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LETTER

Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing

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Supplementary material for this article is available online

Abstract

Tropical deforestation changes the surface energy balance and water cycle, but how much change occurs strongly depends on the land uses that follow deforestation. Here, we quantify how recent (2000–2010) transitions among widespread land uses (i.e., forests, croplands, and pastures) altered the water and energy balance in the Xingu region of southeast Amazonia. Spatial-temporal analyses of multiple satellite data sets revealed that forest-to-crop and forest-to-pasture transitions decreased the net surface radiation (by 18% and 12%, respectively) and latent heat flux (32% and 24%), while increasing sensible heat flux (6% and 9%). Land use transitions during the 2000s reduced contemporaneous evapotranspiration (ET) in the Xingu region by 35 km^3 and warmed the land surface temperature (LST) by 0.3 °C. Forest-to-pasture and forest-to-crop transitions accounted for most of the observed ET reduction (25.5 km^3 and 7 km^3, respectively) and LST increase (0.2 °C and 0.07 °C). Pasture-to-crop transitions reduced ET by an additional 2.5 km^3 and increased LST by 0.03 °C. If land use had changed at a similar rate within the region's protected areas, ET would have decreased by another 4.7 km^3 and the surface would have warmed an additional 0.5 °C. Forests thus play a key role in regulating regional climate in Amazonia, with protected areas able to attenuate regional climate change caused by land use changes. Our findings show how a major non-GHG forcing, in this case agricultural expansion, has significantly altered regional climate in southeastern Amazonia and how protected forests can mitigate such changes.

Introduction

Nearly 20% of Amazonian forests have been clear-cut and converted to other land uses (Morton *et al* 2006, Macedo *et al* 2012). Conversion has been primarily to pastures (TerraClass 2010), but mechanized agriculture (e.g., soy, corn, cotton) is expanding rapidly, replacing both pastures and forests (Morton *et al* 2006, TerraClass 2010, Macedo *et al* 2012). Although deforestation rates since 2005 have dropped to 30% of the historical average (1995–2005 (Nepstad *et al* 2014)) and 54% of remaining forests in the Brazilian Amazon are legally protected by strictly protected parks, indigenous land and sustainable use (Soares-Filho *et al* 2010), there is a large pool of already cleared land. Land use transitions (LUTs) in these deforested areas likely exert a strong influence on regional climate (Costa *et al* 2007, Spracklen *et al* 2012, Oliveira *et al* 2013)—triggering local climate changes above and beyond those predicted due to greenhouse gas emissions (Anderson-Teixeira *et al* 2012, Blunden and Arndt 2013).

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Large-scale agricultural expansion over tropical forests warms land surfaces and may reduce regional rainfall via several mechanisms. First, loss of forest cover increases surface reflectance and decreases the energy available to drive the hydrological cycle (Bonan 2008). Second, it reduces evapotranspiration and increases sensible heat flux, thus reducing humidity and potentially cloud formation. Third, it decreases surface roughness, which reduces the transfer of heat between the biosphere and atmosphere (Bonan 2002), thus potentially warming land surfaces and decreasing convective overturning. These effects may differ between land uses, with croplands (e.g., soy) tending to have stronger effects on the energy balance and rainfall patterns than pastures due to differences in growing season and rooting depth, among other factors (Pongratz *et al* 2006, Costa *et al* 2007).

Recent studies suggest that forest loss is increasing the length of the dry season in some parts of Amazonia (Butt *et al* 2011, Fu *et al* 2013) and altering individual components of the energy budget (e.g., surface temperature (Loarie *et al* 2011), evapotranspiration (Lathuillière *et al* 2012), and cloudiness (Knox *et al* 2011)). These studies have explored the combined impact of land cover changes on water recycling and rainfall. However, the effects of specific LUTs on the surface energy balance remain poorly studied, as does the spatial-temporal variability of these effects. In addition, it is unclear how protected areas along the arc of deforestation reduce the climatic impacts caused by such transitions.

