Communications Earth & Environment https://doi.org/10.1038/s43247-025-03172-6

Article in Press

High profits from soybean-corn agriculture are associated with increased land prices and deforestation rates in Mato Grosso's Amazon forests

Received: 28 April 2025

Accepted: 19 December 2025

Richards Peter & Eugenio Arima

Cite this article as: Peter, R., Arima, E. High profits from soybean-corn agriculture are associated with increased land prices and deforestation rates in Mato Grosso's Amazon forests. *Commun Earth Environ* (2026). https://doi.org/10.1038/s43247-025-03172-6

ANALYSIS

Main Manuscript for

High profits from soybean-corn agriculture are associated with increased land prices and deforestation rates in Mato Grosso's Amazon forests.

Richards, Peter[a] and Eugenio Arima[b]

1. Peter Richards*

   [a]Office of the Chief Economist, United States Department of Agriculture, Washington D.C., USA. The findings and conclusions in this article are those of the authors and do not represent any official U.S. Department of Agriculture or U.S. government determination or policy.

   Email: peter.richards@usda.gov; peter.richards.d@gmail.com

2. Eugenio Arima

   [b]Department of Geography and the Environment, University of Texas, Austin, Texas

   Email: arima@austin.utexas.edu

Competiting Interests

The authors declare no competing interests.

Author Contributions:

PR conceptualized, designed and wrote much of this manuscript; EA contributed significantly to research design and provided expert guidance on approach.

Classification: Sustainability Science

Keywords: Ethanol, Indirect Land Use Change, Brazilian Amazon, Deforestation

This PDF file includes:

Main Text
Figures 1 to 5

* *Corresponding Author*

Abstract

Land clearing in the Brazilian Amazon is strongly influenced by the economics of farming at the forest frontier. Here we examine how rising profits from second-season corn, grown after soybeans, may increase pressure on forests in the state of Mato Grosso. We assemble detailed annual data on crop prices, yields, production costs, land values, and forest loss, and construct measures of both per-hectare farm profits and total regional profits. Using statistical models designed to separate the effects of expected returns from the effects of profit-driven expansion, we show that increases in farm profits raise land prices and are followed by higher levels of forest clearing. These effects persist for several years after a shift in profits. Our results suggest that expanding corn-based ethanol production in frontier regions can indirectly increase deforestation by making farming more profitable, which in turn fuels land speculation and encourages the clearing of new land.

Introduction

Global emissions from land-use change are disproportionately driven by the burning and clearing of humid tropical forests and the draining of carbon-rich peatlands.[1,2] Past research has raised concerns that the loss of tropical forests and peatlands may be driven *indirectly* by demand for biofuels.[3–8] For decades, these concerns rested on the premise that price signals originating in established agricultural regions, such as the U.S. Corn Belt or the sugarcane fields of São Paulo, influenced land clearing decisions in carbon-rich landscapes such as Brazil's Amazon and Cerrado. These concerns led to efforts to account for indirect land use change (ILUC) in biofuel regulations.[9,10]

Until 2017, when Brazil opened its first ethanol refinery designed specifically for processing corn in Lucas do Rio Verde, Mato Grosso, nearly all of the world's ethanol was produced in the U.S. Midwest or southeastern Brazil. Nearly all land suitable for farming in both regions had already been cleared and brought into production, and neither was a major source of emissions from land-use change in the 21st century. However, in concept, global price signals created a bridge between biofuel demand in established regions and land clearing in carbon-rich frontiers.

Biofuel production in carbon-rich frontiers itself raises a new dilemma in the biofuel sector. Producing biofuels in or in proximity to areas of active land use conversions likely creates new risks for forest loss, by influencing markets more directly connected with land clearing decisions. Unlike earlier concerns focused on global price signals, frontier production directly alters regional land and capital markets, which have been directly linked to tropical deforestation.

Nearly all of Brazil's corn ethanol is produced in three states: Mato Grosso, Goiás and Mato Grosso do Sul (Figures 1a-1b). Land continues to be cleared in these states, with newly cleared land often stocked with cattle or used for agriculture. These states are also important source regions for emissions from land use change. Producing biofuels in or in proximity to areas of active land use conversions raises new risks for forest loss.

In this article we argue that corn ethanol production in Mato Grosso may drive forest loss *indirectly*, to the extent that *safrinha* corn serves as an important driver of farm profitability. More specifically, we show that (i) the economic value generated by *safrinha* corn in Mato Grosso has grown over the past decade; that (ii) land markets, widely associated with land clearing decisions in the Amazon,[11–13] are closely linked to agricultural profits; and that (iii) deforestation in Mato Grosso's Amazon region is partially explained by changes in profitability.

Corn Profits and Deforestation in the Amazon

Brazil is the world's fourth largest corn producer and one of two leading corn exporters, globally. Most of Brazil's corn is produced in the country's Center-West region (consisting of Mato Grosso, Mato Grosso do Sul and Goiás), where it is grown as a *safrinha* crop, a second-season planting that follows the main soybean harvest. In 2025, 83 percent of Brazil's corn was projected to be produced as a *safrinha* crop.[14] Approximately one-half of Brazil's *safrinha* corn is grown in Mato Grosso.

In a soybean-*safrinha* corn system, soybeans are planted at the start of the rainy season, typically in September or October, and harvested in January or February. Corn is then planted immediately following the soybean harvest, grown through the end of the rainy season, and harvested early in the dry season, in May or June, when humidity is low.[23,24] This intensive planting rotation, where two highly productive crops are grown in succession within a single growing season, requires both an extended warm period and abundant precipitation (conditions are widely associated with humid tropical forest regions). Farmers in

Brazil's interior, which is or was home to vast tracts of humid tropical forest, now harness these conditions for a highly intensive agricultural rotation.

Until relatively recently, *safrinha* corn was of secondary economic importance to soybeans for many farmers. Subject to drought risk, and with markets for corn in Brazil's interior limited (where climatic conditions were most favorable for the *safrinha* corn harvest), safrinha corn was once valued as much for its stover as its market potential. Many farmers invested little (relative to soybeans) in its production. Yields, as a result, were often low. Since 2010, however, yields to *safrinha* crop corn have increased, reflecting both greater investments in fertilizer and planting, and the development of seed and management technologies better suited for planting as a *safrinha* crop.

