Climate risks to Amazon agriculture suggest a rationale to conserve local ecosystems

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In southern Amazonia, more than half of all cropland is devoted to the production of two rainfed crops per year, an agricultural practice known as "double cropping" (DC). Climate change, including feedbacks between changes in land use and the local climate, is shortening the extent of the historical rainy season in southern Amazonia, increasing the risk of future detrimental environmental conditions, and posing a threat to the intensive DC agriculture that is currently practiced in that region, with potential negative consequences at regional, national, and even global scales. We argue that the conservation of undeveloped forests and savannas in southern Amazonia is supported by socioeconomic justifications and is in the best interests of agribusiness, local governments, and the public.

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Agribusiness is expanding into the tropical forests and savannas of South America, Southeast Asia, and sub-Saharan Africa, fueled by growing global demand for food commodities and attracted by vast expanses of inexpensive land in a climate well suited for intensive agricultural production. However, the capacity of these regions to keep pace with demand may be affected by a largely overlooked factor: the large-scale conversion of remaining undeveloped land to planted pasture- and croplands disrupts the climate-related ecosystem services that such lands provide to farmers, ranchers, and local communities (Strand *et al.* 2018). In addition, agricultural productivity, profitability, and food security will likely be adversely impacted by shifts in seasonality and rainfall patterns. These land-use–climate feedbacks could initiate a self-perpetuating cycle of declining agricultural yields and increasing cropland expansion.

In a nutshell:

- Across much of southern Amazonia, an extended rainy season promotes the production of two rainfed crops per growing season, a practice known as "double cropping"
- Increased concentrations of greenhouse gases along with ongoing land-use change have contributed to climate change, which has already shortened the duration of the region's rainy season; shorter rainy seasons are typically associated with reduced crop output
- Continued reductions in the length of the rainy season will increase the "climate risk" for intensive agriculture systems; however, protecting the region's intact forests and savannas may help local farmers limit this risk
- The increasing threat that a changing climate poses to tropical agriculture provides an opportunity to engage agribusiness as a powerful ally for ecosystem conservation

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To address this topic, we focus on the "climate risk" (defined below) faced by the soy (*Glycine max*)–maize (*Zea mays*) double-cropping (DC) system in the northern Mato Grosso, Brazil. This region straddles the southern fringe of the Amazon biome and the northern fringe of the cerrado (Brazilian savanna) biome (Figure 1). In 2012, 7.1% of the world's soybeans and 1.4% of the world's maize were produced in this region, and between 2004 and 2012, soybean production increased 58% and maize production increased 359% (mainly as a second crop). Located along the Amazon's arc of deforestation (the region in southern and eastern Amazonia where the highest rates of deforestation are found), northern Mato Grosso has lost about 10.9 million ha of rainforest and 8.3 million ha of cerrado over the past several decades, yet 76% of rainforest and 66% of cerrado still remain intact (Dias *et al.* 2016).

The long rainy season characteristic of northern Mato Grosso accommodates production of two crops per growing season (Arvor *et al.* 2014). This DC system has become ubiquitous throughout the region because it provides more revenue per plot, greater income diversification, and reduced pest pressure, as well as helping to maintain a more stable pool of farm labor (Richards *et al.* 2015). Double cropping has also been an important factor in land-use intensification.

Because the region's agriculture is almost exclusively rainfed, yields of both crops are subject to fluctuations in weather patterns. Double-cropped agriculture requires a rainy season that consistently starts within a specific date range, lasts long

