Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil

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Abstract

The state of Mato Grosso, Brazil, has experienced rapid land use changes from the expansion of rain-fed agriculture (primarily soybean and pasture). This study presents changes to evapotranspiration contributions from terrestrial ecosystems in Mato Grosso over the 2000–9 period. Instead of focusing on land use change to infer hydrologic change, in this paper we assess hydrologic changes using remote sensing, meteorological and agricultural production data to determine the rainforest, crop and pasture components of total evapotranspiration. Humid tropical rainforest evapotranspiration represented half of the state’s total evapotranspiration in 2000 despite occupying only 40% of the total land area. Annual evapotranspiration fluxes from rainforest declined at a rate of 16.2 km$^3$ y$^{-1}$ ($R^2 = 0.82, p$-value $< 0.01$) as a result of deforestation between 2000 and 2009, representing a 25% decline in rainforest evapotranspiration since 2000. By 2009, rainforest cover accounted for only 40% of total evapotranspiration. Over the same period, crop evapotranspiration doubled, but this increase was offset by a decline in pasture evapotranspiration. Pasture fluxes were at least five times larger than crop evapotranspiration fluxes in 2000–9, with increases spatially focused at the agricultural frontier. The results highlight the expanding appropriation of soil moisture stocks for use in Mato Grosso’s rain-fed agroecosystems.

Keywords: evapotranspiration, green water, land use change, Mato Grosso, deforestation, agricultural expansion, MODIS, MOD16, Penman–Monteith, FAO56, water productivity, water footprint

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1. Introduction

Recently observed declines in global evapotranspiration (ET) have raised questions about limited soil moisture supply in the Southern Hemisphere (Jung et al 2010). Soil moisture is essential for terrestrial ecosystems that consume these water stocks before returning water vapor to the atmosphere. Falkenmark and Rockstrom (2006) highlighted the intimate link between water management and land management decisions by shifting the focus of water management from
surface water and groundwater to precipitation. Land use change can affect the partitioning of precipitation into vapor flows (ET or ‘green water’) and liquid flows (‘blue water’), in turn impacting the regeneration of precipitation.

ET fluxes are very important to the global water cycle, and collectively regenerate 62% of global terrestrial precipitation (Falkenmark and Rockstrom 2004, Oki and Kanae 2006). ET fluxes from natural terrestrial ecosystems and rain-fed agriculture (crops plus grazing areas) are estimated at 44 700 km$^3$ y$^{-1}$ and 15 100 km$^3$ y$^{-1}$, respectively (Rost et al 2008). Combined, these 59 800 km$^3$ y$^{-1}$ of ET from natural and rain-fed agroecosystems represent 89–95% of the total fluxes from vegetated surfaces globally as estimated by Mu et al (2011), Miralles et al (2011) and Jung et al (2010).

The state of Mato Grosso, Brazil (figure 1), has drawn worldwide attention because of deforestation and agricultural expansion. Since the 1970s, agricultural activity has moved north into the savanna (cerrado) and the Amazon forest (Fearnside 2005, Simon and Garagorry 2005). Recent studies point to the acceleration of land use change this past decade, particularly the relationship between deforestation, pasture and soybean expansion (Macedo et al 2012, Barona et al 2010, Morton et al 2006, Jasinski et al 2005), ecosystem services (Foley et al 2007), carbon emissions due to agricultural expansion (Galford et al 2011, 2010), and the provision of other water-dependent ecosystem services. Greater global demand for meat and soybean products combined with forest degradation and mortality from fires and droughts can significantly affect biogeochemical cycles and rainfall in the Amazon (Nepstad et al 2008), and have global implications for terrestrial components of the hydrologic cycle.

Land use decisions create specific trade-offs among ecosystem services (DeFries et al 2004), but also among potential water uses (Falkenmark and Rockstrom 2004). Countries looking to increase food production are faced with: (1) processes of competition for soil water on the land, and (2) changes in water partitioning of precipitation into green (ET) and blue water (runoff) at the soil (Rockstrom et al 2007). Horizontal expansion of agricultural land may reduce vapor flows by 88% and 61% when either cropland or grassland replaces tropical forest (Miralles et al 2011). This change illustrates the difference in water partitioning at the biosphere–atmosphere interface, which may cause an increase in runoff as a result of agricultural expansion and additional water vapor flow trade-offs between land uses (Karlberg et al 2009). In Mato Grosso, differences in water partitioning have already been observed in forested versus soybean watersheds within the Xingu basin (Hayhoe et al 2011), and 175 360 km$^2$ (or 23% of total drainage area) of the Tocantins river basin for the 1949–98 period (Costa et al 2003). From these studies, increases in stream discharges were observed with land use change, consistent with a drop in annual ET. This is particularly apparent in the Amazon area where 25–50% of precipitation is derived from ET occurring within the region (Fearnside 2005). Moreover, at the continental scale, reduced ET can lead to reduced precipitation and discharge (Coe et al 2009). A 20% decline in rainfall combined with lower ET in Amazonia can reinforce the drying of the rainforest with possible changes towards savanna-type vegetation (Nepstad et al 2008).

