World Development 146 (2021) 105582

Contents lists available at ScienceDirect

World Development

journal homepage: www.elsevier.com/locate/worlddev

Conserving the Cerrado and Amazon biomes of Brazil protects the soy economy from damaging warming

Rafaela Flach [a], Gabriel Abrahão [b], Benjamin Bryant [c], Marluce Scarabello [d], Aline C. Soterroni [d,e], Fernando M. Ramos [d], Hugo Valin [e], Michael Obersteiner [e,f], Avery S. Cohn [a,*]

[a] Tufts University, Friedman School of Nutrition Science and Policy, Boston, United States
[b] Department of Agricultural Engineering, Federal University of Viçosa, Viçosa, Brazil
[c] Independent Consultant, Oakland, United States
[d] National Institute for Space Research, São José dos Campos, Brazil
[e] International Institute for Applied System Analysis, Laxenburg, Austria
[f] Environmental Change Institute, University of Oxford, United Kingdom

ARTICLE INFO

Article history:
Accepted 24 May 2021
Available online 9 July 2021

Keywords:
Ecosystem services
Soy economy
Extreme heat
Climate change
Conservation
Amazon
Agriculture

ABSTRACT

In tropical regions, widespread loss of native forest and savanna vegetation is increasing extreme heat, particularly in agricultural regions. Using the case of rising extreme heat from lost forest and savanna vegetation in Brazilian Amazon and Cerrado regions, we modeled losses to soy production, the region's principal economic activity. We assessed two types of extreme-heat regulation values: the value of avoided extreme-heat exposure of soy from the conservation of neighboring ecosystems and the value of lost revenue due to increased extreme heat exposure from increased ecosystem conversion. Our modeling combines empirical estimates of (1) the influence of ecosystem conversion on extreme heat over neighboring cropland, (2) the impacts of extreme heat on agricultural yields, and (3) native vegetation area, agricultural area, and crop prices. We examine lost soy value from land conversion over the period 1985 to 2012, potential losses from further conversion under plausible land and climate change scenarios (2020–2050), and the future value of conservation of the region's remaining ecosystem area near soy. Soy revenue lost due to extreme heat from native vegetation loss (1985–2012) totaled 99 (2005USD) ha^{-1} for 2012-2013 growing season. By 2050, agricultural growth, ecosystem conversion, and climate change could boost extreme-heat regulation values by 25% to 95%. Future values were strongly sensitive to changes in agricultural density, rates of native vegetation loss, and climate. Extreme-heat regulation values were largest in the Cerrado biome and the southeastern Amazon. Relative to land values, the value of extreme heat regulation was largest relative to the carbon value of biomass in the Cerrado. By regulating the exposure of agriculture to extreme heat, ecosystem conservation can create considerable value for the soy sector.

1. Introduction

In recent decades, Brazil has seen tremendous agricultural growth, fueled in part by its emergence as a major agricultural exporter (Zalles et al., 2019). By boosting exports and buoying the wider economy during moribund periods, the agricultural sector has been a critical engine of economic development (Bustos et al., 2016, 2018). A key contribution to agricultural growth is soybean production, which has increased more rapidly than any other major agricultural sector since 1994. By 2019, soy constituted 49% of cropland area and 41% of agricultural revenues (IBGE, 2020). In 2019, 37% of all soybean produced in the world was planted in Brazil, and the country is now the world's largest soybean producer (United States Department of Agriculture & Foreign Agricultural Service, 2018).

The growth of the soy sector happened both by intensification of production (mean yield growing from 1.7 to 3.2 tons per hectare between 1990 and 2019) and area expansion (from 11.5 to 35.8 million ha between 1990 and 2019) (IBGE, 2020). This growth occurred especially in new agricultural regions to the north and west of established agricultural poles, in the Amazon and Cerrado biomes, respectively (Dias et al., 2016). The economies of emerging centers of soy production have grown faster than the economies of

* Corresponding author.
E-mail addresses: oberstei@iiasa.ac.at (M. Obersteiner), avery.cohn@tufts.edu (A.S. Cohn).

https://doi.org/10.1016/j.worlddev.2021.105582
0305-750X/© 2021 The Author(s). Published by Elsevier Ltd.

otherwise comparable municipalities (Bragança, 2018; VanWey et al., 2013). These emerging "agro-cities" are now some of Brazil's wealthiest places, and soy growth explains the vast bulk of their growth and development (Richards et al., 2015; VanWey et al., 2013).

Several factors suggest that further growth in soy production along Brazil's agricultural frontier is likely. The global appetite for soy meal tends to grow hand in hand with global meat consumption, which has grown proportionally to population growth and affluence (Nepstad et al., 2014). Evidence shows that millions of hectares of low-productivity rangelands and legally convertible ecosystems could accommodate as much as a further doubling of area to increase production and supply steep increases in demand (Soares-Filho et al., 2014). Even greater growth in output would be possible if technological improvements continued to boost yield and to reduce climate, soil and cultivar-related constraints on soy cultivation (Abrahão & Costa, 2018).

Although growth in the Brazilian soy sector is likely, the sustainability of that growth is not assured due to a number of factors both within and outside the control of the sector. One major set of challenges within the sector's control includes direct or indirect ecosystem conversion (primarily through deforestation or other replacement of native vegetation by agricultural land) and the social and environmental effects of this conversion. Direct emissions of greenhouse gases, inputs to soy production that threaten human and environmental health, and numerous indirect consequences of land conversion associated with soy expansion are some of related harms (Arima et al., 2011; Galford et al., 2010; Goldsmith & Cohn, 2017). Association with deforestation has also created a reputational risk for the soy sector, and consumer-focused campaigns have brought international attention to the issue (Lambin et al., 2018).

The soy sector is also vulnerable to anthropogenic climate change. In the lower latitudes of Brazil, where most of the soy expansion is occurring, climate change could push weather outside the envelope of suitable production conditions for soy (Zilli et al., 2020). Ecosystem conversion associated with agricultural expansion could add to these climate risks (Zscheischler et al., 2018). Such conversion has already disrupted precipitation patterns in parts of the Brazilian Amazon (Butt et al., 2011; Khanna et al., 2017; Leite-Filho et al., 2020) and has increased temperatures in parts of both the Amazon and Cerrado regions (Alkama & Cescatti, 2016; Silvério et al., 2015). Continued ecosystem conversion could worsen droughts and lead to die-off of the region's ecosystems (Duffy et al., 2015; Zemp et al., 2017). The connected pressures of anthropogenic climate change and ecosystem conversion can drive and contribute to the spread of emerging diseases (Ellwanger et al., 2020), decrease rural worker productivity (Masuda et al., 2020), and lower local hydropower production (Arias et al., 2020).

In Brazil, ecosystem conversion is resurging amid rising political pressure to relax legal protections on ecosystems (Rochedo et al., 2018). Its persistence, in the face of ecological and climatic risks, suggests a misalignment of private benefits and potential collective benefits that its arrest could achieve (Cohn, 2017).

This paper aims to address the balance between the interests to expand the existing Brazilian agricultural sector and to safeguard its sustainability. To address this issue, this paper explores whether the economic risks to agriculture posed by climate change and exacerbated by ecosystem conversion might meaningfully inform the value of conservation, including the private returns to conservation. We focus on the case of the value of extreme heat regulation by avoided ecosystem conversion for the soy sector in Brazil. We selected this case because of its tractability for study and because we hypothesized it could yield high-magnitude and high-salience ecosystem valuation estimates.

Our approach combines research on the influence of ecosystem conversion on extreme heat over neighboring cropland and the impacts of extreme heat on agriculture, with spatially explicit data on land cover, agricultural area, and agricultural revenues to value the climate regulation that ecosystems provide nearby farms in Brazil. Here we present three different analyses of extreme heat regulation values. The first is the historical analysis, an estimation of the value of lost soy revenue from ecosystem conversion from 1985 to 2012 in the year 2012. The second is the future loss analysis, in which we projected revenue losses in the soy sector as a result of decreased extreme heat regulation due to ecosystem conversion occurring over the period 2020 to 2050, under a range of land cover and agricultural area scenarios. The third is the analysis of the future value of conserved ecosystems, in which we projected extreme heat regulation value supplied by ecosystems conserved over the period 2020 to 2050 under a range of land cover and agricultural area scenarios. We also benchmark both past and future extreme heat regulation value against cropland prices—a widely used proxy for the cost of conserving ecosystems—and the carbon market value of forest biomass.

Ecosystem conversion is causing substantial warming across Brazil's agricultural regions. In those regions where extreme heat is already common, and soy is already densely cultivated, we expect each additional hectare of native vegetation loss to cause considerable future losses of soy output on existing farms due to extreme heat effects. We also hypothesize that the value of heat regulation by ecosystem conservation for soy will rise as the climate warms, native vegetation loss continues, and soy expands.

Our results confirm our hypotheses, and in so doing our study adds novel insight to our understanding of the synergies between ecosystem conservation and agriculture for regional development and prosperity by determining whether the incentives to conserve roughly equal or even outweigh the incentives to develop. This finding should be considered in light of the fact that the benefits of native ecosystem conservation, even for the soy sector alone, go far beyond the ones provided by this climate regulation services.

The benefits of ecosystem conservation on farms and in protected areas might be sufficient to affect land use decisions. Nevertheless, people rarely fully account for the value of ecosystems when making these decisions (Costanza et al., 2014). Policies could help, provided that they take into account consequences for human rights, justice, equality, and inclusion (Timko et al., 2018).

2. Context

Measuring how change in neighboring vegetation impacts soybean productivity through extreme heat regulation—and its economic consequences—requires taking into account factors such as exposures, hazards, and vulnerabilities. Valuing extreme heat regulation can help inform decisions about ecosystem conservation. We chose this particular ecosystem service because it is tractable to model and because we hypothesize it to be salient for conservation decisions.

Extreme heat potently disrupts many economic and social activities (Burke et al., 2015; Carleton & Hsiang, 2016; Masuda et al., 2020). Impacts of extreme heat on agriculture, including soybean production, are well studied (Lobell et al., 2013; Schlenker & Roberts, 2009). The frequency of extreme heat events is growing fastest in the tropics (Fischer & Knutti, 2015; Suarez-Gutierrez et al., 2020). Within the tropics, the fastest growth in heat extremes can be expected where ecosystem conversion compounds warming from greenhouse gas emissions (Alkama & Cescatti, 2016; Zeppetello et al., 2020; Zscheischler et al., 2018).

Many of Brazil's recent native-vegetation loss hotspots are also hotspots of soybean growth or projected soybean growth.

We hypothesize that the regulation of extreme heat exposure in agricultural areas provided by neighboring vegetation could be a high-value ecosystem service. Showing that avoiding the degradation of native vegetation is of value for soy could alter the balance between costs and benefits of conversion in meaningful ways, especially given the importance of soybeans for the Brazilian economy and the role of soy expansion as a driver of land use and land cover change.

In Brazil, a wave of policies and nongovernmental efforts have sought to slow native vegetation loss while making sure that agricultural growth remains a priority. These governance efforts initially enjoyed a degree of success. For example, over the period 2004 to 2008, deforestation rates in the Brazilian Amazon dropped and agricultural growth, while not slowing, intensified on non-forested land (Hargrave & Kis-Katos, 2013). However, recent years have witnessed a resurgence of deforestation and other types of ecosystem conversion (Richards et al., 2016; Rochedo et al., 2018), especially in the Amazon biome. Meanwhile, rates of ecosystem conversion have slowed little in other key regions of the country, such as the Cerrado (Strassburg et al., 2017).

Ecosystem conversion is a complex multi-agent process, but one characterized by somewhat predictable patterns. It typically occurs first and fastest in places where strategic actors expect to extract the highest value through the use and sale of natural resources (Angelsen, 2010). This value can come from mining, ranching, land investment, collection of government subsidies, and agricultural rents (Lambin et al., 2001). Considering both direct and indirect ecosystem conversion, agricultural rents remain an exceedingly good predictor of patterns of ecosystem conversion (Bowman et al., 2012; Cohn et al., 2016a; Richards et al., 2014). In the simplest terms, agricultural rents measure the expected return on factors of agricultural production. These returns scale with, among other things, agricultural productivity, which in turn scales with variability and change in the climate.

Like most staple crops, soybeans suffer yield losses from exposure to extreme heat (Ray et al., 2015), including in the key agricultural regions in Brazil (Cohn et al., 2016b). Exposure to heat helps crops grow, but above a critical threshold, heat exposure results in productivity losses (Schlenker & Roberts, 2009). These losses stem both from direct retardation of vegetative and reproductive growth in crops from heat damage and from indirect losses. Indirect losses include those that occur because increased heat is connected to increased water stress and drought conditions that can also limit growth (Lobell et al., 2013; Tack et al., 2017). The change in the incidence of extreme heat is typically estimated as a function of daily maximum temperature and daily minimum temperature (D'Agostino & Schlenker, 2016). Because minimum and maximum temperatures are typically normally distributed, increases typically disproportionately intensify the incidence of extreme temperatures as the distribution shifts right (Hsiang, 2016).

Rising temperatures are projected to profoundly impact the productivity of soybeans. Studies from the recent past found each additional day of heat above 30 °C reduced soybean yields by 1% to 5% (Hsiang et al., 2013; Schlenker & Roberts, 2009). Although the high latitudes are projected to see the most rapid rise in mean temperatures from increased greenhouse gas concentrations (IPCC, 2014), the tropics are among the regions projected to see the highest rate of increase in extreme heat events (Fischer & Knutti, 2015; Suarez-Gutierrez et al., 2020). Areas of the tropics seeing the combination of increased greenhouse gas emissions and increased ecosystem conversion could see compounded likelihoods of warming and heat extremes (Zscheischler et al., 2018).

