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Intensificação agrícola pode ajudar a proteger a Floresta Amazônica e reduzir o aquecimento global

FABIO RICARDO MARIN [1]; ALENCAR JUNIOR ZANON [1]; Juan Pablo Monzon [1]; José F. Andrade [1]; Evandro H.F.M. Silva [1]; Gean Ritcher [1]; Bruna San Martin [1]; RAFAEL BATTISTI [1]; Alexandre B. Heinemann [1]; PATRICIO GRASSINI [1]

[1]DOCENTE. AV. PADUA DIAS, 11 - PIRACICABA - SP. USP/ESALQ

RESUMO

The Amazon basin includes 550 M ha covered with rainforests, with 60% of this area being in Brazil. Conversion of rainforest for soybean production raises concerns about the degree to which Brazil can reconcile production and environmental goals. Here we investigated the degree to which intensification could help Brazil produce more soybean without further encroachment of the Amazon Forest. Our analysis shows that continuation of current trends in soybean yield and area would lead to conversion of additional 5.7 M ha of forests and savannas during the next 15 years, with an associated 2550 Mt of CO_2eq released into the atmosphere. In contrast, acceleration of yield improvement, coupled with expansion of soybean area only in areas currently used for livestock production, would allow Brazil to achieve similar economic benefits without deforestation and with substantially lower global climate warming.

PALAVRAS-CHAVE: potential yield; crop modeling; emissions; deforestation;

INTRODUÇÃO

The COVID-19 pandemic, together with the war in Ukraine, brought two signals that can have a massive impact on developing countries that rely on commodity crops as a main source of income. One is a sharp increase in crop commodity prices, which have risen *ca.* 75% compared with pre-pandemic levels[1]. The other signal is a strong desire of national governments to quickly recover from the negative economic impact by making use of their comparative advantages[2]. These signals are of critical importance for developing countries with vast tracts of land suitable for farming that are currently covered with fragile ecosystems such as rainforests and savannas, because they can trigger massive land conversion in a relatively short period of time, leading to biodiversity loss and global warming[3-9].

Brazil hosts one of the largest pools of biodiversity in the world, with 516 M ha of forests and savannas (MAPBIOMAS Project - Collection 5.0)[10]. Of special relevance are the vast areas of rainforests located within the Amazon basin, summing to 330 M ha. At the same time, Brazil is the main soybean exporting country, accounting for *ca.* 40% of global exports (FAOSTAT, 2017-2019)[11]. Soybean production has driven massive deforestation during the late 1990s and early 2000s[12,13]. Fortunately, Brazil has made tangible progress in subsequent years to reduce deforestation rates *via* moratoriums and incentive programs funded by foreign countries[14,15]. At question is whether these measures alone will be sufficient to prevent conversion of fragile ecosystems in a context of high grain prices and with governments seeking economic growth *via* increased agricultural output.

Soybean area in Brazil has expanded at 1.4 M ha per year during the 2007-2019 period, with most of this expansion occurring in four regions: Pampa, Atlantic Forest, Cerrado, and Amazonia. The first two regions experienced a massive process of land conversion for agriculture many decades ago and only a small portion of the native vegetation now remains. In contrast, large tracks of pristine forest and savanna remain in Cerrado and especially Amazonia. Unfortunately, one third of the annual land converted for soybean production in Brazil is now occurring in Amazonia, with half of the soybean expansion in this region occurring at expense of tropical rainforest.

OBJETIVOS

Here we investigated the degree to which agricultural intensification, that is, increasing the productivity of existing cropland, could serve as a means of enabling Brazil to simultaneously reconcile production and environmental goals. To evaluate the potential of achieving both outcomes, we combined crop modeling and spatial analysis to investigate different scenarios of intensification and land-use change and associated impact on production, land conversion, and climate change. We discuss the resultant implications for policy makers and priorities in agricultural research and development (AR&D) programs to foster agricultural intensification and protection of fragile ecosystems.