Mato Grosso’s biosphere–atmosphere relationships have also been studied, specifically as they relate to northern forested areas near the ‘arc of deforestation’ (Macedo et al 2012). Typical landscape conversions of forest to pasture or cropland to pasture can affect ET because of differences in water use efficiency between C3 forest vegetation and C4 crops (or C4 pasture grasses and C3 crops) (Pongratz et al 2006), as well as through changes in canopy surface roughness, leaf area index, rooting depth and albedo (Pongratz et al 2006, Costa and Foley 2000). In addition to climatic controls on ET from net radiation, vapor pressure deficit and precipitation in humid tropical forests (Fisher et al 2009), the seasonality of ET in the forest of northern Mato Grosso is also controlled biologically via stomata response to reduced water availability (Costa et al 2010), as well as root access to deep water reserves (Vourlitis et al 2008) unavailable to pasture or crops. At the regional level, conversion of forests to agricultural land can lead to a drop in aggregate ET flows, particularly if there is no expansion in irrigated lands (Gordon et al 2005).

ET contributions from landscapes in Mato Grosso are expected to have changed as a result of deforestation and agricultural expansion but have not been estimated at the state level. Evaluating past changes in ET contributions from the landscape makes for a better consideration of water use in terrestrial ecosystems in light of ecosystem services trade-offs from land use change. The recent release of the MODerate resolution Imaging Spectroradiometer (MODIS) ET product MOD16 (Mu et al 2011) allows for a more direct accounting of the impacts of land use change on ET often inferred in previous research on land use change studies. Mato Grosso is a model case for such a study given rapid land use change over the last decade, and the near complete reliance on precipitation for its expanding agricultural land base as less than 2% of agriculture received irrigation in 2006 (IBGE 2010). The importance of natural ecosystems in recycling precipitation through ET is also essential in understanding the continent wide effects from land use change and from probable forest conversion to savanna in the Amazon region.

In this study, we provide a water-focused description of land use change looking specifically at ET contributions from forested and agricultural ecosystems for Mato Grosso between 2000 and 2009 using data obtained from MOD16 (Mu et al 2011) and ET modeled following Food and Agriculture Organization (FAO) guidelines (Allen et al 1998). The information provided by these data sources allows for a direct picture of changes in ET fluxes with the expanding agricultural land base while identifying trade-offs in soil water consumptive use by terrestrial ecosystems over the study period.

2. Methods

Mato Grosso is one of nine states located in the Legal Amazon (figure 1). It occupies over 900 000 km$^2$ and extends
Figure 1. Brazil and the Legal Amazon with Mato Grosso’s 2009 INPE classified forest cover and boundaries of municipal units used in this study. Pie chart shows the land use breakdown (as a per cent of total Mato Grosso surface area) according to the 2006 census on land use (IBGE 2010) and the Pantanal surface area estimate (dos Santos Vila da Silva and de Moura Abdon 1998).

The state is home to three major biomes separated by transitional landscapes: rainforest in the north, cerrado (savanna) in the center, and seasonally flooded areas within the Pantanal wetland, located in the south (dos Santos Vila da Silva and de Moura Abdon 1998). The region experiences an annual September–April rainy season during which major rain-fed crops are planted: soybean (5.8 Mha), maize (1.7 Mha), cotton (0.4 Mha) and sugar cane (0.2 Mha) as well as enough pasture to support over 27 million heads of cattle (IBGE 2010). The last available land use census of 2006 (IBGE 2010) breaks down landscapes as forest (35% of total Mato Grosso surface area), pasture (24%), and agricultural land as annual and perennial crops (7%). The Pantanal occupies 5% of the state (dos Santos Vila da Silva and de Moura Abdon 1998), with the remaining 29% of the state occurring as a mixture of land covers and land uses including the cerrado ecosystem (figure 1).

The change in land surface contributions to total ET volume ($ET_T$) was examined. First, monthly $ET_T$ and rainforest ET ($ET_F$) were obtained from MOD16 (Mu et al. 2011) analyzed with ESRI ArcGIS 10 Geographic Information System to estimate spatio-temporal changes in ET between forest and non-forest ecosystems. Then, agricultural ET ($ET_{Ag}$), as the sum of cropland ET ($ET_C$) and pasture ET ($ET_P$), was estimated following FAO guidelines (Allen et al. 1998) in combination with agricultural production information made available by the Brazilian Institute of Geography and Statistics (IBGE 2010). This approach allowed for a detailed analysis of ET contributions from rainforest ($ET_F$) and agricultural landscapes ($ET_{Ag}$).

A detailed examination of cerrado landscapes was not possible due to the current lack of comprehensive land

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4 Mato Grosso harvested area for 2009 (IBGE 2010).
use/land cover maps available for the cerrado, which is not monitored by INPE, the Brazilian Institute of Space Research (Camara et al 2006). Land uses other than rainforest and agriculture include cerrado, cities, roads and the Pantanal wetland, and represented 29% of the state in 2006 according to the last available data (IBGE 2010). Evapotranspiration from these sources were aggregated as residual ET (ETR) in this study.

