Protecting the Amazon forest and reducing global warming via agricultural intensification
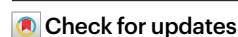
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The Amazon basin includes 550 Mha covered with rainforests, and 60% of this area is in Brazil. The conversion of rainforest for soybean production raises concerns about how Brazil can reconcile production and environmental goals. Here we investigated the degree to which intensification could help Brazil produce more soybean without further encroachment on the Amazon forest. Our analysis shows that the continuation of current trends in soybean yield and area would lead to the conversion of an additional 5.7 Mha of forests and savannahs during the next 15 years, with an associated 1,955 Mt of CO_2e released into the atmosphere. In contrast, the acceleration of yield improvement, coupled with the expansion of soybean area only in areas currently used for livestock production, would allow Brazil to produce 162 Mt of soybean without deforestation and with 58% lower global climate warming relative to that derived from the continuation of current trends.

The COVID-19 pandemic, together with the war in Ukraine, brought two consequences that can have massive impacts 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 nearly doubled compared with pre-pandemic levels[1]. The second is a strong desire of national governments to quickly recover from the negative economic impact by making use of their countries' comparative advantages[2]. These events are critically important for developing countries with vast tracts of land suitable for farming that are currently covered with fragile ecosystems such as rainforests and savannahs, because they can trigger massive land conversion in a relatively short period, leading to biodiversity loss and global warming[3–9].

Brazil hosts one of the largest pools of biodiversity in the world, with 516 Mha of forests and savannahs[10]. Of special relevance are the vast areas of rainforests located in the Amazon basin, summing to 330 Mha. At the same time, Brazil is the main soybean-exporting country, accounting for ca. 40% of global exports in 2017–2019[11]. Soybean production drove massive deforestation during the late 1990s and early 2000s[12,13]. During subsequent years (2005–2015), Brazil has made tangible progress in reducing deforestation rates via moratoriums and incentive programmes funded by foreign countries[14,15]. At question is whether these measures alone will be sufficient to prevent the conversion of fragile ecosystems in a context of high grain prices and governments seeking economic growth via increased agricultural output.

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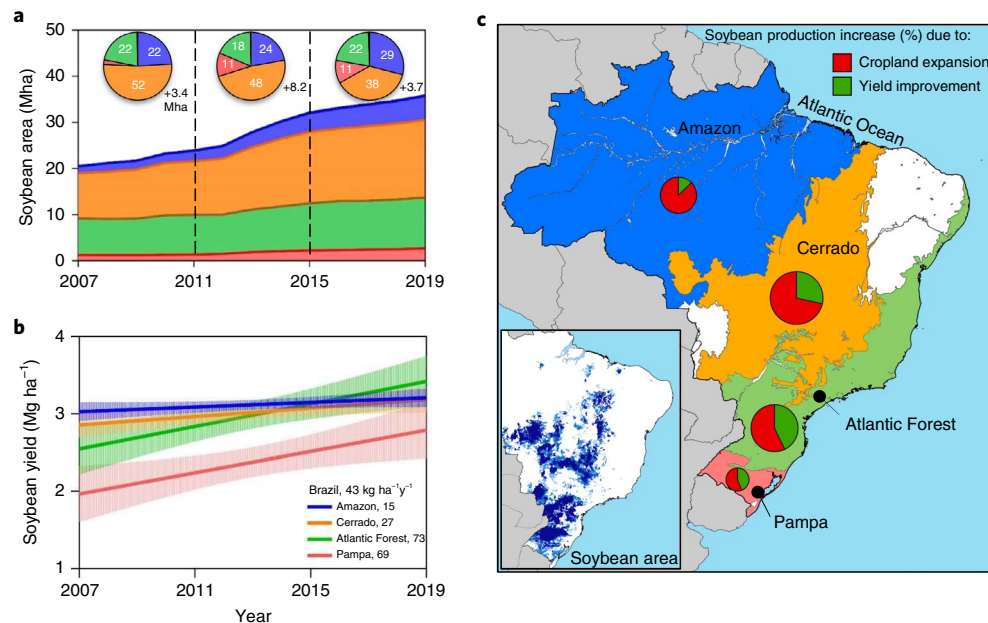
Fig. 1 | Trends in soybean area and yield in main producing areas in Brazil.
a,b, Trends in soybean area and average yield. The pie charts shown in **a** indicate the percentage of soybean expansion occurring in each biome, while the total increase in soybean area in each period is shown next to the pie charts. Shown in **b** is the annual rate of yield improvement for each region during 2007–2019, with shadow bands representing the 95% confidence intervals estimated for the fitted linear regression models. Values indicate the annual rate of yield improvement in each region and for Brazil. **c**, Contribution of cropland expansion and yield improvement to soybean production increase in each region. The size of the pie chart in each region is proportional to the share of national soybean production. The inset shows the soybean area distribution[64]. Across panels, regions are represented with different colours: blue (Amazon), orange (Cerrado), green (Atlantic Forest) and red (Pampa). Yield data from ref. [16]. Biome basemap in **c** adapted with permission from ref. [16], IBGE. Soybean area map in **c** (inset) adapted with permission from ref. [64], IFPRI.