In this study, we used a combination of satellite data (Mu *et al* 2011, Wan *et al* 2004) and maps of land cover (Macedo *et al* 2012) to quantify the individual and combined impacts of the three most widespread LUTs (forest-to-pasture, forest-to-cropland and pasture-to-cropland) in southeastern Amazonia on the following components of the surface energy balance: land surface temperature (LST) (Wan *et al* 2004), net radiation (R_{net}), and R_{net} partitioning between latent (ET) (Mu *et al* 2011) and sensible heat (H). We focused on three questions: (a) How do specific LUTs contribute to observed changes in the energy balance and each of its components (per unit area)? (b) What is the net contribution (forcing) of recent deforestation (2001–2010) to observed changes in regional climate throughout the upper Xingu basin (as measured by ET and temperature)? (c) To what extent do protected areas mitigate historic and potential future changes to the regional ET and temperature?

Methods

We quantified the direct impacts of three LUTs on the linked energy, water and temperature of the upper Xingu basin, a key area of agricultural expansion and production (figure 1). Located in the Amazon's 'arc of deforestation' (Mato Grosso, Brazil), the native vegetation of the upper Xingu (176 892 km^2) is dominated by transitional forests (originally ~80% of the basin) that lie between *cerrado* (savannas) of central Brazil and more humid forests to the north. It includes the Xingu Indigenous Park and adjacent indigenous reserves, which form a large (34 206 km^2) mosaic of forested protected areas, hereafter referred to as the XIP (figure 1). The climate, soil, and social conditions of the upper Xingu basin are broadly representative of the dryer portions (~40%) of the Amazon (Brando *et al* 2014), and similar patterns of LUTs are occurring throughout tropical forests in Southeast Asia and Central Africa (Hansen *et al* 2013).

We performed regression analyses, based on land cover fraction, to evaluate links between specific LUTs and changes in the surface energy balance components (R_{net}, ET, H and LST). Using 250 m gridded land cover maps, we computed the proportion of forest, pasture, and cropland occupying each 1 km grid cell (i.e., fractional cover per pixel at 6.25% intervals) annually for the entire 10-year time series (Macedo *et al* 2012), matching the spatial resolution of other MODIS-derived response variables (1 km). For each of the 1 km grid cells we also derived time series of estimated R_{net} (explained briefly below and in detail in the supplementary information section S2), ET (MOD16, 2001–2010, every 8 days), *H* (the difference between R_{net} and ET) and daytime LST (MOD11A2, 2001–2010, every 8 days). We used the pixels within each LUT (forest-to-cropland, forest-to-pasture, and pasture-to-cropland) to fit linear regression models treating land cover fraction as independent and R_{net}, ET, H and LST as dependent variables (figure 2).

To evaluate the regionally-integrated effect of historic LUTs on ET and LST, we compared observations in pixels that had experienced LUTs in the 2000s (i.e., 100% forest in 2000, but partially or entirely converted before 2011) with mean ET and LST of unconverted neighboring pixels. First we estimated the would-be ET and LST in converted pixels as the mean of unconverted neighboring pixels. We then calculated the difference between observed and estimated values for the entire upper Xingu basin (figures 4(A) and 3(B)), as well as the cumulative sum of ET over time for each LUT (figure 3(C)). Finally, we evaluated the mitigating effect of protected areas by comparing mean LST inside and outside of the XIP from 2001 through 2010 (figure 4(B)), and the relative proportion of ET occurring inside and outside of the XIP in 2010 (see supplementary data for details).