Between 2000 and 2010, and then 2011 and 2020, *safrinha* corn yields increased from 3 to 5t/ha in Brazil, and 3.5 to 5.5t/ha in Mato Grosso Yields have continued to increase, and corn yields in Mato Grosso, the highest for *safrinha* corn in Brazil, now approach 7t/ha.[14]

Profits from safrinha corn relative to soybeans have also increased. In Mato Grosso, we estimate that profits from *safrinha* corn equate to approximately 80 percent of profits from soybeans, or about 40–45 percent of the total joint profits from a soybean-*safrinha* corn planting cycle (Figure 2).[25]

Ethanol refineries provide a stable, local, and year-round demand source for corn. Rather than shipping corn or corn-fed poultry abroad over limited infrastructure, farmers may send their corn to a local refinery. This is particularly important for farmers in Brazil's interior states, such as Mato Grosso. There, climatic conditions may be most suited for farming *safrinha* corn, but farmers are also located farthest from ports or markets on Brazil's coast. This combination of highly productive farmlands in the humid tropics and high transportation costs is likely attractive for the ethanol sector. Ethanol refiners here benefit not only from an abundant supply of corn, but also from corn sold at lower prices than in other regions in Brazil.

In 2024, Brazil produced 7 billion liters of corn ethanol. Mato Grosso alone produced 5 billion liters of corn ethanol. Assuming that 400 liters of ethanol are produced per ton of corn, this implies that approximately 17.5m tons of corn were refined for ethanol across Brazil, and 12.5m tons in Mato Grosso that year. This equates to approximately 15 percent of Brazil's 2024 corn harvest, and 26 percent of Mato Grosso's.

While the precise impact of corn ethanol markets in Brazil on corn prices remains unclear, research on the impact of biofuel demand on corn prices in the U.S. suggest that ethanol markets meaningfully raise corn prices.[4,15] We assume that these markets have positively influenced corn prices and land use in Brazil, and in particular in Mato Grosso. We also recognize that past research has widely tied agricultural expansion and agricultural profits to with forest loss in central Brazil, and in Mato Grosso, specifically.[16,17]

Agricultural expansion and higher profits from agriculture increase the demand for land, and accelerate appreciation in rural land markets. Appreciation in rural land markets incentivizes and rewards land speculation, widely identified as an important driver of land use change, including in Brazil's Amazon region.[11,18] Agricultural profits drive appreciation in rural land markets by increasing expected profits from land, and by increasing the rural capital base for land purchases.[19,20] In Figure 3, we show that real values for rural land in Mato Grosso increased in the early 2010s with the growth of *safrinha* corn as an important capital source (e.g., Figure 2b), and in 2021-2023, presumably in response to the increase in per hectare and sector-level profitability that occurred concurrently during these years.

Results

To identify the relationship between agricultural profits, land prices and deforestation, we first decompose profits into the two components through which they affect land clearing decisions: (i) net profits per hectare, which serves as a proxy for expected future profits from land, and (ii) total sector profits generated from soybeans and *safrinha* corn (net profits multiplied by harvested area), which acts as a measure of the rural capital base available for re-investment after a growing season. Both measures are derived from our cost and return data for soybeans and safrinha corn and described in detail in the supplemental information (see SI tables S.1-S.2).

To isolate the independent influence of each channel, we first regressed sector-level profits on per-hectare profits and estimated the residuals. The residuals represent the effect of sector level profits (a proxy measure of regional investment capital) not explained by changes in per hectare profits. We then estimated the effects of both per-hectare profits and the estimated residuals on land prices and deforestation (see methods).

We find that sector level profits from soybean-*safrinha* corn agriculture are associated with upward pressure on land values in Mato Grosso (Figure 4). A one-percent rise in sector-level profits increased cropland prices by 0.48 percent ($p < 0.01$) and a 0.27 percent increase in pastureland prices ($p < 0.05$). We also find that each one percent increase in sector profits was associated directly with a 1.26 percent increase in forest loss in Mato Grosso's Amazon ($p < 0.05$). Net per-hectare profits also correlate positively with land prices and deforestation, though less strongly than sector-level profits. Estimates are consistent with findings that land markets are driven by rural capital markets, where capital availability is driven by the relative profit surplus generated by the agriculture sector in a growing season.[19,20]

Next, we estimated the influence of sector level soybean-*safrinha* corn profits on deforestation in Mato Grosso's Amazon region. Here we use a finite distributed lag (FDL) model, which reflects our assumption that deforestation in response to a profitability shock occurs over multiple years. Our estimates suggest that each R$1 billion (adjusted to 2024 values, equivalent to approximately 190m $US) increase in year-to-year soybean and *safrinha* corn profits was associated with 11.9 to 13.4 km² of additional Amazon forest loss, distributed over a three-year period.

Finally, to isolate the role of corn profits on deforestation, we compared predicted deforestation outcomes from the FDL model using actual sector profits (soybean + *safrinha* corn) against a counterfactual scenario in which sector profits reflected profits from soybean only. Using this framework, we estimated that the additional profits from *safrinha* corn contributed to approximately 343-390km² of Amazon forest loss in Mato Grosso between 2010 and 2024, or approximately 1.5 percent of all deforestation in the region during that period. However, the profitability spike in *safrinha* corn production likely had an important impact on forest loss in more recent years, as the economic importance of corn has grown. For Notably, we estimate that the increase in profits from *safrinha* corn associated with the 2020 and 2021 harvests were associated with 320-340km² of forest loss in Mato Grosso's Amazon region, or eight percent of forest loss observed during those years (Figure 5).

Discussion

Previous research has suggested that higher demand for biofuel feedstocks in mature agricultural regions may contribute to higher prices for food crops, and raised concerns that greenhouse gas emissions savings from biofuels could be offset by the clearing of carbon rich forests in other regions.[3,21–23] In this article, recognizing that the Amazon and Cerrado regions are now not only major source regions for emissions, but also important biofuel producing regions in their own right, we consider the impact of net returns to *safrinha* corn in these regions on land markets and forest loss.