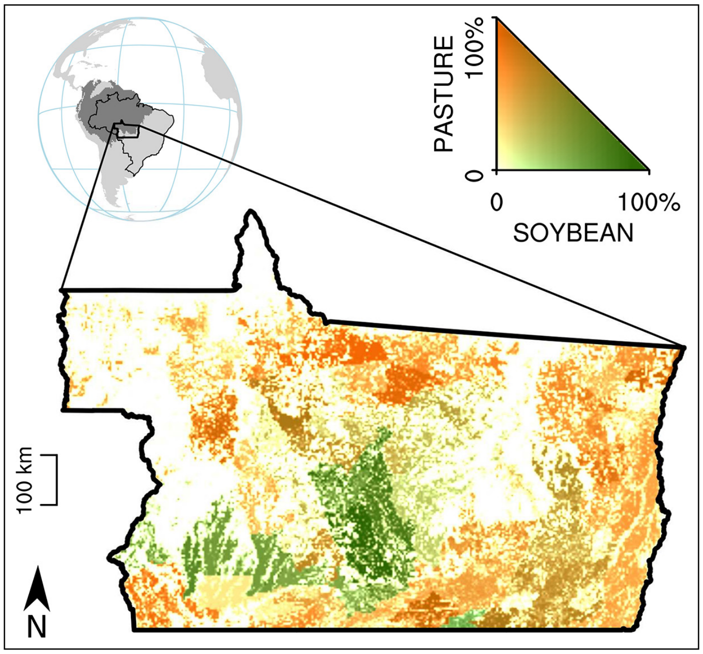

Figure 1. Location of Amazonia (inset, dark gray) in Brazil and the distribution of soybean (*Glycine max*) croplands and pasturelands in northern Mato Grosso state as of 2012. White pixels represent locations where natural vegetation is still present. The figure is based on the land-use dataset from Dias *et al.* (2016).

enough to produce two crops, has sufficient episodes of dry weather during the peak of the rainy season to allow for harvesting, and has minimal exposure to extreme heat (Cohn *et al.* 2016a).

Climate risk is the combination of the likelihood of a specific climate event and its consequences. Farmers may choose to plant two crops in one growing season, but the yield of the second crop depends on the actual duration of the rainy season (D), which is unknown at the time the decision to plant is made. If the rainy season is long enough, profits will increase (all else being equal), but if not, then farmers may experience economic losses.

Farmers' general rationale for managing climate risk in the region is illustrated in Figure 2. If the rainy season begins before early October, a long rainy season is expected (WebFigure 1b), in which case farmers typically choose to plant two short-cycle crops. If the rainy season begins in late October, however, then farmers either take a higher risk on the second crop or choose to minimize risk by maintaining only a single crop that year (Figure 2). Although the yield of the first crop (soy) is less affected by D, there is a strong positive correlation between the observed yield of maize as a second crop and D (Figure 3). The average yield of the maize crop is 4650 kg ha^{-1} for a 210-day rainy season, with an increase of 30 kg ha^{-1} per additional day of rain duration (0.6% per day; Figure 3a), and a similar decrease per day of reduction in rain duration. In addition, DC is practiced only in regions where the climatological (ie long-term mean) rainy season duration ($\bar{D}$) is longer than 200 days (Figure 3b), while yearly data (Figure 3a) indicate low yields when actual rains last between 180 and 200 days. Moreover, by analyzing 2002–2012 Moderate Resolution Imaging Spectroradiometer (MODIS) and Tropical Rainfall Measuring Mission (TRMM) data for the cerrado, Spangler *et al.* (2017) found that the fraction of DC decreased linearly from 100% DC for a rainy season that began before October 10, to 0% DC for a rainy season that began after November 1. This 20-day window between the start of rainy seasons is critical to a farmer's decision to plant one or two crops in that season.

On the basis of Figure 3b, we proposed that the minimum $\bar{D}$ for the success of DC in the region is 200 days, which is consistent with the following soybean–maize system characteristics: (1) the current shortest cycle central Brazil soybean cultivars (first crop) have a cycle of around 110 days (Alliprandini *et al.* 2009); (2) short-cycle maize (second crop) generally has a longer cycle than soybeans under the same climatic conditions; (3) due to the large size of farms in Mato Grosso, the harvest/planting operation for the crops may take >10 days; and (4) it is also assumed that the second crop (maize) will use about 30 days of soil moisture after the end of the rains. Growing two crops when $D < 200$ days implies longer periods of relying on limited reserves of soil moisture, which may increase water stress and reduce yields of crop plants (Figures 2 and 3). However, the climate of southern Amazonia (Panel 1) has begun shifting in ways that put the DC system at risk. Multiple studies have demonstrated that the rainy season in this region has shortened substantially (Marengo 2004; Butt *et al.* 2011; Fu *et al.* 2013), a trend that appears to be attributable to a combination of changes in large-scale atmospheric circulation over a ~28-year cycle (Marengo 2004) and changes in land use (Costa and Pires 2010; Butt *et al.* 2011; Debortoli *et al.* 2015). The onset of the rainy season in the neighboring state of Rondônia, for example, now occurs an average of 15–18 days later than in the period 1970–2000 in deforested landscapes, although it remains unchanged in nearby forested regions (Butt *et al.* 2011).

