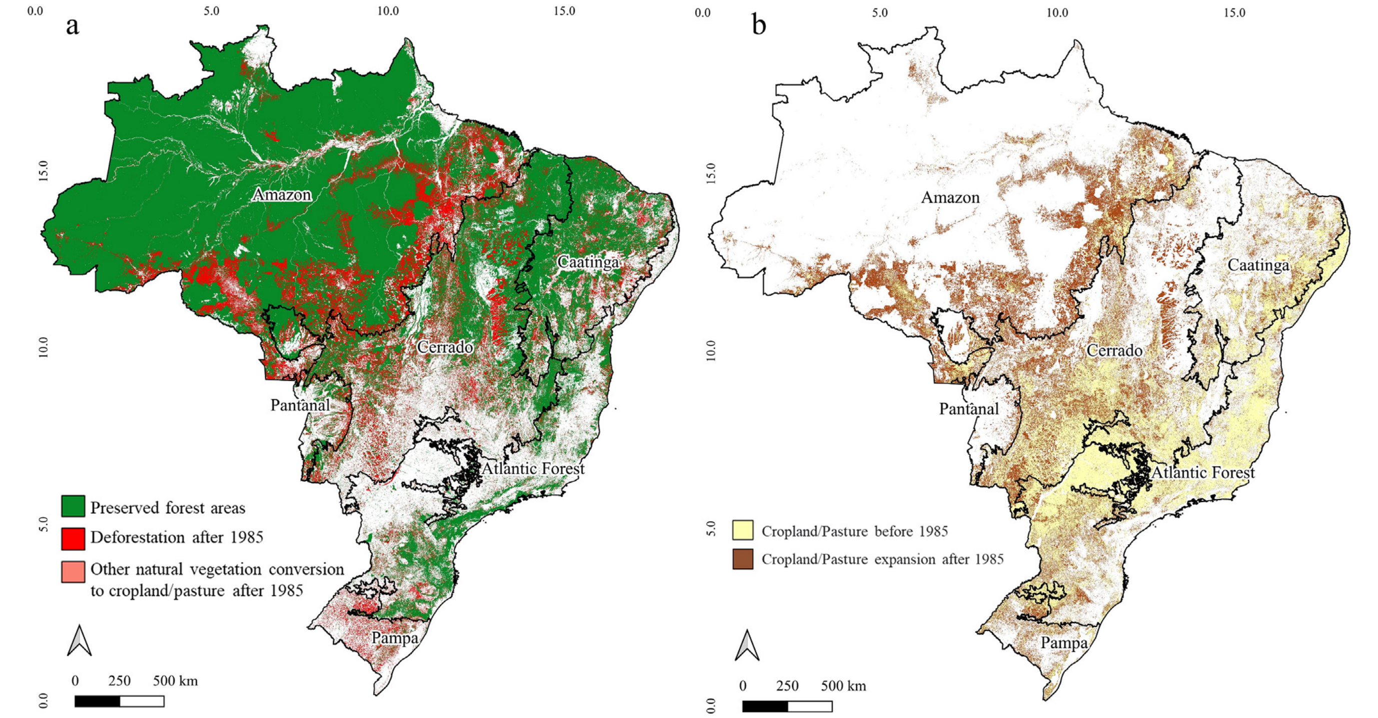

Fig. 2. Land cover transition from 1985 to 2020: (a) Deforested and preserved areas; (b) Cropland and pasture area expansion in the Brazilian territory (data source: MapBiomas, 2021).

the Pampa biome's grasslands to other agriculture activities (42% of the biome in farming), has caused landscape fragmentation, loss of biodiversity, invasion of exotic species, and soil degradation (Carvalho and Batello, 2009; Oliveira et al., 2017).

3. An overview of surface-atmosphere interactions

LULCC can impact weather and climate by modifying biophysical properties of the land-surface, including albedo, energy fluxes, surface roughness and rooting depth (Lejeune et al., 2015; Pielke et al., 2011; Spracklen et al., 2018) and by altering biogeochemical processes including fluxes of carbon, trace gases and aerosols (Perugini et al., 2017; Spracklen et al., 2018).

Forested areas typically have lower albedo and therefore higher net radiation (Rn) compared with pasture or non-forest areas (Fig. 3). Conversion of natural forest vegetation to cropland or pasture increases albedo and decreases Rn. Since cropland/pasture vegetation is shorter with shallower rooting depths than forest, ET is lower and less Rn is converted to LE compared with forest. As a consequence, cropland/pasture has higher sensible heat flux (H) that warms the surface.

The main differences in the energy partitioning between forest and pasture occur in the dry season, when there is an increase in Rn and ET in the forest and a large decrease (33%) in ET in pasture compared with the wet season (Fig. 3). Differences in the energy balances are small between the two sites in the wet season, but seasonal dynamics differ significantly: while in the forest there is a small difference between the wet and dry seasons, in the pasture LE rates decrease (10%) and H rates increase (52%) in the dry season compared with the wet season. There are several reasons for these differences in seasonal dynamics, including: (i) forest vegetation has deep roots that can access stored soil water even in the dry season (Christoffersen et al., 2014; von Randow et al., 2004); (ii) changes in energy partitioning (between H and LE) and vegetation assimilation of the available energy (Rn, which differs from dry to wet season in forests due to the presence of more clouds) for photosynthesis (Priante-Filho et al., 2004; Restrepo-Coupe et al., 2013; Sakai et al., 2004); and (iii) changes in atmospheric conditions between dry and wet seasons (wind speed, relative humidity) that regulate evaporation rates (Priante-Filho et al., 2004; Restrepo-Coupe et al., 2013). The reduction in ET under pasture impacts and correlates with other hydrological variables, including increased runoff (Levy, 2013). Moreover, the changes in energy partitioning may influence

Table 1
Percentage of each biome area in farming in 2020, partitioned by the original land cover in 1985.

	% of biome area in farming in 2020					
Original land cover (1985)	Amazon	Cerrado	Caatinga	Pantanal	Atlantic Forest	Pampa
Total biome area (km^2)	4,212,023	1,984,566	862,599	150,943	1,106,560	193,916
Forest	11%	13%	12%	8%	7%	1%
Non-Forest Natural land cover	0%	3%	1%	5%	1%	16%
Farming	3%	28%	21%	3%	57%	25%
Total farming area (km^2) in 1985	126,361	555,678	181,146	4528	630,739	48,479
Total farming area (km^2) in 2020	589,683	873,209	293,284	24,151	719,264	81,445
Total farming area (%) in 2020	14%	44%	34%	16%	65%	42%
% from natural cover[a]	79%	36%	38%	81%	12%	40%

[a] Percentage of 2020 farming area from conversion of natural 1985 land cover (data source: Mapbiomas, 2021).

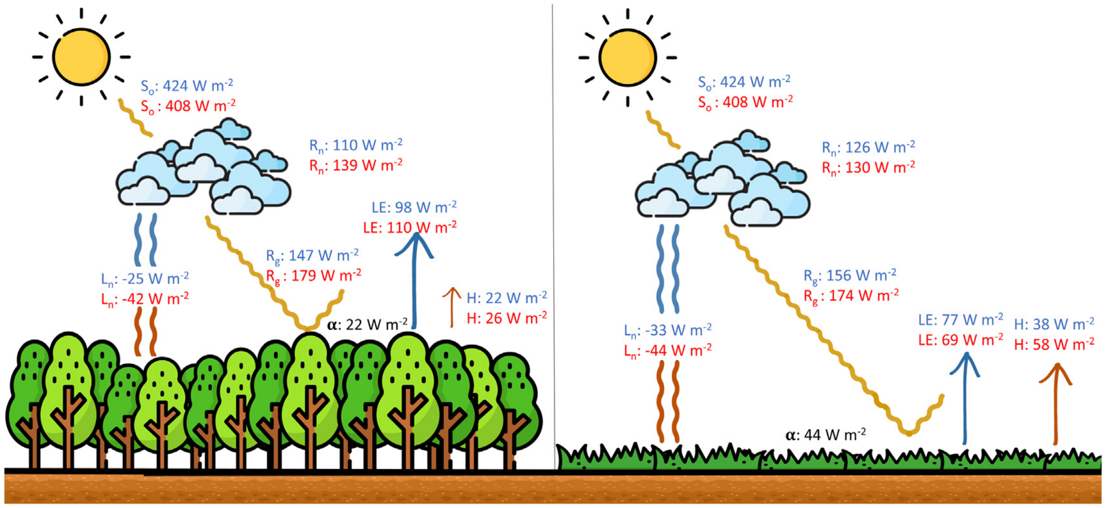

Fig. 3. Surface-atmosphere interactions in a tropical forest and in pasture in the Amazon biome. Data used is from LBA-ECO (CD-32) from the sites K83 (tropical forest, with selective logging) and K77 (pasture) for the year 2001/2002. Values in dark blue are the mean values from the wet season in the region (DEC-MAY – DOY 335–151) and red values are the mean of the dry season (JUN-NOV – DOY 152–334). The sites are at the same latitude (−3.01°) and are approximately 9 km apart. S0: incident radiation in the top-of-atmosphere; Rg: shortwave net radiation; α: albedo; Ln: longwave net radiation; Rn: net radiation; H: sensible heat; LE: latent heat. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

climate dynamics in the region, including longer dry seasons and delayed wet seasons, as discussed in the following sections.