2.1. Spatial characterization and remote sensing

Mato Grosso is subdivided into 141 municipalities which constitute the basis of the information collected by IBGE (2010). However, several political units changed in number, size and shape in 2001, 2005 and 2007. Municipalities that changed over the study time period were aggregated into 14 larger political units such that their overall area remained constant within the time period, as suggested by Barona et al (2010). This merger of political units resulted in a total of 104 municipal units (MUs), which include the municipalities whose shape and size remained unchanged during the study period (figure 1). These 104 MUs represent the basis of the ET analysis into landscape contributions as volumes of ET (from MOD16), ETAg (FAO guidelines with IBGE information) and ETR (unaccounted for ET) components.

Monthly ET_T (km^2 mo^-1) was determined for the entire state as well as the individual MUs after raster extraction from MOD16 (mm mo^-1), which is available at 1 km^2 resolution for 2000–9 and obtained from Mu et al (2011) (ftp://ftp.ntsg.umt.edu/pub/MODIS/Mirror/MOD16/). The improved MOD16 algorithm (Mu et al 2011) combines MODIS satellite observations of land cover, leaf area index, albedo and fraction of absorbed photosynthetically active radiation in combination with daily meteorological inputs to estimate ET using the Penman–Monteith equation (Mu et al 2011). MOD16 was validated by Loarie et al (2011) for the Brazilian central western region (which encompasses Mato Grosso) using 10 eddy covariance flux towers from the large scale biosphere–atmosphere network covering both rainforest and agricultural ecosystems. Results showed that the differences in annual ET estimated from MOD16 and eddy covariance were < ± 4–13% (Loarie et al 2011).

Mato Grosso’s forest cover was obtained from INPE (www.obt.inpe.br), which provides deforestation polygons for the Legal Amazon from 60 m resolution raster images following methods described in Camara et al (2006). INPE’s forest classification does not include cerrado land covers; rather it is limited to tropical rainforest cover (Camara et al 2006). Monthly ETg was obtained by summing MOD16 data using forest cover of each MU as extract masks in ArcGIS 10. Forest cover was only available for 2009 (figure 1), with deforestation rates available for 2000–8. Thus, the previous years’ forest cover was determined by adding annual forest polygons. For example, the 2008 forest cover was obtained by summing the 2009 forest cover with the 2008–9 deforestation polygons. ETg volumes were extracted for the entire state of Mato Grosso and each of the MUs after converting the forest cover polygons to rasters of size equal to the MOD16 data (1 km^2). The non-forest portion of land contains a mixture of mainly cerrado, cropland and pasture whose exact location and use within the MUs was not available through satellite imagery. As a result, the extraction of ETAg using MOD16 was not possible. ETAg was determined using FAO guidelines and information collected by IBGE for each MU.

2.2. Evapotranspiration modeling

2.2.1. FAO guidelines. ETAg was estimated with FAO guidelines (Allen et al 1998) which use the Penman–Monteith equation to determine crop evapotranspiration (ETC) in a disease free environment, with ideal nutrient, soil moisture and soil management conditions. First, reference ET (ET0, mm d^-1) was calculated from equation (1):

\[
ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_e + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \tag{1}
\]

where \(\Delta\) is the slope of the vapor pressure curve (kPa °C^-1), \(R_n\) is the net radiation (MJ m^-2 d^-1), \(G\) is the ground heat flux (MJ m^-2 d^-1) and assumed close to zero for daily time steps (Allen et al 1998), \(\gamma\) is the psychrometric constant (kPa °C^-1), \(T_e\) is the mean air temperature at 2 m above the crop canopy (°C), \(e_s - e_a\) is the vapor pressure deficit (kPa) and \(u_2\) is the wind speed at 2 m above the crop canopy (m s^-1). ETC (mm d^-1) was then calculated from equation (2) using crop coefficients (\(K_C\)) which vary with the crop development cycle:

\[
ET_C = K_C ET_0. \tag{2}
\]

Daily ET0 was calculated and averaged for every 10 day period using meteorological data (Allen et al 1998) available for meteorological stations from the Instituto Nacional de Meteorologia (INMET 2010) described further in the supplemental material (available at stacks.iop.org/ERL/7/204204/mmedia). Given that the exact location of crop and pasture land within the MUs was unknown, ET0 was assumed to be homogeneous within each MU represented by an INMET meteorological station (see supplemental material available at stacks.iop.org/ERL/7/204204/mmedia). These stations record daily temperature, relative humidity, atmospheric pressure, wind speed, wind direction, cloud cover and cumulative daily precipitation (INMET 2010). \(R_n\) was modeled following Allen et al (1998) where station latitude was used to calculate extraterrestrial radiation (\(R_o\)), the Hargreaves radiation formula was used to calculate solar radiation (\(R_s\)) using temperature, and clear sky solar radiation (\(R_{so}\)) was determined from altitude (Allen et al 1998). \(R_s\) and \(R_{so}\) were then used to calculate net longwave radiation (\(R_l\)), while net shortwave radiation (\(R_m\)) was obtained using an albedo of 0.23 for ET0 (Allen et al 1998).

Mean \(K_C\) values were obtained from literature values (table 1) for the initial (\(K_C_{ini}\)), mid-season (\(K_C_{mid}\)), late season (\(K_C_{late}\)) and harvest (\(K_C_{end}\)). ETC was then calculated for the four principal crops grown in Mato Grosso (soybean, maize, cotton, sugar cane) as well as pasture (table 1). The four principal crops of Mato Grosso represented 94–97%
of harvested area for annual crops between 2000–9 (IBGE 2010), while perennial crops represented <2% of harvested areas (IBGE 2010) during the study period.