Several of the climatic changes that are detrimental to DC are projected to continue in the future. The Coupled Model Intercomparison Project 5 (CMIP5) ensemble, which assumes not only increased atmospheric greenhouse-gas (GHG) concentrations but also a gradual decline in Amazon forest cover of ~25–35%, projects a lengthening of the dry season over the Amazon's arc of deforestation (Fu *et al.* 2013), and lower precipitation in September and October (Pires *et al.* 2016). As described below, individual analyses of these future model runs – using both constant (circa 2005) and projected land-use patterns – indicate that continuing deforestation contributes to lengthening the extent of dry seasons.

Here, we analyzed the onset and end of the rainy season along with D in northern Mato Grosso for the four CMIP5 models that best represent these climate features in the period 1971–2000 (WebPanel 1). For all four models, climate projections for 2010–2029 show a reduction in median D relative to

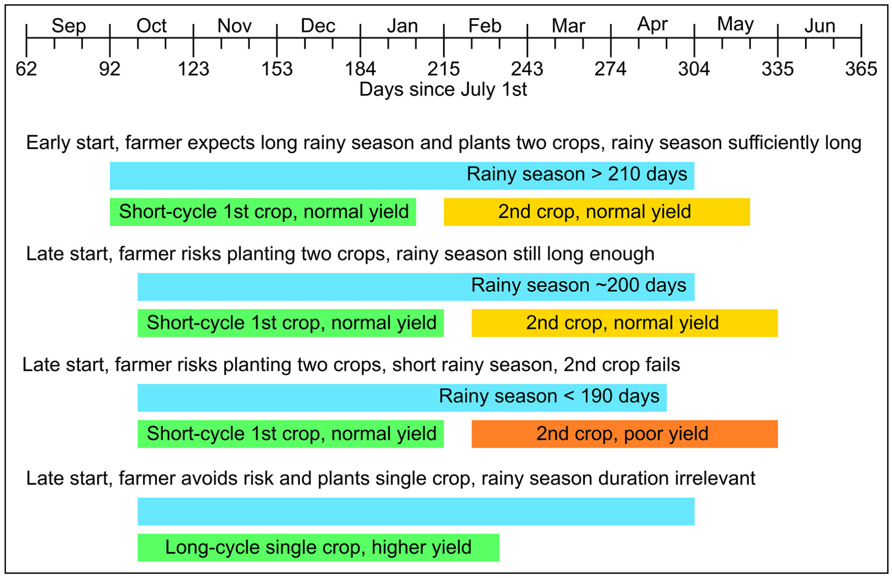

Figure 2. Chart showing farmers' general rationale for managing climate risk in northern Mato Grosso, Brazil. Blue bars indicate the extent of the rainy season; green bars indicate time spent planting, maintaining, and harvesting the first crop (or for the bottom row, a single crop); and light/dark orange bars indicate time spent planting, maintaining, and harvesting the second crop.

1971–2000, and projections for 2030–2049 exhibit an even larger reduction (WebFigure 2). However, the maximum acceptable climate risk for rainfed agriculture is 20% (maximum of one crop failure in five harvests; MAPA 2002), and all four models show larger reductions in D at the 20% percentile (ie the 20% shorter rainy season years, when rainfed crop failures happen) than at the median (WebFigure 2). The patterns of onset and end dates vary across models and periods, but all models indicate both a delay of onset and an earlier end to the rainy season during the 2030–2049 period relative to the 1971–2000 period, particularly for lower levels of climate risk.