R_{net} at the land surface is the sum of net shortwave (RS_{net}) and net longwave (RL_{net}) radiation, where RS_{net} is incoming shortwave solar radiation (RS) minus the fraction reflected by the land surface (RS * albedo) and RL_{net} is the difference between incoming and outgoing longwave radiative fluxes. We estimated all of these R_{net} parameters under all sky conditions, using remotely-sensed data products (MOD43A3, MOD11A2, MOD08E3) and weather station data,

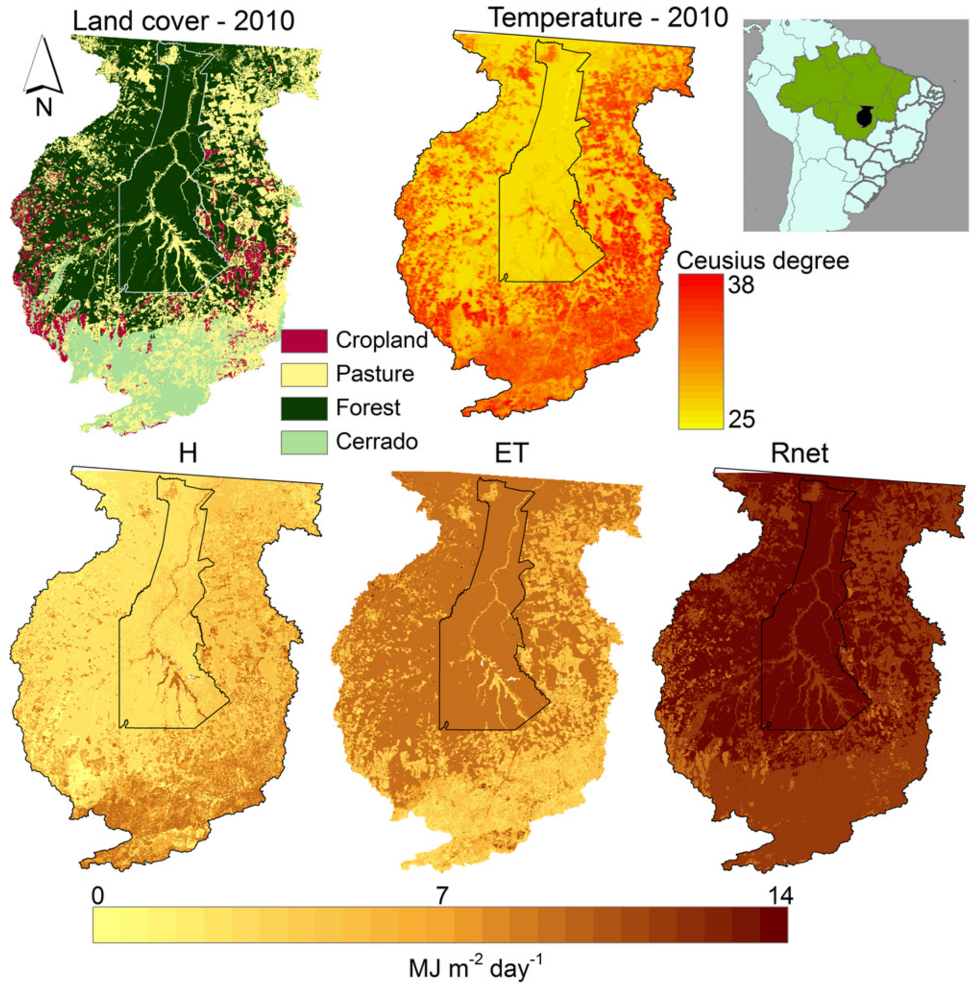

Figure 1. Maps of the upper Xingu basin land cover and energy balance components in 2010. Top row: land cover (left; from Macedo *et al* 2012) and daytime mean of land surface temperature in Celsius degrees (right; from MOD11A2). Bottom row: sensible heat (H, left), latent heat (ET, middle; from MOD16), and net radiation (R_{net}, right) in MJ m^{-2} d^{-1}. Polygons in the center are indigenous protected areas.

following previously published methods (Bisht *et al* 2005, Ryu *et al* 2008, Bisht and Bras 2010). Incoming shortwave solar radiation was mapped at 1 km resolution every 8 days throughout the study area, using direct and diffuse solar irradiance estimates based on solar position, terrain and atmospheric conditions (as implemented in the *insol* R package; see supplementary information section S2).