We find that land markets and deforestation rates in Brazil's Mato Grosso state are closely associated with changes in the profitability of soybean-*safrinha* corn agriculture. We also find that sector level profits from soybean and *safrinha* corn, a measure of rural capital availability, are closely associated with changes rural land markets and forest loss trends. Rising land values both incentivize and reward speculation, long viewed as an important driver of land use change in the Amazon and other tropical frontiers.[11,12,24–27]

Our results build on a robust body of work identifying the market linkages that connect established agricultural regions with areas of active land use change, whether globally[3,22,28–30] , or within Brazil, specifically.[31–35] They also build on and draw from recent work identifying the importance of spatial spillovers associated with agricultural expansion, particularly through land markets.[5,19,36–38]

Research from the U.S. has shown that land conversion risks increase near biofuel refineries.[39–41] If land conversion risks increase similarly near biofuel refineries in the Amazon, which is home to vast tracts of carbon rich forests, then it is likely that producing ethanol in these regions leads to greater emissions from land use change than producing ethanol elsewhere. Similarly, if corn ethanol demand is improving the profitability of agriculture in proximity to clearable forests, then it is likely creating conditions that foster appreciation in rural land markets, and supporting speculative deforestation. This raises new concerns over the relationship between biofuels and forest loss, including that ethanol markets may contribute indirectly to speculative deforestation.[42–44] As ethanol markets evolve, understanding localized land use feedbacks, such as through land markets, will be critical to aligning climate mitigation goals with land governance and biodiversity protection.

Improving local productivity in Brazil has widely been framed as a strategy to reduce forest loss in the Amazon.[35–37] *Safrinha* corn, as a second crop, represents a form of intensification in the Amazon with the potential to reduce land demand. However, intensification in the Amazon has often been associated with forest clearing, precisely because higher profits without constraints to expansion often lead to an expansion of production areas.[30,31,35,45,46] Absent adequate protections for forests- and not only protections against agriculture expanding at their expense- intensification is likely to continue to increase the loss of forests, not spare it. Problematically, because the soybean-*safrinha* corn double harvest depends heavily on an extended growing season and abundant precipitation, this creates perverse incentives to expand production in Brazil's more humid tropical regions- regions that are, or once were, tropical forests.[16,38,42,52,53]

As a second-season crop, *safrinha* corn is highly sensitive to the timing and length of the rainy season. Studies suggest that the rainy season in Mato Grosso has shortened in recent decades, likely due to the loss of natural forest cover.[47] Rising temperatures, particularly at nighttime, and a compressed growing window may reduce *safrinha* yields in the future[48] and projections suggest that by mid-century, suitable areas for double-cropping in Mato Grosso may decline by 15 to 20 percent in the absence of technological breakthroughs.[49] These climatic shifts may push producers to expand into more humid, carbon-rich forest lands perceived as more suitable for harvesting multiple crops per year.

Global demand for biofuels could triple by 2050.[50] Sustainable aviation fuel (SAF) demand alone could rise from 100 million liters today to 44 billion liters by mid-century.[50] Within Brazil, mandates for higher blending rates for ethanol in gasoline (30 percent) and for crop-based diesel (15 percent), will also increase biofuel demand. Biofuels have the potential to greatly reduce greenhouse gas emissions, and decarbonize hard-to-abate sectors. However, realizing that potential will require minimizing the land use change associated with the production of biofuel feedstocks. Sourcing biofuels directly from farms operating at the margins of carbon rich forests such as the Amazon will raise concerns that biofuel production itself may contribute to tropical deforestation and emissions from land use change. To ensure that biofuels produced in proximity to areas of active land use change are not leading to additional forest loss, biofuel incentives should be coupled with strengthened protections for regional forest cover that ensure that biofuel expansion complements, rather than undermines, environmental objectives.

Methods:

Prior research has quantified regional ILUC effects associated with soybean expansion in Brazil. Arima et al. (2011) estimated that a 10% reduction in soybean expansion could have reduced forest loss in heavily forested municipalities by up to 40%. Richards et al. (2014) attributed roughly one-third of Brazil's anthropogenic forest loss from 2002–2011 to the indirect effects of soybean cultivation. More recently, Kuschnig et al. (2021) found that in 2017, approximately three-quarters of forest loss in Mato Grosso was indirectly linked to cropland, with nearly eight hectares of forest cleared for every new hectare of soybean agriculture. We build on this past work by identifying indirect effects not only with soybean agriculture, but with the now widely applied soybean-*safrinha* corn system.

Our estimation framework assumes three potential land uses: cropland, cleared land (e.g., pasture), and uncleared land (e.g., intact forest). Each generates economic value either through current production or anticipated capital gains. Cropland yields both crop income and appreciation in land value, reflecting expectations of sustained profitability. Cleared land may support pasture or cattle production, though in frontier areas such activities often yield little or even negative return. Maintaining cattle may instead serve to demonstrate "productive use" and strengthen property claims.[12] The value of cleared land thus derives from its potential conversion to cropland and its role in formalizing ownership. Its price tends to rise near profitable cropland, since expectations of future returns and access to capital are spatially correlated: when nearby farming is lucrative, capital costs fall as farmers reinvest profits into new land, for example. Speculators or ranchers who sell profitably may likewise reinvest in additional properties, hoping for future.[51] Forested (uncleared) land has little productive value but retains speculative value through its potential conversion to cropland.

Within the above framework, land-use change can be viewed as the outcome of relative returns and clearing risks across these three asset types. When expected profits from agriculture rise, both the rental value of productive land and the capital value of cleared and uncleared land increase. Higher crop profitability attracts investment into land markets, particularly in regions where land conversion remains possible. Farmers with accumulated profits may expand holdings, while speculators purchase land in anticipation of further appreciation. In this way, profitability shocks in the agricultural sector translate into land clearing through both a rent effect, reflecting higher expected returns to production, and an investment effect, driven by greater availability of capital for land acquisition and conversion. The magnitude of these effects depends on local credit conditions, property rights institutions, and proximity to existing agricultural production.

