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Key Points:
- During drought years, ocean sources of precipitation failed while the percent contribution from forests increased
- Rainfall in a key agricultural region of the Amazon is vulnerable to forest loss
- Forests are important for precipitation for this agricultural region of the Amazon, but forests have varying levels of protection

Supporting Information:
- Supporting Information S1

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Forests Mitigate Drought in an Agricultural Region of the Brazilian Amazon: Atmospheric Moisture Tracking to Identify Critical Source Areas

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Abstract Tropical rainforests provide essential ecosystem services to agricultural areas, including moisture recycling. In the Amazon basin, drought frequency has increased in the late 20th and early 21st centuries, but the role of forests, ocean, and nonforested areas in causing or mitigating drought has not been determined. Using a precipitationshed moisture tracking framework, we quantify the contribution sources of evaporation to rainfall in Rondônia in the Brazilian Amazon. Forests account for ∼48% of annual rainfall on average, and more than half of the forest source is from protected areas (PAs). During droughts in 2005 and 2010, moisture supply decreased from oceans and nonforested areas, while supply from forests was stable and compensated for the decrease. Remote sensing and land surface models corroborate the relative insensitivity of forest evapotranspiration to droughts. Forests mitigate drought in the agricultural study region, providing an important ecosystem service that could be disrupted with further deforestation.

Plain Language Summary Tropical rainforests provide ecosystem services for humanity, including moisture recycling, which refers to moisture that evaporates from a forest, travels through the atmosphere, and returns as precipitation downwind. Drought frequency has increased in parts of the Amazon, but the role of forest ecosystem services in mitigating or exacerbating droughts is not known. We used a climate model to examine the contribution of forest, ocean, and nonforested areas, which include agriculture, to rainfall during normal and drought years in the Brazilian State of Rondônia in the Amazon Ocean sources contributed less during severe droughts, and forests contributed more and mitigated the reduction of rainfall. We conclude that the rainfall in this part of the Amazon is vulnerable to forest loss in other parts of the Amazon, which buffers the magnitude of rainfall reduction during drought events.

1. Introduction

The Amazon forest is the largest contiguous tropical forest ecosystem on Earth, covering around 4 million km^2 (Espírito-Santo et al., 2014). By 2012, ∼20% of the Amazon forest cover had been converted to pasture, agricultural lands, and other human-dominated lands (Souza et al., 2013). The Amazon forest is a major moisture source for the atmosphere, so human-induced land cover changes, such as large-scale deforestation, can weaken regional moisture recycling and reduce rainfall (Bagley et al., 2014; Dominguez et al., 2009; Durieux et al., 2003; Ruiz-Vásquez et al., 2020; Spracklen & Garcia-Carreras, 2015; Tuinenburg et al., 2014; Wei et al., 2013), including over agricultural regions (Spera et al., 2016). Eddy flux correlation tower and soil moisture data consistently show that ET over pastures is lower than ET from forests (Gash & Nobre, 1997; Hodnett, Oyama, et al., 1996). In the southern Amazon, ET in pastures is lower than ET in forests in both the wet (20.5% lower) and dry season (41.2% lower) (von Randow et al, 2004). The decrease in ET in both dry and wet seasons is due to higher albedo, higher longwave emission, and lower leaf area in pasture compared to forests, while the larger decreases in the dry season are also due to shallow rooting depths of grasses compared with forests (von Randow et al., 2004; Wright et al., 1996). Remote sensing (Khand et al., 2017) and regional modeling also suggest that deforestation decreases evapotranspiration (ET) and reduces atmospheric moisture of Amazonian origin during the dry season (Eiras-Barca et al., 2020). Relative humidity of the Amazon rainforest has also decreased over the last 20 years due mostly to increased temperatures but also deforestation, increasing evaporative demand, and leaving forests and agroecosystems vulnerable to drought (Barkhordarian et al., 2019).