4. Materials and methods

A significant challenge in land change research is to link observations of local changes with more general causes and consequences, and to go beyond specific case interpretations and "regional differences" (Turner et al., 2007). Synthesis methods are important for establishing systematic knowledge of land change phenomena (Magliocca et al., 2014). Hence, we conducted a systematic review of the types of LULCC occurring in the Brazilian territory and their impacts on surface-atmosphere interactions, focusing on three important variables: P, ET and atmospheric humidity (h). We followed the Preferred Reporting Items for Systematic review and Meta-Analysis (PRISMA) statement (Moher et al., 2010), which is "an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses" (Fig. 4).

An extensive search was carried out to identify peer-reviewed scientific papers that addressed the question of LULCC impacts in surface-atmosphere interactions. The scientific databases used were Scopus, Science Direct and Web of Science. English and Portuguese documents were included, and Boolean functions were applied to match the following keywords in the title, abstract or keywords: ("land cover change" OR "land use change" OR "deforestation") AND ("rainfall" OR "precipitation" OR "evapotranspiration" OR "atmospheric humidity") W/ ("Brazil*"). The first part of the search string identifies papers focusing on LULCC, searching for key words related to LULCC research. The second part of the string identifies papers that analyzed at least one of the three hydroclimatic variables. The last part of the string searches only for papers that included Brazil and its variations. Our search was not limited by the methodology or data used, so studies can include in situ, modeling, and remote sensing data and analysis.

The initial search yielded thousands of documents ($n = 3519$). Title and Abstract of the papers were then read and assessed for whether they mentioned LULCC and/or changes in surface-atmosphere interactions in Brazil. This step excluded a large number of nonrelevant papers (3412). The remaining 107 papers were downloaded and screened to meet all of the following criteria: (1) the study was carried out in Brazilian territory, regardless of its geographic scale; (2) information on at least one of the variables (precipitation, evapotranspiration or atmospheric humidity) was directly provided or could be indirectly estimated from the paper; (3) changes referred to past time periods, and not to simulations for future scenarios (which is not the scope of this study); and (4) changes in hydroclimate were linked to LULCC. From this step, 63 papers were selected.

Each research paper was then coded and basic data compiled, including: "Reference" (Authors and year); "Title"; "Journal"; "Biome" (In which Brazilian biome the study site was located); "Method used to determine the analyzed variables"; "Land cover and/or climate variability analyzed?" (When the study analyzed only LULCC, there is a "YES" to "Land cover analyzed?" and a "NO" to "Climate variability?"; when it analyzed only climate variability, there is a "NO" to "Land cover analyzed?" and a "YES" to "Climate variability?"; when analyzed both, there is a "YES" for both columns; and if it did not analyze either of them (e.g. only identified trends in climate without analyzing cause), there is "NO" in both columns); "Region" (In which region/basin the study was conducted); "Period" of the analysis; "Analyzed variables" (precipitation, evapotranspiration, atmospheric humidity); and, then, the main findings of the study. During the coding process the final selection was carried out and papers that did not mention changes in the analyzed variables were excluded, with 46 papers remaining after this step. Eight additional papers that were not identified by the search in the databases, but were known to evaluate the research question, were included in the review, for a total of 54 papers.

We included theses and dissertations, which we found using Google Scholar, since in Brazil there is not a unified system with all dissertations and thesis. We used the same criteria described above for the paper search, but in Portuguese. Some works from Brazil may not have been discovered using Google Scholar. However, to maintain the reproducibility of the methodology, we believe that this was the best way to proceed in this case. The search yielded in total 174 studies. After screening following the same criteria already described, 10 of those were selected. From the 10 studies, 3 of them had its results published as papers, which were already included in our systematic review of the papers. Therefore, in the end, 61 studies were selected to the systematic review.

5. Results and discussion

5.1. Summary of the studies

The Amazon biome had the most studies (36/61), followed by Cerrado (Fig. 5a), which was expected given the areal coverage and worldwide importance of these two biomes. We found no studies for the Pampa biome, only one that included the Caatinga (along with the Cerrado, in the São

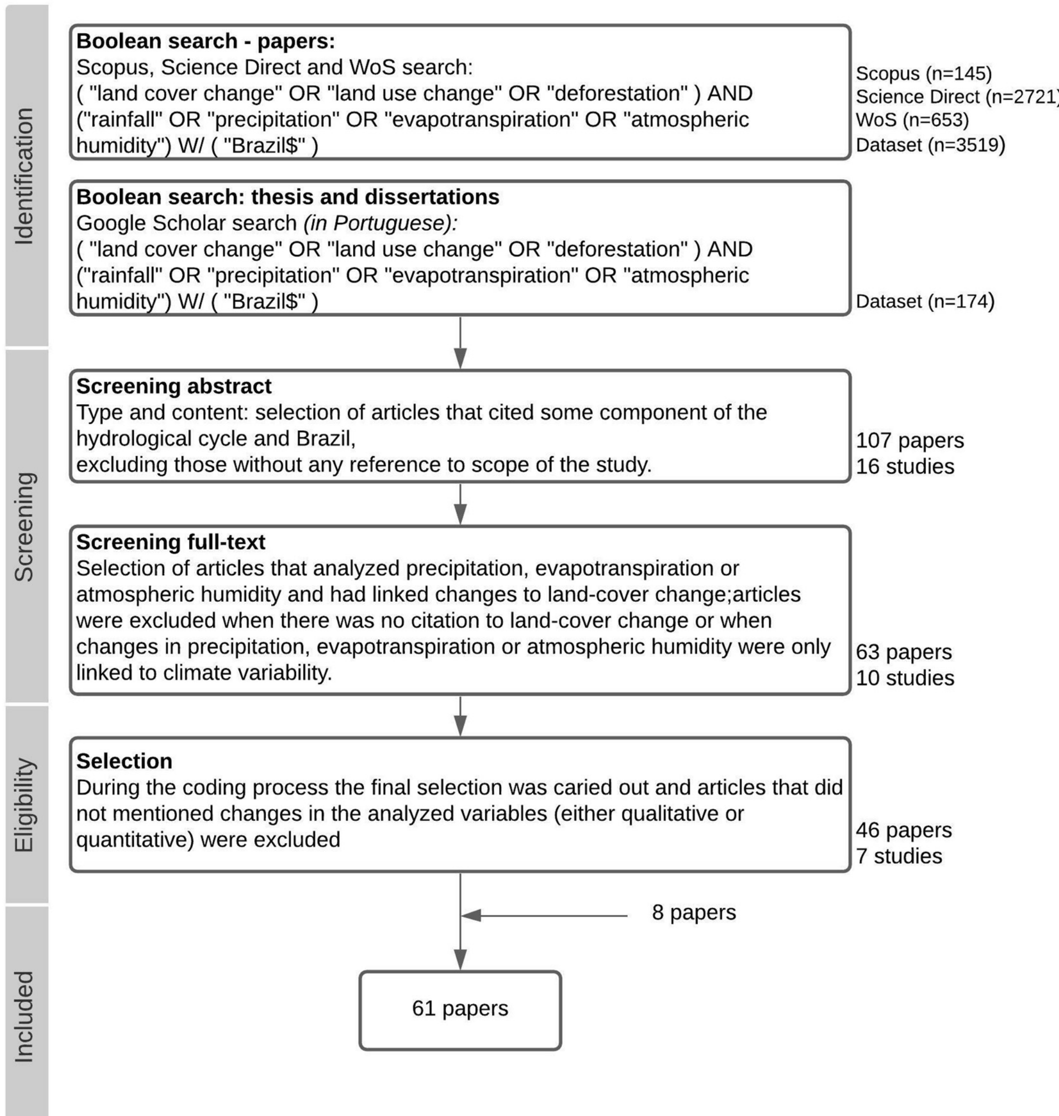

Fig. 4. Flow chart of the studies selection in the review (based on Biesbroek et al., 2018; Moher et al., 2010).