A number of mechanisms operating at scales from tree to biome explain the increased heat risk that can occur after tropical ecosystem conversion (Alkama & Cescatti, 2016; Silvério et al., 2015; Winckler et al., 2017; Zeppetello et al., 2020). These mechanisms include disruptions to the amount of heat absorbed by the earth's surface, changes in precipitation and cloud patterns, and reduced cooling associated with a reduction of evapotranspiration by plants following land use change (Alkama & Cescatti, 2016; Bonan, 2008). Such changes to the climate, which stem from changes in the biosphere and are not caused by greenhouse gas emissions, are known as biogeophysical climate change (Bonan, 2008). Climate change caused by greenhouse gas emissions, on the other hand, is known as biogeochemical climate change.

Over the period 2000–2017, lost evaporative cooling in Brazil was in many instances the single biggest cause of warming in the agricultural frontier (Alkama & Cescatti, 2016; Silvério et al., 2015). Some agricultural locations in the region experienced mean daily maximum near-surface air temperatures as much as 4 °C in excess of expected temperatures absent land conversion (Alkama & Cescatti, 2016). Warming also stems from neighboring ecosystem conversion. Cohn et al. (2019) found that a 25 percentage point decline in forest cover at a distance of 1 km to 50 km from locations of temperature observation caused an increase of 0.4–1.1 °C in daily maximum temperature. Given that many regions of Brazil have in recent years experienced forest cover declines of this magnitude, these findings, taken together, suggest a potentially sizable economic consequence for soy from changes in ecosystem area.

3. Methods

3.1. General modeling framework

This study integrates and extends methods applied previously in the literature to create a new framework for estimating the potential magnitude and economic value of ecosystem conservation from extreme heat regulation for agriculture. We focused on the case of soybean production in the Amazon and Cerrado biomes in Brazil, assessing the potential of nearby native vegetation to provide extreme heat regulation for this annual crop. We performed this analysis for past (1985–2012) and projected future (2020–2050) land use and land cover change. We henceforth refer to analysis within the 1985–2012 period as the historical analysis and to analysis in the 2020–2050 period as future scenario analysis. The time period for the historical analysis was determined by data availability. The future scenario analysis takes into consideration three scenarios of land use change and one scenario of greenhouse gas-related climate change. The land use change scenarios provide estimates of future changes in vegetation and agricultural area as well as the components of crop yield that are not sensitive to climate.

We analyzed the value of native vegetation in providing extreme heat regulation for soy production using two complementary approaches: value lost from conversion and value gained from conservation. For the conversion analysis, we valued per hectare and total loss to the soy sector in light of how neighboring native vegetation loss could lead to revenue loss through productivity loss as a result of increased exposure to extreme heat. For the conservation analysis, we modeled the value of conserved native vegetation in light of that vegetation's impact on neighboring agriculture through extreme-heat regulation. We estimate conversion losses both historically and in the future. The conservation analysis looks only at the present value of future conservation.

The four steps to this approach are identified by numbers in Fig, 1, summarized in Table 1, and described in each of the following sections. Our analysis focuses on two main Brazilian biomes, the Amazon and the Cerrado.

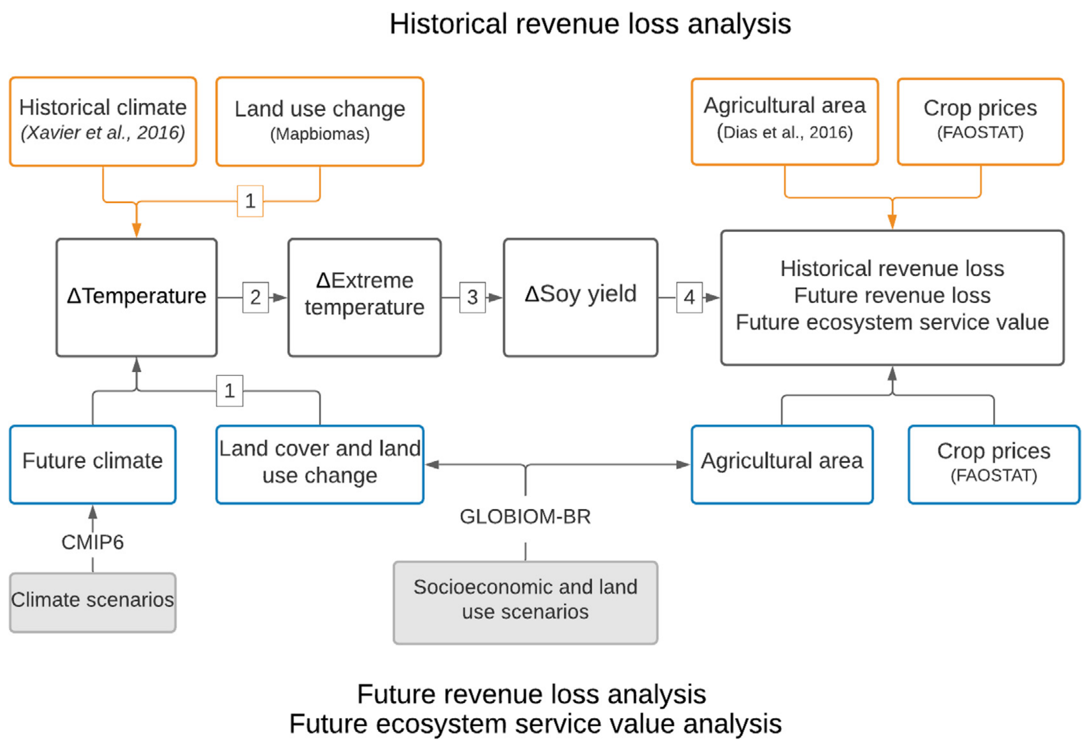

Fig. 1. Schematic showing materials and methods used in this paper to estimate extreme-heat regulation value for soybean farming from nearby native vegetation. The orange boxes show inputs to estimates of lost revenue from historical vegetation loss. The blue boxes show inputs to the two future scenario analyses, one of losses from conversion and one of ecosystem services value from conservation. The numbers indicate methodological steps detailed in Table 1.

Table 1
Summary of main steps in our modeling approach. Numbers correspond to the numbered linkages show in Fig. 1.

	Step	Short description
1	Temperature change from climate change and ecosystem conversion	We estimated the influence of ecosystem conversion on nearby near-surface air (2 m) temperature, using an approach adapted from Cohn et al. (2019), which estimates the influence of forest conversion on nearby near-surface air temperature. Additional details of the method and the findings can be found in the Supplementary Material.
2	Relationship between temperature change and extreme heat	We translate temperature warming to estimated extreme-heat incidence using a widely used degree day estimation technique (Wilson and Barnett 1983).
3	Agricultural output from ecosystem conservation	We parameterize crop yield loss (lost productivity per area) from exposure to extreme heat on the basis of a model adapted from Schlenker and Roberts (2009)
4	Extreme-heat regulation value	We apply our framework for valuing climate regulation services for agriculture to the case of valuing extreme-heat regulation by native vegetation in Brazil for soy. In the historical analysis, we calculated the historical extreme-heat regulation value of losses due to ecosystem conversion. We also estimated two future extreme-heat regulation values—loss from conversion and gain from conservation.

3.1.1. Study area

Because our analysis concerns the effects of ecosystem conservation and ecosystem conversion on soybean agriculture, we focus on the areas where soybean production was identified in the historical record or projected in future scenarios. From a universe of 2,014 0.5° gridcells covering the Cerrado and Amazon biomes, we selected 711 gridcells in which soy production occupied > 1% of the land area in either the historical record or in at least one of the future GLOBIOM scenarios. Of the selected gridcells, 28.1% were located in the Amazon biome and the remaining 71.9%, in the Cerrado. The extent of the study area and the selected gridcells can be found in Fig. 2.

The data sources used for the extreme-heat regulation value analysis were available at a variety of spatial scales; the choice of the 0.5° scale for the analysis was to enable processing tractability, allow for representativeness of the soy economy, and facilitate interoperability with the land economy model outputs used for the future scenario analysis. As a consequence, the scale in which we analyze extreme-heat regulation values in this study is coarse in comparison with the micro-scale in which the relationship between land cover change and temperature of interest exist. Within 0.5° gridcells, land conversion is not uniformly distributed. It tends to be tightly spatially correlated with cropland areas, including soybean areas. In addition, because the extreme-heat regulation effect decays with distance, modeling at a relatively coarse scale without correcting for the soy-land use change correlation would likely lead to an underestimation of the conversion loss. The reverse is also true for the modeling of conservation gains. Within a gridcell, intact forests tend to be inversely correlated with areas of crops and soy. To estimate and correct these biases, we developed a downscaling approach for bridging the gridcell scale, and the scale in which the land use change happens within the

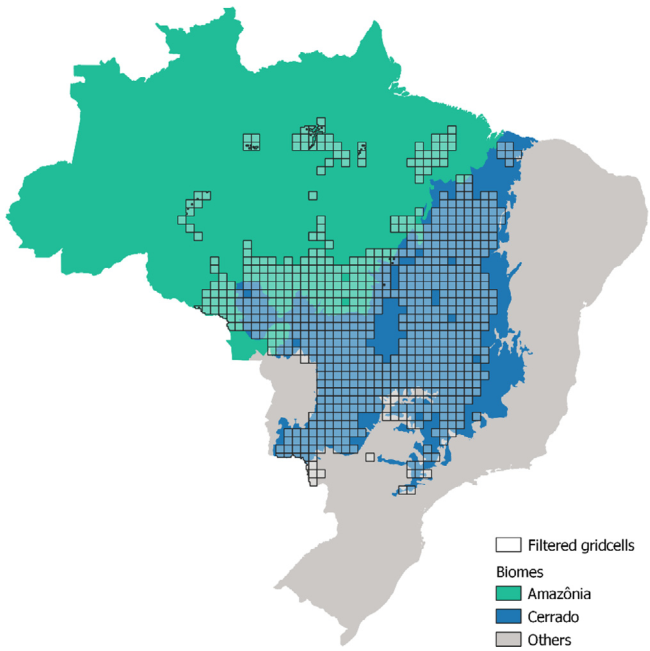

Fig. 2. Study area and filtered gridcells. The map highlights the two Brazilian biomes Amazonia (green) and Cerrado (blue) that are the focus of this study. The map also shows the 711 grid cells that we selected for analysis within the biomes. These gridcells had or were projected to have greater than 1% of land cover devoted to soybean production.

gridcells. The downscaling approach is detailed in section 3.2.1 and in section 2 of the Supplementary Material.

3.1.2. Temperature change from climate change and ecosystem conversion

Here, we refer to climate change caused by greenhouse gas emissions as biogeochemical climate change and to climate change stemming from changes in the biosphere rather than from greenhouse gas emissions as biogeophysical climate change. We assume, here, that the near-surface air temperature changes are the sum of the greenhouse gas-related temperature changes drawn from global climate change scenarios ($\Delta T^{\text{biogeochemical}}$) and the temperature changes related to land use change ($\Delta T^{\text{biogeophysical}}$):

$$\Delta T_{it} = \Delta T_{it}^{\text{biogeochemical}} + \Delta T_{it}^{\text{biogeophysical}} \tag{1}$$

where ΔT refers to mean temperature change, *i* indexes gridcells, and *t* indexes time step.

Changes in land cover can affect temperature through alteration of albedo, evapotranspiration, and surface roughness. The general effect that follows from replacing native vegetation with pastures or agriculture is that evapotranspiration is reduced and surface-sensible heat flux is increased, leading to a rise in surface temperature (Gash & Nobre, 1997). In tropical forests, ecosystem conversion generally leads to warming, which stems primarily from a reduction in evapotranspiration (Bonan, 2008; Lawrence & Vandecar, 2015). When ecosystem conversion happens, natural land-cover types that are dense in biomass and that transpire a lot of water are replaced with crops, pasture, and other land-cover types that have low evapotranspiration rates for most of the year (Spera et al., 2016). The result is warming due to reduced evaporative cooling both at the location of land conversion (Alkama & Cescatti, 2016) and at nearby locations over which the warming horizontally diffuses or is advected by wind (Cohn et al., 2019; Winckler et al., 2017).

The calculation of temperature change induced by land use and land cover change takes into account two effects: a "local" effect constituting the on-site ecosystem conversion effect (Alkama & Cescatti, 2016) and a "non-local" effect constituting the effect of nearby but not on-site ecosystem conversion (Cohn et al., 2019), as shown in Equation (2):

$$\Delta T_{it}^{\text{biogeophysical}} = \Delta T_{it}^{Local} + \Delta T_{it}^{Non-local} \tag{2}$$

Here, we consider only micro-scale "non-local" effects that stem from changes on a 1 km-to-50 km radius around the affected area. On larger scales, these effects are influenced by broader circulation patterns and are better analyzed with the use of general circulation models.

Non-local effects are calculated on the basis of parameters obtained from regression modeling performed specifically for this analysis, using an adapted form of the methodology developed by Cohn et al. (2019) and described in section 2 of the Supplementary Material.