Large areas of the Amazon basin experienced severe droughts in 2005, 2010, and 2015 (Panisset et al., 2018). Amazonian droughts are triggered by ocean conditions: El Niño Southern Oscillation (ENSO) events were important in the droughts of 1982, 1987, 1997–1998, and 2015, while droughts in 2005 and 2010 were mainly caused by high sea surface temperature anomalies in the North Atlantic Ocean, which created a dipole that increased subsidence and decreased rainfall over the southern Amazon (Marengo et al., 2015; Zeng et al., 2008). Land surface conditions can either mitigate or exacerbate reduced moisture supply from the ocean: Forest and pasture systems both have deep roots that allow them to access moisture and maintain ET even during drought conditions (Hodnett et al., 1996b; Nepstad et al., 1994), thereby maintaining water supply to the atmosphere, though pastures are generally more sensitive to drought than forests (Oliviera et al., 2019), and a reduction in ET by pastures could exacerbate drought. While ocean conditions are important drivers of drought, the role of forest and nonforest cover in mitigating or exacerbating drought in agricultural areas of the Amazon have not been quantified.

Keys et al. (2012) introduced the concept of "atmospheric watersheds," or precipitationsheds, to better understand how evaporation from upwind ocean and land surfaces contributes to a given location's precipitation. Using the WAM-2layers land-surface hydrological model and ERA-Interim climate reanalysis, we track the evaporation sources and identify the precipitationshed for Rondônia from 1981 to 2018. We quantify the moisture sources from the ocean, forested and nonforested areas, and the temporal variability in those sources. We also assess the protection status of forests in the precipitationshed and quantify the fraction of rainfall from protected vs. unprotected forests. Our main two research questions are: (1) What is the relative contribution of the ocean, forest, and nonforested areas to precipitation in Rondônia? (2) How do those contributions change during droughts: does the forest compensate for or exacerbate any reduction in ocean sources during droughts?

2. Materials and Methods

2.1. Study Area

The study area is in Rondônia, Brazil (Figure S1) (7.98–13.69°S, 59.77–66.81°W), which covers 243,000 km^2 of the Brazilian Legal Amazon's 5,000,000 km^2 (Guild et al., 2004). Rondônia is at the western-most extent of the "arc of deforestation" in the southern Amazon and is one of the key agricultural regions in the Amazon basin, with important markets in coffee, beef, milk, and fish. The climate of the region is humid tropical, with a dry season from June to August, a dry-to-wet season transition from September to October, and a peak wet season from December to March (Butt et al., 2011). Rondônia has gently undulating topography with an elevation range between 14 and 1,100 m above sea-level.

2.2. Moisture Tracking Model

An offline Eulerian moisture tracking model called the Water Accounting Model-2layers (WAM-2layers) was used to document the sources of moisture that contribute to rainfall in Rondônia (Van der Ent, 2014). WAM-2layers uses gridded data from the European Center for Medium-Range Weather Forecasts Interim reanalysis (ERA-Interim) (Dee et al., 2011) as input. Van der Ent (2014) updated and improved the previous one-layer model by expanding it into WAM-2layers, which tracks both the vertical flux of evapotranspiration and the horizontal fluxes of water vapor. The moisture tracking procedure is based on the atmospheric water balance (van der Ent et al., 2010, 2014), in which precipitation is the result of two sources of moisture to the atmospheric column: ET from the surface and moisture flux convergence associated with wind circulation (Keys et al., 2014). Backward tracking implemented in WAM-2layers is used to map the moisture sources of precipitation (precipitationshed) for the sink region—Rondônia (Benedict et al., 2020). The output of WAM-2layers is an evaporation contribution from a given grid cell that constitutes a depth of rainfall in the sink region. Only cells that contribute at least 1 mm of precipitation per year to the sink region are retained for analysis.

ERA-Interim data were downloaded at the global level and gridded at 1.5×1.5 resolution. Parameters required by WAM-2layers were extracted, including surface pressure, specific humidity, horizontal and vertical winds, northern and eastern water vapor flux, total column water, and total precipitation and evaporation. Precipitation and evaporation were downloaded at 3-hourly resolution and all other variables at 6-hourly resolution.