Francisco River basin), and one analyzing changes in P over the Pantanal. Moreover, most studies (54/61) were published in the last 10 years (Fig. 5c), which could be related to the advancement of new technologies, mainly the use of remote sensing (RS), in hydroclimate studies (Fassoni-andrade et al., 2021) (Fig. 5e; see Table SI1 for more details on methods). Precipitation was the most studied variable (45 studies) (Fig. 5d), but ET was also widely studied (33). Very few studies ($N = 4$) analyzed atmospheric humidity changes due to LULCC in Brazil.

Both climate variability and LULCC can affect observed trends in hydroclimate variables. In our search, we tried to only select studies that investigated the impacts of LULCC or in its discussion tried to separate the effects of LULCC and climate variability in the observed changes. However, some studies (6/61; Fig. 5b) did not evaluate LULCC, but we included them. For instance, Almeida et al. (2016) and Cauduro Dias De Paiva and Clarke (1995) did not directly evaluate the impacts of LULCC, however the changes observed in P were associated with deforestation by the authors (Table SI1). Oliveira et al. (2014) evaluated trends in P and ET over the Cerrado, but did not attribute the results to LULCC or climate variability. When LULCC and climate variability were assessed, some studies attributed part of the change in P, ET or humidity to one or another. For example, Panday et al. (2015) found that climate variability and deforestation had opposite effects on the water balance in eastern Amazon, but also that deforestation (decrease in forest cover from 80% of the basin in 2001 to 73% of the basin in 2010) alone caused a 3% decrease in ET across the basin.

5.2. Impacts of land use and land cover change on precipitation

Precipitation (P) varies through space and time and is affected by changing ocean conditions, atmospheric composition, land cover, and their interactions. Therefore, attributing trends in P to LULCC is challenging. Diverse factors will interfere in the results, such as the length period analyzed, the extent of LULCC in the area, and the methodology applied to detect the changes. P trends in Brazil have been widely studied including in 45 studies in our survey, nearly half ($N = 30$) of which were over the Amazon biome (Fig. 5d). Below we summarize the studies by biome.

5.2.1. Amazon biome

A wide range of P trends due to LULCC were reported over the Amazon, with different time periods, spatial scales, and methodologies (Table 2, Table SI2*)*. Analyzing the entire Amazon Basin, some studies found no trends in annual P (Table 2) (Arias et al., 2018; Cavalcante et al., 2019; Costa and Foley, 1999; Espinoza et al., 2019a; Furlan, 2009; Silva Junior et al., 2018). By contrast, negative trends were frequently reported for the

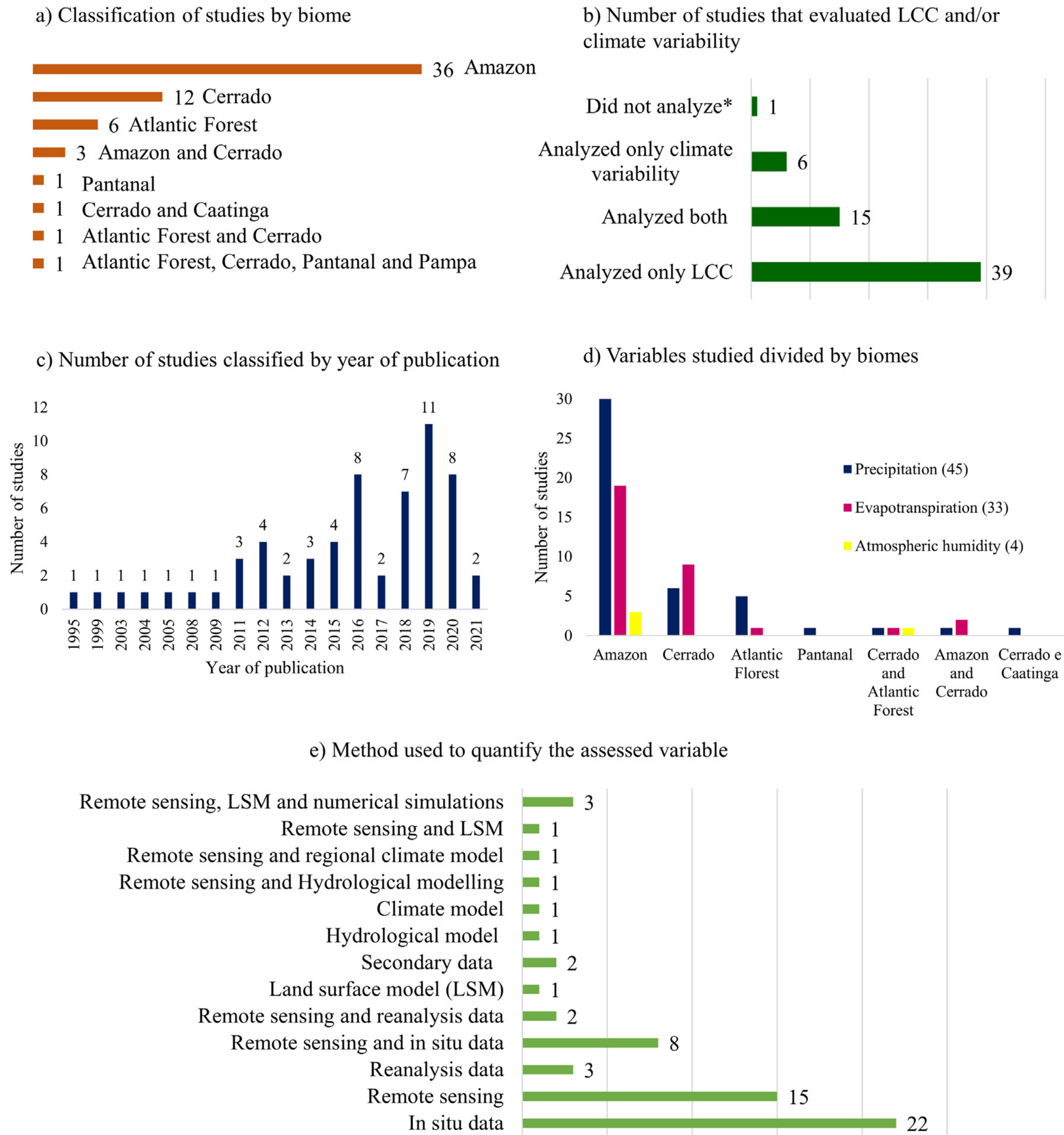

Fig. 5. Summary of the 61 studies included in the systematic review (see Table SI1). a) Classification of studies by biome; b) Number of studies that evaluated LULCC and/or climate variability (*Only analyzed trends, not relating them to either LULCC or climate variability); c) Number of studies classified by year of publication; d) Variables studied by biome; e) Method used to quantify the analyzed variable.

dry season, in some cases more negative at the end of the dry season (Almeida et al., 2016; Barkhordarian et al., 2019; Dubreuil et al., 2012; Espinoza et al., 2019a; Silva Junior et al., 2018). Decreasing dry season P diminishes soil water availability, which can reduce ET and further delay the onset of the wet season (Barkhordarian et al., 2019; Dubreuil et al., 2012; Leite-Filho et al., 2019, 2020). Debortoli et al. (2016) report a shorter wet season and longer dry season. In some cases, P increased in the wet season in some Amazon regions (Debortoli et al., 2016; Espinoza et al., 2019b; Heerspink et al., 2020; Santos, 2016).

In addition to examining trends in P, some studies compared the influence of land cover on P. Debortoli et al. (2016) showed that seasonal and annual P were not correlated with forest cover at the local scale in the southern Amazon (1–15 km) but at a regional level (30–50 km), negative trends in P overlap with areas with the most deforestation. Corroborating these findings, Khanna et al., 2017 showed that deforestation results in a shift from a thermally- to a dynamically-dominated convective regime, resulting in non-precipitating clouds. Similarly, de Oliveira et al. (2018) evaluated differences in P between four forested and deforested areas in the Amazon. Although there were no statistically significant differences in P between the two land covers, monthly P was modestly higher over small areas (< 10,000 km^2) within deforested regions, that could be related to changes in the local atmospheric dynamics due to vegetation removal, especially increased sensible heat flux and convection over deforested areas compared with forested area. Casagrande et al. (2018) found similar total annual P in forest and pasture of the Brazilian Amazon (2204 ± 285 mm year^{-1} in forest and 2163 ± 224 mm year^{-1} in pasture). The main differences between forest and pasture were found in the partitioning of P, with higher transpiration and canopy interception in forests than for pastures.