We used measurements from a net radiometer installed on a tower in Sinop, Mato Grosso (−13.06 ° S, −52.38 °W) to validate our R_{net} estimates. The comparison indicates that our MODIS-based estimates capture the actual R_{net} in terms of magnitude (error lower than 1% at annual scale and 10% at 8-day resolution), and seasonality (see supplementary information section S4). Our input land cover maps had an estimated accuracy of 92% (Macedo *et al* 2012); LST data was estimated to be accurate within 1 °C (Wan *et al* 2004); and ET data had an estimated uncertainty of 5% for tropical forests (Mu *et al* 2011). Solar radiation and MODIS-derived land cover maps were also inputs to the ET data product, which could introduce additional uncertainty to our study. In the MODIS ET calculation, land cover maps are used primarily to parameterize stomatal and leaf conductance (Mu *et al* 2011). This is likely to result in underestimation of ET for areas converted from forest to pasture or soybean. To account for this uncertainty, we performed two sensitivity analyses to ensure that our results were robust (see supplementary information section S4).

Results

Historical transitions

Between 2001 and 2010, approximately 12% (18 838 km^2) of the Xingu region's forests were converted to croplands (3347 km^2; 2.4%) or pasturelands (15 491 km^2; 9.6%), decreasing the region's forest cover from 61% to 49%. This forest loss occurred almost entirely on private lands outside the Xingu Indigenous Park. At the same time, 4962 km^2 of pasture were converted to crop.