10.1029/2020GL091380

2.3. Land Cover and Sensitivity Analysis

The moisture contribution to precipitation in Rondônia from forested, nonforested, and ocean was calculated by combining the gridded moisture contribution grids from WAM-2layers with land cover data. The fraction of moisture contribution from land cover j (f_j) is calculated as:

$$f_j = \sum_{1}^{n} f_{ri} \times f_{ji} \tag{1}$$

where f_{ri} is the fraction of annual precipitation in Rondônia coming from moisture provided by cell i, and f_{ji} is the fractional area in land cover j in cell i. f_{ri} is calculated by dividing the amount of moisture (mm y^{-1}) from cell i by the sum of moisture sources from all cells in the 1-mm precipitationshed. f_{ji} was calculated using two land cover datasets: Mapbiomas version 4.1, which has the land cover for 2018 (Mapbiomas Project, 2019) and the Global Land Cover Characteristics (GLCC) (Loveland et al., 2000), which is used in ERA-Interim. Each land cover data set will bias the results in different ways: the ERA-Interim model uses the 1992–1993 GLCC land cover data without changes over time; using it to summarize moisture sources will accurately reflect the model-calculated sources, but will tend to underestimate the contribution of nonforested areas and overestimate the forest contribution for periods after 1992–1993, since nonforested areas are more common after 1992–1993 (Table S1). The 2018 Mapbiomas data will overestimate the contribution of nonforested areas and underestimate the contribution of forests, as Mapbiomas nonforested areas that are represented as forests in the ERA-Interim model will have ET rates reflective of forests, rather than of nonforested areas. We tested for the impact of land cover data source by calculating the moisture sources using both land cover datasets. Most of the precipitationshed for Rondônia was under forest in 2018, with relatively little difference from 1992 to 1993, so the calculated moisture supply from forest and nonforested areas changed relatively little between the two datasets (Table S2). Here, we present the results from using Mapbiomas 2018.

Moisture sources by cover type (forest, nonforested area, and ocean) were determined for the mean over 1981–2018, and for drought years in 2005 and 2010. A third drought in 2015 was highlighted but left out of the additional calculations because we did not have evapotranspiration data for all ET datasets in 2015 to compare with the ERA-Interim modeled ET.

A protected area (PA) status database was obtained from another study (De Sales et al., 2020). PAs include State and Federal areas designated as National Forests, Biosphere Reserves, Extractive Reserves, and Indigenous Territories. The different designations provide different levels of protection; here we lump all PAs together into one category. The fraction of ET coming from PAs was calculated using Equation 1, where f_{ji} is the fraction of the area of cell i that is both forest and protected.

2.4. Remote Sensing Estimates of Evapotranspiration

Changes in moisture supply rate from a given cover type (ocean, forest, nonforested areas) to a given sink could be caused by either a change in the rate of evaporation from the source or changes in atmospheric circulation. We compared the rate of moisture supply to the atmosphere (ET) from forests and nonforested areas during drought and nondrought conditions from the ERA-Interim model, another land surface model (GLDAS-2.1; Rodell et al., 2004), and two remote sensing products: MOD16A2 (Mu et al., 2007, 2011), and Paca et al (2019) (hereafter PacaET), who fused six global ET products from 2003 to 2013. Mean ET from forest and nonforested areas was calculated using the Mapbiomas 2018 land cover data set.

3. Results and Discussion

3.1. Climatology and Spatial Variability

The moisture tracking procedure suggests that there are two major moisture source regions for Rondônia: northern South America and the Atlantic Ocean (Figure 1), including a moisture transport belt from the Amazon basin and the South Atlantic Ocean. A gap in the precipitationshed between the eastern Amazon and the Atlantic Ocean includes the arid and semi-arid northeast of Brazil.