Figure 4 illustrates the spatial distribution of past and projected $\bar{D}$, including either the effects of changing radiative forcing (RF; caused by increased concentrations of GHGs) with fixed 2005 land use (LU) (Land-Use and Climate, Identification of Robust Impacts project [LUCID] runs; Brovkin *et al.* 2013), or the combined effects of RF and of projected changes in LU (CMIP5 runs). All results were simulated by the HadGEM2-ES climate model (the only model included in both the CMIP5 and LUCID experiments), which has a small climate bias (ie deviation from observed climate). All other models have considerable bias, simulating a rainy season that is too short for DC in any case (WebFigures 3 and 4). Figure 4a displays simulations for 1971–2000, with respect to historical patterns of RF and LU; Figure 4b and Figure 4c both show projections for 2010–2029 RF, but the former considers fixed 2005 LU whereas the latter considers projected LU patterns. The difference between Figure 4b and Figure 4c is depicted in Figure 4d, which is essentially the effect of deforestation on $\bar{D}$ under 2010–2029 projected RF. As can be seen, $\bar{D}$ decreases from 1 to 15 days throughout most of the region, but especially in the east. Current rainfed DC systems are present only in areas where $\bar{D} > 200$ days (Figure 3b), and projections for 2010–2029 show an increasing risk of actual $D < 200$ in the southeast of the study area when increasing deforestation is taken into consideration. Regions with low climate risk for DC in this period will be limited to the northwestern portion of Mato Grosso state, the area where the intensive DC systems will be forced to migrate if climate risk is not mitigated.

As the window for planting becomes shorter, production systems that depend on a longer rainy period (ie early soybean cultivars planted in central-northern Brazil in the transition from dry to wet season) will be the most affected by delayed rainfall or variable onset (Pires *et al.* 2016). In the unmitigated climate-change scenario described above, the risk of DC failure (ie rains start late, projected $D < 200$ days, and the second crop is not planted) is as high as 50% for the soy-intensive areas of Mato Grosso (Figure 4f) and MATOPIBA (a predominant soy-producing area where the states of Maranhão, Tocantins, Piauí, and Bahia intersect; Pires *et al.* 2016; Abrahão and Costa 2018).

The projected reductions in $\bar{D}$ of up to 15 days (Figure 4d) can be considered extremely conservative, as future land-use scenarios included in the HadGEM2-ES model assume little vegetation suppression (deforestation and other forms of land clearing) after 2005; Amazonia deforestation increases from

Panel 1. The climate of southern Amazonia and how it is affected by land cover

The climate of southern Amazonia (8°S–14°S) is transitional between the permanently wet climate to the north and the seasonal (half wet/half dry) climate to the south. The rainy season begins in the spring, following the southward movement of the Sun, the warming of the continent, and the onset of the South American Monsoon System. The moistening of the planetary boundary layer by water vapor flux from the Atlantic Ocean is important, but local thermodynamic processes provide conditions ideal for rainy season onset (Fu *et al.* 1999). The local and upwind land cover affects both the moisture and energy components. Changes in albedo, surface roughness, and the ratio between sensible and latent heat loss can all affect both surface energy and water fluxes, and consequently modify the regional climate. In the Amazon, during the onset and end of the rainy season, differential land-surface conditions are more relevant as a source of water vapor and energy to trigger convection, and as such the natural vegetation is responsible for generating a longer rainy season (Costa and Pires 2010).