To estimate the effect of agricultural profits, and by extension, the effect of profits from *safrinha* corn, we focus on two sets of analyses. First, we estimate the relative effect of changes in net per hectare profits vs. net sector profits on changes in land prices, and on Amazon deforestation in Mato Grosso. Second, drawing on work by Richards and Arima (2018), we use a finite distributed lag model to estimate the effect of changes in net sector profitability on deforestation. This latter approach treats changes in the sum of agricultural profits from soybeans and corn (e.g., net sector profits) as a proxy for new capital for investment. Implicitly, here we acknowledge that historical inflation and high borrowing costs in Brazil increase incentives for reinvesting liquid capital into land or productive assets such as infrastructure or farm machinery.[63–67] When total (not necessarily per hectare) returns are higher than in previous years, farmers have more cash available to invest in land purchases, clearing, and infrastructure, which effectively reduces capital constraints, increases investment activity, and accelerates land clearing (which we view as a form of investment). Conversely, when returns are less than in previous years, investment capital is scarce and acts as a brake on forest loss. We further assume that the effects of agricultural returns on deforestation are not immediate. Instead, these effects unfold over several years as investments are made, markets adjust, and displaced operations or speculators identify new opportunities.

Profits, Land Markets and Forest Loss

Land markets reflect both the expected net present value of returns from land and the cost of capital. We use year-to-year changes in net per-hectare profits in Mato Grosso as a proxy for changes in the expected net present value of cropland. We use year-to-year changes in net sector profits (i.e., per-hectare profits from soybeans and *safrinha* corn multiplied by their respective harvested areas in Mato Grosso) as an indicator of changes in capital availability. We refer to the effect of expected net per-hectare profits as the land rent effect, and the effect of sector-level capital as the investment effect. Our use of the term "rent" follows conventions in land economics, where land rents represent the residual returns to land.[52–56]

Sector-level profits are mechanically related to per-hectare profits. However, we can assess the distinct influence of these effects through a two-step orthogonalized regression that residualizes sector-level profits with respect to per-hectare returns. This approach follows the Frisch–Waugh–Lovell (FWL) theorem.[57,58]

In the first stage, we regress year-to-year changes in the log of net sector profits (I_t) on changes in the log of net per hectare profits (R_t) to remove the component of sector-level profits explained by returns.

$$I_t = \gamma_0 + \gamma_1 R_t + u_t \tag{1}$$

where, u_t represents the component of net sector profits orthogonal to R_t. Because we estimate this regression on first-differenced time-series data, $u_t$varies across years, capturing year-specific deviations in sector-level profits unrelated to per-hectare returns, our proxy for the investment or capital-availability effect. γ_0 and γ_1 are additional coefficients to be estimated.

In the second stage, for each land use type $l \in$ *{Amazon Forest, Pastureland, and Cropland}*, we regress year-to-year changes in the log of land price (L_{lt}) on R_t and u_t:

$$L_{lt} = \beta_{0l} + \beta_{1l} R_t + \beta_{2l} u_t + \varepsilon_{lt} \tag{2}$$

Separately, for year-to-year changes in the log of Amazon deforestation in Mato Grosso, D_t, we estimate:

$$D_t = \delta_0 + \delta_1 R_t + \delta_2 u_t + \eta \tag{3}$$

The coefficients β_{1l} and δ_1 capture the land rent effect associated with changes in net per hectare profits, while β_{2l} and δ_2 capture the investment effect associated with net sector profits, after removing the mechanical co-movement between sector-level profits and per hectare profits.

Before estimation, we conducted unit root and cointegration tests for all key variables over the 2001–2024 period. Augmented Dickey–Fuller tests indicated non-stationarity in level form, but suggested stationarity in first differences (Tables S.3, S.4). Co-integration tests applied to residuals from bivariate regressions revealed limited evidence of cointegration among first differenced observations. This suggests that while changes in land prices, per-hectare profits, sector-level capital, and deforestation may co-move in the short run, they are not governed by stable long-run equilibrium relationships (Table S.5).

Given the non-stationarity of variables in levels and their stationarity in first differences, we estimate equations (1-3) using first differences, or changes in the logged-transformed variables. Log transformation allows for consistent estimation of short-term responsiveness, avoids spurious correlation due to trending series, and aligns with the stationarity properties of our data. We estimate the differenced specifications to reduce spurious correlation and to interpret short-run elasticities of deforestation and land values with respect to profitability shocks.

Our estimates suggest that- since 2001- each one percent increase in the change in net per hectare profits (the rent effect) was associated with a 0.16 percent increase in cropland prices, a 0.11 percent increase in pasture prices, and a 0.25 percent increase in deforestation (Table S.6). These effects are significant and positive. However, they are outweighed by the effects associated with 'investment' (net sector profits independent from net per hectare profits). We estimate that each one percent change in the residuals associated with changes in net sector profits (the investment effect) effect was associated with a 0.47 percent increase in cropland prices and a 0.27 percent increase in pasture prices (Figure 4).

For deforestation, we find that changes in capital availability (the investment effect) are associated with an impact approximately five times greater than that of changes in net per-hectare profits. These findings are consistent with arguments that land valuation and clearing may be driven more by capital flows and speculative investment than by expected agricultural returns.

Fixed Distributed Lag Model and Predicted Effects

To isolate the effect of *safrinha* corn on deforestation via its contribution to investment capital, we estimated the relationship between changes in sector-level agricultural profits from a soybean-*safrinha* corn system and changes forest loss. Here, we utilized a finite distributed lag (FDL) model to allow profits shocks from a single year to affect multiple years of clearing decisions. This model structure acknowledges that capital-intensive actions (land purchases, infrastructure purchases and installations, land clearing), are likely to unfold only over multiple years.

We restrict this analysis to 2010-2024, reflecting changes in environmental governance of Brazilian forests in the late 2000s and the post-2009 transformation and expansion of *safrinha* corn.

Here we let D_t denote the change in Amazon deforestation (in square kilometers) in year *t* and I_t the change in sector profits (in billions of reais, the Brazilian currency).

We write the FDL as:

$$D_t = \alpha + \theta I_t + \Phi I_{t-1} + \Psi I_{t-2} + P_t + \varepsilon_t \tag{4}$$

Where P_t is an indicator for changes in governance after 2016 ($P_t = 1 \; for \; t > 2016$).