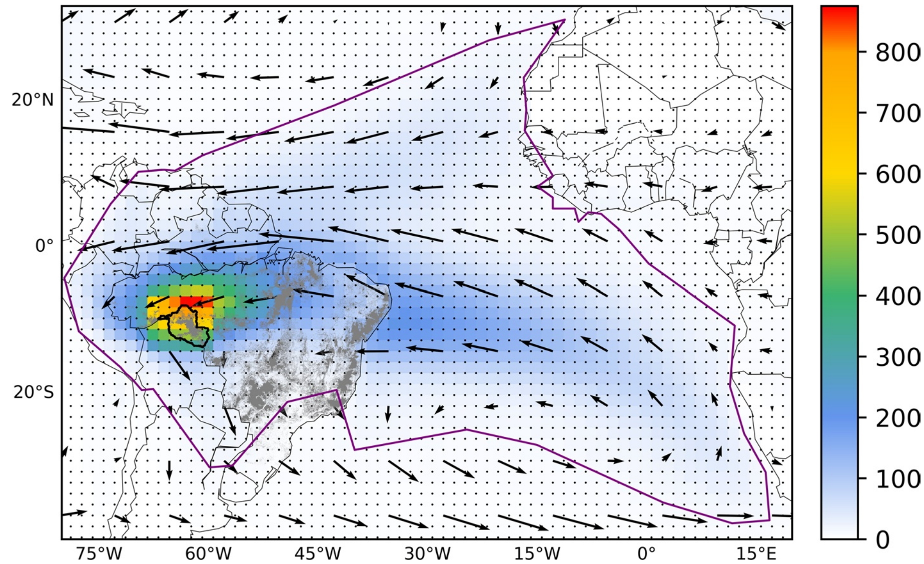

Figure 1. Moisture sources for annual precipitation in Rondônia from 1981 to 2018 (mm y^{-1}); the region in the map accounts for 94.4% of the moisture sources. The magenta line indicates the 1-mm precipitationshed boundary. Arrows indicate the average horizontal (vertically integrated) moisture flux. Gray areas indicate nonforested areas (Mapbiomas Project 2019).

Forests contributed 47.9% of the moisture that fell as precipitation in Rondônia from 1981 to 2018. The Atlantic Ocean contributed slightly less than forests (46.5%), and nonforested areas contributed the least moisture (1.0%–5.6%). The terrestrial recycling percentage in Rondônia, which is the percent of rainfall derived from continental sources (53.5%) is higher than the average for the Amazon basin (24%–35%) (Tuinenburg et al., 2020; Van der Ent et al., 2010; Zemp et al., 2014). PAs in the Brazilian Amazon accounted for 27.0% of Rondônia's precipitation and unprotected forests contributed 20.9%.

The moisture sources for Rondônia are spatially diffuse: a relatively small area (308,025 km^2) in and northeast of Rondônia, where forests are the dominant land cover, has a high area-normalized contribution (~> 500 mm y^{-1}) (Figure 1), but this high "core" accounts for only 15% of total annual precipitation and 27% of the terrestrial contribution. Sources within the state accounted for just 5.4% of annual precipitation. A majority of the terrestrial source is from cells that have relatively low area-normalized contributions, but combined cover a large area. The ocean source was also diffuse, with most of the ocean contribution coming from cells with low supply rates (~<120 mm y^{-1}).

3.2. Moisture Sources During Drought Years

Large areas of the Amazon basin, including Rondônia, experienced severe droughts in 2005, 2010, and 2015 (Marengo et al., 2011; Panisset et al., 2018). During drought years, the moisture contribution from forest sources remained stable (−4% to +1% change from nondrought years), while oceanic and nonforested areas sources decreased, resulting in an increase in the percent contribution from forests from a long-term mean of 47.9%–54.0% (2005) and 53% (2010) (Figure 2, Tables 1 and S2). By contrast, the moisture contribution of nonforested areas decreased during the droughts, accounting for 4.1% and 4.3% of the tracked moisture in 2005 and 2010 compared with a long-term mean of 5.6% (Mapbiomas Project 2019). Compared with the long-term mean (1981–2018), moisture supply from the west and south of Rondônia and the Atlantic Ocean decreased significantly during the drought years (Figure 3).