Hilker et al. (2014) demonstrated that annual P decreased in Southeastern Amazon over 2000–2012. Most of the eastern and southeastern parts of the Amazon basin and the areas bordering the subtropical grasslands had a net decrease in P (approximately 25%). Vergopolan and Fisher (2016) evaluated ET and P and its relation with deforestation for

Table 2
Summary of the main trends on precipitation and evapotranspiration reported in the selected studies.

Biome/Region	Trends Reported	Precipitation	Evapotranspiration	Predominant methods used[a]
Entire Amazon Basin	No annual trends	Arias et al. (2018), Cavalcante et al. (2019), Costa and Foley (1999)[a], Silva Junior et al. (2018), Espinoza et al. (2019a), Furlan (2009)	Costa and Foley (1999)[b]	in situ data, remote sensing, and reanalysis data
	Decreasing annual trends	–	Barkhordarian et al. (2019), Vergopolan and Fisher (2016)	reanalysis data and remote sensing
	Decreasing dry season trends	Barkhordarian et al. (2019); Silva Junior et al. (2018)	–	reanalysis data and remote sensing
	Increasing wet season trends	Heerspink et al. (2020)		remote sensing
Eastern Amazon	No annual trends	Cavalcante et al. (2019)	–	in situ data
	Decreasing annual trends	Panday et al. (2015)[c]; Hilker et al. (2014)	Cavalcante et al. (2019); Panday et al. (2015)	in situ data, LSM and remote sensing data
	Decreasing dry season trends	Almeida et al. (2016)[b]	–	in situ data
	Increasing dry season trends	Cauduro Dias De Paiva and Clarke (1995)[b]	–	in situ data
Central Amazon	Increasing annual trends	Heerspink et al. (2020)	Heerspink et al. (2020)	remote sensing
Western Amazon	Increasing annual trends	Heerspink et al. (2020)	Heerspink et al. (2020)	remote sensing
Northern Amazon	Decreasing annual trends	–	Heerspink et al. (2020)	remote sensing
	Increasing dry season trends	–	Baker and Spracklen (2019)	remote sensing
North-western Amazon	Increasing dry season trends	–	Barkhordarian et al. (2019)	reanalysis data
Southern Amazon	Increasing annual trends	–	Furlan (2009)	in situ data
	Decreasing annual trends	Espinoza et al. (2019b); Li et al. (2008); Rizzo et al. (2020); Heerspink et al. (2020)	Espinoza et al. (2019b)	in situ data, remote sensing, and reanalysis data
	Decreasing dry season trends	Dubreuil et al. (2012)	–	in situ data
	Increasing dry season trends	–	Baker and Spracklen (2019)	remote sensing
	Decreasing wet season trends	Dubreuil et al. (2012)	–	in situ data
	Increasing wet season trends	Debortoli et al. (2016); Espinoza et al. (2019b)	–	in situ data, remote sensing, and reanalysis data
	Shortening of the wet season	Dubreuil et al. (2012); Leite-Filho et al., 2020	–	in situ data and remote sensing
	Prolongation of the dry season	Debortoli et al. (2016), Espinoza et al. (2019a)	–	in situ data, remote sensing, and reanalysis data
	Delay in the onset of the wet season	Leite-Filho et al., 2019; Leite-Filho et al., 2020	–	in situ data and remote sensing
	Delay in the offset of the wet season	Leite-Filho et al., 2020	–	remote sensing
	No annual trends	Arias et al. (2018)	–	in situ data
South-eastern Amazon	Decreasing annual trends	Hilker et al. (2014)	–	in situ data
	Increasing wet season trends	Arias et al. (2018)	–	in situ data
South-western Amazon	Decreasing annual trends	–	Ichii et al. (2003)	in situ data
	Decreasing dry season trends	von Randow et al., 2004; Souza et al. (2019a)	–	remote sensing and in situ data
	Increasing dry season trends	–	Souza et al. (2019a)	remote sensing
	Decreasing wet season trends	Souza et al. (2019a)	Souza et al. (2019a)	remote sensing
Cerrado	No annual trends	Oliveira et al. (2014), Silva et al. (2020b)	–	remote sensing and in situ data
	Decreasing annual trends	Anache et al. (2019), Santos (2016)	Spera et al. (2016)	in situ data and remote sensing
	Increasing annual trends	–	Oliveira et al. (2014)[d]	remote sensing
	Decreasing dry season trends	Silva et al. (2020b), Salazar et al. (2016), Santos (2016)	Salazar et al. (2016), Nóbrega et al. (2017)[e], Andrade et al. (2014)	in situ data, model simulation, and remote sensing
	Decreasing wet season trends	Silva et al. (2020b); Salazar et al. (2016); Bezerra et al. (2019)[f], da Silva (2020)	–	in situ data, model simulation, and remote sensing
	Increasing wet season trends	Santos (2016)	Salazar et al. (2016)	remote sensing, in situ data and model simulation
Atlantic Forest	No annual trends	Webb et al. (2005)	–	in situ data
	Decreasing annual	Salazar et al. (2016)	Gomes et al. (2020)	model simulation and

Table 2 (*continued*)

Biome/Region	Trends Reported	Precipitation	Evapotranspiration	Predominant methods used[a]
	trends			hydrological model
	Increasing annual trends	Gomes et al. (2020), Martins et al. (2016), Xavier et al. (2020), Chagas and Chaffe (2018)	–	hydrological model and in situ data
	Decreasing dry season trends	Xavier et al. (2020), Salazar et al. (2016)	Salazar et al. (2016)	in situ data and model simulation
	Increasing wet season trends	Salazar et al. (2016)	Salazar et al. (2016)	model simulation

[a] More details of the methodology used in each study individually can be found in Table SI1.
[b] Changes were attributed to climate variability.
[c] No significant trend.
[d] ET increased for the entire biome; specific regions had decreasing trends (see Table SI3 from supplementary material);
[e] ET reductions for pasture (−45%) and Cerrado (−24%) vegetation from the wet to the dry season.
[f] Cerrado and Caatinga Biomes.

the years of 2000 to 2012 in transitional zones of forest and deforest areas of the Amazon basin. Annual P increased in all land covers but by less in deforested areas (+18.0 ± 3.9 mm), compared with forested-deforest boundaries (21.6 ± 4.0 mm), and forest (25.9 ± 4.0 mm).

Lathuillière et al. (2019) quantified indicators that reflected changes in P partitioning and the distribution of green and blue water resources of different land covers (cropland, rainfed to irrigated, and cattle) in the Amazon and Cerrado Biomes. The replacement of native vegetation by cropland had greater precipitation reduction potential (PRP, reduction in regional precipitation returning to the same basin) in the Amazon than in the Cerrado, especially for the rain-fed cropland, therefore indicating a decline in P (656m^3 in the Amazon and 304m^3 in the Cerrado).

These results show that the scale of the deforestation has a significant impact in the reported changes in P: at small scales (a few kilometers), deforestation tends to increase the H and therefore convection and P locally. At large scales deforestation decreases P by reducing regional atmospheric moisture and changing circulation patterns (Khanna et al. (2017); De Sales et al. (2020)).

5.2.2. Cerrado biome

In the Cerrado biome, trends and impacts of deforestation on P differ by study location and scale (Table 2). While Anache et al. (2019) and Santos (2016) reported decreasing trends in annual P (study site in São Paulo and Minas Gerais, respectively), others reported no trends for the entire biome (Oliveira et al., 2014) and for a basin located in Minas Gerais state (Silva et al., 2020b). Bezerra et al. (2019) reported significant decreasing trends in the average P on wet days and in the average number of consecutive dry days in the São Francisco River Basin, which is corroborated by Silva et al. (2020b), Da Silva (2020) and Salazar et al. (2016), who reported negative trends in P in the wet season and dry season. Campos (2018) found that annual P decreased 8.4%, however with insignificant negative correlation (−0.31) between mean annual P and deforested area. P trends over the Cerrado biome indicate that LULCC has caused a drier dry season, though more studies are needed.

5.2.3. Pantanal biome

Only one selected study (Bergier et al., 2018) analyzed P trends for the Pantanal biome, and found no significant change in mean P over all the seasons of the year (from 1926 to 2016). However, the mean rainfall rate on rainy days showed significant increasing trends (0.04 to 0.06 mm/day per year), suggesting an increase in rainfall intensity and extreme rainfall events in both wet and dry seasons. Spatiotemporal analysis suggested that the Amazon biome has an important control on summer P in the Pantanal.