The equation for temperature change attributable to non-local ecosystem conversion takes the following form:

$$\Delta T_{it}^{Non-local} = k_{it}^{Non-local} * \Delta Native\ vegetation_{it} \tag{3}$$

where $k^{NON-LOCAL}$ refers to the non-local coefficient derived from the regression modeling mentioned above. It serves to capture the effect of change in native vegetation on temperature and to scale that effect to reflect historical spatial dynamics at the sub-gridcell level. Note that, for the conversion loss analyses, $\Delta \text{Nativevegetation}_{\text{ik}}\Delta \text{Nativevegetation}_{\text{it}}$ refers to area of lost forest and savanna vegetation. For the conservation gain analyses, $\Delta Nativevegetation_{it}$ is the standing area of forest and savanna (and is thus effectively assuming the counterfactual to be zero forest and savanna). For the analysis of conversion loss, the $k^{NON-LOCAL}$coefficient for estimation of changes in maximum temperature was of 3.397 °C/100p.p. in the Amazon and 3.206 °C/100p.p. in the Cerrado. For conservation gain, the corresponding values for the $k^{NON-LOCAL}$coefficient are 1.420 °C/100p.p and 1.475 °C/100p.p. The methods for obtaining these values are detailed in the Supplementary Material.

For its use as a term in equation (3), we define $\Delta LUC_{ik}^{NATIVE.VEG}$ as the reduction of native vegetation cover in the year in question, compared with the baseline in 1985, relative to the area of the entire gridcell.

$$\Delta Native\ veg_{it} = \frac{-1 * (Native\ veg_{it} - Native\ veg_{i1985})}{Gridcell\ area_i} \tag{4}$$

Taken together, the equations above state that, within the ranges of ecosystem conversion considered, conversion of a given fraction of a gridcell from native vegetation to agriculture will cause an increase in temperature proportional to the constant $k^{NON-LOCAL}$. The local effect (Alkama & Cescatti, 2016) is applied only to agriculture on land that was native vegetation during the study period (1985–2012 for the historical analysis and 2020–2050 for the future analysis).

$$\Delta T_{it}^{Local} = k_i^{Local} * Crop\ fraction_{it}^{Native\ veg} \tag{5}$$

where

$$Crop\ fraction_{it}^{Native\ veg.} = \frac{\text{CROP}_{\text{it}}^{\text{Native veg.}}}{\text{CROP}_{\text{it}}} \tag{6}$$

The k^{Local}refers to the local effect coefficient. The denominator $CROP_{it}$ is the total area of cropland in the gridcell in time step *t*, and $CROP_{it}^{Native\ veg.}$ is the area of cropland that sits on land that was native vegetation in the study period.

Based on Alkama and Cescatti (2016), ecosystem conversion leads to 2.03°C warming of the maximum temperature in the tropics, 4.43°C in arid areas, and 2.63°C in temperate areas. The tropical, arid, and temperate zones were differentiated according to the Köppen-Geiger classification (Kottek et al., 2006). The local effect parameters are summarized in Table S9.

In the analysis of historical- and future-scenario revenue loss, we took into consideration both the local and the non-local effect. For the analysis of future ecosystem service value, only the non-local effect was considered.

3.1.3. Change in extreme heat exposure from temperature change

Small increases in temperature can lead to greater-than-linear increases in extreme heat (Blanc & Schlenker, 2017). Extreme heat exposure is typically a powerful, linear predictor of climate damage to many economic and social activities (Carleton & Hsiang, 2016). Extreme degree days (EDDs) are a measure of crop exposure to extreme temperatures. Increased EDD conditions pose a potent non-linear climate risk to agricultural productivity (D'Agostino & Schlenker, 2016). EDD is a measure of how many days a crop is exposed to a maximum temperature above a certain threshold extreme temperature, usually considered to be 30 °C for soy. EDD for a certain year is estimated as follows:

$$EDD_i = \sum_{d=planting\ date}^{harvesting\ date} D_{ihd} D_{ihy} = \begin{cases} 0 if T_{ihd} \le z \\ T_{ihd} - z if T_{ihd} > z \end{cases} \quad (7)$$

where i refers to the gridcell, d is Julian day, h is the hour-of-day, and z is the threshold temperature. An increase in temperature ΔT causes an increase in EDD (ΔEDD) that, for the temperature ranges in Brazil, is supralinear (e.g., an increase of 2 °C causes more than double the ΔEDD than that caused by an increase of 1 °C).

To calculate ΔEDD for a given scenario, we first evaluate the baseline EDD of each pixel for the soybean-growing season by applying the previous equation to daily minimum and maximum temperature data from the Xavier et al. (2016) gridded weather dataset for Brazil in the 1995–2015 period and taking the average of all years for each pixel. The growing season is defined as a 120-day period centered at the average between the earliest government-recommended planting date and 130 days after the latest recommended planting date for each municipality (Bambini et al., 2015), so that municipalities have the same length of growing season. Then, we add the ΔT_i of the scenario to minimum and maximum temperatures of all days within the growing season of all years in the baseline period and reevaluate EDD_{it}. The ΔEDD_{it} for a given scenario in each pixel is the difference between the ΔEDD_{it} with the added ΔT_{it} and the baseline EDD_{i0} for that pixel.

3.1.4. Agricultural output from ecosystem conservation

Increases in EDD have been found to negatively affect crop yields in several studies (Butler & Huybers, 2015; Roberts et al., 2013; Schlenker & Roberts, 2009). Here, we use the relationships obtained by Schlenker and Roberts (2009), who estimated a linear relationship between log yields of soybeans and EDD of β = 0.005 log(ton ha^{-1}) EDD^{-1}. To estimate the change in soy yield in a given year (ton ha^{-1}) due to a given ΔEDD, we multiply the estimated fractional change to the average historical yields in the period 2000–2010 ($Yield_{i,2000\text{-}2010}$) obtained from the official Pesquisa Agrícola Municipal reports.

$$\Delta soy\ yield = (e^{-\beta \Delta EDD_{i,t}} - 1) soy\ yield_{i,2000-2010} \quad (8)$$

3.1.5. Extreme-heat regulation value

Extreme-heat regulation value can comprise either lost revenue due to increased exposure to extreme heat from ecosystem conversion or the value of additional revenue from conservation.

Equation (9) shows how, in one set of calculations, we estimated total extreme-heat regulation value for each gridcell (i), in each time step (t), and over each analysis (j). Here, j, comprises historical conversion loss, future conversion loss, and future conservation gain. The extreme-heat regulation value for a given year for the historical or the future scenario is calculated as the average avoided soy-production revenue loss per hectare of vegetation in that scenario, in 2005USD.

$$Extreme\ heat\ regulation\ value_{ijt} = \Delta soy\ yield_{ijt} * soy\ price_t * soy\ area_{ijt} \quad (9)$$

Next, we calculate the extreme heat value per unit area, where soy area is the area of soy for the historical loss and future loss analyses and the area of natural vegetation for the future conversion analysis. Note that, for the loss analyses, the area terms in the denominator and numerator cancel one another.

$$Areal\ extreme\ heat\ regulation\ value_{ijt} = \frac{\Delta soy\_yield_{ijt} * soy_{price_t} * soy\_area_{ijt}}{area_{ijt}} \quad (10)$$

This conception of extreme-heat regulation value is derived from a revenue term rather than a profit term. Although revenue is typically an upper bound on profit, in this study we are examining variations in production due to climate shocks, which may or may not inspire significant changes in inputs as part of an adaptation strategy. It is therefore not clear *a priori* whether proportional adjustments to profit or revenue are likely to represent the true economic impact, and revenue metrics require far less data than profit metrics. To the extent inputs are adjusted but are derived from within the regional community, variations in revenue can still represent a regional economic impact, even if not a true direct cost. These factors should be borne in mind when interpreting our benchmarking results.

3.2. Extreme heat scenarios

The future of the land economy and climate are inherently uncertain. We explore this uncertainty by simulating scenarios of future agricultural expansion, ecosystem conversion, and climate change.

3.2.1. Climate scenario

The effects of greenhouse gas-related climate change on surface temperature are estimated per gridcell and time step for one climate change scenario on the basis of an ensemble of CMIP6 global earth system model runs (Eyring et al., 2016). This scenario refers to the SSP2, RCP 4.5. The model ensemble uses model runs from all 12 models for which both historical and SSP2-RCP4.5 runs were available as of April 2020.

To minimize model-specific bias, $\Delta T^{biogeochemical}$ was calculated as follows: First, for each model, mean monthly temperatures at 2 m height were calculated for both the 1995–2005 period and each five-year period starting at the GLOBIOM time-step years from 2015 (2015–2019, 2020–2024 ... 2045–2049). Next, growing season means for each of these periods were calculated using the same growing season months as those used for the EDD calculations. Then, $\Delta T^{biogeochemical}$ for each time step was calculated per model as the difference between the growing season average of the time step in the future scenario (SSP2-RCP4.5) and the growing season average of the historical period (1995–2005) of each model. The final $\Delta T^{biogeochemical}$ for each time step is the average of $\Delta T^{biogeochemical}$ of all models. The CMIP6 models used for calculation of the model ensemble are CC-CSM2-MR, MIROC6, CAMS-CSM1-0, MRI-ESM2-0, FGOALS-g3, CESM2-WACCM, CanESM5, CESM2, IPSL-CM6A-LR, and GFDL-CM4.

3.2.2. Land use change scenarios

For scenarios of land use and agricultural area, we use results from the recursive dynamic, global, bottom-up partial equilibrium model GLOBIOM-Brazil (Soterroni et al., 2018, 2019). GLOBIOM-Brazil is based on the GLOBIOM model (Havlik et al., 2011; Havlík et al., 2014), and it includes a series of refinements to reflect the Brazilian context. This partial equilibrium model simulates the competition for land among the main sectors of the land use economy, subject to restrictions in terms of resources, technology, and policy.

The results from three GLOBIOM-BR scenarios were used in the analysis presented in this paper (Soterroni et al., 2018). The first scenario—No Forest Code—is the most extreme scenario in terms of vegetation loss; it assumes no implementation of the Brazilian Forest Code, a policy that prohibits conversion of on-farm natural vegetation (for more information, see Soterroni et al., 2018). The scenario allows both legal and illegal ecosystem conversion at all time steps. The second scenario—Baseline—assumes imperfect illegal ecosystem conversion control, in which there is a moderate probability of enforcement of illegal ecosystem conversion control measures. Finally, the third scenario—Zero Deforestation—simulates no native vegetation loss after 2020.

The results of the GLOBIOM-BR scenario runs that are used in this analysis are the native vegetation (savanna and forest in the Cerrado and the Amazon, respectively) loss, cropland area, and soy harvested area for each time step and gridcell.

3.3. Benchmarking analysis

We compared the stream of benefits from extreme-heat regulation value against two benchmarks: the possible cost of conservation (using land prices as a proxy) and the biogeochemical climate-regulation value. The biogeochemical climate-regulation value is represented by the carbon value of vegetation biomass, another climate regulation service with a relatively established market. Because both land prices and standing vegetation biomass carbon encapsulate the present value of future benefits, we use the present value of future extreme-heat regulation value, instead of annual values, when benchmarking extreme-heat regulation values against land and carbon prices.

We use an indicative annual discount rate of 10%. This rate is very high for policy and intergenerational climate analysis, but our interest is in private sector incentives that govern land prices, so we use an estimate informed by typical estimates of the weighted average cost of capital in the Brazilian agricultural sector.

3.3.1. Land prices

Average, annually updated cropland prices in nominal BRL per hectare were obtained from the agricultural consultancy FNP for each municipality in Brazil for the period 2003 to 2015, and these prices were converted to 2005USD. For the future scenario analysis, we considered a fixed cropland price based on the 2015 price in each municipality.

3.3.2. Carbon value of biomass

We estimated the carbon value of forest biomass at the sample locations by multiplying a recent multi-model synthesis of forest biomass per hectare (Avitabile et al., 2016) by the price of forest carbon described in a recent report on forest carbon trade (Hamrick & Goldstein, 2016). We considered the carbon price fixed, and obtained the carbon values by multiplying forest biomass by an indicative carbon price of 10 (2005USD) per ton C^{-1} (Hamrick & Goldstein, 2016).

4. Results

The results are structured as follows: section 4.1 presents the changes in temperature and extreme heat exposure in 2012 in response to native vegetation loss between 1985 and 2012, the values of the lost soy revenue resulting from these changes in land use and land cover, and the spatial and temporal variation of these values. Section 4.2 shows the estimated future changes in extreme-heat regulation values due to biogeochemical and biogeophysical climate change for future scenarios. The future analysis includes both the analysis of loss of soy revenue due to increased exposure to extreme heat as a result of ecosystem conversion and the analysis of additional soy revenue as a result of ecosystem services from protected ecosystems. Section 4.3 presents the results of the benchmarking analysis, in which the present value of future additional soy revenue through ecosystem heat regulation is benchmarked against costs associated with ecosystem conservation, ecosystem restoration, or both.

4.1. Historical climate regulation by native vegetation

4.1.1. Changes in extreme heat related to ecosystem conversion

Extreme heat exposure was derived from estimating the extreme degree day (EDD) parameter. Higher exposure to extreme heat (and the related increase in EDD) is a result of changes in temperature that result from changes in land cover. Fig. 3 shows the chain of effect involved in the estimation of changes in extreme heat due to ecosystem conversion.