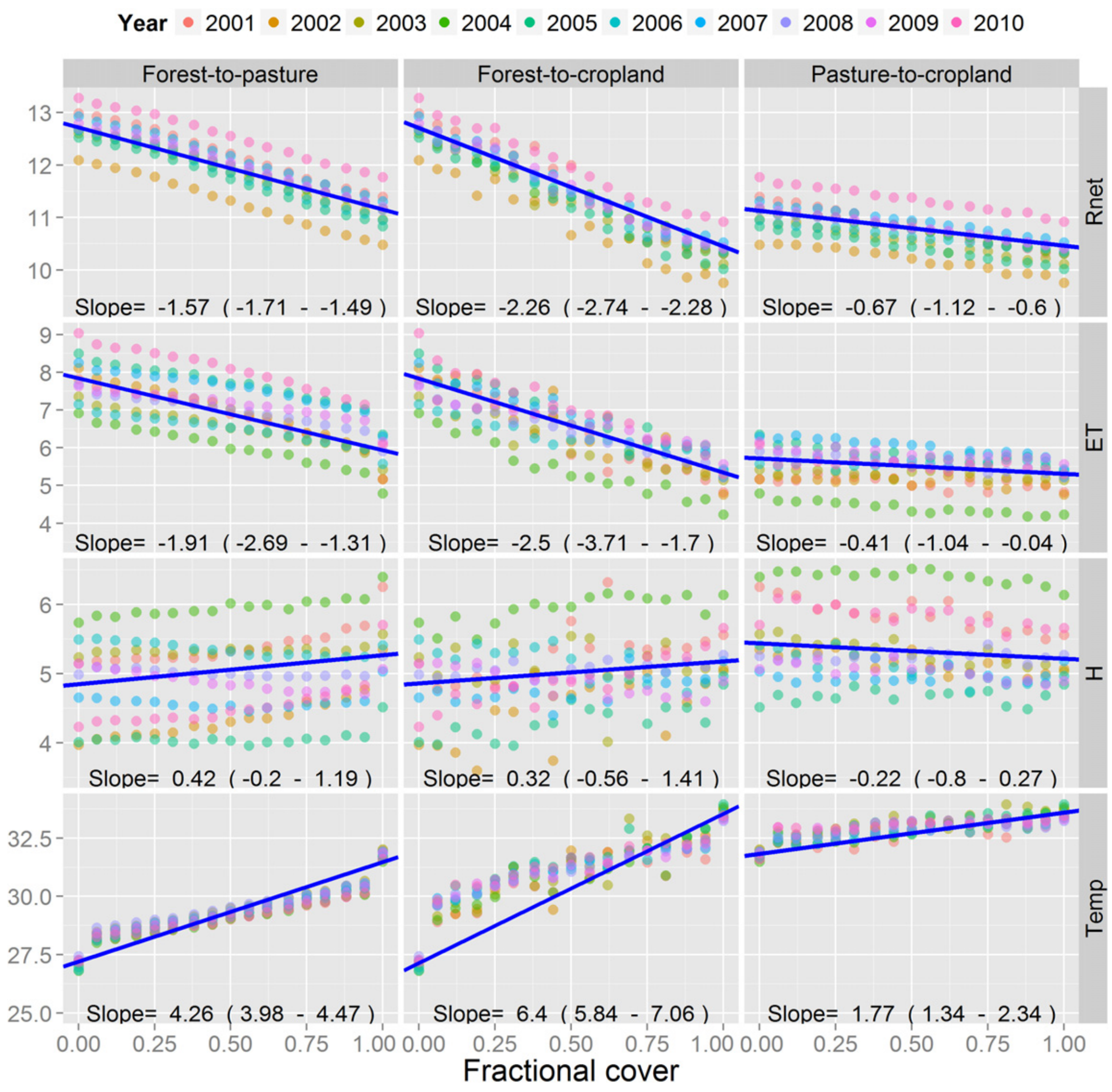

Figure 2. Changes in net radiation (R_{net}), latent heat (ET), sensible heat (H) and land surface temperature (Temp) as a function of fractional change in land cover, estimated from yearly remotely-sensed data (dots) using linear regressions (solid lines). The slopes in parentheses indicate the minimum and maximum slopes calculated for each year from 2001–2010. Temp is in degrees Celsius and other variables are in MJ m^{-2} d^{-1}.

LUT contributions to observed change

All LUTs significantly altered the surface energy budget, hydrological cycle, and LSTs in the Xingu, particularly transitions involving forest clearing. For example, when a given unit area of forest was converted to crop or pastureland, R_{net} decreased by 18% and 12%, respectively (figure 2). Seventy-five percent of the R_{net} decrease was a result of increased outgoing long wave radiation (figure S9) and 25% from increased surface albedo (see supplementary information, table S4). The partitioning of R_{net} into ET and H was also strongly affected. Forest-to-crop and forest-to-pasture transitions decreased ET (by 32% and 24%, respectively) and increased H (6% and 9%). As a result of these energy balance shifts, LST was 6.4 °C higher over croplands and 4.3 °C higher over pasturelands, compared to the forests they replaced (figure 2). These patterns of change were consistent over time in areas that experienced LUTs during the study period (see supplementary information, figure S4). Within already deforested lands, pasture-to-crop transitions reduced R_{net} by 4% and ET by 7%, while increasing LST by 1.8 °C (figure 2). On a per unit area basis, land cover conversion to cropland thus had the strongest influence on the energy balance in the Xingu region, particularly when it replaced forests directly.

Regional effects of LUTs

We estimate that 35.0 km^3 less water was returned to the atmosphere from the entire Xingu region in the 2000s, representing a 2% decrease in regional ET relative to a scenario with no deforestation or pasture-to-cropland transitions during that period. Despite the higher per-unit-area effect of croplands, pastures had a greater cumulative impact on the regional energy balance of the upper Xingu basin because the total area of pasture expansion over the 2000s far exceeded all other LUTs (figure 3(A)). Forest-to-pasture