5.2.4. Atlantic forest

Six studies evaluated P in the Atlantic Forest (Table 2). Increases in annual P were reported in four (Chagas and Chaffe, 2018; Gomes et al., 2020; Martins et al., 2016; Xavier et al., 2020), while Webb et al. (2005) reported no trends for annual P, and Salazar et al. (2016) reported decreasing trends. Salazar et al. (2016) reported P increases in the wet season, and decreases in P were found by both Salazar et al. (2016) and Xavier et al. (2020). These changes are unlikely due to LULCC given the high fraction of the bioma already converted to farming (Table 1).

5.2.5. Summary of impacts on P

In most biomes, few studies found trends in annual P. Seasonal trends in may offset each other (mainly Amazonia and Cerrado), which can mask the changes in the annual average. Trends in monthly and seasonal P were relatively common, most notably a reduction of P in the dry season, but this varies by the region of study, by the deforestation rate during the study period and by methodology.

5.3. Impacts of land use and land cover change on evapotranspiration

Replacing natural vegetation with other land covers can impact the surface energy balance: albedo typically increases and net radiation decreases (Fig. 3). The partitioning of surface energy into LE (ET) and H may also change, due to changes in surface and aerodynamic roughness, to changes in leaf area index, and to changes in the capacity of the vegetation to access soil water (root depth). The magnitude of impacts on ET will depend on the original and replacement land cover types, and on water availability, which is determined primarily by soil type and precipitation.

In this systematic review, we found a wide range of trends for ET in Brazil. However, there is a widespread consensus that replacement of forests at small spatial scales decreases ET rates. Studies analyzing the impact of LULCC on ET were mainly carried out in the Amazon and Cerrado, likely because of their global importance of playing a key hole in water and energy cycles, and historical and current high rates of deforestation and agricultural expansion.

5.3.1. Amazon biome

Conversion of forest to pasture and croplands is the main LULCC in the Amazon biome (Fig. 1). Many studies have analyzed ET trends in the Amazon (Table 2). Some reported positive trends in dry season ET (northern and southern amazon: Baker and Spracklen (2019); south-western Amazon: Souza et al. (2019a); north-west Amazon: Barkhordarian et al. (2019)). Heerspink et al. (2020) reported increasing annual ET in central and western Amazon and decreasing ET in northern Amazon. Furlan (2009) reported increasing annual actual and potential ET in the Rondônia State (south-western Amazon). Seven studies reported negative trends in ET. Barkhordarian et al. (2019) and Vergopolan and Fisher (2016) found decreasing ET in the entire Amazon basin. In the Eastern Amazon, Cavalcante et al. (2019) and Panday et al. (2015) also reported decreasing annual ET. Decreasing annual ET was also reported for the Southern Amazon (Espinoza et al., 2019b) and for the South-western Amazon (Ichii et al., 2003). Souza et al. (2019a) reported decreasing ET in the wet season over the south-western Amazon.

Conversion of forest to pasture or crops reduced ET in many studies (Baker and Spracklen, 2019; de Oliveira et al., 2018; Dias et al., 2015; Furlan, 2013; Lathuillière et al., 2012; Silvério et al., 2015; Vergopolan and Fisher, 2016). Baker and Spracklen (2019) found that annual mean ET was higher in intact forests than in non-intact and forest patches; areas where tree cover decreased by 70% between 2000 and 2013 showed the largest changes in mean annual ET ($-1.5. \pm 0.4$ mm month^{-1}). Furlan (2013) also reported annual ET was 33% lower in non-forest areas. ET seasonality increases with increasing deforestation, with greater differences at the end of the dry season. Vergopolan and Fisher (2016) also reported lower ET in deforested areas compared to forest-pasture border areas, although ET was higher in deforested patches located at regions of more exposed pasture-forest borders, possibly due to the high surface temperatures and high heat of convection.

For the south-western Amazon, Casagrande et al. (2018) found that annual ET was 31% higher in rainforest than in pasture, and Ichii et al. (2003) observed a strong correlation between the variation of forest cover fraction and ET, which decreased in a rate of 20 mm year^{-1} at the in situ station evaluated. de Oliveira et al. (2019) found that dry season ET was higher in forest (4.01 mm day^{-1}) than agriculture (0.84 mm day^{-1}). Also, in the south-western Amazon, von Randow et al. (2004) found that H was 28–45% higher while the annual ET rates are 20–41% lower in pasture compared with forest.

Silvério et al. (2015) reported that ET in southeast Amazon decreased by 32% in forest-to-crop transitions, and by 24% in forest-to-pasture transitions. In already deforested areas, ET decreased by 7% in pasture-to-crop transitions, croplands had the greatest impact on the energy balance, compared with forests. Dias et al. (2015) simulated annual ET, which was 39% lower in agricultural ecosystems (pasture and soybean cropland) compared with natural ecosystems (tropical rainforest and Cerrado) in the southeastern Amazon. ET was higher in the dry season than in the wet season for the forest, Cerrado, and perennial pasture, while soybean cropland had higher ET rates over its growing season (wet season, Nov to Feb) than in the dry season. de Oliveira et al. (2018) showed that ET in four deforested areas was lower than in four forested ones, and the range between seasonal maximum and minimum values was higher in deforested areas. ET rates were higher in the rainy season, with similar values in forested and deforested areas, while dry season ET was higher in the forested area and decreased to approximately 50 mm month^{-1} in deforested areas (a decrease of approximately 90 mm month^{-1} or approximately 30% of the wet season ET).

Lathuillière et al. (2012) analyzed changes in ET in rainforest, crop, and pasture in an area of the Amazon and Cerrado biomes from 2000 to 2009. In 2000, rainforest occupied 40% of the study area (900,000 km^2), contributing 50% of the annual total ET. Annual ET from the rainforest declined at a rate of 16.2 km^3 year^{-1} between 2000 and 2009, and by 2009, ET from the forest accounted for 40% of annual total ET. During the same period, the volume of crop ET doubled, but this increase was offset by the decline in ET from pastures. During 2000–2009, the volume of pasture ET was at least five times the crop ET volume, and the increase was spatially concentrated in the agricultural frontier. Laipelt et al. (2020), in a transitional zone between the Amazon and Cerrado biomes, found that converting forest vegetation to cropland and pasture substantially changes surface energy (H and LE) and water (ET) fluxes. Estimates of daily ET ranged between 2.0 (pasture) and 4.2 mm day^{-1} (forest), while grassland, savanna vegetation, and cropland presented rates of 2.9, 3.1, and 3.2 mm day^{-1}, respectively.

5.3.2. Cerrado biome

For the Cerrado biome, studies mainly evaluated the impacts of changes from natural vegetation to other land uses on ET. LULCC studies were conducted around 2010, when Brazil was the world's largest sugar-cane producer due to its biofuel program (Loarie et al., 2011). ET was generally higher in natural Cerrado vegetation when compared to anthropic land covers (Anache et al., 2019; Arantes et al., 2016; da Silva et al., 2015; Georgescu et al., 2013; Loarie et al., 2011; Nóbrega et al., 2017; Oliveira et al., 2014; Spera et al., 2016).

ET in the Cerrado biome decreased during the dry season (Table 2; Andrade et al., 2014; Nóbrega et al., 2017; Salazar et al., 2016) and increased during the wet season (Salazar et al., 2016). Spera et al. (2016) reported decreasing annual ET. By contrast, Oliveira et al. (2014) found increasing annual ET but also decreasing annual ET (by up to 45 mm year^{-1}) in some areas, including western Mato Grosso, northern Maranhão (two states that had the greatest deforestation, 40%, in the Cerrado between 2002 and 2010) and parts of São Paulo and Minas Gerais. Increasing ET, up to 183 mm year^{-1}, was found near the Pantanal Biome and in northern parts of Tocantins (near the Amazon Biome). Oliveira et al. (2014) suggested three hypotheses for increased annual ET: (i) anthropic activities that reduce ET can be offset by other anthropic activities, like reservoir construction and irrigation, that increase ET; (ii) LULCC in the Cerrado biome (pasture to crops) could have increased the ET; and (iii) increased evaporative demand from rising radiative forcing from greenhouse gases and increased temperatures. Another possible cause would be LULCC from already deforested areas: da Silva et al. (2015) showed that ET of eucalyptus plantations is very similar to that of the natural Cerrado vegetation, while Loarie et al. (2011) found increasing ET when crops/pasture transitioned to sugarcane plantations. Cropland management also impacts differences in ET compared to native Cerrado vegetation. Spera et al. (2016) found that double cropping diminished the differences in ET between crops and native vegetation by 39%. Seasonality also impacts ET rates over the Cerrado Biome, with reduced rates of ET in the dry season and, in the wet season, increases in ET (Arantes et al., 2016; Nóbrega et al., 2017; Salazar et al., 2016).