Temperature change is an indicator of biophysical changes in climate; EDD is a measure of the change in exposure of soybean crops to harmful heat levels due to this change in temperature. Our calculations revealed EDD to have wide spatial variation, but values are almost always positive given that our data shows net forest loss in nearly all gridcells. This spatial variation is primarily driven by differences in native vegetation loss, but also by differences in base temperature because EDD increases super-linearly with temperature. The highest variation in EDD was concentrated in the most active conversion frontiers during the study period: southern Amazon and the northern portion of Brazil, particularly in the Matopiba region in the far northeast of our gridcell set.

4.1.2. Historical lost soy revenue from native vegetation loss

We present results for climate regulation value through reduced extreme-heat exposure provided by native vegetation in 2012 in light of accumulated native vegetation loss in the 1985–2012 period. We henceforth define the extreme-heat regulation value for the (past) period between 1985 and 2012 as the historical loss of revenue due to increased exposure to extreme-heat. We find that value to amount to \$112.6 and \$56.25 $ha^{-1}year^{-1}$ on average in 2012 for the Amazon and Cerrado regions, respectively. When considering the amount of soy area in each gridcell as weights (and thus representative of the soy sector), the weighted mean of the lost revenue values in 2012 increases to \$158.5 $ha^{-1}year^{-1}$ for the Amazon region and \$85.4 $ha^{-1}year^{-1}$ for the Cerrado region. The difference between the weighted and unweighted means stems from the greater native vegetation loss in areas with greater soy area. The value per annum grew during the period, driven by a combination of agricultural expansion, rising temperatures, rising soy prices, and native vegetation loss and associated warming. As Table 2 reveals, the values of revenue loss in the year of 2012 vary greatly from one biome to another, in large part as a result of different exposures to extreme heat.

The dependence of historical extreme-heat regulation value on the different factors can be seen in Fig. 4 and Fig. S10. The value of estimated revenue loss scales with planted soy area and was high-

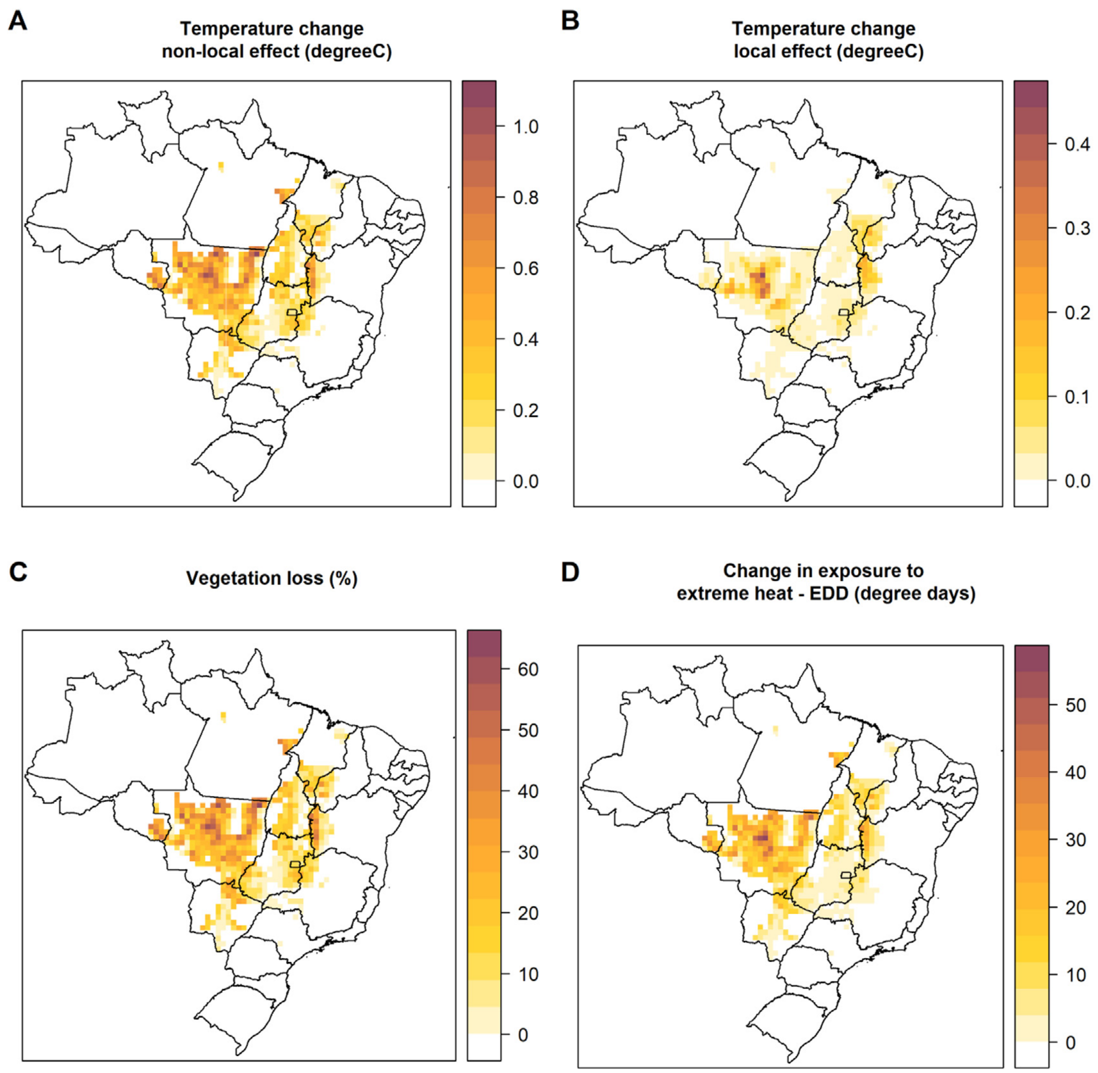

Fig. 3. The drivers and patterns of changes in exposure to extreme heat in 2012, taking into account changes in land cover over the historical period between 1985 and 2012. Above, maps show the estimated changes in mean temperature (°C) due to the non-local effect (Panel A) and the local effect (Panel B). Panel C shows the native vegetation loss (%) observed in this period. Panel D shows the changes in soybeans' exposure to extreme heat, described as the amount of additional exposure to extreme degree days (degree days).

Table 2
General statistics—mean, standard deviation, and weighed mean—on historical extreme-heat regulation value and related parameters for the year 2012, relative to 1985. The weighted mean is weighted according to the proportion of soy area (%) in each gridcell.

Parameter	Mean (standard deviation)			Weighted mean		
	Amazon	Cerrado	Total	Amazon	Cerrado	Total
Lost revenue (2005USD /ha yr)	112.59 (69.4)	56.25 (51.56)	69.91 (61.3)	158.52	85.4	99.11
Lost revenue: local effect only (2005USD ha^{-1} yr^{-1})	13.85 (19.21)	9.69 (15.45)	10.7 (16.52)	36.69	22.2	24.92
Change in EDD (degree days)	20.48 (10.1)	8.32 (7.56)	11.27 (9.75)	26.79	12.53	15.21
Temperature change (°C)	0.26 (0.13)	0.14 (0.12)	0.17 (0.13)	0.37	0.22	0.25
Change in productivity (%)	−9.62 (4.49)	−4.01 (3.53)	−5.37 (4.48)	−12.34	−5.93	−7.13
Native vegetation loss (%)	29.62 (13.3)	13.88 (10.46)	17.7 (13.08)	34.45	18.01	21.09
Soy area per gridcell (%)	6.41 (8.03)	8.88 (9.3)	8.28 (9.06)	–	–	–

est in regions retaining some, but not extensive, vegetation: Peak values are concentrated in regions with 25% to 50% native vegetation cover, below which they increase because there is some vegetation left to present the benefit and above which they reduce as vegetation fraction becomes large because there is less soy to benefit. This finding suggests a special role for extreme-heat regulation value from neighboring ecosystems to play in conversion frontiers.

Fig. 4 also shows the strong connection between areas with concentration of soy production and high extreme-heat regulation values. The areas where soy represents more than 20% of land

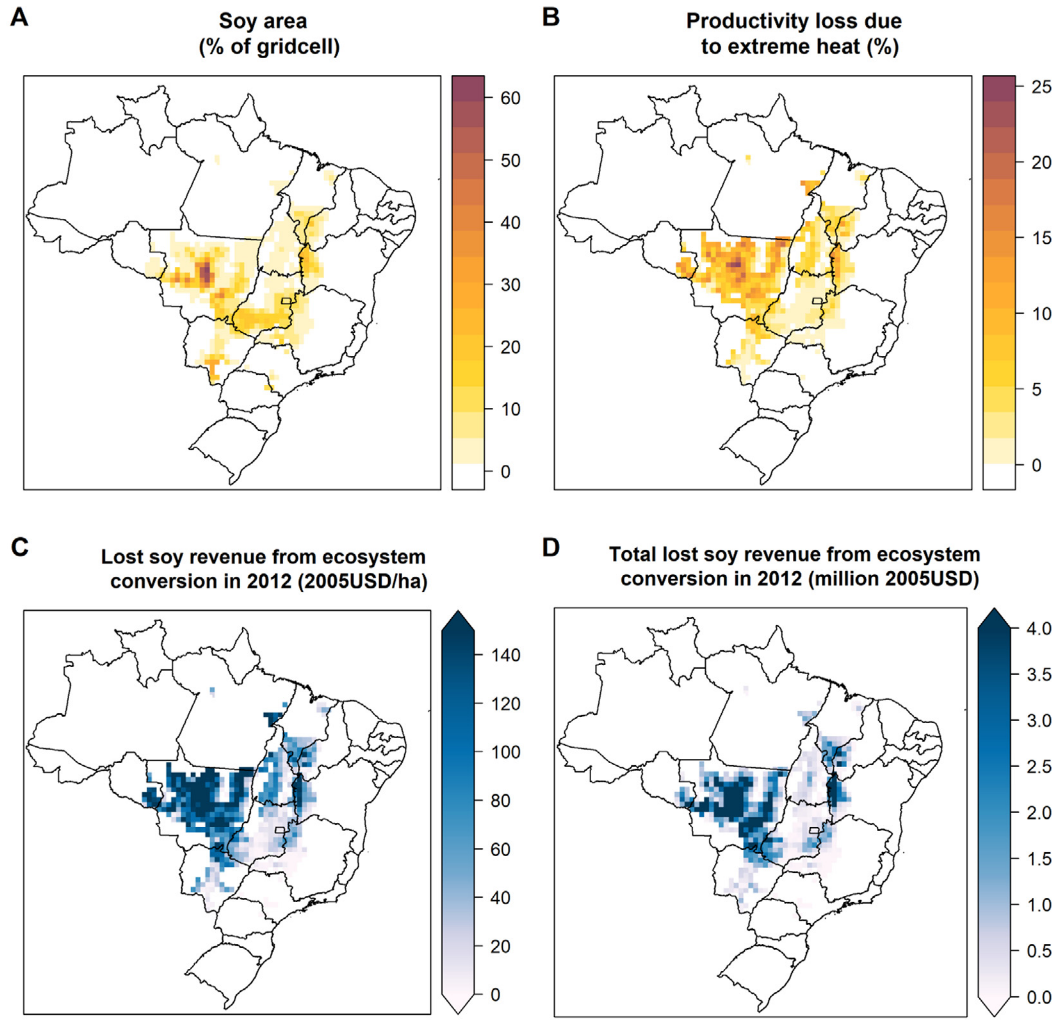

Fig. 4. Geographical distribution of drivers of lost soy revenue from ecosystem conversion. Panel A shows density of soybean cropland, expressed as percentage of total gridcell area (%). Panel B shows productivity loss due to extreme heat exposure resulting from vegetation loss between 1985 and 2012 (%). Panel C shows loss of soy revenue due to ecosystem conversion-related extreme-heat exposure in 2012 (2005USD/ha). Panel D shows total loss of soy revenue due to ecosystem conversion-related extreme heat exposure in 2012, per gridcell (2005USD).

cover are located mostly in central Mato Grosso at the frontier between the Cerrado and Amazon biomes, and in smaller degree in the Matopiba region.

4.2. Future extreme-heat regulation value

4.2.1. Extreme heat in future scenarios

Agricultural area and biogeophysical forcing from ecosystem conversion were projected to grow in the future scenarios. The representation of the projected trends in native vegetation loss and agricultural area from GLOBIOM-BR can be found in figs. S6, S7, and S8 in the supplementary material. As seen in Fig. 5, for future scenarios, the changes in extreme heat exposure by soybean agriculture, measured in extreme degree days (EDDs), are a result of both greenhouse gas-related (biogeochemical) climate change and ecosystem conversion-related (biogeophysical) climate change. Because the relationship between the increase in temperature and the changes in EDD is non-linear, the total EDD change is larger than the sum of the changes related to land use and climate change combined. Fig. 5 shows the results for the Baseline land use and agriculture scenario; the EDD results for the No Forest Code and Zero Deforestation scenarios can be found in Fig. S9.

4.2.2. Future lost soy revenue due to extreme heat and extreme-heat regulation ecosystem services

Next, we estimated the future values of lost soy revenue due to ecosystem conversion as well as the additional soy revenue from ecosystem services provided by native vegetation in the vicinity of agriculture. These results refer to the effects on cropping areas that are exposed to extreme heat during the period from 2020 to 2050.

Fig. 6 demonstrates the effect of different scenarios of deforestation in the overall future extreme-heat regulation value. The scenarios with higher ecosystem conversion rates (Baseline and No Forest Code) show further increases in the value of the remaining native vegetation when compared to the zero-deforestation scenario (Zero Deforestation).