MATERIAL E MÉTODOS

Study regions and recent trends in land-use change

Our analysis focuses on four biomes (referred to as 'regions' in the rest of the text), accounting for nearly all soybean area in Brazil: Pampa, Atlantic Forest, Cerrado, and Amazonia **(Supplementary Material, Section 1)**. Soybean production is negligible in Pantanal and Caatinga so these two regions were excluded from our analysis. We focused on soybean-based systems in Brazil, either those that include one crop per year (single soybean), or those including a second-crop maize. In the latter system, soybean is sown in Sept-Oct and maize is sown right after soybean harvest in late Jan-Feb. Single soybean is common in Pampa, where drier climate does not allow double cropping. In contrast, higher precipitation allows double cropping in Amazonia, Cerrado, and most of the Atlantic Forest **(Supplementary Material, Section 2)**.

Recent trends in yield, area, and production for soybean and second-crop maize were derived from official statistics for the 2007-2019 period[16]. We fitted linear models to derive the annual rate of yield improvement and harvested area for soybean and second-crop maize, separately for each region **(Figure 1 and Extended Data Figure 1)**. Land use change arising from soybean expansion was estimated using data from the MAPBIOMAS project (v5.0)[10] **(Supplementary Table 1)**. Our estimation of land-use change accounted for the time lag between land conversion and beginning of soybean production, which can include transitional stages such as cultivation of upland rice or short-term pasture-based livestock systems[33]. To do so, we looked at the new land brought into soybean production during the 2008-2019 period, and we analyzed how much of this land was under a different land use type (forest, savanna, grassland, pasture, other crops) around the year 2000 **(Extended Data Figure 2).**

Estimation of yield potential and yield gaps

We used results on yield potential for Brazil generated by the authors through the Global Yield Gap Atlas project (GYGA)[34] using well-validated process-based crop models and best available sources of weather, soil, and management data. Briefly, we selected a total of 32 sites to portray the distribution of the soybean harvested area within the country, following protocols that ensure representativeness and a reasonable coverage of national crop area[35]. The 32 sites collectively accounted for half of soybean harvested area in Brazil. In turn, these sites were located within agro-climatic zones accounting for 86% national soybean production and accounted for 72-92% of soybean area in each region. Following protocols that give preference to measured data at a high level of spatial and temporal resolution[36], databases on weather, soil, management, and crop yields were collected for soybean for each site, and also for second-crop maize at those sites where double cropping is practiced **(Supplementary Tables 2-3; Supplementary Material Section 3)**.

Yield potential was simulated for widespread cultivars in each region using CROPGRO soybean model embedded in DSSAT v 4.5[37] and Hybrid-Maize model[38]. We first evaluated CROPGRO and Hybrid Maize models on the ability to reproduce measured phenology and yields across 40 well-managed experiments located across the four regions. Models showed satisfactory performance at reproducing measured values **(Extended Figure 3)**. Subsequently, we simulated soybean yield potential for the dominant agricultural soils at each site (usually two to three), as determined from the soil maps generated by the Radambrasil project[39]. Simulations were based on long-term (1999-2018) measured daily weather data retrieved from Brazilian Institute of Meteorology (INMET)[40]. We also simulated yield potential for second-crop maize crop for those sites where double cropping is practiced. To estimate average yield potential for each site, simulated values for each soil types was weighted by soil area fraction at each site. In all cases, simulations assumed no limitations to crop growth due to nutrient deficiencies and incidence of biotic stresses such as weeds, insect pests, and pathogens. Results were up-scaled from site to region and then to country following van Bussel et al.[35]. Briefly, average yield potential for each region was estimated by averaging simulated yields across the sites located within each region, weighing sites according to their share of the soybean area within each region. A similar approach was followed to upscale yield potential from region to national level. Details on crop modeling, data sources, and upscaling is provided in **Supplementary Material Section 3.**

Average farmer yield was calculated separately for soybean and second-crop maize based on the average yield reported over the 2012-2017 period for the municipalities that overlap with each site, weighing municipalities based on their share of the soybean or maize area within each site[16]. Including more years before 2012 would have led to a biased estimate of average actual yield due to the technological yield trend in Brazil. Average farmer yields were estimated at region and country levels following the same upscaling approach as for yield potential. Finally, the exploitable yield gap was calculated as the difference between attainable yield and average farmer yield. The attainable yield was calculated as 80% of the simulated yield potential, which is considered a reasonable yield for farmers with adequate access to inputs, markets, and technical information **(Supplementary Material Section 2)**.