Here we investigated the degree to which intensification (that is, increasing the productivity of existing agricultural areas) 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 modelling and spatial analysis to investigate different scenarios of intensification and land use change and associated impacts on production, land conversion and climate change. We discuss the resultant implications for policymakers and priorities in agricultural research and development (AR&D) programmes to foster agricultural intensification and protection of fragile ecosystems.

Recent patterns of soybean area expansion and yield gains

Soybean area is concentrated in four regions: the Pampa, the Atlantic Forest, the Cerrado and the Amazon (Fig. 1). The first two regions experienced a massive process of land conversion for agriculture many decades ago (1970s–1990s), and only a small portion of the native vegetation now remains. In contrast, large tracts of pristine forest and savannah remain in the Cerrado and especially the Amazon. Soybean area has expanded at 1.4 Mha per year during the recent 2007–2019 period, driven by the availability of suitable soils for crop production and favourable weather in the Amazon and the Cerrado, 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 (Fig. 1a, Extended Data Figs. 1 and 2, Supplementary Table 1 and Supplementary Section 1). Of special concern for biodiversity and climate change is the increase of soybean expansion in the Amazon, which accounted for one third of the land converted for soybean production in Brazil between 2015 and 2019, with half of soybean expansion in this region occurring at the expense of tropical rainforest[16]. Yield improvement has been slower in the Cerrado and the Amazon than in other regions (Fig. 1b). Slower yield improvement in the Cerrado and the Amazon could be attributed to the shorter history of soybean production in these regions, where large-scale soybean production started in the early 2000s, compared with the historical soybean-producing region in southern Brazil, where soybean was introduced 50 years ago.