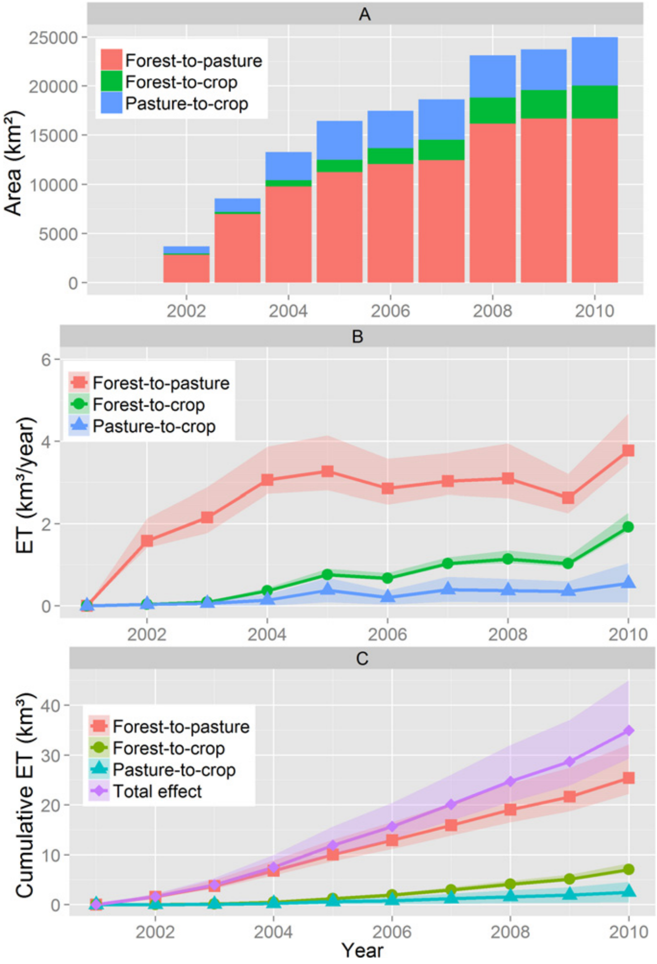

Figure 3. Effect of land use transitions (LUT) on evapotranspiration (ET; from MOD16). (A) Cumulative area of each LUT from 2001–2010. (B) Annual effect of each LUT on ET. (C) Cumulative effect of each LUT on ET. Shaded areas represent the first and third quartiles.

Figure 4. Effect of land use transitions (LUT) on daytime land surface temperature (LST from MOD11A2). (A) Effect on temperature in the entire upper Xingu region during the 2000s for each of three LUTs (shaded areas represent the first and third quartiles). (B) Trends in annual mean surface temperature for the entire upper Xingu basin (regional), inside and outside the Xingu Indigenous Park (XIP).

conversions contributed 25.5 km^3 of the total 35 km^3 reduction in ET, whereas forest-to-cropland contributed 7.0 km^3 (figure 3(C)). Areas converted from pastures to croplands during the 2000s, following earlier (pre-2000) deforestation, reduced the Xingu ET by an additional 2.5 km^3 (figure 3(C)). Although the area with pastures and croplands across the Xingu remained relatively constant from 2008 to 2010 (figure 3(A)), we observed substantial differences in ET between land uses due to climate variability (figure 3(B)). For example, precipitation in 2010 was below average (regional drought), with a particularly intense dry season. Because forests can access deeper soil water reserves, they are able to evapotranspire more in very dry years (relative to crops and grasses). This explains the larger difference in ET for forest-to-pasture transitions in 2010 (figure 3(B)).

Together the three LUTs considered here caused a mean basin-wide increase in surface temperature of 0.3 °C during the 2000s (figure 4(A)). Forest-to-pasture transitions had the greatest cumulative impact, increasing LST by 0.2 °C. Forest-to-cropland conversion increased the mean LST of the upper Xingu basin by 0.07 °C, while pasture-to-cropland contributed the remaining 0.03 °C increase. Though significant, the observed effects of LUTs on ET and temperature represent just a fraction of the probable changes due to historic (pre-2001) deforestation. Based on satellite time series for the 2000s, we estimate that the annual mean ET in the Xingu Basin would have been 6% higher and LST 0.7 °C cooler (see supplementary information, figure S3) if there had been no historic deforestation.