ETC was compared to effective rainfall to determine whether ETC was limited under rain-fed conditions. Effective rainfall was determined using the USDA SCS method (Dastane 1978) and computed using FAO Cropwat 8.0 (FAO Water 2011a) with meteorological station precipitation aggregated monthly as inputs.

Pasture does not follow the same development cycle as soybean, maize, sugar cane or cotton because of frequent grazing. Pasture Kc values were selected from literature (grazing pasture, extensive grazing in Allen et al. (1998)) and have been shown to also vary based on precipitation (Meirelles et al. 2011) and, thus, rather than comparing pasture ET (ETP) to effective precipitation, we used precipitation levels as thresholds for enhanced transpiration by pasture grass following precipitation (table 2). ETP (mm) was calculated using Kc values from Allen et al. (1998) (table 1) that were applied based on precipitation events: for dry days ETP was equal to \( K_{C_{ini}} \times E_T \), and for days with rain ETP was equal to \( K_{C_{mid}} \times E_T \).

A sensitivity analysis was conducted by selecting two modeling assumptions consisting of planting dates for crops and precipitation thresholds for pasture (table 2). Two sets of planting dates for soybean, maize and cotton were selected to evaluate the impact of agronomic practices on ETC (table 2). Soybean in Mato Grosso is typically planted at the beginning of the rainy season (October–November), with maize or cotton planted immediately following soybean harvests. Sugar cane was assumed to be established and undergoing the same development cycle as cotton because of frequent grazing. Pasture was assumed to be established and undergoing the same development cycle as soybean, maize, sugar cane or cotton because of frequent grazing.

2.2.3. Pasture area determination. Information on pasture area was only available for two census years (1996 and 2006). Pasture area was determined for non-census years following the method described by Barona et al. (2010) who define the total livestock unit (TLU) in equation (3):

\[
TLU(t, i) = \sum_k N(i, t, k)f_{AU}(t, k)
\]

where \( N \) is the population of animal ‘i’ in MU ‘t’ and year ‘r’, and \( f_{AU} \) is the animal unit factor, a conversion factor of animal unit equivalents to account for the differences in forage

| Crop                     | Initial \( K_{C_{ini}} \) (days) | Development \( K_{C_{dev}} \) slope (days) | Mid-season \( K_{C_{mid}} \) (days) | Late season \( K_{C_{late}} \) slope (days) | End \( K_{C_{end}} \) | Source                        |
|--------------------------|----------------------------------|-------------------------------------------|-----------------------------------|-------------------------------------------|---------------------|--------------------------------|
| Soybean                  | 0.56 (13)                        | 0.024 (40)                                | 1.50 (43)                         | −0.0333 (30)                             | 0.50                | Farias et al. 2001, FAO Water 2011b |
| Maize                    | 0.60 (30)                        | 0.04 (20)                                 | 1.40 (20)                         | −0.027 (30)                              | 0.60                | Bastos et al. 2009               |
| Sugar cane               | 0.4 (30)                         | 0.019 (45)                                | 1.25 (225)                        | −0.083 (60)                              | 0.75                | Alves de Oliveira et al. 2010   |
| Cotton                   | 0.4 (20)                         | 0.022 (30)                                | 1.05 (65)                         | −0.022 (35)                              | 0.65                | Embrapa algodao 2003             |
| Pasture                  | 0.30                             |                                            | 0.75                              |                                           |                     | Allen et al. 1998               |

Table 2. Modeling assumptions with planting dates and precipitation thresholds used for major crops and pasture considered in the sensitivity analysis of this study.
consumed by grazing animals (Barona et al. 2010). Animal unit factors of cattle, horses, buffaloes, donkeys, mules, goats and sheep were obtained from Ramos (2005) for Mato Grosso and the Pantanal region assuming equal $f_{AU}$ for all MUs within the same region. Pantanal-specific $f_{AU}$ values were used for MUs that correspond to the Pantanal delineation of dos Santos Vila da Silva and de Moura Abdon (1998). Then, using the census years, 1996 and 2006, with known pasture area and animal population, livestock density (LSD, livestock units ha$^{-1}$) was determined after Barona et al. (2010) for each year $t$ and each MU $i$ as:

$$\text{LSD}(t, i) = \frac{T\text{LU}(t, i)}{A_p(t, i)} \quad (4)$$

where $A_p$ is the pasture area (ha). Simple linear regression models with LSD (1996, $i$) and LSD (2006, $i$) from the census years were constructed to estimate pasture area in the remaining years using animal population estimated by IBGE from expert surveys. These same regression models were used for 2006–9 assuming a constant increase in livestock density given the strong linear increase reported since 1980 in mean cattle population ($R^2 = 0.98$, $p$-value $< 0.05$, IBGE (2010)). Cattle represent about 93% of the total animal population in Mato Grosso (see supplemental material available at stacks.iop.org/ERL/7/024024/mmedia).

All above calculations were carried out using $R$ statistical software (R Development Core Team 2011).