Given stochastic trends in both deforestation and sector profits (Tables S.3–S.4), we estimate equation (4) in first differences and report Newey–West standard errors to address heteroskedasticity and autocorrelation. The distributed lag terms (θ, ϕ, ψ) capture the dynamic response to a profit shock over three years, beginning in the year that profits are received. Coefficients are interpretable as marginal effects associated with a 1 billion $Rs change (real values, adjusted to 2024 values) in sector profits on changes in deforestation in square kilometers. Estimated results are included in the Table S.7. Brazilian farmers typically harvest soybeans and *safrinha* corn within the first six months of the year, suggesting that initial investment responses may occur within the same year that a harvest is collected.

We generated counterfactual predictions by replacing the change in combined sector level soybean and *safrinha* corn profits with changes in profits associated with only soybeans while holding the model coefficients fixed. We then attributed the difference between the baseline prediction and the "no-corn" (soybean-only) prediction to profitability changes associated with *safrinha* corn (e.g. Figure 5). Full model results are included in Tables S.8 and S.9.

Data Availability Statement

We used six primary datasets in this analysis. These data cover: commodity prices[59] (S&P Global), production costs[60,61] (CONAB), crop yields and area[14,62] (CONAB), deforestation[63] (INPE-PRODES), land values by use type[64] (S&P Agribusiness / ANUALPEC), and corn ethanol production statistics[65] (CONAB). All data were harmonized to the annual level, with prices and costs deflated to constant Q2 2024 values using Brazil's GDP deflator[66] (NGDPDSAIXBRQ). Detailed descriptions of each dataset, deflation procedures, and variable construction are provided in the Supplementary Information. Additional information on data sources and construction are included in supplemental information (SI). All data are publicly available.

References

1. Gibbs, H. K. *et al.* Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences* 107, 16732–16737 (2010).

2. Houghton, R. A. *et al.* Carbon emissions from land use and land-cover change. *Biogeosciences* 9, 5125–5142 (2012).

3. Searchinger, T. *et al.* Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science (1979)* 319, 1238–1240 (2008).

4. Lark, T. J. *et al.* Environmental outcomes of the US renewable fuel standard. *Proceedings of the National Academy of Sciences* 119, e2101084119 (2022).

5. Lapola, D. M. *et al.* Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences* 107, 3388–3393 (2010).

6. Zilberman, D. Indirect land use change: much ado about (almost) nothing. *Gcb Bioenergy* 9, 485–488 (2017).

7. Lambin, E. F. & Meyfroidt, P. Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* 108, 3465–3472 (2011).

8. Page, S. E., Rieley, J. O. & Banks, C. J. Global and regional importance of the tropical peatland carbon pool. *Glob Chang Biol* 17, 798–818 (2011).

9. Prussi, M. *et al.* CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. *Renewable and Sustainable Energy Reviews* 150, 111398 (2021).

10. Breetz, H. L. Regulating carbon emissions from indirect land use change (ILUC): US and California case studies. *Environ Sci Policy* 77, 25–31 (2017).

11. Miranda, J., Börner, J., Kalkuhl, M. & Soares-Filho, B. Land speculation and conservation policy leakage in Brazil. *Environmental Research Letters* 14, 045006 (2019).

12. Bowman, M. S. *et al.* Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production. *Land use policy* 29, 558–568 (2012).

13. Richards, P. D., Walker, R. T. & Arima, E. Y. Spatially complex land change: The indirect effect of Brazil's agricultural sector on land use in Amazonia. *Global Environmental Change* 29, (2014).

14. CONAB. *Séries Históricas Das Safras- Milho*. https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/safras/series-historicas/graos/milho (2024).

15. Carter, C. A., Rausser, G. C. & Smith, A. Commodity storage and the market effects of biofuel policies. *Am J Agric Econ* 99, 1027–1055 (2017).

16. Nepstad, D. *et al.* The end of deforestation in the Brazilian Amazon. *Science (1979)* 326, 1350–1351 (2009).

17. Morton, D. C. *et al.* Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences* 103, 14637–14641 (2006).

18. Pendrill, F. *et al.* Disentangling the numbers behind agriculture-driven tropical deforestation. *Science (1979)* 377, eabm9267 (2022).

19. Arima, E. Y., Richards, P. & Walker, R. T. Biofuel expansion and the spatial economy: implications for the Amazon Basin in the 21st century. *Bioenergy and land use change* 53–62 (2017).

20. Richards, P. & Arima, E. Capital surpluses in the farming sector and agricultural expansion in Brazil. *Environmental Research Letters* 13, 075011 (2018).

21. Arima, E., Barreto, P., Taheripour, F. & Aguiar, A. Dynamic Amazonia: The EU–mercosur trade agreement and deforestation. *Land (Basel)* 10, 1243 (2021).

22. Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P. Land clearing and the biofuel carbon debt. *Science (1979)* 319, 1235–1238 (2008).

23. Zhao, X., Taheripour, F., Malina, R., Staples, M. D. & Tyner, W. E. Estimating induced land use change emissions for sustainable aviation biofuel pathways. *Science of the Total Environment* 779, 146238 (2021).

24. Reydon, B. P., Fernandes, V. B. & Telles, T. S. Land governance as a precondition for decreasing deforestation in the Brazilian Amazon. *Land use policy* 94, 104313 (2020).

25. Laurance, W. F., Albernaz, A. K. M., Fearnside, P. M., Vasconcelos, H. L. & Ferreira, L. V. Deforestation in amazonia. *Science (1979)* 304, 1109–1111 (2004).

26. Hecht, S. B. The logic of livestock and deforestation in Amazonia. *Bioscience* 43, 687–695 (1993).

27. Campbell, J. M. Speculative accumulation: property-making in the Brazilian Amazon. *J Lat Am Caribb Anthropol* 19, 237–259 (2014).

28. Liu, J., Herzberger, A., Kapsar, K., Carlson, A. K. & Connor, T. What is telecoupling? *Telecoupling: Exploring land-use change in a Globalised World* 19–48 (2019).

29. Lambin, E. F. *et al.* The role of supply-chain initiatives in reducing deforestation. *Nat Clim Chang* 8, 109–116 (2018).