Influence of protected areas

To evaluate the role of protected areas in stabilizing regional climate, we compared ET and LST changes inside and outside the XIP during the 2000s. We then developed hypothetical scenarios with and without protected areas to quantify how the protected area mosaic has mitigated the effects of recent LUTs on climate changes across the Xingu (see supplementary information, section S3). Although the XIP represents 19% of our study area, it cycled 39.2 km^3 of water in 2010, accounting for 29% of total Xingu ET that year. By comparison, the Amazon protected area network cycled 2879 km^3 of water in 2010 and accounted for 50% of total Amazon ET (supplementary information, figure S8).

LST inside the XIP was 1.9 °C cooler than the upper Xingu basin average outside the XIP in 2001. This difference increased to 2.5 °C by 2010 due to warming outside the XIP driven by land cover change (figure 4(B)). If the XIP had been deforested following the pattern in its surroundings, the mean basin day time temperature would be 30.1 °C [CI = 29.8–30.3], 0.5 °C warmer than observed in 2010 (figure 4(B)). Using observations from deforested regions (i.e., slopes in figure 2), we estimate that converting all remaining forests in the upper Xingu to pastures (80%) and crops (20%) would result in a regional daytime LST of 31.3 °C [CI = 30.6–31.9], which is 1.7 °C warmer than the current average. The XIP has thus contributed to stabilizing regional climate by conserving large blocks of standing forests that recycle more water and maintain cooler LSTs than agricultural lands.

Discussion

Our results show that widespread agricultural expansion is already significantly warming the Xingu River Basin and reducing the region's ET. These changes in climatic variables are primarily associated with the expansion of crops and pastures at the expense of Amazon forests, but also with the replacement of pastures by croplands in already deforested areas. Satellite time series data available since 2000 enabled us to quantify the effects of specific LUTs on ET and temperature across the Xingu, while providing new insights into the impacts of historic deforestation. Our analyses demonstrate that recent LUTs have had a large effect on the energy balance of the Xingu, adding to the even larger cumulative changes due to LUTs before 2001. The rapid changes in the regional energy balance observed in this study are probably already operating over a much larger geographical area than studied here. Much of the Amazon's 'arc of deforestation', for example, will likely show similar effects given that crop and pasture expansion over native forests have been widespread in this entire region since the 1980s (Morton *et al* 2006, TerraClass 2010, Nepstad *et al* 2014).

The observed changes in the surface energy balance directly affect other components of the local hydrological cycle. By definition, if rainfall is held constant, a decrease in ET will increase runoff to streams and rivers by the same amount (Coe *et al* 2011, 2009, Hayhoe *et al* 2011). Studies have shown that runoff in Xingu headwater streams represents 7% of precipitation in forested watersheds, but 31% in soybean watersheds (Hayhoe *et al* 2011). This increase in runoff is consistent with the decrease in ET observed in areas of forest-to-soy transitions in this study (32%). Forest-to-pasture transitions caused a smaller decrease in ET than forest-to-crop, presumably because pasture grasses have a much longer growing season (and therefore higher cumulative ET) than soybeans. During the 3-month growing season, soybeans evapotranspire more than pasture grasses (Ponte de Souza *et al* 2011), but over the course of the growing year pastures evapotranspire more than croplands. Decreased ET, increased sensible heat flux, and lower surface roughness lead to increased surface temperature (Baldocchi 2014). Integrated over the entire Xingu basin, the historical land conversions would be consistent with a 15% increase in discharge assuming no change in precipitation (Panday *et al* 2015). Furthermore, increased LST in pastures and agricultural fields (>3 °C) contributes to widespread warming of headwater streams, which may alter water chemistry (e.g., dissolved oxygen, nutrient cycling) and the metabolic rates of stream organisms (Macedo *et al* 2013).