### 3. Results and discussion

#### 3.1. MODIS derived total and forest evapotranspiration contributions

Monthly $\text{ET}_T$ varied with precipitation, with values typically highest during the wet season between January and March (127.2 ± 2.9 km$^3$ mo$^{-1}$; mean ±95% CI) and lowest in August and September (68.0 ± 6.0 km$^3$ mo$^{-1}$) (figure 2). The seasonality of $\text{ET}_T$ illustrates the typical response from atmospheric demand and soil moisture supply on the landscape. Precipitation supplies water to the landscape during the rainy season, which returns to the atmosphere as $\text{ET}$ at a maximum rate close to Mato Grosso’s average potential $\text{ET}$, estimated by Ahn and Tateishi (1994) as 132 mm mo$^{-1}$ for January and 126 mm mo$^{-1}$ for March. $\text{ET}_T$ declines into the dry months, together with reduced precipitation and increased atmospheric demand (e.g. vapor pressure deficit) also shown by increased potential ET results in the dry season (see MOD16 potential ET from Mu et al. (2011) in the supplemental material available at stacks.iop.org/ERL/7/024024/mmedia). In the dry months, rainfall and cerrado $\text{ET}$ becomes limited due to declining soil water stocks (Rocha et al. 2009), but also leaf water potential and leaf area index (Vourlitis et al. 2002). Analysis of potential ET from MOD16 (Mu et al. 2011) showed that all but four months in the 2000–9 period had $\text{ET}_T$ less than potential $\text{ET}_T$ further suggesting limitations in soil moisture supply from the combined landscapes of Mato Grosso (see supplemental material available at stacks.iop.org/ERL/7/024024/mmedia).

The seasonal minima of 113.6 ± 3.4 km$^3$ mo$^{-1}$ estimated for February are due to short dry periods in the middle of the wet season, locally known as the veranico, when reduced precipitation causes $\text{ET}$ to become limited by soil moisture stocks. This limitation has been shown to be more severe as annual precipitation declines across the biome gradient from tropical rainforest to transition forest and savanna in Brazil (Rocha et al. 2009). The smallest $\text{ET}_T$ was recorded in September 2005 at 56.6 mm mo$^{-1}$. This period coincides with a drought experienced in the Amazon region (Aragao et al. 2007) with precipitation anomalies in northern Mato Grosso of approximately one standard deviation below the 1998–2006 observations (Saleska et al. 2007).

Forests, which represented about 40% of the land cover in 2001, played an important role in the water cycle as half of Mato Grosso’s water vapor was supplied by the landscape as ET in the 2001 hydrologic year (593.2 km$^3$ y$^{-1}$) (figure 3). For the study period, the mean wet (1st October to 30th April) and dry season (1st May to 30th September) $\text{ET}_T$ were 103 mm mo$^{-1}$ and 76.4 mm mo$^{-1}$ respectively, with a mean maximum flux of 118 mm mo$^{-1}$ occurring during the rainy season (figure 2, bottom). These values are similar to those reported previously, where Vourlitis et al. (2002) found a forest $\text{ET}$ of 128 mm mo$^{-1}$ for February, and Shuttleworth (1988) reported 110 mm mo$^{-1}$ with 20% fluctuations near Manaus, central Amazon. The majority of $\text{ET}_T$ comes from transpiration rather than evaporation processes (Miralles et al. 2011), meaning that $\text{ET}_T$ has mostly been used for plant growth.

$\text{ET}_T$ represented a larger portion of $\text{ET}_F$ in the dry season (49%) than the wet season (40%) (figure 2, top) likely due to deeply rooted forests which have shown to have important impacts on water balance functions not only in the rainforest, but also in the cerrado (Vourlitis et al. 2008, Oliveira et al. 2005). Annual $\text{ET}_T$ contributions to $\text{ET}_F$ dropped over the decade from 50% in 2000 to only 40% in the 2009 hydrologic year (figure 3). Annual volumetric $\text{ET}_F$ fluxes declined at a rate of 16.2 km$^3$ y$^{-1}$ between 2000 and 2009 ($R^2 = 0.82$, $p$-value $< 0.01$), equivalent to a 25% decline in $\text{ET}_F$ fluxes over the study period. Mean annual, January and August discharge for two watersheds located in northern Mato Grosso did not show any statistically significant changes between the 2001 and 2007 hydrologic years despite a decrease of at least 13% in $\text{ET}_T$ in those watersheds.

The non-forest portion of $\text{ET}_T$ showed a 10 year mean flux of 96.0 mm mo$^{-1}$ (wet season) and 59.0 mm mo$^{-1}$ (dry season), and was lower than the forest flux in most dry months (figure 2, bottom). These fluxes represent the average fluxes of agricultural land ($\text{ET}_A = \text{ET}_C + \text{ET}_P$) and land unaccounted for by the mapping products: cerrado, cities, and the Pantanal wetland which are aggregated into residual land use fluxes ($\text{ET}_R$). From the 2006 census (figure 1), the non-forest land comprised 65% of Mato Grosso’s surface area with the largest contributors coming from cerrado (included in the residual at 29% of Mato Grosso’s land base) and pasture (24%).