The results were highly sensitive to factors such as projections of agricultural land use extent, ecosystem conversion, temperature change from greenhouse gas emissions, and the relationship between extreme temperature and land use change.

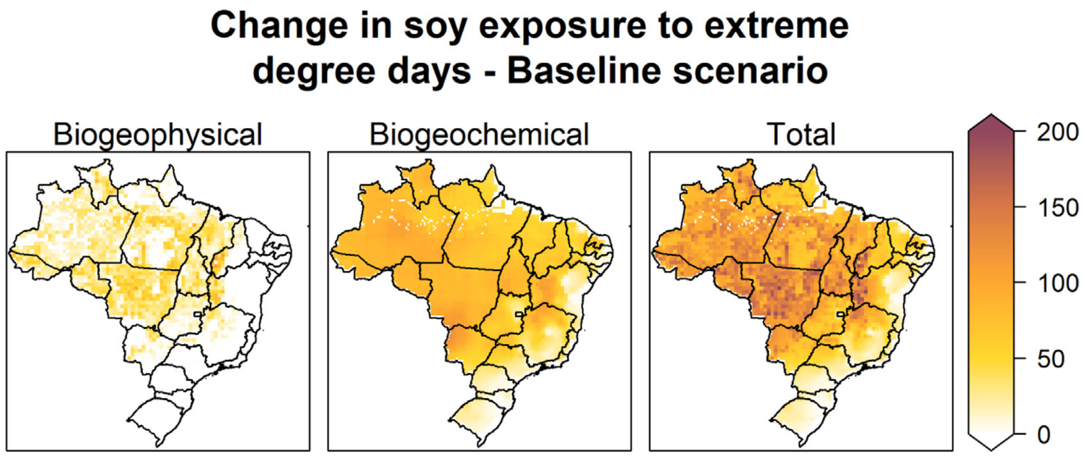

Fig. 5. Changes in soybean exposure to temperatures greater than 30 °C (EDD30C). Changes in heat exposure in 2050 related to land use change (left), changes in heat exposure under greenhouse gas-related climate change (center), and changes in EDD resulting from the combination of the two effects (right). The land use changes in this plot refer to the GLOBIOM-BR Baseline scenario. The same changes for other scenarios can be found in Fig. S9.

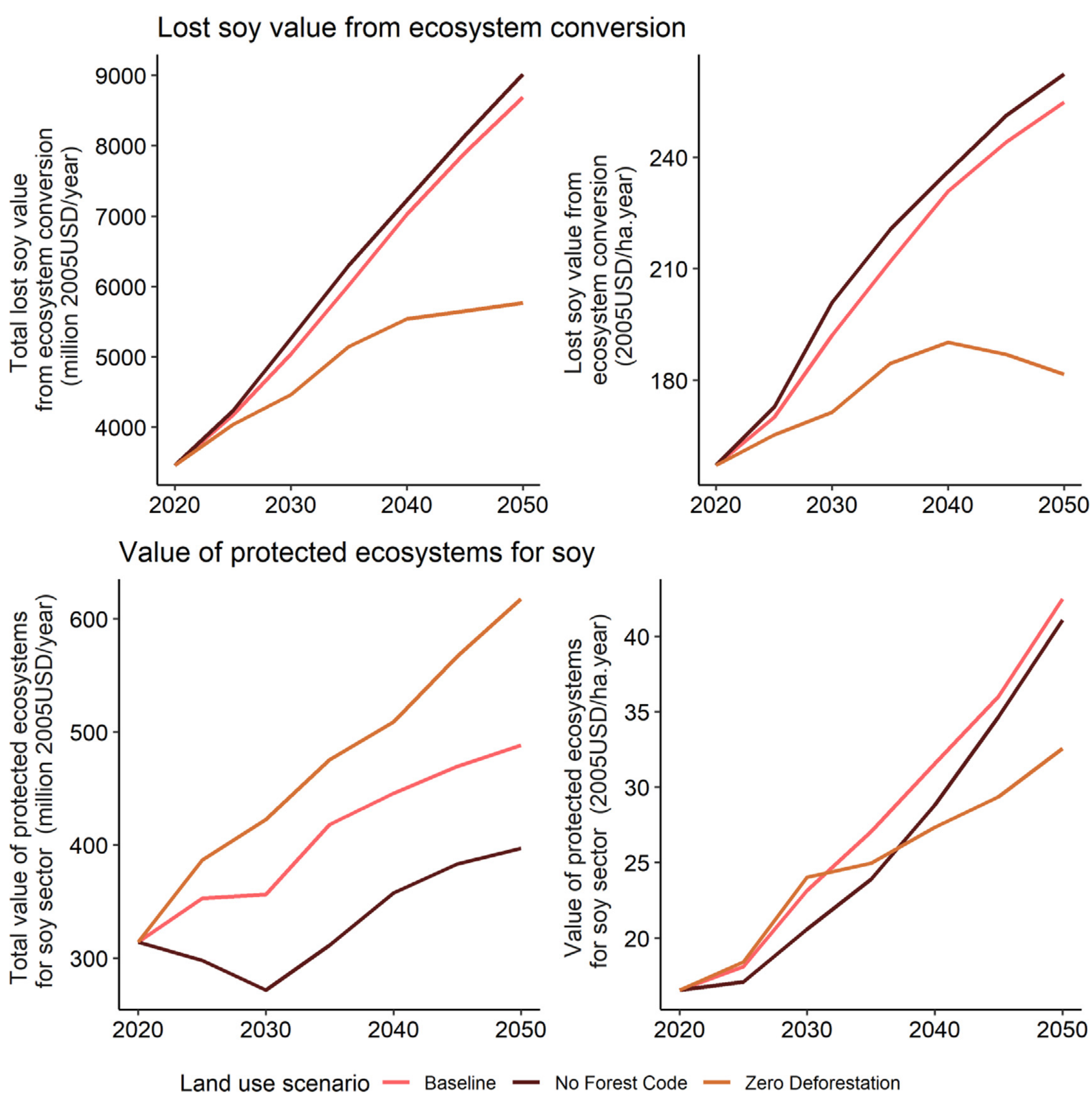

Fig. 6. Analysis of future scenarios. Panels A and B show, respectively, the evolution of total and specific lost soy revenue due to exposure to extreme heat resulting from ecosystem conversion (2005USD/year and 2005USD/ha year). Panels C and D show the evolution of total and specific additional revenue of soy due to ecosystem services of extreme-heat regulation (conversion (2005USD/year and 2005USD/ha year).

4.3. Benchmarking with costs of conservation

A useful way of contextualizing the value of ecosystem services is to benchmark the services against costs associated with ecosystem conservation, ecosystem restoration, or both. We benchmarked the present value of extreme-heat regulation services between 2020 and 2050 against land values, which are often used as a proxy for the cost of conserving ecosystems (Naidoo & Ricketts, 2006), and against the carbon value of biomass, another germane and readily calculable contributor to climate regulation service in the region. By our estimates, the value of a hectare of cropland in Brazil was roughly $3,000 (2005 USD) on average in 2003 and can be expected to rise to roughly $8,000 (2005 USD) per ha^{-1} by 2050.

Table 3 shows the present value of the two types of extreme-heat regulation value estimated for the three future scenarios. In agreement with Fig. 6, the results show that in scenarios with lower loss of native vegetation, the marginal value of losses and of the ecosystem services provided becomes smaller, albeit the differences are small in relation to the differences between areas with

Table 3
Summary statistics of the present values estimated from the future scenario analysis (2020–2050). The present values were estimated using a discount rate of 10%. The weighted mean is weighted according to the proportion of soy area (%) in each gridcell.

Scenario	Lost soy revenue from ecosystem conversion-related extreme heat exposure (2005USD/ha)		Additional soy revenue from extreme-heat regulation ecosystem services (2005USD/ha)	
	Mean	Weighted mean	Mean	Weighted mean
Baseline	1353	1618	408	271
No Forest Code	1379	1649	406	262
Zero Deforestation	1306	1551	403	249

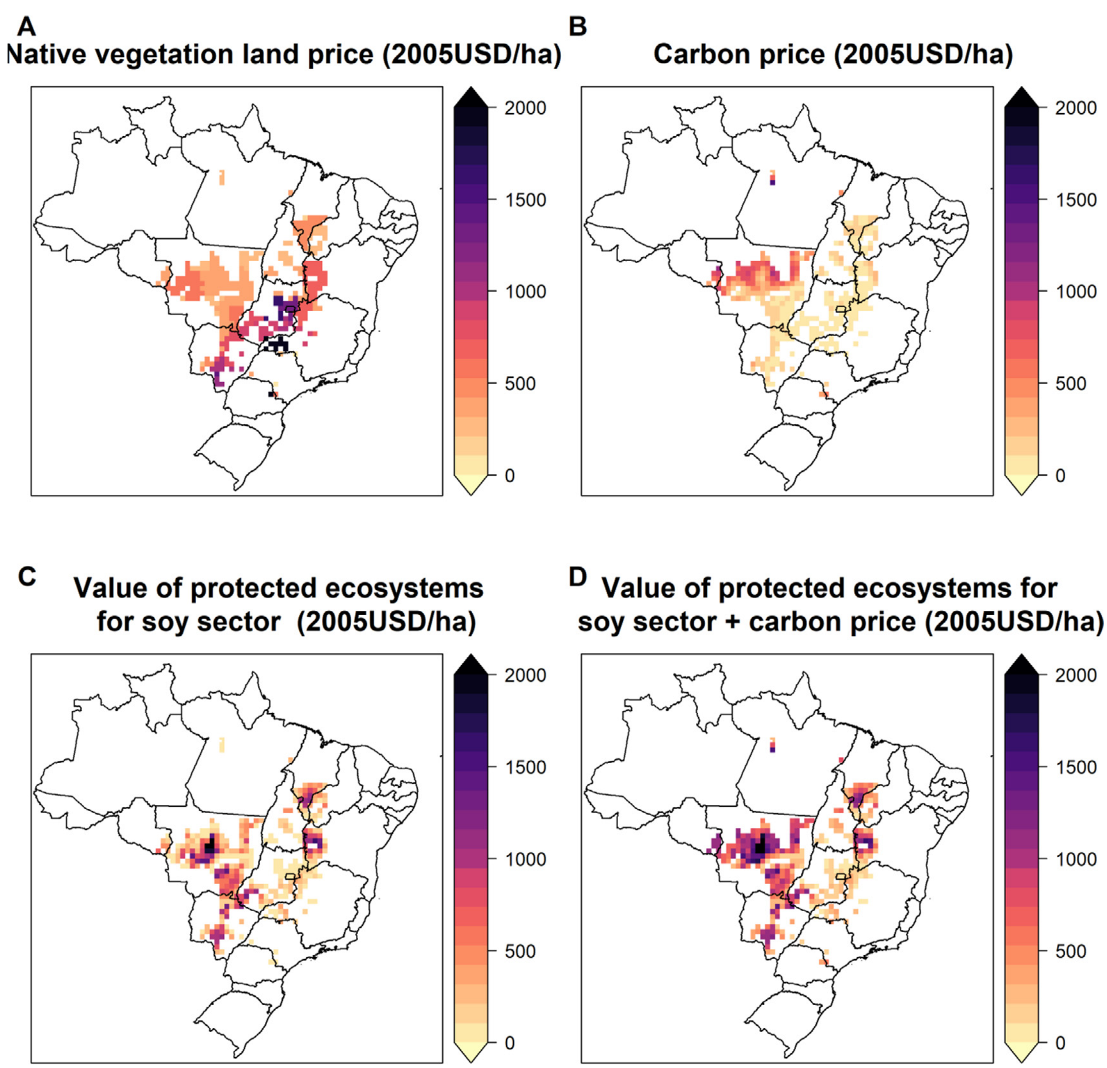

Fig. 7. Benchmarking analysis of the present value of extreme-heat regulation ecosystem services with carbon and native vegetation land values. Panel A shows the geographical variation of native vegetation land prices in Brazil. Panel B shows the estimated carbon prices in Brazil. Panel C shows the distribution of the present value of future extreme-heat regulation ecosystem services provided by native vegetation in the vicinity of soybean agriculture. Panel D shows the addition of the values in panels B and C.

higher or lower soy cover. The average present value of additional soy revenue from extreme-heat regulation ecosystem services was of a magnitude similar to that of land and carbon prices and with a geographical distribution similar to that for carbon values (see Fig. 7).

5. Discussion

Below, we (1) discuss the challenges to our approach to estimate extreme-heat regulation services by neighboring native vegetation and how they may be improved, (2) contextualize our results relative to findings for other forest-related ecosystem services, and (3) explore the potential implications of our results for policy, local development, and the economy at large.

5.1. Uncertainty and opportunities for future analysis

Our estimates of extreme-heat regulation values could eventually be improved by incorporating additional data and components into our modeling framework. Additional data that could improve our valuation include spatially explicit information on soy yield, soy prices, cropping frequency, and climate impacts of extreme heat. Incorporating such information for other crops would also diversify our analysis and make it more comprehensive.

In Brazil, transportation costs constitute a substantial fraction of the costs of agricultural production; as a result, producer prices for crops greatly vary. When we use a single traded price, associated with transactions at transport hubs, our standard practice is to use the soy price associated with the highest transportation costs. As a result, we may be somewhat overestimating extreme-heat regulation values at frontier areas.