Assessment of different scenarios of intensification and land-use change

We explored three scenarios with different soybean and maize yields and area by year 2035 and assessed their outcomes in terms of production, land use change, and GWP **(Supplementary Table 4)**. A 15-year future timespan is long enough to facilitate the implementation of long-term policies, investments, and technologies devoted to close the exploitable yield gap and to implement land-use policies, but it is short enough to minimize long-term effects from climate change on crop yields and cropping systems. In the business-as-usual (BAU) scenario, historical (2007-2019) trends of soybean and second-crop maize area and yield (**Extended Data Figure 1**) remain unchanged in all regions between the baseline year (2019) and final year (2035). Likewise, soybean area expands following the same pattern of land-use change observed during 2008-2019 (**Extended Data Figure 2**).

To explore the available opportunity for increasing production on existing production area, we considered an intensification (INT) scenario in which there is no physical expansion of cropland while full closure of the exploitable yield gap occurs in the regions where current yield gaps are small (Pampa and Atlantic Forest) and 50% closure of the exploitable yield gap takes place in regions where current yield gap is large (Amazonia and Cerrado) **(Supplementary Table 4)**. These rates are comparable to historical yield gains in Pampa and Atlantic Forest. In contrast, a scenario of full yield closure in Amazonia and Cerrado would have been unrealistic as it would have required rates of yield improvement that are three-to-four times higher than historical rates and much higher than those in Pampa and Atlantic Forest and well beyond those reported for main soybean producing countries. In the case of second-maize crop, we assumed full closure of the exploitable yield gap by 2035 because historical rates of yield improvement are adequate to reach that yield level. In the case of second-crop maize area, we projected the proportion of double cropping to increase from current 47% (Amazonia), 39% (Cerrado), and 31% (Atlantic Forest) to 100%, 70%, and 50%, respectively, as determined based on the degree of water limitation in each region **(Supplementary Material Section 4)**.

Finally, we explored a third scenario of intensification plus target area expansion (INT+TE), in which identical yield gain rates and adoption of double cropping equivalent to those in the INT scenario were assumed, but with physical expansion of the soybean-maize system allowed in low-C ecosystems. In this scenario, soybean expansion is limited to 10% of existing pastures and grasslands in Pampa, Atlantic Forest, and Cerrado (total of 11.4 M ha) as a result of a parallel intensification in the pasture-based livestock sector that frees up land for soybean production. Such intensification would require a modest 10% increase in stocking rate, which is a reasonable target within a relatively short timeframe, as reported in previous studies[25,26]. Another assumption is that the yield potential of pasture and grasslands converted for soybean production is similar to that in existing soybean areas in each region. Cropland expansion into grassland and pastures was allowed in all regions, except for Amazonia to prevent 'leaking' effects and the impact of road development on land clearing[41,42]. Similarly, conversion of area cultivated with food crops for soybean production is not allowed to avoid the negative impact of indirect land use change[43].

Estimation of global warming potential and gross income

We estimated greenhouse gas emissions (GHG), including carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O) associated with land conversion (GHG_{LUC}) and crop production (GHG_{PROD}) for the baseline year (2019) and for the three scenarios by year 2035 (BAU, INT, INT+TE). The GHG_{LUC} includes emissions associated with changes in C stocks from aboveground and belowground biomass when land is converted for soybean production (GHG_{BIO}), and also GHG emissions derived from associated changes in soil organic C (GHG_{SOC}). For each land use type, annual GHG_{BIO} was estimated based on the change in C stocks between the land use type that was converted for production **(Supplementary Table 5)** and, depending on the scenario and region, the average C stocks of the new cropping system[44-46]:

$$GHG_{CON} = ?\ (TDM_{i} - TDM_{crop}) * Ai \quad \text{Eq. [1]}$$

where *i* is the land cover type, *TDM* is the total dry matter (t C ha^{-1}) in land cover type *i* and in cropland (*crop*), and *Ai* is the annual area converted from land use type *i* for soybean cultivation **(Supplementary Table 4)**. C stocks for single soybean and soybean-second maize systems were assumed at 2 and 5 t C ha^{-1}, respectively[44-46]. Changes in soil organic C (SOC) stocks was estimated following the IPPC 2019 guidelines[45] and the SOC estimated for each region[47,48]:

$$GHG_{SOC} = ?\ (SOC_{REF\ i} * F_{LU} * F_{MG} * F_{I}) * Ai \quad \text{Eq. [2]}$$

where *i* is the land cover type, SOC_{REF} is the soil organic C stock for mineral soils in the upper 30 cm for the reference condition (t C ha^{-1})[47] in land cover type *i* **(Supplementary Table 5)**, F_{LU} is the stock change factor for SOC land-use systems for a particular land-use, F_{MG} is the stock change factor for SOC for management regime, F_{I} is the stock change factor for SOC for the input of organic amendments, and *Ai* is the annual area converted from land use type *i* **(Supplementary Table 4)**. We used a $F_{LU} = 0.84$ that corresponds to area converted to annual crops in tropical wet regions, $F_{MG} = 1.04$ that corresponds to reduced tillage in tropical wet regions, and $F_{I} = 1.0$ representative for annual cropping with cereals where all crop residues are returned to the field. We assumed that GHG_{BIO} and GHG_{SOC} occurred during the first year after land conversion and were expressed as CO_2 equivalents by multiplying changes in C stocks by 3.67.

Annual GHG emissions derived from soybean and second-crop maize production (GHG_{PROD}) were calculated for each scenario and included those derived from manufacturing, packaging, and transportation of agricultural inputs, fossil fuel use for field operations, and soil N_2O emissions derived from application of nitrogen (N) fertilizer, and domestic grain transportation. For the baseline year (2019), annual GHG from N, phosphorous (P), and potassium (K) fertilizers and other inputs (lime, pesticides, and fuel) was calculated based on current average input rates for soybean and second-crop maize in each region as derived from the crop management data collected for each region **(Supplementary Table 6; Supplementary Material Section 3.4)**. To calculate GHG emissions associated with manufacturing, packaging, and transportation of N, phosphorous (P), and potassium (K) fertilizers and lime, we used specific updated emissions factors for South America[49], selecting those fertilizer sources that are most commonly used for soybean and second-crop maize production: urea (N), monoammonium phosphate (P), and potassium chloride (K). Our calculations also included the extra lime application that is needed to correct soil acidity converted areas. Emission factors associated with seed production, pesticides and diesel were derived from Lal (2014)[50]. Soil N_2O emissions derived from N fertilizer application were calculated assuming a N_2O emission factor of 1.6% of the applied N fertilizer applied based on the IPCC emission factor for mineral soils in tropical regions[45]. Emissions derived from domestic grain transportation for each region were estimated using the GHG per ton of grain as reported by previous studies for each region[51]. We assumed that inputs other than nutrient fertilizer will not change relative to the baseline in the BAU scenario. In the case of the INT and INT-TE scenarios, applied inputs were calculated based on those reported for current high-yield fields where the yield gap is small. In the case of fertilizer nutrient rates, we estimated them for the three scenarios following a nutrient-balance approach that depends upon the projected yield for each scenario **(Supplementary Table 6; Supplementary Material Section 3.4)**

The GHG_{PROD} in the baseline year (2019) and for the three scenarios in 2035 (BAU, INT, and INT-TE) was estimated for each region by multiplying the emissions per unit of area by the annual soybean harvested area, summing them up to estimate GHG emissions at national level. Overall 100-y GWP was estimated as the sum of GHG_{LUC} and GHG_{PROD}, both expressed as CO_2 equivalents (CO_2eq) to account for the higher warming potential of CH_4 and N_2O, which are 25 and 298 times the intensity of CO_2 on per mass basis, respectively. The gross income was estimated for each scenario by multiplying annual crop production by the average price for soybean and maize grain during the past ten years (453 and 184 US$ t^{-1} for soybean and maize, respectively[1]). Finally, to combine the environmental and economic impact into one metric, we calculated the GWP intensity as the ratio between GWP and gross income.