#### 3.2. Modeling description of agricultural evapotranspiration contributions

We modeled $\text{ET}_A$ as the sum of $\text{ET}_C$ and $\text{ET}_P$. $\text{ET}_C$ was dominated by soybean ET ($\text{ET}_{\text{soy}}$) which represented between

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Figure 2. Monthly total evapotranspiration (ET) and rainforest evapotranspiration (ETF) volumes (km$^3$ mo$^{-1}$, top panel); monthly mean fluxes (mm mo$^{-1}$) of ETF and evapotranspiration fluxes from non-forested areas and mean precipitation from 12 INMET stations of Mato Grosso (INMET 2010) (bottom panel).

Table 3. Mean water productivity (m$^3$ ton$^{-1}$) and mean annual evapotranspiration (ET) for cropland and pasture for municipal units containing a meteorological station (2000–9). Evapotranspiration values are shown as a range with mean minimum and maximum values calculated between 2000 and 2009. Values in brackets represent the standard deviations (sd) for each minima and maxima across the municipal units containing a meteorological station.

| Crop       | Mean water productivity (m$^3$ ton$^{-1}$) | ET (mm y$^{-1}$) min (sd)-max (sd) A I | ET (mm y$^{-1}$) min (sd)-max (sd) A II |
|------------|--------------------------------------------|----------------------------------------|----------------------------------------|
| Sugar cane | A I (R$^2$)=A II (R$^2$) 160 (0.93)         | 1010 (156)–1250 (191)                   | Same as A I                            |
| Pasture    | n/a                                        | 822 (18)–889 (77)                      | Same as A I                            |
| Soybean    | 1530 (0.98)–1750 (0.99)                     | 412 (86)–540 (26)                      | 363 (58)–469 (26)                      |
| Cotton     | 740 (0.96)–610 (0.96)                       | 210 (50)–292 (40)                      | 150 (48)–242 (31)                      |
| Maize      | 670 (0.94)–510 (0.95)                       | 239 (54)–312 (20)                      | 157 (51)–244 (15)                      |

*a A: modeling assumptions (see table 2); n/a: there is no water productivity value for pasture since pasture is estimated from animal population.

77% and 84% of ET$_C$. ET$_C$ increased significantly between 2000 and 2009 (p-value < 0.01, table 3) from 16 to 32 km$^3$ y$^{-1}$ (average of modeling assumptions) representing 8%–15% of ET$_{Ag}$ in 2000 and 2009, respectively. The increase in ET$_C$ was accompanied by a decrease in ET$_P$, such that ET$_{Ag}$ increased by 12 km$^3$ y$^{-1}$ from 208 to 220 km$^3$ y$^{-1}$ over 2000–9. Annual ET$_P$ went from being ten times the value of ET$_C$ in 2000 to only four times ET$_C$ in 2009. These results reflect the impact on ET sources due to replacement of pasture by cropland, particularly soybean, in Mato Grosso.

The 2005–7 period showed important changes in ET$_{Ag}$ particularly as influenced by ET$_P$ and ET$_{Soy}$. ET$_{Ag}$ increased from 17% to 21% of ET$_T$ (206–235 km$^3$ y$^{-1}$) between 2000 and 2005 before dropping back to 18% of ET$_T$ (220 km$^3$ y$^{-1}$) in 2009 (figure 3). This change was primarily driven by ET$_P$ which increased 8% between 2000 and 2005, from
Figure 3. Top panel: annual pasture ET (ET_P) and agricultural ET (ET_Ag) volumes (km³ y⁻¹) for 1st Aug–31st Jul hydrologic years between 2000 and 2009 with per cent forest and agricultural contributions to total evapotranspiration (Et_T). Note that ET_Ag represents the sum of cropland ET (ET_C) and ET_P, and is presented as the average of modeling assumptions. Bottom panel: evolution of cropland and agricultural ET fluxes (average of modeling assumptions) with cropland contributions expressed as a percentage of ET_Ag and ET_P, and agricultural contributions expressed as a percentage of ET_T.

190 to 205 km³ y⁻¹, before dropping 17% between 2006 and 2009 to 187 km³ y⁻¹. ET_Soy, the largest contributor of ET_C, declined 16% between 2005 and 2006 (from 29 to 26 km³ y⁻¹). The temporary declines in ET_P and ET_Soy may be a result of an intersection of climatic conditions (2005 drought) and micro- and macro-economic factors. Barona et al (2010) reported strong correlations between soybean and cattle prices with deforestation in the Legal Amazon. The devaluations of theBrazilian real in 1997–2003 followed by its 25% increase compared to the US dollar is believed to have been an important component of land use decisions (Nepstad et al 2006) and, consequently, corresponding ET_Ag. Negative soybean profits incurred between 2004 and 2006 (Aprosoja 2011) and a commodity price crash in 2006 and 2007 (Macedo et al 2012) might have led some farmers to utilize areas normally planted to soybean for other purposes. The change in cattle prices may have impacted the number of heads farmers decided to raise, which would indirectly impact the pasture and estimates used as a proxy for ET_P calculations.

ET_Soy measurements were unavailable for direct comparison in Mato Grosso. Modeling results found in this study for the growing season (363–540 mm y⁻¹ or 2.95–4.39 mm d⁻¹ averaged over the growing season considering both modeling assumptions) were similar to those measured for rain-fed soybean in Nebraska (420–440 mm y⁻¹ by (Suyker and Verma 2009)), but greater than those determined in Argentina (1.85 mm d⁻¹ average from Nosetto et al 2012). Daily ET_P modeled in this study was comparable to two studies of Brachiaria brizantha pasture in the Brazilian savannah region: 1.55–4.25 mm d⁻¹ for a short term study by Meirelles et al (2011) and 2.1–3.2 mm d⁻¹ in Northern Mato Grosso by Priante-Filho et al (2004).