Additional sources of uncertainty, variation, or both in our estimates stem from the need to project commodity price trends and agricultural technological innovation. The partial equilibrium model GLOBIOM-BR makes projections of future land use on the basis of assumptions about technological improvement and regulatory policies, but it does not consider feedback from the changes in agricultural productivity estimated in this study. The endogenization of the impacts of land use change on extreme heat exposure and on agricultural productivity in the model could shed light on how the land sector could adapt and adjust to the changes we are analyzing in this study. Extreme heat regulation service values are dependent on soy prices, which vary with time. In the case of our analysis, we relied on the soy price relative to the year 2012, when soy prices were particularly high in the international markets. Since both the extreme heat regulation service values and the value of other land uses scale with soy prices, it is the relative value - the benchmarking ratio - that matters the most.

In a future climate, we might expect a number of changes with implications for extreme heat regulation. Forest ecosystems resilience could be undermined by climate feedbacks that have the potential to affect native vegetation cover, thus affecting extreme-heat regulation provision (Coe et al., 2013). Meanwhile, other climate metrics relevant to agriculture productivity could change in ways that are correlated with extreme heat, exacerbating or attenuating the influence of extreme heat on productivity (Auffhammer et al., 2013). In our approach, we take into consideration possible hazards and exposure to climate. However, in reality, climate impacts on agriculture are the residual of the influence of climate on crops minus measures employed by farmers to offset or to adapt to these impacts (Hsiang, 2016). We expect adaptive measures (such as irrigation, use of adapted cultivars, and changes to cropping calendars) to vary by farm, household, and location. For example, income diversification (Ma & Maystadt, 2017), agricultural diversification (Gil et al., 2017), and access to infrastructure (Darrouzet-Nardi & Masters, 2017) each have been shown to limit the influence of climate shocks on agriculture. These and other drivers of adaptive capacity vary spatially, and they depend on many factors that include local estimated water availability from both surface water and rainfall and access to smallholder farmer insurance (Challinor et al., 2014; Minoli et al., 2019).

One limitation of our approach is that we explore only one pathway that ecosystem conversion affects crop yields—via increased incidence of extreme heat in the growing season. Ecosystem loss also alters a number of global and local drivers of crop yield—most notably patterns of precipitation. Beyond a threshold, native vegetation loss in our study region also reduces rainfall, causing impacts on agricultural productivity and revenue of similar magnitude to our findings (Leite-Filho et al., 2021). In addition, diminished precipitation worsens the marginal effect of heat on crops (Agnolucci et al., 2020).

Consideration of multi-cropping systems, agricultural adaptation strategies, and land-cover climate feedbacks are other ways in which our study could be improved on. Beyond directly impacting the productivity of soy, changes in climate can affect the productivity and feasibility of multi-cropping systems, including systems in which soybeans are the main crop. Changes in cropping frequency per growing season can be a direct source of climate losses (Cohn et al., 2016b). They also are associated with the use of varieties with different exposures and vulnerabilities to climate.

Finally, our analysis would be improved by refined estimations of the opportunity costs of conservation. Land prices are often an excellent proxy for the opportunity cost of conservation (aidoo & Ricketts, 2006), but it would also be useful to compare extreme-heat regulation values to the costs of both active and passive landscape restoration (Brancalion et al., 2016), given legal requirements under the Brazilian Forest Code (Soares-Filho et al., 2016) for landholders to restore ecosystems.

5.2. Extreme heat regulation in the context of other ecosystem services

Extreme heat regulation is only one type of climate regulation service that can be provided by ecosystems. Other forms of climate regulation services provided by natural ecosystems include regulating downstream precipitation (Keys et al., 2016), local precipitation (Leite-Filho et al., 2021), precipitation seasonality (Costa et al., 2019; Leite-Filho et al., 2020), and other precipitation-mediated climate feedbacks (Coe et al., 2013).

We compared our case and findings with previous benefits estimated to be associated with ecosystem services from tropical native vegetation. Anderson-Teixeira et al. (2012) estimate the core portion of the Amazon forest to provide climate regulation services equivalent to 200 Mg CO_2 50 yr^{-1} (an amount encompassing both biogeochemical and biogeophysical climate regulation). With a middle-of-the-road social cost of carbon of $50 (2005USD) Mg^{-1}, this amount corresponds to $10,000 (2005USD) ha^{-1} 50 yr^{-1} or $200 (2005USD) ha^{-1}. Note that this cost reflects cost based on a longer public policy time horizon. Our estimates range from $68 to $167 (2005USD) ha^{-1}, consistent with Strand et al. (2018), who estimated total ecosystem services in the Amazon area to be between US$56.72 ± 10 ha^{-1} yr^{-1} and US$737 ± 13 4 ha^{-1}, with soy agriculture representing around US$100. 00 ± 10 ha^{-1}.

However, given that we have investigated just one aspect of the biogeophysical regulation of climate, our estimates are quite conservative in valuing ecosystem loss and protection. Our climate regulation values are particularly noteworthy, given that they are provided to beneficiaries of a very local nature. Extreme heat regulation boosts soy yields for producers who conserve vegetation on their farms, and the ensuing benefits accrue to those producers' neighbors, friends, and business associates.

All ecosystem services can be classified according to the degree of spatial disconnect between service beneficiaries and providers (Serna-Chavez et al., 2014). For each ecosystem service, we can divide the world into production regions, beneficiary regions, and regions of production and beneficiary overlap. Biogeophysical extreme-heat regulation is notable for its substantial amount of overlap relative to other ecosystem services such as biogeochemical extreme-heat regulation or pollination. Nevertheless, biogeophysical extreme-heat regulation may constitute a small share of tropical vegetation ecosystem services. For example, the value of the biogeophysical climate regulation estimated by Anderson Teixeira constitutes only 5% of the value of ecosystems services estimated by Costanza et al. (2014). The total value of those 17 ecosystem services, including water and climate regulation, was estimated at $5,310 (2005USD) ha^{-1}.

5.3. Implications for political economy and development pathways

Extreme heat regulation is a mechanism through which native vegetation can be viewed as bolstering agricultural productivity in Brazilian agriculture. Such regulation could help provide a pathway to prosperity if decision makers were to take it into consideration. One of the main questions that can be posed is, who can benefit from the value of extreme heat regulation? It is likely that the vast majority of ecosystems with high extreme-heat regulation value are privately held and that even larger amounts of these ecosystems will come into private hands (Freitas et al., 2018). According to our analysis, both suppliers and service beneficiaries could benefit from extreme heat regulation. In many cases, a property owner might both supply and benefit from it.

One recent study of Mato Grosso state, a critical region for ecosystem conversion, found the bulk of standing forest carbon to be located on a small number of large properties (Richards et al., 2016). For landholders, revenue from extreme-heat regulation services provided by native ecosystems that they own could constitute a meaningful form of livelihood diversification if the appropriate policy conditions were put in place. Income diversification, including the use of natural resources by the predominantly agricultural rural poor, has been widely shown to facilitate poverty alleviation (Barrett et al., 2001). However, less evidence exists on income diversification as a pathway to prosperity, a more germane question in the context of the medium- and large-scale farms dominating the frontier of the Brazilian Amazon.

People not directly involved in agriculture also benefit from climate regulation services. As in much of the developing world, agriculture in northern Brazil is closely associated with economic development, and it can be argued that the relationship is causal (Irz & Tiffin, 2006; Richards et al., 2015). Mechanisms for this development include the generation of surplus, particularly supply of investment capital, and release of labor (Mellor, 2017). Evidence is particularly strong that agriculture value added per worker increases GDP per capita (Irz & Tiffin, 2006). This finding is consistent with the notion that intensification of agriculture leads to GDP growth. This finding isn't limited to developing countries, but rather is observed across all income strata. Evidence of intensive agricultural margin benefits for economic growth can be found in micro-level studies such as Minten and Barrett (2008) and macro-modeling such as de Janvry and Sadoulet (2001).

In terms of political impacts, extreme heat regulation could affect land institutions, resulting in different configurations for the legal reserve and riparian areas provided for under the Brazilian Forest Code. Extreme-heat regulation values also suggest different economics and possibly different politics for the code in general. In particular, the code has been critiqued as an uncompensated transfer of global public goods from Brazilian agricultural land owners—but our work shows that the landowners are also significant beneficiaries of the extreme-heat regulation value afforded by the conservation that the code requires. In the long view, while the Brazilian Forest Code has likely slowed agricultural expansion, it may have unintentionally promulgated landscape patchiness. The crop mosaic landscape created by the code may lead to increased domination of Brazilian and global landscapes by agricultural land use. On the other hand, local political elites and agribusiness actors have made achieving zero illegal ecosystem conversion difficult. Demonstration of the local value of standing native vegetation's extreme heat regulation could change the political economy of illegal ecosystem conversion.

6. Conclusions

We estimated the past and future value of ecosystems associated with reducing the exposure of neighboring farmland to extreme heat. Our research focused on the case of soybean production in two main Brazilian biomes, the Amazon and the Cerrado. For the most part, estimates of extreme-heat regulation value were smaller than estimates of land value, suggesting that extreme heat regulation alone would provide an insufficient case for ecosystem conservation in most locations. However, in combination with carbon price, the value of extreme heat regulation and other ecosystem services could exceed the opportunity cost of conservation, particularly in the region at the southeastern fringe of the Amazon Basin, where land conversion rates are currently high and soybean cultivation is widespread, owing to limited conservation measures.

Across the tropics, global greenhouse gas emissions and biogeophysical changes from the conversion of ecosystems to agriculture are combining to cause climate change that can affect biodiversity, the productivity of agriculture, bioenergy, hydropower, and rural infrastructure. In tropical agricultural frontiers, the costs of climate change from ecosystem conversion can rival or exceed those of climate change from greenhouse gases (Cohn et al., 2019; Lawrence & Vandecar, 2014; Salazar et al., 2015). Yet many policy, planning, investment, and business decisions in the tropics neglect climate risk in general and especially climate risk from ecosystem conversion. The result is a missed opportunity to reduce ecosystem conversion and to promote regional prosperity (Chaplin-Kramer et al., 2015). Quantifying the economic value of climate regulation from ecosystem conservation can help to address a key challenge for ecosystem conservation and restoration—gaining the support of agribusinesses and other stakeholders. These stakeholders greatly benefit from ecosystem services, and their decisions can strongly shape the efficacy of ecosystem conservation and restoration efforts and, ultimately, regional development.

Conflicts of interest

None.

CRediT authorship contribution statement

Rafaela Flach: Conceptualization, Methodology, Software, Writing - review & editing, Project administration. **Gabriel Abrahão:** Methodology, Software, Writing - review & editing. **Benjamin Bryant:** Methodology, Writing - review & editing. **Marluce Scarabello:** Software, Data curation, Writing - review & editing. **Aline C. Soterroni:** Software, Writing - review & editing. **Fernando M. Ramos:** Software. **Hugo Valin:** Writing - review & editing. **Michael Obersteiner:** Writing - review & editing. **Avery S. Cohn:** Conceptualization, Methodology, Project administration, Writing - review & editing.

Acknowledgements

We wish thank Anaya Hall and Jake Campolo for research assistance. This research was supported by the Gordon and Betty Moore Foundation (grant #6895) and the World Bank Pathways to Prosperity program.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.worlddev.2021.105582.

References

Abrahão, G. M., & Costa, M. H. (2018). Evolution of rain and photoperiod limitations on the soybean growing season in Brazil: The rise (and possible fall) of double-cropping systems. *Agricultural and Forest Meteorology, 256–257*(March), 32–45. https://doi.org/10.1016/j.agrformet.2018.02.031.

Agnolucci, P., Rapti, C., Alexander, P., De Lipsis, V., Holland, R. A., Eigenbrod, F., & Ekins, P. (2020). Impacts of rising temperatures and farm management practices on global yields of 18 crops. *Nature Food, 1*(9), 562–571. https://doi.org/10.1038/s43016-020-00148-x.

Allen, R., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop requirements. *Irrigation and Drainage Paper No. 56, FAO, 56*, 300. https://doi.org/10.1016/j.eja.2010.12.001.

Alkama, R., & Cescatti, A. (2016). Biophysical climate impacts of recent changes in global forest cover. *Science, 351*(6273), 600–604. https://doi.org/10.1126/science.aac8083.

Anderson-Teixeira, K. J., Snyder, P. K., Twine, T. E., Cuadra, S. V., Costa, M. H., & Delucia, E. H. (2012). Climate-regulation services of natural and agricultural ecoregions of the Americas. *Nature Climate Change, 2*(3), 177–181. https://doi.org/10.1038/nclimate1346.

Angelsen, A. (2010). Policies for reduced deforestation and their impact on agricultural production. *Proceedings of the National Academy of Sciences of the United States of America, 107*(46), 19639–19644. https://doi.org/10.1073/pnas.0912014107.

Arias, M. E., Farinosi, F., Lee, E., Livino, A., Briscoe, J., & Moorcroft, P. R. (2020). Impacts of climate change and deforestation on hydropower planning in the Brazilian Amazon. *Nature Sustainability, 3*(6), 430–436. https://doi.org/10.1038/s41893-020-0492-y.

Arima, E. Y., Richards, P., Walker, R., & Caldas, M. M. (2011). Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environmental Research Letters, 6*(2), 024010. https://doi.org/10.1088/1748-9326/6/2/024010.

Auffhammer, M., Hsiangy, S. M., Schlenker, W., & Sobelz, A. (2013). Using weather data and climate model output in economic analyses of climate change. *Review of Environmental Economics and Policy, 7*(2), 181–198. https://doi.org/10.1093/reep/ret016.