3.3. Evapotranspiration From Forest and Nonforest: Model and Remote Sensing Comparison

Modeled (ERA-Interim and GLDAS) and remotely sensed ET products (MOD16, PacaET) all suggest that forest ET is larger than nonforest ET, and that forest ET decreases only slightly (−6% to 0%) or increases

10.1029/2020GL091380

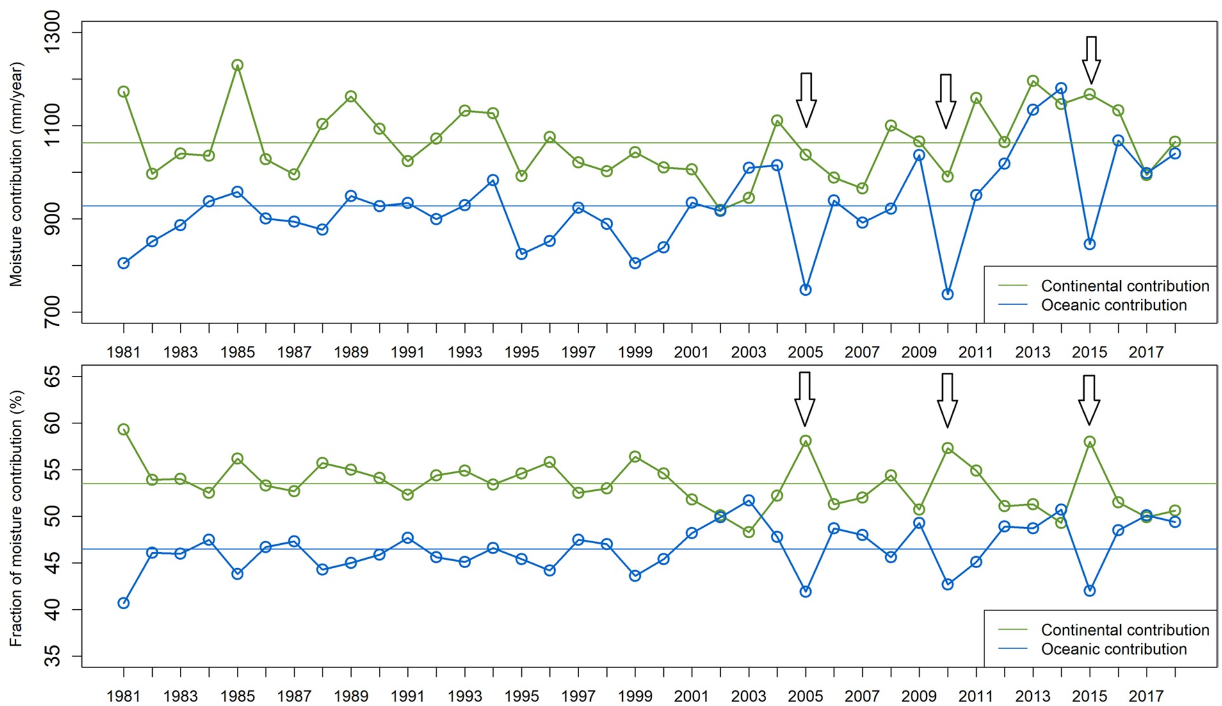

Figure 2. Continental and oceanic moisture contributions from 1981 to 2018. Horizontal lines indicate the mean values. Arrows indicate drought years (2005 and 2010, and 2015).

during drought years (Table 2), which is consistent with the moisture tracking results (Table 1) where the absolute contribution from forests (mm y^{-1}) changes only slightly (−4% to +1%) during droughts. ET from nonforest decreased as much or more than ET from forests during drought years, except for MOD16 in 2010 when ET from nonforest increased. ERA-Interim has lower ET than other products in all categories and shows less impact of drought on ET (Table 2), suggesting that our moisture recycling results based on ERA-Interim likely underestimate the forest contribution. More research is needed on the changes and timing of ET that contributes to moisture that becomes precipitation during agriculturally significant times of the year. Regardless of the mechanism and timing, forests are an important moisture source during drought years for this important agricultural region.