Average water productivity values in the present study (table 3) for soybean (1530–1750 m³ ton⁻¹) and sugar cane (160 m³ ton⁻¹) were within the ranges reported by Falkenmark and Rockström (2004; 1250–1960 m³ ton⁻¹ for soybean), FAO Water (2011b; 125–200 m³ ton⁻¹ for sugar cane), and Mekonnen and Hoekstra (2011; 1924 m³ ton⁻¹ for soybean and 148 m³ ton⁻¹ for sugar cane in Mato Grosso).
Average water productivity values for maize in the present study (510–670 m\(^3\) ton\(^{-1}\)) were less than values reported by Falkenmark and Rockstrom (2004; 940–1460 m\(^3\) ton\(^{-1}\)) and Mekonnen and Hoekstra (2011; 1359 m\(^3\) ton\(^{-1}\)) in Mato Grosso. Finally, average water productivity values for cotton in the present study (610–740 m\(^3\) ton\(^{-1}\)) were also lower than those reported by Mekonnen and Hoekstra (2011; 2223 m\(^3\) ton\(^{-1}\)) in Mato Grosso. Differences were attributed to modeling assumptions related to the nature of maize and cotton cultivation in Mato Grosso. These crops are mainly planted immediately after the soybean harvest as a secondary, short-season crop. Further discussion on modeling results is available in the supplemental material (available at stacks.iop.org/ERL/7/024024/mmedia).

Between 2000 and 2006, 12–24% of newly established cropland in Mato Grosso was derived from cerrado/cerrado locations (savanna woodland) (Galford et al 2010), while 2–7% of cropland area was established from previously forested areas (Galford et al 2010). This suggests that the source of ET partially switched from natural terrestrial ecosystems to agricultural land as attested by the increase in ET\(_{Ag}\) until 2005 and the decline in ET\(_{F}\) for 2000–9 (figure 3). Macedo et al (2012) describe different soybean expansion dynamics within the decade: while the 2001–5 increase in soybean production was mainly driven by cropland expansion into pasture (74%) and forest (26%), expansion in 2006–9 mainly occurred in areas that were previously cleared for pasture (91%) with some increases in production coming from yield (22%) (Macedo et al 2012). Such conversions may also explain part of the decline in ET\(_{Ag}\) between 2006 and 2009, given that ET\(_{Soy}\) is smaller than ET\(_{p}\) (table 3). The ‘Soybean Moratorium’ that was implemented in 2006 (Macedo et al 2012, Nepstad et al 2008) to address environmental and social concerns surrounding rapidly expanding soybean production may have also had an effect on the direct conversion of forest to soybean, thus favoring pasture conversions to soybean which represented the bulk of land use transitions between 2000 and 2009 (Macedo et al 2012).

3.3. Evapotranspiration contributions from other sources

ET from sources other than rainforest and agriculture, such as cerrado savanna and woodlands, the Pantanal wetland and urbanized areas were aggregated as ET from residual land classes (ET\(_{R}\)). ET\(_{R}\) increased from 394 km\(^3\) y\(^{-1}\) in 2000 to 522 km\(^3\) y\(^{-1}\) in 2009 (average of both modeling assumptions). Three MUs in the south were located in the Pantanal region (5% of Mato Grosso surface area (dos Santos Vila da Silva and de Moura Abdon 1998)), in which ET also comes from largely flooded areas as evaporation, rather than via vegetation as transpiration.

While ET\(_{R}\) contains cerrado/cerradoo landscapes which are not included in INPE’s tropical rainforest classification (Camara et al 2006), estimates of its magnitude depend strongly on ET\(_{F}\) and ET\(_{Ag}\) since ET\(_{R}\) = ET\(_{T}\) − ET\(_{F}\) − ET\(_{Ag}\). Considering that there were minimal changes in ET\(_{F}\) between 2000 and 2009, any reduction in ET\(_{F}\) between 2000 and 2009, or drop in ET\(_{Ag}\) such as observed in the 2005 and 2006 hydrologic years, will result in an increase in ET\(_{R}\). Loarie et al (2011) report 57% of original cerrado remaining in Mato Grosso in the year 2008 with 5% cleared in 2002–8 meaning that our estimate for the change in magnitude of ET\(_{R}\) is not necessarily dominated by changes in cerrado/cerrado land cover.

The exact composition of ET\(_{R}\) is uncertain however, given the lack of land use information on cerrado/cerrado at the time of study that would disaggregate residual land uses. ET\(_{R}\) depends strongly on the land use composition, especially cerrado/cerrado located across the Mato Grosso biome gradient. Sanches et al (2011) reported an average ET for a Vochysia divergens forest in Pocone (Pantanal) as 4 mm d\(^{-1}\) and 2.5 mm d\(^{-1}\) for the wet and dry seasons respectively. Oliveira et al (2005) reported ET values for tree dominated cerrado of 5.8 mm d\(^{-1}\) and 1.4 mm d\(^{-1}\) for the wet and dry season respectively. These values were compared to grass dominated cerrado where ET values ranged from 0.9 mm d\(^{-1}\) to 4.5 mm d\(^{-1}\) for wet and dry seasons respectively (Oliveira et al 2005). All these values were greater than those measured for cerrado in the state of Sao Paulo at 1 mm d\(^{-1}\) (Rocha et al 2009).