Avitabile, V., Herold, M., Heuvelink, G. B. M., Lewis, S. L., Phillips, O. L., Asner, G. P., ... Willcock, S. (2016). An integrated pan-tropical biomass map using multiple reference datasets. *Global Change Biology, 22*(4), 1406–1420. https://doi.org/10.1111/gcb.2016.22.issue-410.1111/gcb.13139.

Bambini, M. D., Junior, A. L., Romani, L. A. S., Otavian, A. F., Koenigkan, L. V., & Evangelista, S. R. de M. (2015). Manual on-line do sistema Agritempo versão 2.0. agritempo.gov.br.

Barrett, C. B., Reardon, T., & Webb, P. (2001). Nonfarm income diversification and household livelihood strategies in Rural Africa: Concepts, dynamics and policy implications. *Food Policy, 26*(4), 315–331. https://doi.org/10.1016/S0306-9192(01)00014-8.

Blanc, E., & Schlenker, W. (2017). The use of panel models in assessments of climate impacts on agriculture. *Review of Environmental Economics and Policy, 11*(2), 258–279. https://doi.org/10.1093/reep/rex016.

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science, 320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121.

Bowman, M. S., Soares-Filho, B. S., Merry, F. D., Nepstad, D. C., Rodrigues, H., & Almeida, O. T. (2012). Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production. *Land Use Policy, 29*(3), 558–568. https://doi.org/10.1016/j.landusepol.2011.09.009.

Bragança, A. (2018). The economic consequences of the agricultural expansion in Matopiba. *Revista Brasileira de Economia, 72*(2), 161–185. https://doi.org/10.5935/0034-7140.20180008.

Brancalion, P. H. S., Schweizer, D., Gaudare, U., Mangueira, J. R., Lamonato, F., Farah, F. T., Nave, A. G., & Rodrigues, R. R. (2016). Balancing economic costs and ecological outcomes of passive and active restoration in agricultural landscapes: The case of Brazil. *Biotropica, 48*(6), 856–867. https://doi.org/10.1111/btp.12383.

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature, 527*(7577), 235–239. https://doi.org/10.1038/nature15725.

Bustos, P., Caprettini, B., & Ponticelli, J. (2016). Agricultural productivity and structural transformation: Evidence from Brazil. *American Economic Review, 106*(6), 1320–1365. https://doi.org/10.1257/aer.20131061.

Bustos, P., Castro-Vincenzi, J., Monras, J., & Ponticelli, J. (2018). Labor-saving agricultural technical change and industrial development. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3178274.

Butler, E. E., & Huybers, P. (2015). Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase. *Environmental Research Letters, 10*(3), 34009. https://doi.org/10.1088/1748-9326/10/3/034009.

Butt, N., De Oliveira, P. A., & Costa, M. H. (2011). Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *Journal of Geophysical Research Atmospheres, 116*(11). https://doi.org/10.1029/2010JD015174.

Carleton, T., & Hsiang, S. (2016). Social and economic impacts of climate. Science, 353, aad9837–aad9837. https://doi.org/10.1126/science.aad9837.

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change, 4*(4), 287–291. https://doi.org/10.1038/nclimate2153.

Chaplin-Kramer, R., Jonell, M., Guerry, A., Lambin, E., Morgan, A., Pennington, D., Smith, N., Franch, J., & Polasky, S. (2015). Ecosystem service information to benefit sustainability standards for commodity supply chains. *Annals of the New York Academy of Sciences, 1355*, 77–97. https://doi.org/10.1111/nyas.12961.

Coe, M. T., Marthews, T. R., Costa, M. H., Galbraith, D. R., Greenglass, N. L., Imbuzeiro, H. M. A., Levine, N. M., Malhi, Y., Moorcroft, P. R., Muza, M. N., Powell, T. L., Saleska, S. R., Solorzano, L. A., & Wang, J. (2013). Deforestation and climate feedbacks threaten the ecological integrity of south-southeastern Amazonia. *Philosophical Transactions of the Royal Society B: Biological Sciences, 368*(1619), 20120155. https://doi.org/10.1098/rstb.2012.0155.

Cohn, A. (2017). Leveraging climate regulation by ecosystems for agriculture to promote ecosystem stewardship. Tropical Conservation Science, 10. https://doi.org/10.1177/1940082917720672.

Cohn, A. S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J., & Thompson, S. (2019). Forest loss in Brazil increases maximum temperatures within 50 km. *Environmental Research Letters, 14*(8). https://doi.org/10.1088/1748-9326/ab31fb 084047.

Cohn, A. S., Gil, J., Berger, T., Pellegrina, H., & Toledo, C. (2016). Patterns and processes of pasture to crop conversion in Brazil: Evidence from Mato Grosso State. *Land Use Policy, 55*, 108–120. https://doi.org/10.1016/j.landusepol.2016.03.005.

Cohn, A. S., Vanwey, L. K., Spera, S. A., & Mustard, J. F. (2016). Cropping frequency and area response to climate variability can exceed yield response. *Nature Climate Change, 6*(6), 601–604. https://doi.org/10.1038/nclimate2934.

Costa, M. H., Fleck, L. C., Cohn, A. S., Abrahão, G. M., Brando, P. M., Coe, M. T., Fu, R., Lawrence, D., Pires, G. F., Pousa, R., & Soares-Filho, B. S. (2019). Climate risks to Amazon agriculture suggest a rationale to conserve local ecosystems. *Frontiers in Ecology and the Environment, 17*(10), 584–590. https://doi.org/10.1002/fee.v17.1010.1002/fee.2124.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., & Turner, R. K. (2014). Changes in the global value of ecosystem services. *Global Environmental Change, 26*(1), 152–158. https://doi.org/10.1016/j.gloenvcha.2014.04.002.

D'Agostino, A. L., & Schlenker, W. (2016). Recent weather fluctuations and agricultural yields: Implications for climate change. *Agricultural Economics, 47*(S1), 159–171. https://doi.org/10.1111/agec.2016.47.issue-S110.1111/agec.12315.

Darrouzet-Nardi, A. F., Masters, W. A., & van Wouwe, J. P. (2017). Nutrition smoothing: Can proximity to towns and cities protect rural children against seasonal variation in agroclimatic conditions at birth?. *PLoS ONE, 12*(1), e0168759. https://doi.org/10.1371/journal.pone.0168759.

de Janvry, A., & Sadoulet, E. (2001). World poverty and the role of agricultural technology: direct and indirect effects. *Journal of Development Studies, 38*(4), 1–26. https://doi.org/10.1080/00220380412331322401.

Dias, L. C. P., Pimenta, F. M., Santos, A. B., Costa, M. H., & Ladle, R. J. (2016). Patterns of land use, extensification, and intensification of Brazilian agriculture. *Global Change Biology, 22*(8), 2887–2903. https://doi.org/10.1111/gcb.2016.22.issue-810.1111/gcb.13314.

Duffy, P. B., Brando, P., Asner, G. P., & Field, C. B. (2015). Projections of future meteorological drought and wet periods in the Amazon. *Proceedings of the National Academy of Sciences of the United States of America, 112*(43), 13172–13177. https://doi.org/10.1073/pnas.1421010112.

Ellwanger, J. H., Kulmann-Leal, B., Kaminski, V. L., Valverde-Villegas, J. M., Veiga, A. B. G. D., Spilki, F. R., Fearnside, P. M., Caesar, L., Giatti, L. L., Wallau, G. L., Almeida, S. E. M., Borba, M. R., Hora, V. P. DA., & Chies, J. A. B. (2020). Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health. *Anais Da Academia Brasileira de Ciencias, 92*(1). https://doi.org/10.1590/0001-3765202020191375.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development, 9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., & Alsdorf, D. E. (2007). The shuttle radar topography mission. *Reviews of Geophysics, 45*(2). https://doi.org/10.1029/2005RG000183.

Fischer, E. M., & Knutti, R. (2015). Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change, 5*(6), 560–564. https://doi.org/10.1038/nclimate2617.

Freitas, F. L. M., Sparovek, G., Berndes, G., Persson, U. M., Englund, O., Barretto, A., & Mörtberg, U. (2018). Potential increase of legal deforestation in Brazilian Amazon after Forest Act revision. *Nature Sustainability, 1*(11), 665–670. https://doi.org/10.1038/s41893-018-0171-4.

Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., & Huang, X. (2010). MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment, 114*(1), 168–182. https://doi.org/10.1016/j.rse.2009.08.016.

Galford, G. L., Melillo, J., Mustard, J. F., Cerri, C. E. P., & Cerri, C. C. (2010). The Amazon frontier of land-use change: Croplands and Consequences for greenhouse gas emissions. *Earth Interactions, 14*(15), 1–24. https://doi.org/10.1175/2010EI327.1.

Gash, J. H. C., & Nobre, C. A. (1997). Climatic Effects of Amazonian Deforestation: Some Results from ABRACOS. *Bulletin of the American Meteorological Society, 78*(5), 823–830. https://doi.org/10.1175/1520-0477(1997)078<0823:CEOADS>2.0.CO;2.

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., ... Takahashi, K. (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: A dataset of harmonized emissions trajectories through the end of the century. *Geoscientific Model Development, 12*(4), 1443–1475. https://doi.org/10.5194/gmd-12-1443-2019.

Gil, J. D. B., Cohn, A. S., Duncan, J., Newton, P., & Vermeulen, S. (2017). The resilience of integrated agricultural systems to climate change. *Wiley Interdisciplinary Reviews: Climate Change, 8*(4), 1–15. https://doi.org/10.1002/wcc.461.

Goldsmith, P., & Cohn, A. (2017). Commercial agriculture in tropical environments. *Tropical Conservation Science, 10*(August), 2–5. https://doi.org/10.1177/1940082917727994.

Gourdji, S. M., Sibley, A. M., & Lobell, D. B. (2013). Global crop exposure to critical high temperatures in the reproductive period: Historical trends and future projections. *Environmental Research Letters, 8*(2), 024041. https://doi.org/10.1088/1748-9326/8/2/024041.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-resolution global maps of 21st-century forest cover change. *Science (New York, N.Y.), 342*(6160), 850–853. https://doi.org/10.1126/science:1244693.

Hamrick, K., & Goldstein, A. (2016). Raising Ambition (State of the Voluntary Carbon Markets 2016). Forest Trends' Ecosystem Marketplace, 1–58. www.forest-trends.org.

Hargrave, J., & Kis-Katos, K. (2013). Economic causes of deforestation in the Brazilian Amazon: A panel data analysis for the 2000s. *Environmental and Resource Economics, 54*(4), 471–494. https://doi.org/10.1007/s10640-012-9610-2.

Havlik, P., Schneider, U. A., Schmid, E., Bottcher, H., Fritz, S., Skalsky, R., Aoki, K., De Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., & Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. Energy Policy, 39(10), 5690–5702. https://doi.org/doi.org/10.1016/j.enpol.2010.03.030.

Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M. C., Mosnier, A., Thornton, P. K., Böttcher, H., Conant, R. T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., & Notenbaert, A. n. (2014). Climate change mitigation through livestock system transitions. *Proc. Natl. Acad. Sci. USA, 111*(10), 3709–3714.

Hsiang, S. (2016). Climate econometrics. *Annual Review of Resource Economics, 8*(1), 43–75. https://doi.org/10.1146/annurev-resource-100815-095343.

Hsiang, S., Roberts, M., & Schlenker, W. (2013). Climate and Crop Yields in Australia, Brazil, China, Europe and the United States. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2977571.

Hsu, K. L., Gao, X., Sorooshian, S., & Gupta, H. V. (1997). Precipitation estimation from remotely sensed information using artificial neural networks. *Journal of Applied Meteorology, 36*(9), 1176–1190. https://doi.org/10.1175/1520-0450(1997)036<1176:PEFRSI>2.0.CO;2.

IBGE. (2020). Levantamento Sistemático da Produção Agrícola. https://sidra.ibge.gov.br/tabela/6588.

IPCC. (2014). Summary for policymakers. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1–32). Cambridge University Press.

Irz, X., & Tiffin, R. (2006). Is agriculture the engine of growth?. *Agricultural Economics, 35*(1), 79–89. https://doi.org/10.1111/agec.2006.35.issue-110.1111/j.1574-0862.2006.00141.x.

Keys, P. W., Wang-Erlandsson, L., Gordon, L. J., & Bilotta, G. S. (2016). Revealing Invisible Water: Moisture Recycling as an Ecosystem Service. *PLOS ONE, 11*(3), e0151993. https://doi.org/10.1371/journal.pone.0151993.

Khanna, J., Medvigy, D., Fueglistaler, S., & Walko, R. (2017). Regional dry-season climate changes due to three decades of Amazonian deforestation. *Nature Climate Change, 7*(3), 200–204. https://doi.org/10.1038/nclimate3226.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift, 15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Lambin, E. F., Gibbs, H. K., Heilmayr, R., Carlson, K. M., Fleck, L. C., Garrett, R. D., le Polain de Waroux, Y., McDermott, C. L., McLaughlin, D., Newton, P., Nolte, C., Pacheco, P., Rausch, L. L., Streck, C., Thorlakson, T., & Walker, N. F. (2018). The role of supply-chain initiatives in reducing deforestation. *Nature Climate Change, 8*(2), 109–116. https://doi.org/10.1038/s41558-017-0061-1.

Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., ... Xu, J. (2001). The causes of land-use and land-cover change: Moving beyond the myths. *Global Environmental Change, 11*(4), 261–269. https://doi.org/10.1016/S0959-3780(01)00007-3.