RESULTADOS E DISCUSSÃO

The COVID-19 pandemic, together with the war in Ukraine, brought two signals that can have a massive impact on developing countries that rely on commodity crops as a main source of income. One is a sharp increase in crop commodity prices, which have risen *ca.* 75% compared with pre-pandemic levels[1]. The other signal is a strong desire of national governments to quickly recover from the negative economic impact by making use of their comparative advantages[2]. These signals are of critical importance for developing countries with vast tracts of land suitable for farming that are currently covered with fragile ecosystems such as rainforests and savannas, because they can trigger massive land conversion in a relatively short period of time, leading to biodiversity loss and global warming[3-9].

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Here we investigated the degree to which agricultural intensification, that is, increasing the productivity of existing cropland, could serve as a means of enabling Brazil to simultaneously reconcile production and environmental goals. To evaluate the potential of achieving both outcomes, we combined crop modeling and spatial analysis to investigate different scenarios of intensification and land-use change and associated impact on production, land conversion, and climate change. We discuss the resultant implications for policy makers and priorities in agricultural research and development (AR&D) programs to foster agricultural intensification and protection of fragile ecosystems.

Soybean area in Brazil has expanded at 1.4 M ha per year during the 2007-2019 period, with most of this expansion occurring in four regions: Pampa, Atlantic Forest, Cerrado, and Amazonia **(Figure 1a; Extended Data Figures 1 and 2; Supplementary Table S1; Supplementary Material Section 1)**. The first two regions experienced a massive process of land conversion for agriculture many decades ago and only a small portion of the native vegetation now remains. In contrast, large tracks of pristine forest and savanna remain in Cerrado and especially Amazonia. Unfortunately, one third of the annual land converted for soybean production in Brazil is now occurring in Amazonia, with half of the soybean expansion in this region occurring at expense of tropical rainforest (**Extended Data Figure 2)**. Soybean expansion into the Amazonia and Cerrado has been driven by availability of suitable soils for crop production and favorable weather, which allow farmers to achieve high and stable soybean yields and to cultivate an additional maize crop (hereafter referred to as 'second-crop maize') in the same cropping season (**Extended Data Figure 1)**. Yield improvement has been comparably slower in Cerrado and Amazonia compared to that in other regions **(Figure 1b)**, which has led to soybean production increasing mostly from cropland expansion **(Figure 1c)**.

CONCLUSÃO

In the current context of high grain prices and food supply disruptions, we believe there is a critical need for major crop producing countries to re-assess their potential to produce more on existing cropland. Our national assessment for Brazil moves beyond previous efforts to quantify yield gaps at local level[29,30], showing that intensification can help achieve a reasonable balance between crop production and protection of fragile ecosystems. We are aware of other approaches to protect natural ecosystems. For example, previous studies in Brazil have shown that moratoriums, certification, and incentive programs can help protect fragile ecosystems from conversion[15,31]. However, recent examples for Brazil and other countries showed that these programs fall short in protecting forests in countries that depend heavily on crop commodity exports, especially when the socio-economic context is favorable for converting natural ecosystems to agricultural production (e.g., high crop prices, poor enforcement of land-use policy)[7,32]. Intensification can complement these other approaches to protect fragile ecosystems, providing a means to reconcile economic and environmental goals. To be effective, however, intensification would require proper policy and enforcement to ensure that land savings derived from crop yield improvement led to land sparing for nature. The main message still remains: without an emphasis on intensifying crop production within the existing agricultural area, it would be difficult to protect the last bastions of forests and biodiversity in the planet.

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