30. Hertel, T. W., West, T. A. P., Börner, J. & Villoria, N. B. A review of global-local-global linkages in economic land-use/cover change models. *Environmental Research Letters* 14, 053003 (2019).

31. Barretto, A. G. O. P., Berndes, G., Sparovek, G. & Wirsenius, S. Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975–2006 period. *Glob Chang Biol* 19, 1804–1815 (2013).

32. Goulart, F. F., Chappell, M. J., Mertens, F. & Soares-Filho, B. Sparing or expanding? The effects of agricultural yields on farm expansion and deforestation in the tropics. *Biodivers Conserv* 32, 1089–1104 (2023).

33. Barr, K. J., Babcock, B. A., Carriquiry, M. A., Nassar, A. M. & Harfuch, L. Agricultural Land Elasticities in the United States and Brazil. *Appl Econ Perspect Policy* 33, 449–462 (2011).

34. Hausman, C. Biofuels and Land Use Change: Sugarcane and Soybean Acreage Response in Brazil. *Environ Resour Econ (Dordr)* 51, 163–187 (2012).

35. Kaimowitz, D. & Angelsen, A. Will livestock intensification help save Latin America's tropical forests? *Journal of Sustainable Forestry* 27, 6–24 (2008).

36. Kuschnig, N., Cuaresma, J. C., Krisztin, T. & Giljum, S. Spatial spillover effects from agriculture drive deforestation in Mato Grosso, Brazil. *Sci Rep* 11, 21804 (2021).

37. Barona, E., Ramankutty, N., Hyman, G. & Coomes, O. T. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters* 5, 024002 (2010).

38. de Sá, S. A., Palmer, C. & Di Falco, S. Dynamics of indirect land-use change: empirical evidence from Brazil. *J Environ Econ Manage* 65, 377–393 (2013).

39. Li, Y., Miao, R. & Khanna, M. Effects of ethanol plant proximity and crop prices on land-use change in the United States. *Am J Agric Econ* 101, 467–491 (2019).

40. Brown, J. C. *et al.* Ethanol plant location and intensification vs. extensification of corn cropping in Kansas. *Applied Geography* 53, 141–148 (2014).

41. Wright, C. K., Larson, B., Lark, T. J. & Gibbs, H. K. Recent grassland losses are concentrated around US ethanol refineries. *Environmental Research Letters* 12, 044001 (2017).

42. Gurgel, A. C. *et al.* Contribution of double-cropped maize ethanol in Brazil to sustainable development. *Nat Sustain* https://doi.org/10.1038/s41893-024-01424-5 (2024) doi:10.1038/s41893-024-01424-5.

43. Colussi, J., Paulson, N., Schnitkey, G. & Baltz, J. Brazil Emerges as Corn-Ethanol Producer with Expansion of Second Crop Corn. *farmdoc daily* 13, (2023).

44. Moreira, M. M. R. *et al.* Socio-environmental and land-use impacts of double-cropped maize ethanol in Brazil. *Nat Sustain* 3, 209–216 (2020).

45. Merry, F. & Soares-Filho, B. Will intensification of beef production deliver conservation outcomes in the Brazilian Amazon? *Elem Sci Anth* 5, 24 (2017).

46. Garrett, R. D. *et al.* Intensification in agriculture-forest frontiers: Land use responses to development and conservation policies in Brazil. *Global Environmental Change* 53, 233–243 (2018).

47. Commar, L. F. S., Louzada, L., Costa, M. H., Brumatti, L. M. & Abrahão, G. M. Mato Grosso's rainy season: past, present, and future trends justify immediate action. *Environmental Research Letters* 19, 114065 (2024).

48. Spera, S. A., Winter, J. M. & Partridge, T. F. Brazilian maize yields negatively affected by climate after land clearing. *Nat Sustain* 3, 845–852 (2020).

49. Pires, G. F. *et al.* Increased climate risk in Brazilian double cropping agriculture systems: Implications for land use in Northern Brazil. *Agric For Meteorol* 228–229, 286–298 (2016).

50. IEA. *Renewables 2022*. (2022).

51. Almeida, A. L. O. de & Campari, J. S. *Sustainable Settlement in the Brazilian Amazon.* (1995).

52. Fujita, M. & Thisse, J. The von Thünen model and land rent formation. *Economics of agglomeration: cities, industrial location, and globalization* 59–98 (2013).

53. Dunn, E. S. The location of agricultural production. *(No Title)* (1954).

54. Alonso, W. Location and Land Use: Toward a general theory of land rent. *Harvard University Press google schola* 2, 16–22 (1964).

55. Walker, R. The impact of Brazilian biofuel production on Amazônia. in *The New Geographies of Energy* 228–237 (Routledge, 2013).

56. Walker, R. *et al.* Ranching and the new global range: Amazônia in the 21st century. *Geoforum* 40, 732–745 (2009).

57. Lovell, M. C. Seasonal adjustment of economic time series and multiple regression analysis. *J Am Stat Assoc* 58, 993–1010 (1963).

58. Frisch, R. & Waugh, F. V. Partial time regressions as compared with individual trends. *Econometrica* 387–401 (1933).

59. S&P. Soybean and Corn Cash Prices- Brazil. Preprint at https://connect.ihsmarkit.com/data-browser (2024).

60. CONAB. *Série Histórica - Custos - Soja - 1997 a 2024*. https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/custos-de-producao/arquivos-custo-de-producao/agricolas/serie-historica-custos-soja-1997-a-2024-1/view (2024).

61. CONAB. Série Histórica - Custos - Milho - 1997 a 2024. https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/custos-de-producao/arquivos-custo-de-producao/agricolas/milho/milho_2_safra_serie_historica_2005-2024.xls/view (2024).

62. CONAB. Séries Históricas das Safras- Soja. https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/safras/series-historicas/graos/soja (2024).

63. PRODES. Monitoramento do Desmatamento da Amazônia Brasileira por Satélite. *Instituto Nacional de Pesquisas Espaciais* Preprint at https://dados.gov.br/dados/conjuntos-dados/prodes (2024).