5.3.3. Atlantic Forest biome

For the Atlantic Forest Biome, the studies (Table 2) agree that LULCC caused a decrease in ET rates, though the magnitude of these changes differed by season. This biome has historically suffered from LULCC and has only a few fragments of intact forest left. Gomes et al. (2020) analyzed the impacts of LULCC (pasture, forest, and coffee) on ET from 1990 to 2015, and reported the area of pasture in the region has decreased from 76% to 58%, the forest coverage has increased from 18% to 24%, and the coffee area has increased from 3% to 11%. During the same period ET decreased -15.7 mm year^{-1}, which was due to LULCC after controlling for precipitation variability.

Analyzing the historical impacts of LULCC on ET in the Atlantic Forest is complicated by the lack of data, both of land cover and meteorological variables, in the period prior to large scale land cover change. Already quite anthropized and with several reforestation activities, the Atlantic Forest has had relatively few studies on the effects of LULCC on hydrological variables.

Ruscica et al. (2021) analyzed the P variability and LULCC impacts on austral summer ET over the Southeastern South America, more specifically in the South Atlantic Convergence Zone (SACZ) region, upper La Plata Basin (uLPB), and lower La Plata Basin (lLPB), encompassing areas from Atlantic Forest, Cerrado, Pantanal and Pampa Brazilian biomes. In the lLPB, ET was driven by P variability and showed a positive trend between 2 and 4 mm/season/decade. In the uLPB, LULCC caused a negative ET trend. For the SACZ region, ET trends were uncertain.

To summarize the main results (Fig. 6, Table 3): in the Amazon biome, the most reported trends where ET decrease annually and increases in the dry season. For P, studies diverged, reporting either decreasing or no trends for annual. Overall, there is an increase in the dry season severity over the biome. For the Cerrado, ET decreased in the dry season, except in irrigated areas, and P decreased in the wet season. For the Atlantic Forest, annual P increased, however P decreased in the dry season. Wet season ET increased, however annual and dry season ET decreased. Increases in P and ET may be in part because the region was already extensively deforested and has experienced recent reforestation.

5.4. Impacts of land use and land cover change on atmospheric humidity

Atmospheric humidity transports energy and mass through continental moisture recycling. ET increases the water vapor content in the

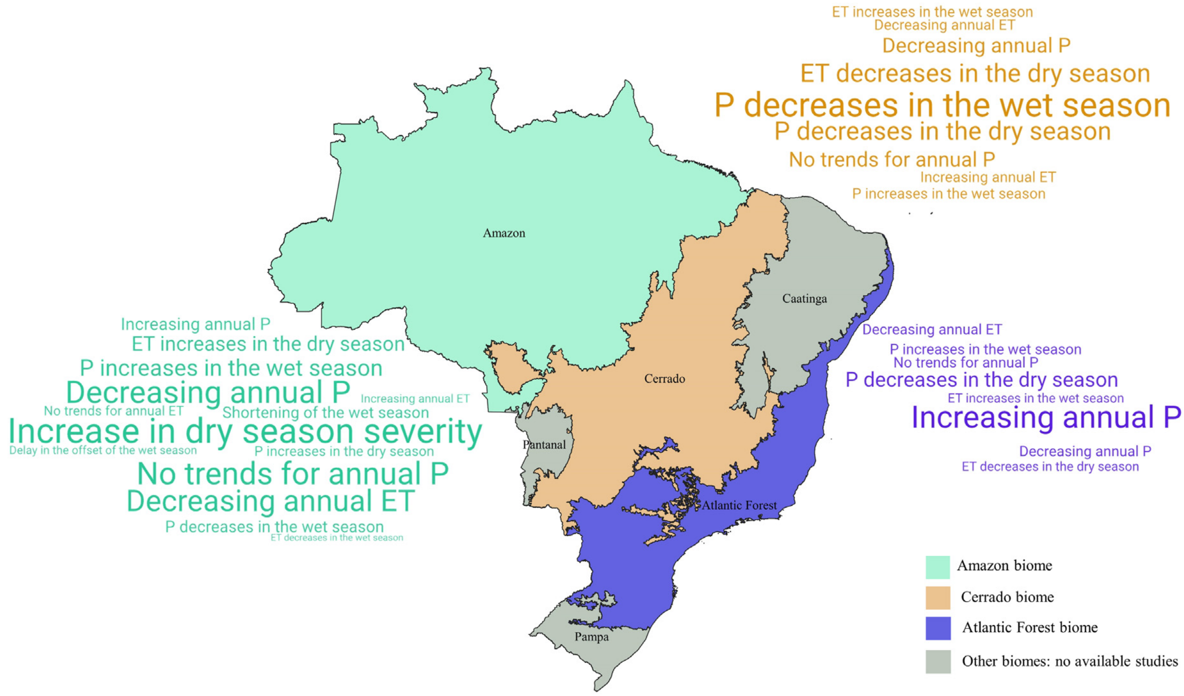

Fig. 6. Synthesis of the main results found for P and ET trends over the Brazilian biomes Amazon (blue green), Cerrado (orange), and Atlantic Forest (purple). Number of studies (N) for each biome: Amazon ($N = 36$), Cerrado ($N = 12$), and Atlantic Forest ($N = 6$). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

atmosphere, which will contribute to P in that region or another location (Sorí et al., 2018). Moreover, forest cover can generate a large-scale pressure gradient through moisture evaporation and condensation, thereby forming a convergence of the ocean and land water vapor flux, thereby producing rainfall (Makarieva and Gorshkov, 2007).

Despite the key role that atmospheric humidity plays in the hydrological cycle, our systematic review revealed a gap in studies analyzing the effects of LULCC on this variable in Brazil. Four studies analyzed the effects of LULCC on atmospheric humidity, including trends in Vapor Pressure Deficit (VPD) over tropical forests (Barkhordarian et al., 2019), trends in atmospheric transport of water vapor in the Amazon basin (Costa and Foley, 1999), differences in specific humidity in the dry and wet seasons over forest and pasture in the Amazon (von Randow et al., 2004) and, lastly, deforestation impacts on atmospheric moisture in the Cerrado and Atlantic Forest (Salazar et al., 2016).

Barkhordarian et al. (2019) separated the impacts of internal and external forcing on atmospheric humidity over tropical South America (2003–2016). VPD increased in response to LULCC in dry months. Over the south-eastern Amazon, VPD increased approximately 6 ± 2 mb over the period 1987–2016, caused by approximately +2 °C warming that increased the saturation vapor pressure and decreased the dew point (approximately −2.5 °C). Continental ET (LE flux) in the southeastern Amazon represents an important source of moisture for the onset of the wet season. Drier and longer dry seasons have been aggravated by LULCC activities, such as biomass burning and deforestation, though regional warming caused by increased greenhouse gas concentrations was the primary cause of increasing VPD.

Costa and Foley (1999) examined a 20-year record (1976–1996) and found a decreasing trend in the atmospheric transport of water vapor both into and out in the eastern part of the Amazon basin, where water vapor is advected in from the tropical South Atlantic. Since no significant changes were found for ET in the basin, and an increase was observed in the recycling ratio of the basin (quantity of water vapor contributing through local ET), the authors associated the change in water vapor to large-scale changes in the general circulation of the tropical atmosphere, causing a reduction in the source of water vapor into the Amazon basin.

von Randow et al. (2004) observed much lower specific humidity and P in the dry season compared with the wet season over 1999–2002 in both pasture and forest in the southwestern Amazon. Specific humidity was higher in the forest (15.8 g kg^{-1} in the dry seasons to 17.5 g kg^{-1} in the wet seasons) compared with the pasture (13.4 in the dry and 16.0 g kg^{-1} in the wet seasons).

Salazar et al. (2016) modelled vegetation–climate interactions for a 30-year period (1981–2010) for non-Amazonian South America biomes, including the Cerrado and Atlantic Forest in Brazil. They found negative trends in atmospheric humidity in the dry season, concurrent with deforestation. This decrease was more accentuated in areas where forests were converted to crops and pasture. Temporal and spatial changes of ET were accompanied by a decrease in relative humidity (RH). The Atlantic Forest and Cerrado had the largest average reductions in RH (6% of the value in 1981), with a maximum of 22% in areas with the largest reductions in LAI. During the wet season, RH of the Atlantic Forest decreased significantly by 6%. In contrast, Cerrado's RH did not change significantly.