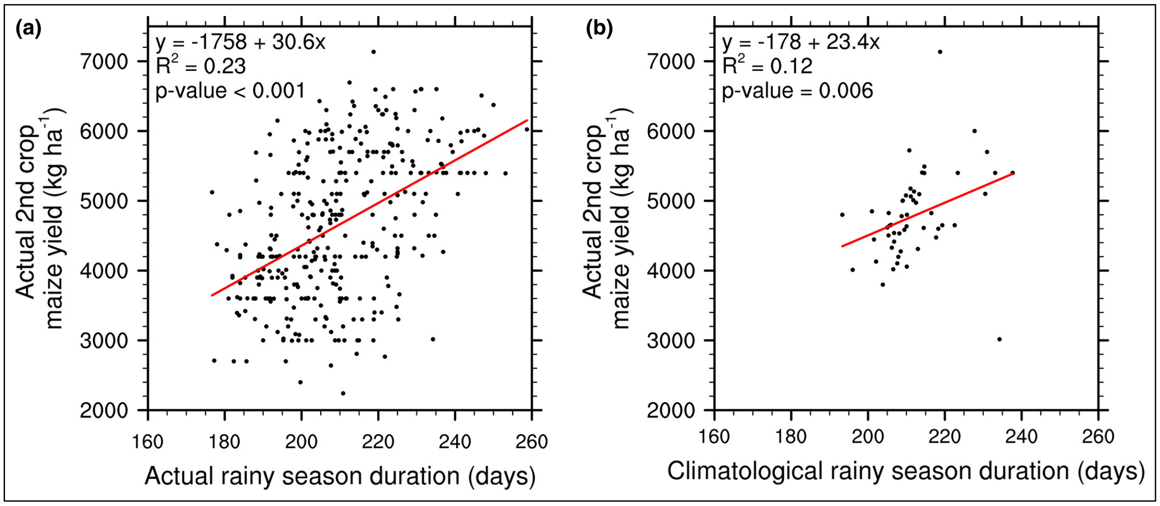

Figure 3. Relationship between yield of maize as second crop (Municipal Agricultural Survey, Table 839, https://sidra.ibge.gov.br/tabela/839) and rainy season duration (derived from Tropical Rainfall Measuring Mission [TRMM] product 3B42, calculated as shown in WebPanel 1). Both datasets are from the period 2003–2015. (a) Actual yearly data for every municipality in the study region; (b) averages for the period of study, with each point representing a municipal average.

12% in 2005 to 13% in 2010–2029 (on average) and cerrado suppression increases from 53% to 59% in the same period (Riahi *et al.* 2011; Pires *et al.* 2016). This assumes ~4000 $km^2\ yr^{-1}$ of Amazon deforestation, below the already low rates of 5000–8000 $km^2\ yr^{-1}$ reported since 2010, which climbed in recent years (www.obt.inpe.br/prodes; Soares-Filho and Rajão 2018), and ~8800 $km^2\ yr^{-1}$ of cerrado suppression, also far below the 2002–2008 suppression rates of 14,000 $km^2\ yr^{-1}$ (Brasil 2011). Higher deforestation rates imply a shorter rainy season (Panel 1), with negative consequences for second-crop yields.

Repeated or widespread climate-driven second-crop failure may prompt a return to single cropping (Spera *et al.* 2014; Cohn *et al.* 2016a), a shift that could reduce the region's agricultural output, raise global food prices, and increase incentives to convert regional ecosystems to agricultural land. Further agricultural expansion into ecosystems would amplify climate change; the larger the extent of natural vegetation lost, the shorter the rainy season will be, due to climate feedbacks from changes in land use (Panel 1). This will trigger a spiraling decline of the rainforests and rainfall over southern Amazonia and other critical agricultural regions that depend on Amazonian forests for the generation of precipitation (Oliveira *et al.* 2013; Lawrence and Vandecar 2015; Pires *et al.* 2016).

Adaptation and mitigation needs

Currently, farmers in northern Mato Grosso have few alternatives for adapting to climate change. Irrigation is rare in the region and unlikely to become a solution in the majority of the state because of water resource limitations at the beginning of the rainy season, the high cost of irrigation systems relative to land prices, and, most importantly, the limited availability of energy infrastructure (WebPanel 2). Purchasing new cropland (~US$1500 per hectare) is still cheaper than investing in irrigation systems (US$2500–3500 per hectare), and the current power infrastructure is sufficient for irrigation of only 0.8 million ha, or ~4% of the crop/pastureland already opened in northern Mato Grosso. In addition, to minimize climate risk, farmers could adapt by selecting crops based on the rainy season onset date, but doing so would require a system for forecasting that date, which is not yet available.

For farmers unable to adapt to a shortened rainy season, mitigating climate change is perhaps the only alternative. Of the two main causes of climate change that pose a threat to DC systems in northern Mato Grosso (rising GHGs and ecosystem loss), only slowing the latter offers a near-term option for reducing local climate risk. Reducing GHG emissions to mitigate climate change will require decades, and is dependent on global efforts and agreements. By the time global and regional climates have stabilized, millions of hectares of forest and cerrado may have been lost as a result of crop failures and subsequent further changes in land use. In contrast, promoting native vegetation and restoring degraded lands at large scales could help to constrain local climate risks to DC by stabilizing the time of onset of the rainy season and possibly *D*, and by limiting crop exposure to extreme heat.