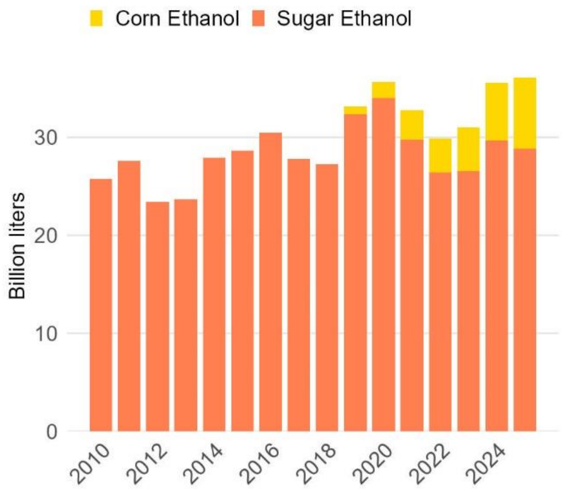
64. S&P. *Cropland Prices in Brazil*. *https://www.spglobal.com/commodityinsights/en/ci/products/agribusiness-brazil.html* https://www.spglobal.com/commodityinsights/en/ci/products/agribusiness-brazil.html (2024).

65. CONAB. Séries Históricas das Safras- Cana-de-Açúcar. https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/safras/series-historicas/cana-de-acucar/industria (2024).

66. IMF. Gross Domestic Product Deflator for Brazil. *Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/NGDPDSAIXBRQ* (2024).

Figure 1a: ***Total Ethanol Production in Brazil by Feedstock***

Figure 1b: ***Corn Ethanol Production by State***



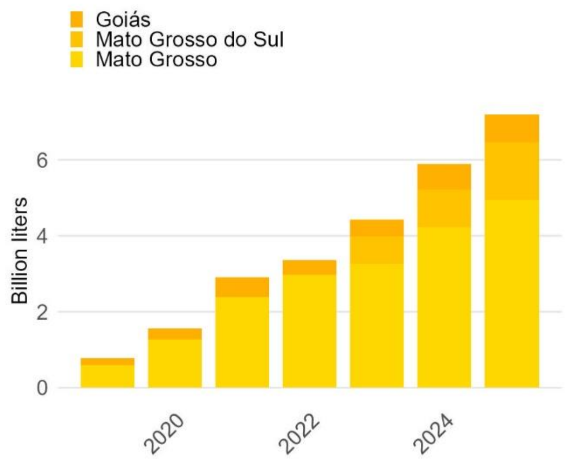
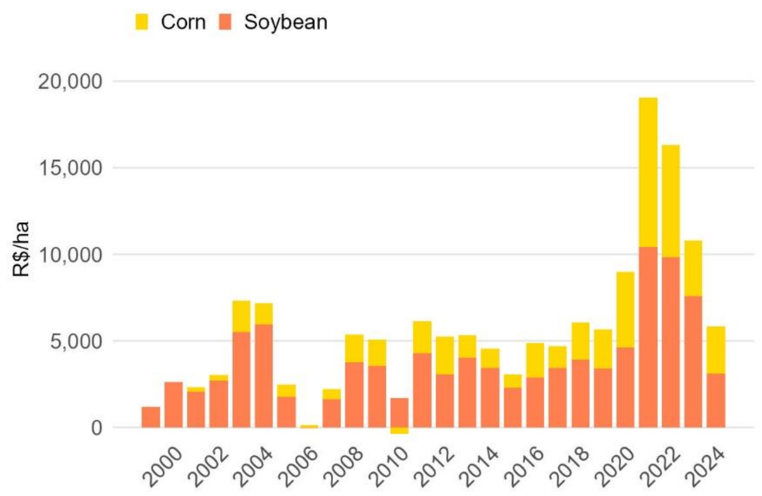


Figure 1a: *Annual ethanol production from sugarcane and corn in Brazil, 2010–2024. Volumes are reported in billions of liters. Corn ethanol, introduced more recently, has grown rapidly since 2019. Data from CONAB.*[14]

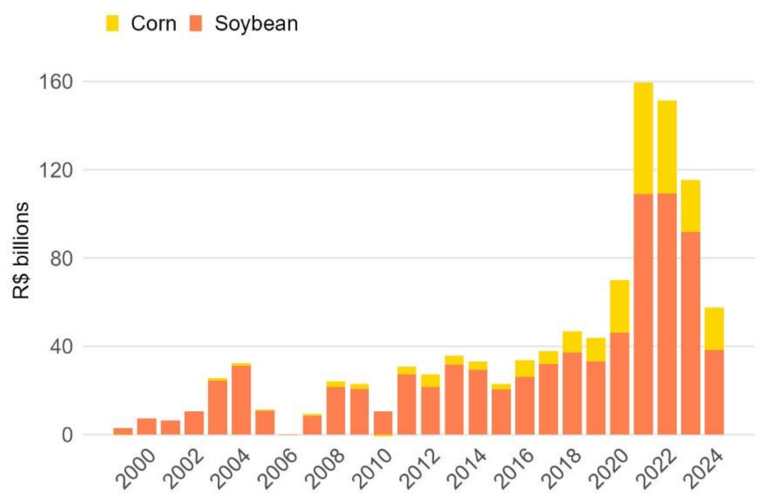
Figure 1b: *Annual corn ethanol production by state in Brazil, 2019–2025. Mato Grosso accounts for the largest share of national production, followed by Mato Grosso do Sul and Goiás. Volumes are reported in billions of liters. Data from CONAB.*[14]

Figure 2a: Per-Hectare Profits in Mato Grosso (1999–2024) from soybean and *safrinha* corn