Table 3
Summary of trends in P and ET by biomes. -, 0 and + indicate negative, no, and positive trends, and the numbers indicate the number of studies.

	Amazon	Cerrado	Atlantic Forest
P			
Annual	- (7) 0 (6) + (1)	- (2) 0 (2)	- (1) 0 (1) + (4)
Dry season	- (6) + (1)	- (3)	- (2)
Wet season	- (2) + (4)	- (4) + (1)	+ (1)
ET			
Annual	- (7) 0 (1) + (2)	- (1) + (1)	- (1)
Dry season	+ (3)	- (3)	- (1)
Wet season	- (1)	+ (1)	+ (1)

Continental moisture recycling is essential for the South American hydrological cycle (Zemp et al., 2014). The Amazon rainforest has a key role in this process, where 25% to 35% of the moisture is regionally recycled (Eltahir and Bras, 1994). Especially in the wet season, moisture from the Amazon Basin is drained from the basin and transported along the Andes through the South American Low-Altitude Jet (SALLJ), which promotes precipitation in the La Plata Basin (Satyamurty et al., 2013; Sorí et al., 2018; Van Der Ent et al., 2010; Zemp et al., 2014). LULCC from natural to anthropic land covers often reduces ET, resulting in a decline in the water vapor supply to atmospheric transport, which may impact P not only locally, but regionally (Van Der Ent et al., 2010).

Spracklen et al. (2012) demonstrated the importance of ET from dense forests to moistening air masses exposed to them, increasing the amount of P that this air mass will yield. Evaporation rates over land are lower than over the ocean, so the air becomes drier when it is transported over land, but air masses exposed to more vegetation remain moist. Makarieva et al. (2009) showed that global forest cover has an important role in the atmospheric circulation and water cycling on land: in areas without forests, P decreases with the distance from the ocean, but in forest-covered regions P does not decrease or even increases over several thousand kilometers inland. Moreover, Baudena et al. (2021) found a nonlinear relationship between atmospheric moisture and precipitation, estimating that on average a 13% reduction in atmospheric moisture due to transpiration loss from deforestation could potentially cause a 70% reduction in average P annually. Maintaining natural forests intact is important to sustain continental moisture recycling and P rates over regions that depend on it.

5.5. Limitations and future prospects

In order to discuss the main limitations of the reviewed studies, we primarily focused on the methods used to measure the studied variable. In situ data were used most frequently ($N = 22$), followed by remote sensing (RS) measurements ($N = 15$). The use of observational data, although it can accurately measure a specific variable and its trends, can have limited spatial representation, data availability, and network operation and maintenance can be challenging. For instance, Almeida et al. (2016) and Cauduro Dias De Paiva and Clarke (1995) analyzed P trends using data from 47 and 48 stations, respectively, for all Amazon basin, which despite being a significant number of stations, did not cover the entire region equally. This data limitation can cause bias in trends detection. Other studies included a significant number of stations, such as Chagas and Chaffe (2018) who analyzed in situ data from 675 rain gauges for the entire south of Brazil, deeply and carefully addressing the quality of the data. When utilizing only in situ data to detect trend analysis, it is important to carefully address errors, missing data, and the spatial distribution of the observational sites. New catchment datasets have become available for large-sample hydrological studies in Brazil. CAMELS-BR (Chagas et al., 2020) and CABra (Almagro et al., 2021) provide long-term hydrometeorological data for all Brazil, representing a unique opportunity to enhance hydrometeorological studies at a national scale.

Remote sensing data are a useful alternative to estimate hydrological and meteorological variables especially due to its spatial and temporal resolution, enabling temporal and large-scale studies (Fassoni-andrade et al., 2021; Kandus et al., 2018; Zhang et al., 2016). However, quantification of the quality of the data is needed in order to verify its applicability to the studied region, given possible biases and errors. New and existing remote sensing products and databases are important sources of data that can be explored in many and different ways to realize studies on LULCC impacts in surface-atmosphere interactions, hydrological cycle, water availability, energy balance, and climate change. Remote sensing products were used alone but also combined with reanalyzes data (Espinoza et al., 2019a, 2019b), compared with hydrological models (Casagrande et al., 2018) and used as an input data to regional climate models (Khanna et al., 2017), land surface models (Panday et al., 2015), and both (Spracklen et al., 2012).

Reanalysis data were used by Barkhordarian et al. (2019), Costa and Foley (1999) and Li et al. (2008). Reanalysis data are alternatives for spatial and temporal evaluations at different scales (Bhattarai et al., 2019), and have been combined with remote sensing-based models and in situ data. Laipelt et al. (2021) implemented an algorithm (geeSEBAL) for ET estimation on Google Earth Engine (GEE) environment, utilizing meteorological inputs from reanalysis data (ERA5 Land). When comparing with ground measurements at the flux towers, results yielded similar errors and reanalysis data was found to provide satisfactory ET estimations over Brazil.

P is the main dynamic input for most hydrological analyses and predictions, and it was the most analyzed variable in the reviewed studies. Often, especially in developing countries, surface-based data sources are insufficient to provide spatial resolution consistent with the spatial variability of other key controls of the surface hydrological cycle (Lettenmaier et al., 2015). Satellite precipitation products represent an essential source of data for these areas. Algorithms based on TRMM (and now GPM) precipitation radar combined with multiple passive microwave sensors have made possible satellite-only products that are useful in hydrology and may not require adjustments from in situ measurements (Lettenmaier et al., 2015). However, these datasets present some common issues, such as errors that are often passed on to the multi-satellite products and orographic enhancement or precipitation suppression is often mishandled (Shige et al., 2013). In Brazil, the CHIRPS product has often been used to detect trends in P (e.g. Paca et al., 2020), but the number of stations used for its calibration has decreased sharply since 2000 (Mu et al., 2021a). Assimilation of newly-available rain gauge data can be used to improve calibration of CHIRPS and other remote sensing-based P products, which can detect trends in P, such as drying in agricultural areas of the Amazon, that are not observed in other datasets (Mu et al., 2021a).

Due to its cost-effectiveness, wide coverage, repeatability, and reasonable accuracy, satellite remote sensing for ET estimation has been widely used. There are different methods that can be used to retrieve ET from satellite images, each with its own advantages and limitations (see Zhang et al., 2016 for details on the different methods and limitations). Calibration and validation of these datasets is important to assess their accuracy and appropriateness for specific applications (Lettenmaier et al., 2015). Therefore, combining already available in situ data with remote sensing products can reduce uncertainties from remote sensing products and upgrade the spatial and temporal analysis of studies. From the selected studies, 7 (seven) used in situ observations to validate remote sensing ET estimations. de Oliveira et al. (2019) and Laipelt et al. (2020) used the Surface Energy Balance Algorithm for Land model (SEBAL) to estimate ET in different areas using satellite images, validating the results with flux tower observations. RS products can be used and validated with in situ measurements in order to bring more accuracy to the results. MOD16 tends to underestimate ET in areas with sparse vegetation and high rates of soil evaporation (Biggs et al., 2016; Souza et al., 2019b) has lower accuracy in heterogeneous landscapes (Li et al., 2019) and higher accuracy in dense and homogeneous forested areas (Kim et al., 2012). Therefore, these particularities of the different available products have to be taken into account when using them, especially when they are used as an input to the water balance or other models, such as LSM. ET estimates from RS have also been used as observational benchmarks to evaluate land surface (LSM) models (Mueller et al., 2013; Schwalm et al., 2013).

Each ET method is sensitive to the choice of input data and algorithm or model used. Since errors in ET calculations usually appear as biases rather than random errors, ET estimations over large areas may be affected by these small deviations being amplified (Pascolini-Campbell et al., 2021). Moreover, there are still substantial uncertainties in parameters such as albedo, aerodynamic temperatures, and surface emissivity (Lettenmaier et al., 2015). Further, there is a limited number of ground verification sites, which also have measurement limitations and bias (Lettenmaier et al., 2015; Pascolini-Campbell et al., 2021).