From 2000 to 2010 expansion of pastures and croplands caused a surface warming of 0.3 degrees across the Xingu Region. This exceeds temperature changes attributed to increased atmospheric greenhouse gas concentrations as of 2012 (Blunden and Arndt 2013). The observed warming was not due to increased net radiation (as is the case with GHG warming), but rather to a decrease in ET and increase in H. These regional temperature changes are thus not expected to alter global climate. Nevertheless, they exert a strong influence on ecological processes at the regional scale and need to be considered when developing mitigation and adaptation strategies for anthropogenic climate change. For example, warm surfaces in agricultural fields bordering forested areas lead to dryer and warmer forest edges (Cadenasso *et al* 1997), which increase forest flammability and the overall likelihood of wildfires (Brando *et al* 2014). Alencar *et al* (2015), for instance, showed that the occurrence of widespread fires in the region during the 2000s was largely associated with forest fragmentation and the probable climatic impacts of deforestation on forest edges.

Regional changes in the energy balance also have important implications for the ecosystem services provided by the remaining Xingu forests. The onset of the rainy season in eastern Amazonia is associated with changes in the convective boundary layer and an increase of moisture supply at the end of the dry season (Silva Dias *et al* 2002, Butt *et al* 2011), a process that depends in part on R_{net} and ET. Reductions in R_{net} and ET—such as those observed in this study as a result of regional LUTs—may help explain delays in the onset of the rainy season occurring in other regions of Amazonia that experience large scale agricultural expansion (Butt *et al* 2011, Fu *et al* 2013). If such trends were to persist, they have the potential to affect future crop productivity or force changes in cropping strategies (e.g., double cropping). For example, areas that today are dominated by rainfed agriculture might no longer have a sufficiently long (or predictable) rainy season to support two crops in one season. Regional modeling suggests that precipitation changes associated with climate feedbacks from LUTs could ultimately reduce food production in the Amazon by as much as 30% by 2050 (Oliveira *et al* 2013), barring a major change in crop varieties or cropping strategies.

At regional scales, private and public protected forests may play a critical role in buffering against climate change caused by LUTs in the tropics. Landscape-scale land use planning and management may therefore offer a direct mitigation strategy to combat regional climate change—and be a valuable complement to the effect of any global efforts to reduce greenhouse gas emissions. Quantifying the energy balance impacts of different LUTs is key to a comprehensive evaluation of national policies and market conditions that alter land use trajectories. These drivers may ultimately influence the future climate of Amazonia and other tropical regions with competing demands for land. Long-term maintenance of ecosystem services provided by protected areas and other forest fragments must take into account these indirect effects of regional LUTs (Coe *et al* 2013, Stickler *et al* 2013).

Conclusion

Here, we quantified how transitions among forests, croplands, and pastures have altered the water and energy balance of southeast Amazonia over the course of a decade. Our spatial-temporal analyses of multiple satellite data sets revealed that the conversion of forests to crops and pastures significantly warmed the land surface and reduced water cycling and the available surface energy (R_{net}), primarily due to an increase in outgoing longwave radiation and surface albedo. Although forest-to-cropland conversion caused the largest per-unit-area reductions, more of the region's forests have been converted to pastures than to croplands. Forest-to-pasture transitions have therefore had a greater overall influence on the region's energy balance. Such changes could affect ecosystem services that maintain forest health and the productivity of rainfed crops. Similar climate changes linked to LUTs are likely operating over a much larger region and may contribute to recent delays in the onset of the rainy season observed in other parts of Amazonia. Understanding the energy balance impacts of specific LUTs is critical to a comprehensive evaluation of how land use trajectories may influence the future climate of this and other tropical forests.

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Author contributions

PMB, MTC, MNM, PSAB, and DVS designed the study. DVS, MNM, and PSAB conducted the analysis. All authors wrote the paper.

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