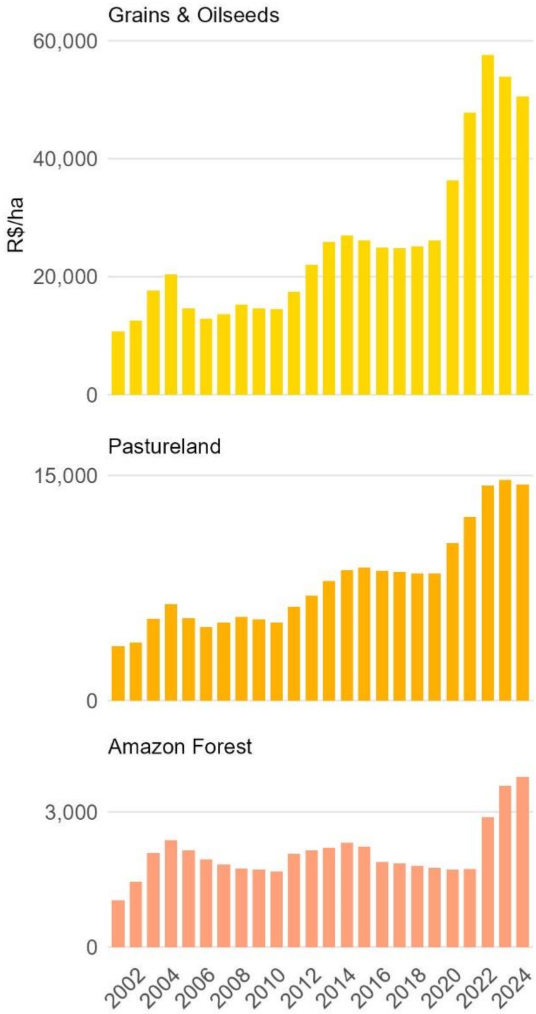
Stacked annual per-hectare profits from soybeans and safrinha corn in Mato Grosso, Brazil. Values represent net profits after accounting for real operational costs (R$/Ha), with income computed using adjusted yield and prices per 60 kg sack. Bars are stacked to show the contribution of each crop to overall per-hectare profitability. Years are shown along the x-axis to highlight changes over time. All values are real values, adjusted for inflation.

Figure 2b: Sector-Level Profits in Mato Grosso (1999–2024) from soybean and *safrinha* corn



Stacked annual total sector profits (R$) from soybean and safrinha corn production in Mato Grosso. Sector profits are calculated as per-hectare net profits multiplied by total planted area each year. The figure shows the relative and absolute contributions of each crop to the aggregate agricultural profitability of the region. Note the rapid expansion in total profits after 2020, primarily driven by corn. All values are real values, adjusted for inflation.

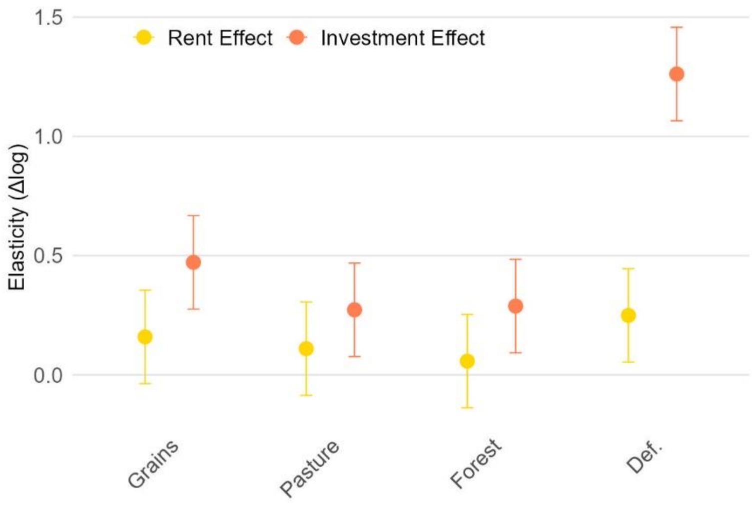
Figure 3: Annual Land Prices in Mato Grosso by Land Use Type, 2001–2024



Trends in average land prices (R$ per hectare) for cropland (Grains & Oilseeds), pastureland, and Amazon forest in Mato Grosso. Cropland prices increased in 2010 with the growth in safrinha corn as a new market crop in Mato Grosso; and in 2020, concurrent to a spike in profitability. Pasture prices, and to a lesser extent, forest prices, show similar directional trends, consistent with spatially correlated land markets.

Figure 4

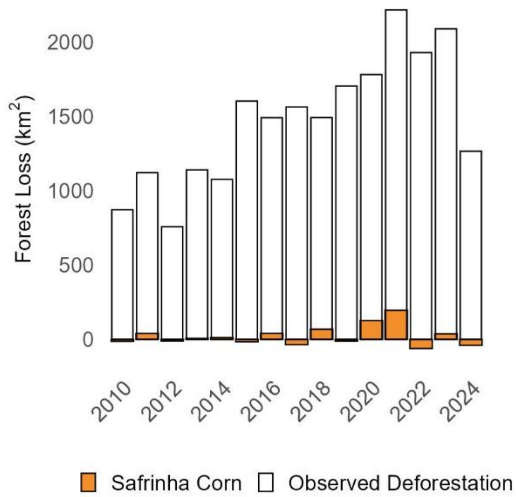
Profit Effects on Land Prices and Deforestation



Estimated elasticities of first-differenced log land prices and deforestation with respect to agricultural profits per hectare ("Rent Effect") and the residual component of sectoral profits orthogonal to per-hectare profits ("Investment Effect"). Coefficients are derived from a two-stage orthogonal regression procedure applied to differenced log variables. Confidence intervals represent 95% robust standard errors. Results indicate that investment effects are generally larger and more statistically significant than rent effects.

Figure 5:

Estimated Contribution of *Safrinha* Corn Profits to Deforestation in Mato Grosso



Estimated contribution of safrinha corn profitability to deforestation in Mato Grosso, Brazil (2010–2024). Using a finite distributed lag model with first-differenced data, we estimate the share of observed forest loss attributable to year-over-year changes in sector-wide profits from safrinha corn. Colored bars represent the model-predicted impact of corn profitability on deforestation, while the full bar height corresponds to the observed deforestation in each year. Negative values reflect years in which declining profits were associated with lower forest loss.

Editorial summary:

In Mato Grosso, Brazil, an increase in profits from safrinha corn indirectly increases land values and forest loss, and these effects persist for several years after a shift in profits, according to an analysis that combines crop, cost, and yield data with a statistical model.

Peer review information:

Communications Earth & Environment thanks Bastiaan Philip Reydon and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Jinfeng Chang and Martina Grecequet. A peer review file is available