3.4. Spatial variability of evapotranspiration contributions

Statistically significant increases in ET\(_{T}\) during 2000–9 (p-value < 0.05) were found in MUs with important agricultural activity in the state throughout the time period (figure 4), while the areas with declining ET\(_{T}\) were located near the rainforest in northwestern Mato Grosso. Annual ET\(_{T}\) only experienced significant decreases in the arc of deforestation and south central Mato Grosso. ET\(_{T}\) declined by up to 40% over 2000–9 for some MUs.

The MU analysis showed the spatial distribution of ET\(_{Soy}\) and ET\(_{p}\) over the study period (figure 5). ET\(_{Soy}\) increased in central Mato Grosso while ET\(_{p}\) decreased in most MUs, except 14 in the central and southern part of the state, and 19 near the rainforest. These results are consistent with Barona et al (2010) who described important links between forest-to-pasture conversion in the arc of deforestation, and pasture-to-soybean conversion in central Mato Grosso. Moreover, Macedo et al (2012) showed that most deforestation occurred in the first half of the 2000–10 decade, with most deforested areas converted to pasture, with lesser direct conversion from forest to cropland pre-2006. Deforestation rates dropped significantly in the second half of the decade (Macedo et al 2012).

Simple linear regression was used to interpret land use effects on observed changes in annual ET\(_{T}\) for each MU over the 9 hydrologic years (1st August to 31st July) between 2000 and 2009. Annual deforestation, calculated as the change in annual rainforest cover (km\(^2\) y\(^{-1}\)), explained 13% of variance in ET\(_{T}\) when considering either all MUs (df = 936) or MUs\(^5\) with >50% forest cover in 2000 (df = 108). In MUs with statistically significant changes in ET\(_{T}\) over time,

\(^5\) Degrees of freedom (df) are the number of hydrologic years (9) times the MUs used for the regression analysis.
deforestation explained 24% of variance in ET\_T (df = 450), and up to 27% of ET\_T when considering MUs with >50% forest cover in 2000. The sum of agricultural land (as cropland and pasture) explained up to 20% of variance in ET\_T when considering MUs with significant increases in ET\_T (df = 351). Simple linear regression models did not explain all impacts of land use change on ET\_T. Fisher et al (2009) found that 87% of variance in tropical forest ET was explained by net radiation, 14% from vapor pressure deficit, and 6% from precipitation. These relationships explain some of the changes observed in figure 2 where the lowest annual ET\_T was observed in 2005, the same year as the Amazonia drought (Aragao et al 2007) and coincident with economic conditions unfavorable to soybean production. Moreover, sudden changes in ET\_C from individual farmer decisions on planting area can also change ET\_C contributions.

4. Conclusion

In the context of observed declines in soil moisture supply in South America (Jung et al 2010), the present study provides an assessment of changes in state level ET fluxes and a first account of ET by rainforest and agricultural ecosystems.
in Mato Grosso in a decade of important deforestation and agricultural expansion activities. Annual \( ET_F \) dropped from 50% to 40% of \( ET_T \) at an annual rate of 16.3 km\(^3\) y\(^{-1}\) and an aggregate loss of 25% in \( ET_F \) fluxes between 2000 and 2009. This decline was accompanied by an increasing contribution of \( ET_{Ag} \) to \( ET_T \). The composition and magnitude of \( ET_{Ag} \) from year to year depended on the trade-offs in soil water use from pasture and soybean areas. For example, a decline in \( ET_F \), the primary contributor to \( ET_{Ag} \), was offset by the expansion of \( ET_{Soy} \).

Although there was no statistically significant change in \( ET_T \) over the 2000–9 period, this study shows significant effects of land use change on the components of \( ET_T \), some of the variance of which was explained by deforestation and agricultural expansion. Declines in \( ET_F \) were found in the arc of deforestation in the north of Mato Grosso while \( ET_{Soy} \) increased in the agricultural frontier. Based on important land use changes in the region and the role of terrestrial ecosystems in regenerating precipitation, further studies detailing the contributions of the cerrado would further highlight the land use effects on \( ET_F \) fluxes within the state. As suggested in previous literature (Barona \textit{et al.} 2010), more detailed information from the combination of data obtained from remote sensing and on-the-ground \( ET \) measurements would also help reduce uncertainty in these findings.

Our results reinforce the role of forests in recycling precipitation by returning a large portion of the state’s soil moisture to the atmosphere, while showing a progressive human appropriation of water vapor from natural ecosystems. In Mato Grosso, precipitation is used by terrestrial ecosystems to provide ecosystem services in natural and managed ecosystems, contributing to economic growth through the production and export of rain-fed agricultural products. As demand for soybean and beef produced in Mato Grosso continues to increase worldwide, impacts described in this study should be considered in future deforestation and agricultural expansion policies to ensure the sustainability of rain-fed agriculture in the region.

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