Lawrence, D., & Vandecar, K. (2014). The impact of tropical deforestation on climate and links to agricultural productivity. *Nature Climate Change, 5*(January). https://doi.org/10.1038/nclimate2430.

Lawrence, D., & Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. *Nature Climate Change, 5*(1), 27–36.

Leite-Filho, A. T., Costa, M. H., & Fu, R. (2020). The southern Amazon rainy season: The role of deforestation and its interactions with large-scale mechanisms. *International Journal of Climatology, 40*(4), 2328–2341. https://doi.org/10.1002/joc.v40.410.1002/joc.6335.

Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M., & Börner, J. (2021). Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nature Communications, 12*(2591), 1–7. https://doi.org/10.1038/s41467-021-22840-7.

Lobell, D. B., Hammer, G. L., McLean, G., Messina, C., Roberts, M. J., & Schlenker, W. (2013). The critical role of extreme heat for maize production in the United States. *Nature Climate Change, 3*(5), 497–501. https://doi.org/10.1038/nclimate1832.

Ma, J., & Maystadt, J.-F. (2017). The impact of weather variations on maize yields and household income: Income diversification as adaptation in rural China. *Global Environmental Change, 42*, 93–106. https://doi.org/10.1016/j.gloenvcha.2016.12.006.

Masuda, Y., Garg, T., Anggraeni, I., Wolff, N. H., Ebi, K. L., Game, E. (Eddie), Krenz, J., & Spector, J. (2020). Heat exposure from tropical deforestation decreases cognitive performance of rural workers: an experimental study. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abb96c.

Mellor, J. W. (2017). Agricultural Development and Economic Transformation. In Journal of Farm Economics (Vol. 49, Issue 2). Springer International Publishing. https://doi.org/10.1007/978-3-319-65259-7.

Minoli, S., Müller, C., Elliott, J., Ruane, A. C., Jägermeyr, J., Zabel, F., Dury, M., Folberth, C., François, L., Hank, T., Jacquemin, I., Liu, W., Olin, S., & Pugh, T. A. M. (2019). Global response patterns of major rainfed crops to adaptation by maintaining current growing periods and irrigation. *Earth's Future, 7*(12), 1464–1480. https://doi.org/10.1029/2018EF001130.

Minten, B., & Barrett, C. (2008). Agricultural Technology, Productivity, and Poverty in Madagascar. World Development, 36(5), 797–822. https://econpapers.repec.org/RePEc:eee:wdevel:v:36:y:2008:i:5:p:797-822

Naidoo, R., & Ricketts, T. H. (2006). Mapping the economic costs and benefits of conservation. *PLoS Biology, 4*(11), e360. https://doi.org/10.1371/journal.pbio.0040360.

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Seroa da Motta, R., Armijo, E., Castello, L., Brando, P., Hansen, M. C., McGrath-Horn, M., Carvalho, O., & Hess, L. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science, 344*(6188), 1118–1123. https://doi.org/10.1126/science:1248525.

Peterson, T. C., & Vose, R. S. (1997). An overview of the global historical climatology network temperature database. *Bulletin of the American Meteorological Society, 78*(12), 2837–2849. https://doi.org/10.1175/1520-0477(1997)078<2837:AOOTGH>2.0.CO;2.

Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature Communications, 6*(1), 5989. https://doi.org/10.1038/ncomms6989.

Richards, P., Arima, E., VanWey, L., Cohn, A., & Bhattarai, N. (2016). Are Brazil's deforesters avoiding detection?. *Conservation Letters, 10*(4), 470–476. https://doi.org/10.1111/conl.12310.

Richards, P. D., Walker, R. T., & Arima, E. Y. (2014). Spatially complex land change: The indirect effect of Brazil's agricultural sector on land use in Amazonia. Global Environmental Change, 29(October 2020), 1–9. https://doi.org/10.1016/j.gloenvcha.2014.06.011.

Richards, P., Pellegrina, H., VanWey, L., Spera, S., & Lightfoot, D. A. (2015). Soybean development the impact of a decade of agricultural change on urban and economic growth in Mato Grosso, Brazil. *PLoS ONE, 10*(4), e0122510. https://doi.org/10.1371/journal.pone.0122510.

Roberts, M. J., Schlenker, W., & Eyer, J. (2013). Agronomic weather measures in econometric models of crop yield with implications for climate change. *American Journal of Agricultural Economics, 95*(2), 236–243. https://doi.org/10.1093/ajae/aas047.

Rochedo, P. R. R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, A. F. P., Koberle, A., Davis, J. L., Rajão, R., & Rathmann, R. (2018). The threat of political bargaining to climate mitigation in Brazil. *Nature Climate Change, 8*(8), 695–698. https://doi.org/10.1038/s41558-018-0213-y.

Rohde, R., Muller, R., Jacobsen, R., Perlmutter, S., & Mosher, S. (2013). Berkeley earth temperature averaging process. *Geoinformatics & Geostatistics: An Overview, 01*(02). https://doi.org/10.4172/2327-458110.4172/2327-4581.1000103.

Sacks, W. J., Deryng, D., Foley, J. A., & Ramankutty, N. (2010). Crop planting dates: An analysis of global patterns. *Global Ecology and Biogeography, 19*(5), 607–620. https://doi.org/10.1111/j.1466-8238.2010.00551.x.

Salazar, A., Baldi, G., Hirota, M., Syktus, J., & McAlpine, C. (2015). Land use and land cover change impacts on the regional climate of non-Amazonian South

America: A review. *Global and Planetary Change, 128*, 103–119. https://doi.org/10.1016/j.gloplacha.2015.02.009.

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences, 106*(37), 15594–15598. https://doi.org/10.1073/pnas.0910618106.

Serna-Chavez, H. M., Schulp, C. J. E., Van Bodegom, P. M., Bouten, W., Verburg, P. H., & Davidson, M. D. (2014). A quantitative framework for assessing spatial flows of ecosystem services. *Ecological Indicators, 39*(April), 24–33. https://doi.org/10.1016/j.ecolind.2013.11.024.

Silvério, D. V., Brando, P. M., Macedo, M. N., Beck, P. S. A., Bustamante, M., & Coe, M. T. (2015). Agricultural expansion dominates climate changes in southeastern Amazonia: The overlooked non-GHG forcing. *Environmental Research Letters, 10*(10), 104015. https://doi.org/10.1088/1748-9326/10/10/104015.

Soares-Filho, B., Rajao, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., & Alencar, A. (2014). Cracking Brazil's Forest Code. *Science, 344*(6182), 363–364. https://doi.org/10.1126/science.1246663.

Soares-Filho, B., Rajão, R., Merry, F., Rodrigues, H., Davis, J., Lima, L., Macedo, M., Coe, M., Carneiro, A., Santiago, L., & Mertens, F. (2016). Brazil's Market for Trading Forest Certificates. *PlosOne, 11*(4), e0152311. https://doi.org/10.1371/journal.pone.0152311.

Soterroni, A. C., Mosnier, A., Carvalho, A. X. Y., Câmara, G., Obersteiner, M., Andrade, P. R., Souza, R. C., Brock, R., Pirker, J., Kraxner, F., Havlík, P., Kapos, V., zu Ermgassen, E. K. H. J., Valin, H., & Ramos, F. M. (2018). Future environmental and agricultural impacts of Brazil's Forest Code. *Environmental Research Letters, 13*(7), 074021. https://doi.org/10.1088/1748-9326/aaccbb.

Soterroni, A. C., Ramos, F. M., Mosnier, A., Fargione, J., Andrade, P. R., Baumgarten, L., Pirker, J., Obersteiner, M., Kraxner, F., Câmara, G., Carvalho, A. X. Y., & Polasky, S. (2019). Expanding the Soy Moratorium to Brazil's Cerrado. *Science Advances, 5*(7), eaav7336. https://doi.org/10.1126/sciadv.aav7336.

Souza, C. M., Shimbo, J. Z., Rosa, M. R., Parente, L. L., Alencar, A., Rudorff, B. F. T., ... Azevedo, T. (2020). Reconstructing three decades of land use and land cover changes in Brazilian Biomes with landsat archive and earth engine. *Remote Sensing, 12*(17), 2735. https://doi.org/10.3390/rs12172735.

Spera, S. A., Galford, G. L., Coe, M. T., Macedo, M. N., & Mustard, J. F. (2016). Land-use change affects water recycling in Brazil's last agricultural frontier. *Global Change Biology, 22*(10), 3405–3413. https://doi.org/10.1111/gcb.13298.

Strand, J., Soares-Filho, B., Costa, M. H., Oliveira, U., Ribeiro, S. C., Pires, G. F., Oliveira, A., Rajão, R., May, P., van der Hoff, R., Siikamäki, J., da Motta, R. S., & Toman, M. (2018). Spatially explicit valuation of the Brazilian Amazon Forest's Ecosystem Services. *Nature Sustainability, 1*(11), 657–664. https://doi.org/10.1038/s41893-018-0175-0.

Strassburg, B. B. N., Brooks, T., Feltran-Barbieri, R., Iribarrem, A., Crouzeilles, R., Loyola, R., Latawiec, A. E., Oliveira-Filho, F. J. B., de M. Scaramuzza, C. A., Scarano, F. R., Soares-Filho, B., & Balmford, A. (2017). Moment of truth for the Cerrado hotspot. Nature Ecology and Evolution, 1(0099). https://doi.org/doi.org/10.1038/s41559-017-0099.

Suarez-Gutierrez, L., Müller, W. A., Li, C., & Marotzke, J. (2020). Hotspots of extreme heat under global warming. *Climate Dynamics, 55*(3–4), 429–447. https://doi.org/10.1007/s00382-020-05263-w.

Tack, J., Barkley, A., & Hendricks, N. (2017). Irrigation offsets wheat yield reductions from warming temperatures. *Environmental Research Letters, 12*(11), 114027. https://doi.org/10.1088/1748-9326/aa8d27.

Timko, J., Le Billon, P., Zerriffi, H., Honey-Rosés, J., de la Roche, I., Gaston, C., Sunderland, T. C., & Kozak, R. A. (2018). A policy nexus approach to forests and the SDGs: Tradeoffs and synergies. *Current Opinion in Environmental Sustainability, 34*(October), 7–12. https://doi.org/10.1016/j.cosust.2018.06.004.

United States Department of Agriculture., & Foreign Agricultural Service. (2018). Oil seeds: World Markert and Trade. https://apps.fas.usda.gov/psdonline/circulars/oilseeds.pdf.

VanWey, L. K., Spera, S., de Sa, R., Mahr, D., & Mustard, J. F. (2013). Socioeconomic development and agricultural intensification in Mato Grosso. *Philosophical Transactions of the Royal Society B: Biological Sciences, 368*(1619), 20120168. https://doi.org/10.1098/rstb.2012.0168.

Wan, Z., Zhang, Y., Zhang, Q., Li, Z., & Liang (2002). Validation of the land-surface temperature products retrieved from terra moderate resolution imaging spectroradiometer data. *Remote Sensing of Environment, 83*(1–2), 163–180. https://doi.org/10.1016/S0034-4257(02)00093-7.

Wessel, P., & Smith, W. H. F. (1996). A global, self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research, 101*(B4), 8741–8743. https://doi.org/10.1029/96JB00104.

Wilson, L. T., & Barnett, W. W. (1983). Degree-days: An aid in crop and pest management. *California Agriculture, 37*(1), 4–7.

Winckler, J., Reick, C. H., & Pongratz, J. (2017). Robust identification of local biogeophysical effects of land-cover change in a global climate model. *Journal of Climate, 30*(3), 1159–1176. https://doi.org/10.1175/JCLI-D-16-0067.1.

Xavier, A. C., King, C. W., & Scanlon, B. R. (2016). Daily gridded meteorological variables in Brazil (1980–2013). *International Journal of Climatology, 36*(6), 2644–2659. https://doi.org/10.1002/joc.2016.36.issue-610.1002/joc.4518.

Zalles, V., Hansen, M. C., Potapov, P. V., Stehman, S. V., Tyukavina, A., Pickens, A., Song, X.-P., Adusei, B., Okpa, C., Aguilar, R., John, N., & Chavez, S. (2019). Near doubling of Brazil's intensive row crop area since 2000. *Proceedings of the National Academy of Sciences, 116*(2), 428–435. https://doi.org/10.1073/pnas.1810301115.

Zemp, D. C., Schleussner, C.-F., Barbosa, H. M. J., Hirota, M., Montade, V., Sampaio, G., Staal, A., Wang-Erlandsson, L., & Rammig, A. (2017). Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature Communications, 8*(1), 14681. https://doi.org/10.1038/ncomms14681.

Zeppetello, L. R. V., Parsons, L. A., Spector, J. T., Naylor, R. L., Battisti, D. S., Masuda, Y. J., & Wolff, N. H. (2020). Large scale tropical deforestation drives extreme warming. *Environ. Res. Lett., 15*(8), 084012. https://doi.org/10.1088/1748-9326/ab96d2.

Zilli, M., Scarabello, M., Soterroni, A. C., Valin, H., Mosnier, A., Leclère, D., Havlík, P., Kraxner, F., Lopes, M. A., & Ramos, F. M. (2020). The impact of climate change on Brazil's agriculture. *Science of The Total Environment, 740*, 139384. https://doi.org/10.1016/j.scitotenv.2020.139384.

Zscheischler, J., Westra, S., Van Den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., Aghakouchak, A., Bresch, D. N., Leonard, M., Wahl, T., & Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change, 8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3.