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# Rain-fed and irrigated cropland-atmosphere water fluxes and their implications for agricultural production in Southern Amazonia

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ABSTRACT

Cropland has increasingly occupied large areas in Southern Amazonia since the 1990s, yet few direct field-based evapotranspiration (ET) measurements are available. We used the eddy covariance method to measure ET on a farm with multiple cropping cycles per year over September 2015 through February 2017. This period covered two soybean crops and associated rotations in each of two adjacent fields: a rain-fed field planted to soybean, maize, brachiara, and soybean, and an irrigated field planted to soybean, rice, bean, and soybean. Total ET during these crop cycles was 1265 ± 294 mm and 1414 ± 181 mm respectively for rain-fed and irrigated fields compared to 3099 mm of precipitation. Soybean ET was similar in both rain-fed and irrigated fields and ranged from 332 ± 82 mm (October 2015–February 2016) to 423 ± 99 mm (October 2016–February 2017), while rain-fed maize ET was 313 ± 68 mm (February–July 2016). The main difference between the fields was observed in the dry season (June–August 2016) when irrigation was applied for bean production. A crop model validated with the field data, showed that (1) crop transpiration represented 48–52% of ET for both soybean and maize, and (2) that irrigation for soybean planted at the end of the dry season resulted in marginal improvements to crop water productivity. Results provide insight into the use of irrigation to increase cropping frequency rather than yield with regional land and water implications at the Brazilian agricultural frontier.

## 1. Introduction

Brazil has been the center of international attention for its rapid increase in agricultural production. Between 1990 and 2015, the total area planted to non-perennial crops increased from 46 Mha to 71 Mha (IBGE, 2017), mostly driven by commodities such as soybean (*Glycine max*), maize (*Zea mays*), and sugar cane (*Saccharum officinarum* L.) which, together, represent 90% of cropland area (Dias et al., 2016). As the leading crop, soybean production almost tripled from 20 Mtons produced on 12 Mha of land in 1990 (IBGE, 2017) to an estimated 104 Mtons produced on 34 Mha in 2017 (USDA, 2017a), making Brazil the second largest producer in the world closely behind the United States (117 Mtons in 2016) (USDA, 2017b). To increase its agricultural output, Brazil has historically relied on both land use change and increases in yields (Dias et al., 2016). Soybean cropping areas have expanded from southern to northern Brazilian states into the Cerrado and Amazon biomes (Barona et al., 2010; Dias et al., 2016; Simon and Garagorry, 2006), and soybean yields almost doubled from a mean national yield of 1.7 t $ha^{-1}$ in 1990 to 3.0 t $ha^{-1}$ in 2015 (IBGE, 2017).

Southern Amazonia is the largest producing soybean region in Brazil, with production concentrated in the state of Mato Grosso and its Amazon and Cerrado biomes (Fig. 1) with a predominance of Oxisols in the region (Maia et al., 2010). Agricultural expansion has been more evident in this region with the rapid conversion of humid tropical forest and savanna landscapes into soybean and pasture, both of which have been produced almost exclusively under rain-fed conditions (Barona et al., 2010; Macedo et al., 2012). At the same time, the rapid growth of double cropping systems (i.e., two crop cycles per year within the same field) has allowed further intensification of agricultural output by planting maize, cotton (*Gossypium hirsutum* L.) or rice (*Oriza sativa*) immediately after the soybean harvest to take advantage of rainfall and residual soil moisture at the end of the wet season (Arvor et al., 2014).

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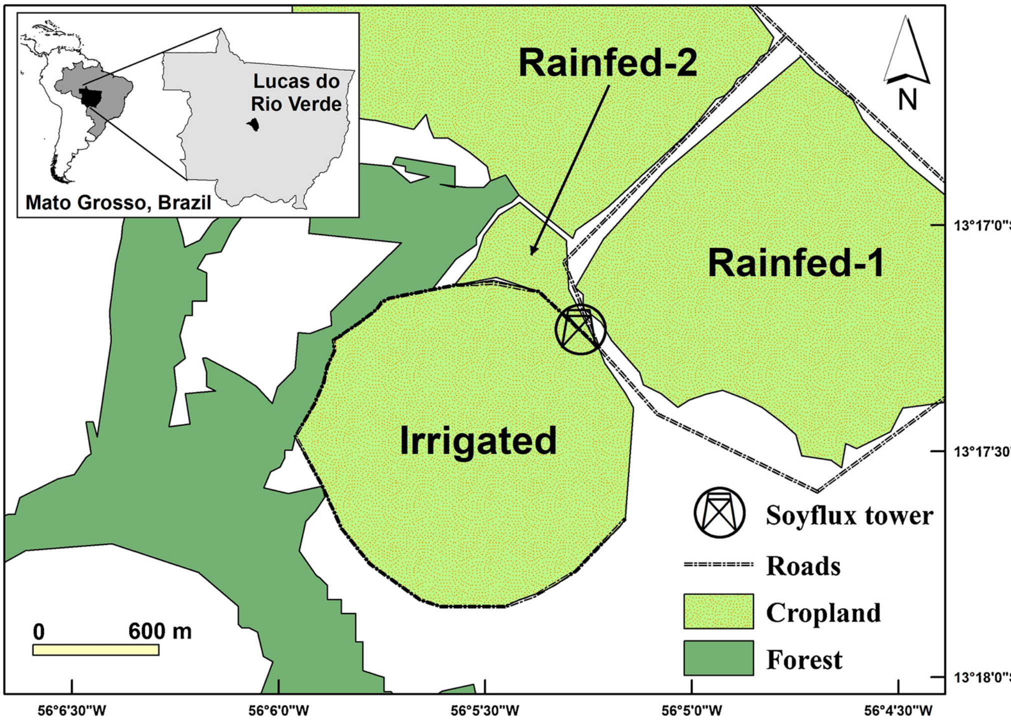