RS and LSM products may underestimate interannual variability in ET (Pascolini-Campbell et al., 2021), mainly when analyzing large areas, where ET is usually estimated as the residual of precipitation and streamflow (water balance approach) (Lettenmaier et al., 2015). Missions such as GRACE and GRACE Follow-on, which estimates the water storage, will improve ET estimations based in the water-balance approach. Advancements and improvements of modeling and remote sensing data are enabling almost independent estimates of the water components, and future new technologies may achieve water budget closure of satellite-retrieved water components (Lettenmaier et al., 2015; Zhang et al., 2016). Nonetheless, more precise estimation of ET is still limited by the accuracy and frequency of current satellite retrievals of the multiple variables and land surface conditions that control ET (Lettenmaier et al., 2015). To improve ET estimates and reduce uncertainty, ensemble approaches merging multiple products (Jung et al., 2010; Mueller et al., 2013) and data fusion methods (Yao et al., 2014) have been used (Zhang et al., 2016).

Table 4 provides an overview of the main limitations in research on LULCC impacts on P and ET for each biome, as well as the main findings and the research opportunities. Overall, the main limitation found is the lack of studies analyzing LULCC impacts on surface-atmosphere interactions in the Brazilian biomes Pampa, Pantanal and Caatinga. Impacts on atmospheric humidity were also not well analyzed.

For the Pampa biome, exploring the increase of irrigated agriculture is an excellent opportunity to analyze impacts on ET. This biome has been suffering from significant LULCC over the years, with replacement of its natural grasslands to croplands and pasture (Oliveira et al., 2017). Remote sensing products can be an easy and manageable opportunity to study impacts on the surface-atmosphere interactions in this biome.

More studies that investigate already anthropized biomes, such as the Atlantic Forest, and their influence on surface-atmosphere interactions are required. Different models for ET and land surface temperature retrieval using satellite images, such as Landsat, are also available. Areas with reforestation are an opportunity to analyze the impacts of preservation or restoration, and can demonstrate the importance forests for ecosystem services.

The Caatinga biome has high temporal and spatial variability of P, with a dynamic ecosystem adapted to quickly respond to P fluctuations (Silva et al., 2020a). Extensive droughts have been occurring in the decade from 2011 to 2020, with severe drought in 2012 and 2016 (Silva et al., 2020a). Extensive burning and replacement of natural vegetation with agriculture has accelerated environmental degradation and susceptibility to desertification over some parts of the biome, especially during severe drought (Cunha et al., 2020; Silva et al., 2020a). The water surface area also decreased by 17.5% from year 1985 to 2020 (MapBiomas, 2021). There is a growing need to observe the condition and response of vegetation to high land cover pressure and more severe dry seasons (Silva et al., 2020a).

Understanding how LULCC affects surface-atmosphere interactions in the different biomes of Brazil is key to analyze both local effects and impacts on distant locations via teleconnections. ET from The Amazon biome is a significant source of moisture for southeastern South America through low-level atmospheric transport ("flying rivers") (Pearce, 2020; Van Der Ent et al., 2010). Martinez and Dominguez (2014) estimated that the southern Amazon contributes approximately to 20% of the atmospheric moisture that precipitates annually over the La Plata River Basin. The forest and lateral transport of its atmospheric moisture is also an important buffer against drought in agricultural regions (Mu et al., 2021b). Moisture tracking algorithms based on climate models (see overview by Keys et al., 2014) can be used to trace sources of moisture to a given location and could be used to understand lateral moisture transport among biomes in Brazil.

Several studies agree that dry seasons have become longer and drier, but all studies evaluated only local LULCC impacts on P. Therefore more studies that analyze teleconnections between LULCC and P over other regions are recommended, combining LULCC-caused changes in surface-atmospheric interactions and alterations on climate in a regional perspective (Costa and Pires, 2010; Salazar et al., 2015). For instance, more frequent long dry seasons in the southern Amazon can impact atmospheric moisture transport towards northern South America and the Caribbean region, enhancing atmospheric moisture content over the Caribbean and northern South America regions, and reducing total and recycled atmospheric moisture in the southern Amazon (Agudelo et al., 2019).

Table 4
Summary synthesis of the main limitations and research opportunities found.

Biome	Limitations	Opportunities
Amazon	Significant differences among different regions of the biome, either in relation to the results found in the studies, or in relation to the dynamics of land cover; Few studies of the impact of LULCC on atmospheric humidity.	Remote sensing products and reanalysis data are an opportunity to research impacts of LULCC on atmospheric circulation in order to analyze not only vertical atmospheric fluxes but also horizontal transport, to effectively understand the impacts of Amazon deforestation on other areas.
Cerrado	Most studies analyzed surface-atmospheric fluxes comparing different land covers locally, which cannot be spatialized over the entire biome.	Remote sensing products allied with in situ data can provide a valuable resource to understand the impacts of historical LULCC over surface-atmospheric interactions more spatially.
Caatinga	Lack of research analyzing surface-atmosphere interactions in this biome; Region with high precipitation variability.	Remote sensing products combined with in situ data can overcome the challenge of spatial and temporal variability over the biome.
Pantanal	Only one study analyzed surface-atmosphere interactions.	The biome has been suffering with severe temperature and drought events, therefore monitoring these events in order to understand the causes and consequences of them are important.
Atlantic Forest	Overall studies analyzed local impacts of LULCC, not over the entire biome; Already very anthropized; Cover a significant proportion of the Brazilian territory with strong climate conditions.	Understand how the anthropic pressure has affected surface-atmosphere interactions; Significant number of preserved areas and regions with reforestation are an opportunity to analyze the impacts of preservation and restoration efforts; Remote sensing products can overcome the challenge of spatial and temporal analyses over the biome.
Pampa	Lack of research analyzing surface-atmosphere interactions.	Advancement of irrigated agriculture over natural grasslands, therefore analyzing the quantity of water used for irrigation, through ET, is essential to understand water availability in the region.

Deforestation in one region can also affect other regions on the globe. Many scientists have claimed that historical deforestation was the cause of desertification in the Australian Outback and West Africa (Pearce, 2020). What could be the effects of actual and future deforestation of the Amazon rainforest on regional and global climate? Deforestation can change weather patterns outside the flying rivers (Pearce, 2020). Ruiz-Vásquez et al. (2020) analyzed the changes in atmospheric moisture transport towards tropical South America during the period 1961–2010 using two different scenarios (deforestation of 28 and 38% the Amazon basin), observing that deforestation over the Amazon basin increases the frequency of longer dry seasons in the central-southern Amazon (by between 29 and 57%) and continental sources reduce their contributions to northern South America at an annual scale by an average of between 40 and 43%. Some studies have addressed the impacts of deforestation and climate variability on atmospheric circulation, however, analysis is needed of the impacts of LULCC on both vertical and horizontal moisture fluxes.

6. Conclusion

This study reviewed literature to analyze and demonstrate the main impacts that land use and land cover change (LULCC) has had on surface-atmosphere interactions, namely precipitation, evapotranspiration and atmospheric humidity, in the biomes of Brazil. Significant LULCC has occurred in all biomes, with significant replacement of forest and natural vegetation by pastures and agriculture of tropical forests in the Atlantic Forest, Amazon, as Cerrado. We also reviewed some of the main impacts of LULCC changes on surface-atmosphere interactions, with conversion of forest to pasture/agriculture causing changes in albedo, turbulent fluxes (LE, H), and therefore P, ET and atmospheric humidity.

Most studies in our systematic review assess the Amazon and Cerrado biomes, with few assessing the Atlantic Forest, one in Caatinga and none in the Pampa. P is the most frequently analyzed variable, followed by ET. Few papers analyzed LULCC impacts on atmospheric humidity. Papers showed a wide range of trends, however, for the Amazon, LULCC seems to be decreasing P in the dry season and decreasing annual and dry season ET. For the Cerrado, P decreased in the wet season and ET decreased in the dry season, with ET increasing due to irrigation also reported. For the Atlantic Forest, annual P increased and ET decreased in dry season and annually, and also increases in ET in the wet season, likely due to reforestation. Cerrado has experienced increased ET due to irrigation expansion. The unexpected increase in ET in the Atlantic Forest and Cerrado biomes shows 1) the importance of the position of a given biomes in the long-term (decadal to centennial) land cover transition process; some heavily deforested regions may be experiencing reforestation or irrigation and increasing ET, and 2) of the local climate, which dictates whether irrigation will expand and increase ET.

Our overview summarizes local results in order to synthesize the impacts of LULCC in Brazil, which is still experiencing extensive LULCC in its biomes, especially in the Amazon rainforest, with implications for local, regional, and global climate.

CRediT authorship contribution statement

C.B·C and A.R. designed the study and implemented the research. C.B·C analyzed the results and wrote the manuscript with input from all authors. A.R and T. B supervised and revised. All authors have read and agreed to the published version of the manuscript.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.152134.

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