3.4. Limitations and Suggestions

Together, the results suggest that forests decrease the severity of droughts, which are caused predominantly by a weakening of the ocean source, by maintaining or increasing moisture supply to the atmosphere during drought years. The failure of the ocean source was identified as the cause of the 2005 and 2010 droughts

Table 1
Moisture Contribution in 2005, 2010, and 1981–2018 Based on the Mapbiomas Data

	Drought year 2005				Drought year 2010				1981–2018	
Region	mm y^{-1}	PC	Δ mm y^{-1}	Δ PC	mm y^{-1}	PC	Δ mm y^{-1}	Δ PC	mm y^{-1}	PC
Forest	964	54.0	+10 (+1%)	+6	918	53.1	−36 (−4%)	+5	954	47.9
Nonforested areas	73	4.1	−38 (−34%)	−2	74	4.3	−37 (−33%)	−1	111	5.6
Ocean	748	41.9	−178 (−19%)	−5	736	42.7	−190 (−21%)	−3.8	926	46.5
Total	1,785	100	−205 (−10%)	–	1,728	100	−263 (−13%)	–	1,991	100

Note. Δ is the change in moisture source compared with the long-term mean (1981–2018) in mm y^{-1} and as a percent of the long-term mean. PC is the percent contribution to the total rainfall, and ΔPC is the change in PC between drought years and the long-term mean.

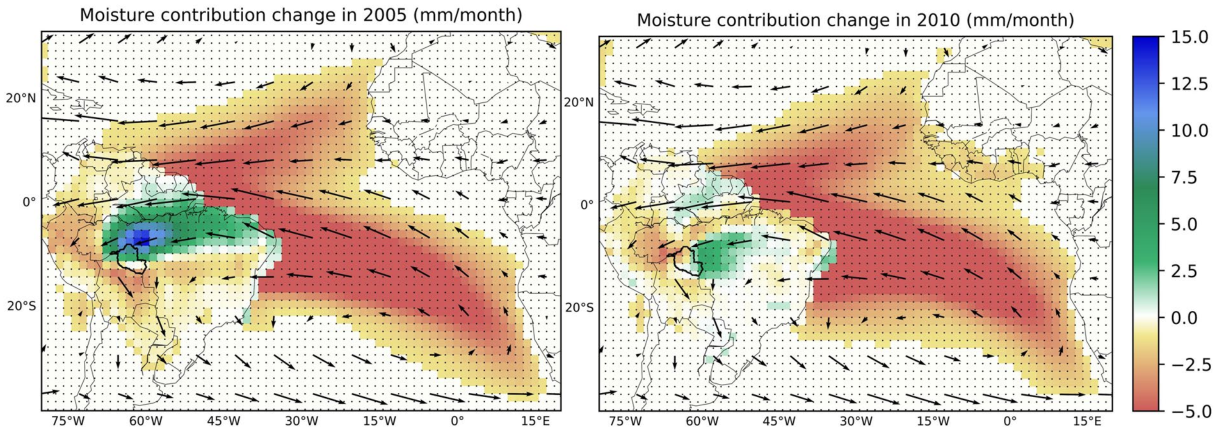

Figure 3. Moisture contribution change in 2005 and 2010 compared with the long-term mean (mm month^{-1}). Arrows indicate the average horizontal moisture flux.

when high Sea Surface Temperature (SST) in North Atlantic suppressed flow from the southern Atlantic into the Amazon (Marengo et al., 2011; Zeng et al., 2008).