**Fig. 1.** Location of the Soyflux site of Capuaba farm in Lucas do Rio Verde, Mato Grosso, Brazil. Adapted from Graesser and Ramankutty (2017).

Maize cultivation as a second annual crop expanded rapidly in Mato Grosso between 2001 and 2011, with total area increasing from 0.5 Mha to 2.9 Mha during this period (Spera et al., 2014).

Research on the impacts of Southern Amazonia's changing land use and land cover has largely focused on dynamics between agricultural production and deforestation (Barona et al., 2010; Gollnow and Lakes, 2014; Macedo et al., 2012), indirect land use change dynamics between soybean and pasture expansion (Arima et al., 2011), as well as regional greenhouse gas emissions from deforestation (Galford et al., 2011, 2010) linked to agricultural output (Karstensen et al., 2013; Novaes et al., 2017; Zaks et al., 2009). In addition, land use change effects on the local water cycle have been described in relation to local impacts to water quantity (Dias et al., 2015), quality (Neill et al., 2013; Riskin et al., 2017), stream temperature (Macedo et al., 2013), regional-scale effects on water yields (Castello and Macedo, 2016), and water vapor flows to the atmosphere (Lathuillière et al., 2016). Forest-to-cropland and forest-to-pasture transitions are typically accompanied by a drop in landscape evapotranspiration (ET), which, when accumulated across the landscape, can reduce water vapor transfers to the atmosphere (Silvério et al., 2015; Lathuillière et al., 2016). This change in atmospheric feedback can in turn affect surface temperatures (Pongratz et al., 2006; Silvério et al., 2015), as well as regional precipitation recycling (Bagley et al., 2014), with potential effects on natural ecosystems and rain-fed agriculture (Davidson et al., 2012; Oliveira et al., 2013). This effect, however, may be reduced by additional water vapor transfers to the atmosphere following an expansion of irrigation practices in the region (Lathuillière et al., 2016). The last available agricultural census of 2006 showed a total irrigation area of 214,000 ha in Mato Grosso, the majority of which was used for soybean (< 2% of a total of 5.8 Mha planted to soybean) (IBGE, 2017), in a region of important irrigation potential for future production (FEALQ, 2014). On-farm land and water decisions to expand either rain-fed or irrigated agricultural production will therefore carry trade-offs with respect to the regional water cycle, although the magnitude is currently unknown.

Direct field measurements of ET are still lacking in Southern Amazonia, especially for cropland and pasture. Research efforts in the 1990s led to an initial network of eddy covariance towers in Brazil to be installed to measure carbon and water fluxes in natural ecosystems of the Amazon biome (Grace et al., 1996; Malhi, 2002; Da Rocha et al., 2004; Keller et al., 2004; Hutyra et al., 2005; da Rocha et al., 2009); this network has since expanded to other biomes in the region (Rodrigues et al., 2014; Vourlitis et al., 2015). Such direct ET measurements can elucidate the effects of modeling assumptions on modeled ET already achieved for tropical forest vegetation (Christoffersen et al., 2014) which should be repeated for cropland and pasture. However, no direct ET measurements have been published to date to evaluate the magnitude of and controls on ET for typical agricultural systems in the region, and potential differences between rain-fed and irrigated systems.

In this study, we used eddy covariance to measure cropland ET with a micrometeorological tower located between two adjacent fields (rain-fed and irrigated) with three objectives: (1) to provide a detailed water balance of cropland containing soybean, (2) to measure crop characteristics and crop coefficients for crop modeling purposes, and (3) to explore differences in crop transpiration and productivity with irrigation practices through crop modeling. In addition to providing key observations for future land-atmosphere and crop models, our results provide insight into the differences between current agricultural production practices based on rain-fed cropland with potential future production practices using irrigation.

## 2. Materials and methods

### 2.1. Site description

The research site consists of a seven-meter tall micrometeorological tower installed at Capuaba farm (13° 17′ 15.036″ S, 56° 05′ 17.354″ W, 427 m altitude) in the municipality of Lucas do Rio Verde, Mato Grosso (Fig. 1). The 1500 ha farm is located in the Cerrado biome and was established in the late 1980s after clearing natural vegetation. The farm produces soybean as the primary crop, and maize as the secondary (or double) crop, but also produces rice and bean (*Phaseolus vulgaris*) as well as other cover crops based on the time of year (e.g., *Brachiara ruziziensis*). General farming practices consist of minimizing soil disturbance through direct seeding (or no-tillage) and the use of a wide variety of cover crops