Public policies and private governance efforts

Existing policies and programs have already helped to protect and restore ecosystems in southern Amazonia, without sacrificing agricultural growth. Since 2004, deforestation rates in the Brazilian Amazon biome dropped by 75%, the largest GHG emission reduction effort on the planet. This unprecedented success is due to several factors, including the creation of

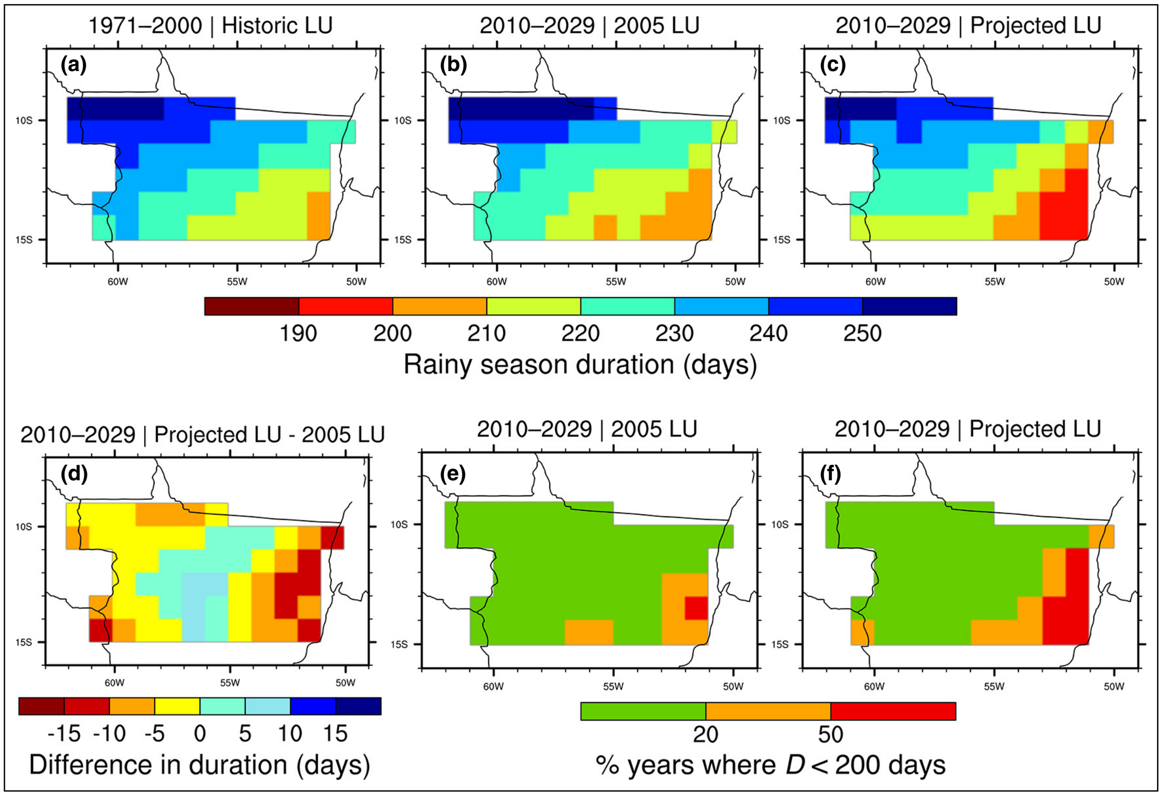

Figure 4. Simulated duration of rainy season (D) for (a) the period 1971–2000, with historical land-use patterns (LU); (b) the period 2010–2029, with fixed 2005 LU; (c) the period 2010–2029, with projected LU; (d) difference between (b) and (c). Spatial distribution of frequency of years with $D < 200$ days for the period 2010–2029 based on (e) the fixed 2005 LU and (f) the projected LU.

additional protected areas, improved collaboration between government agencies, restriction of financial credits to municipalities in which deforestation is occurring at high rates, boycotting of soy and beef produced on recently deforested land, and targeted enforcement. Deforestation in Mato Grosso has been reduced by 84% from pre-2004 rates while agricultural production has increased over the same time period: from 2004 to 2012, soybean production increased by 58%, maize production increased by 359% (primarily as a second crop), and cattle herd size has increased by 10% (Dias *et al.* 2016). The combination of reduced deforestation and increased agricultural output demonstrates that it is possible to reconcile production and environmental protection. Unfortunately, deforestation rates have recently begun to increase in Amazonia, indicating that private and public incentives for forest protection and restoration, combined with disincentives for deforestation, are insufficient to halt deforestation (Moutinho *et al.* 2016).