The difference in moisture flux between the mean and 2005 drought year shows a large decrease in moisture flows from the southern Atlantic Ocean to the continent, with smaller reductions in moisture flux from land to the east into Rondônia, which was also observed by Zeng et al. (2008). The decrease in flux from the southeastern Amazon into Rondônia is relatively small, and there is still a positive moisture flux from land into Rondônia (Figures 3 and S2). The difference maps suggest that changes in circulation were critical for drought in Rondônia and may explain why the contribution from nonforest decreased even though the ERA-Interim ET values from nonforested areas did not change significantly during the drought.

Our results on the difference in ET between forests and nonforested areas agree with other studies, where forests access deep soil moisture (Oliveira et al., 2005) and have higher ET compared with grass (Caioni et al., 2020; Hodnett et al., 1996a, 1996b). Saleska et al. (2016) and Gabriele et al. (2018) find that dry-season forest greening is prevalent in the Amazon, though other satellite observations suggest that the greenness of the Amazon forest either does not change (Samanta et al., 2010), decreases during drought (Hilker et al., 2014) or gives conflicting results (Asner & Alencar, 2010). Our ET intercomparison suggests that the impacts of drought on the forest ET are modest, but further study is needed. Similar to our moisture tracking results, Staal et al. (2018) find that forest-rainfall cascades buffer the effects of drought across the Amazon and that the continental contribution increases in dry years. However, a threshold may exist for the mitigation effect from forests, as increased drought intensity may reduce ET of some parts of the Amazon forest, increasing the overall risk of extreme drought (Wunderling et al., 2020).

Table 2
Evapotranspiration of Forests and Nonforested Areas in 2005, 2010, and Nondrought Years (mm y^{-1})

	Drought year 2005				Drought year 2010				Nondrought years	
	Forest		Nonforested		Forest		Nonforested		Forest	Nonforested
Product	ET mm y^{-1}	Δ mm y^{-1} and (%)	ET mm y^{-1}	Δ mm y^{-1} and (%)	ET mm y^{-1}	Δ mm y^{-1} and (%)	ET mm y^{-1}	Δ mm y^{-1} and (%)	Mean mm y^{-1}	Mean mm y^{-1}
PacaET	1,384	−22 (−2%)	1,157	−40 (−3%)	1,406	0 (0%)	1,165	−32 (−3%)	1,406	1,197
MOD16	1,338	−42 (−3%)	1,115	−114 (−9%)	1,401	+21 (+2%)	1,261	+32 (+2%)	1,380	1,229
GLDAS	1,282	−85 (−6%)	1,164	−80 (−6%)	1,383	+16 (+1%)	1,216	−23 (−2%)	1,367	1,244
ERA-Interim	1,150	−2 (−0%)	1,138	−5 (−0%)	1,157	+5 (+0%)	1,139	−4 (−0%)	1,152	1,143

Δ is the change in ET between the drought and nondrought years in mm y^{-1} and as a percentage of ET in nondrought years

4. Conclusions

An atmospheric water balance and precipitationshed for an agricultural region (Rondônia) of the Brazilian Amazon suggests that forests mitigated drought severity by maintaining ET and moisture supply when ocean sources failed. Protected forest areas are important for the precipitation of Rondônia, though a large fraction of the moisture source (21%) is from forests that are not protected. Forest loss from fire, logging, droughts and potential feedbacks among them (Hilker et al., 2014; Nepstad et al., 2008; Staal et al., 2018) could threaten the forest moisture source, increasing the risk of reduced rainfall and consequent impacts on agricultural productivity and ecosystem function.

Data Availability Statement

The WAM-2layers model data are available through Van der Ent, 2014. The ERA-Interim reanalysis data are available through Dee et al., 2011 and from the ECMWF (https://www.ecmwf.int/en/forecasts/datasets/), and the Mapbiomas data are available through MapBiomas Project 2019. Global Land Cover Characteristics (GLCC) data set is available through Loveland et al., 2000. MOD16A2 ET data are available through Mu et al., 2011, and GLDAS-2.1 are available through Rodell et al., 2004.

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