Several existing public policies and private governance efforts are well positioned to further advance ecosystem protection, but may need more support before they can be scaled up. First, federal and state policies – such as the Forest Code; the Low-Carbon Agriculture (ABC) plan; the Nationally Determined Contribution (NDC) to the UN Framework Convention on Climate Change; and Mato Grosso's Produce, Conserve, Include (PCI) Strategy – set goals and provide credits for restoration and reforestation, as well as require establishing minimum conservation targets on private properties (see WebPanel 3 for a more detailed description of these policies). Second, 4.9–6.4 million ha (31–42%) of land in northern Mato Grosso is degraded pastureland (Cohn *et al.* 2016b; Dias *et al.* 2016), which could accommodate cropland expansion and sustainable intensification without the need to expand the agricultural frontier for many years to come. The Novo Campo Program, led by the non-governmental organization Instituto Centro de Vida, has successfully piloted a deforestation-free, climate-smart beef supply chain that restores degraded pasturelands and increases farm productivity while cutting GHG emissions by 60–90%. Unfortunately, scaling up this and similar programs to encompass larger areas would require billions in investment capital and a qualified technical assistance network, something that the state currently lacks. Finally, engagement with agribusiness supply chains is crucial for implementing programs in a timely fashion and slowing deforestation. The expansion of soy fields and pastures used predominantly for raising beef cattle have been the major drivers of deforestation in Mato Grosso. Each of these two value chains are controlled by a handful of traders and processors, including ADM, Bunge, Cargill, Louis Dreyfus, Amaggi, JBS, Marfrig, and Minerva, and their trade associations ABIEC, ABIOVE, and ANEC. This high concentration of trade and processing among relatively few agents offers a promising opportunity for corporate engagement with the state. Moreover, two private initiatives have strongly influenced decisions made by actors within the soy and beef supply chains: the soy moratorium, initiated by Greenpeace in 2006, has been effective in reducing deforestation pressure from soy expansion into the Amazon biome in the state (Nepstad *et al.* 2014; Gibbs *et al.* 2015), while the beef agreements, initiated by Greenpeace and the Federal Public Prosecutor's Office, appear to be having a similar effect on the beef supply chain (Gibbs *et al.* 2016).

Conclusions

Furthering ecosystem stewardship depends on support from agribusinesses, local governments, and scientists. For example, conservation efforts in the cerrado biome have been less effective than those in the Amazon biome, and deforestation rates have once again increased in Mato Grosso and across much of Amazonia (Soares-Filho and Rajão 2018). We believe that as long as land is inexpensive and productive, and as long as the demand for converting land to produce food, feed, fiber, and fuel continues to grow steadily, ending the conversion of undeveloped land with native vegetation to agricultural lands will be enormously difficult. It is crucial that agribusinesses and local governments are made aware of the value of the climate regulation services provided by functioning, intact ecosystems. If people are not provided with sufficient reasons to protect the ecosystems in which they reside, then habitat destruction and degradation are expected to continue.

While evidence of the interdependence of climate, land-use changes, and food production continues to mount, further research is needed to better understand the complex interactions between these factors. Interdisciplinary science will play a central role in building a compelling case for various stakeholders to take effective action toward the protection and restoration of native ecosystems. Several matters subject to continuing investigation involve the agents whose decisions affect ecosystem conservation, including evaluation of the reduced profit margins and decreasing land values that farmers and ranchers might experience; quantification of investments in irrigation networks, energy supply, and transmission lines required to power irrigation systems; estimation of changes in price volatility, supply shortages, and insurance costs; assessment of the need to relocate or expand agribusiness supply chains to new regions, at the expense of losing long-established investments in developing local supply chains (Rautner *et al.* 2016); and evaluations of the effects on jobs, tax revenue, and economic growth as climate change induces shifts in agricultural production.

Channeling sufficient international and national incentives to the state, as well as fostering coordinated actions among federal and local governments and leading agribusiness companies in the beef and soy sectors, could help catalyze change at the needed scale, thereby allowing the various stakeholders to continue benefiting from the climate services provided by the intact forest and savanna systems of southern Amazonia.

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