Available opportunity for increasing crop yields

Yield potential is the yield of a well-adapted cultivar when grown without nutrient limitations and in the absence of yield-reducing factors such as weeds, insect pests and pathogens (Supplementary Section 2). Here we estimated the yield potential for soybean and second-crop maize in Brazil using well-validated crop simulation models and detailed weather, soil and agronomic data (Fig. 2, Extended Data Fig. 3 and Supplementary Tables 2 and 3). Our assessment revealed an average yield potential of 5.5 Mg ha⁻¹ for soybean in Brazil, but with higher and more stable yield potentials in the Cerrado and the Amazon than in the Atlantic Forest and the Pampa. In the case of second-crop maize, which is grown in all regions except the Pampa and part of the Atlantic Forest due to climatic constraints, the yield potential was 10.6 Mg ha⁻¹. At question is how much room exists in each region to increase soybean and second-crop maize production on existing cropland via intensification. Reaching the yield potential in farmer fields is difficult, as it requires copious amounts of inputs and a high degree of sophistication to eliminate yield-reducing factors, leading to reduced profit and a large negative environmental impact. In contrast, attaining 80% of the simulated yield potential (hereafter referred to as attainable yield) is considered a reasonable level of yield-gap closure for a population of farmers with adequate access to inputs, markets and extension services (Supplementary Section 2). Here we estimated the exploitable yield gap as the difference between the attainable yield and the average yield and found that the exploitable yield gap for soybean in Brazil increases northwards, from 10% and 25% in the Pampa and the Atlantic
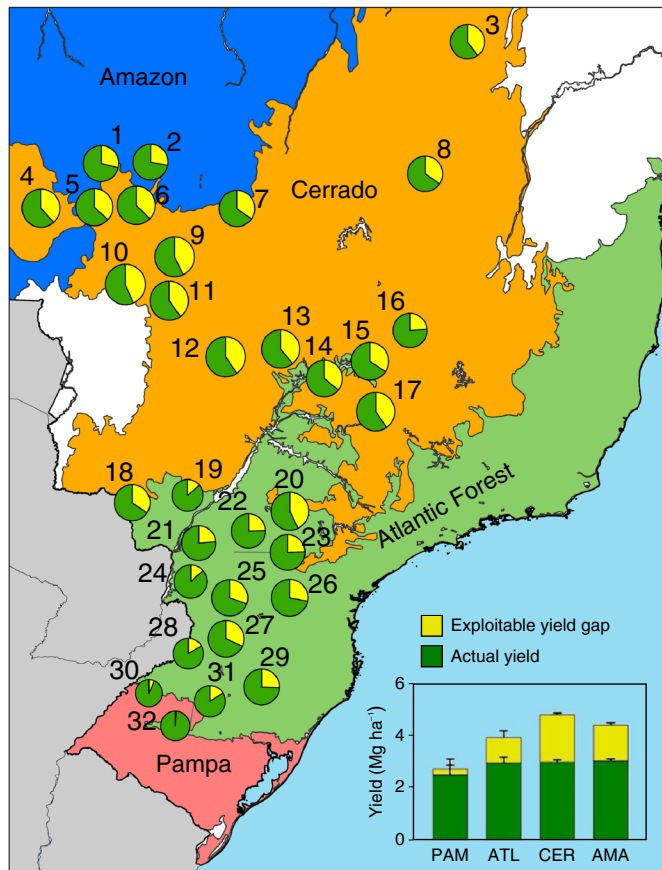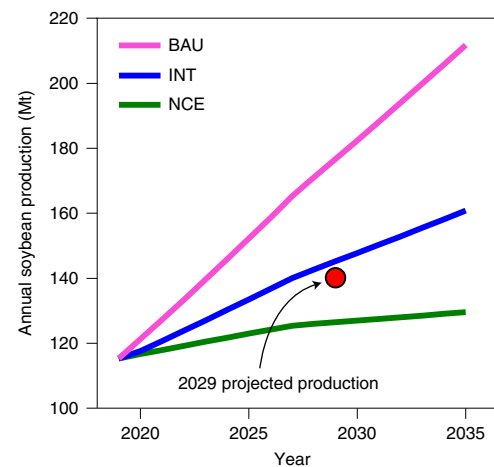
Fig. 2 | Attainable yield and yield gaps across soybean-producing areas in Brazil. The pie charts show the actual yield (green) and the exploitable yield gap (yellow) as percentages of the attainable yield, estimated for 32 sites across the soybean harvested area in Brazil. The size of each pie chart is proportional to the magnitude of the attainable yield. The values next to the pie charts are the site identification codes; the associated names, locations and means are shown in Supplementary Tables 2 and 3. The inset shows the current average yield, the exploitable yield gap and the standard errors for each region: the Pampa (PAM), the Atlantic Forest (ATL), the Cerrado (CER) and the Amazon (AMA). Biome basemap adapted with permission from ref. [16], IBGE.

Fig. 3 | Changes in soybean production with different yield and land use change scenarios in Brazil. Three scenarios are shown: BAU, NCE and INT. Also shown is the projected soybean production in Brazil for the year 2029[17].

Forest, respectively, to 35% in the Amazon and the Cerrado (Fig. 2 and Supplementary Table 2). In the case of second-crop maize, the exploitable yield gap represents 32–44% of the attainable yield across regions (Supplementary Table 3).

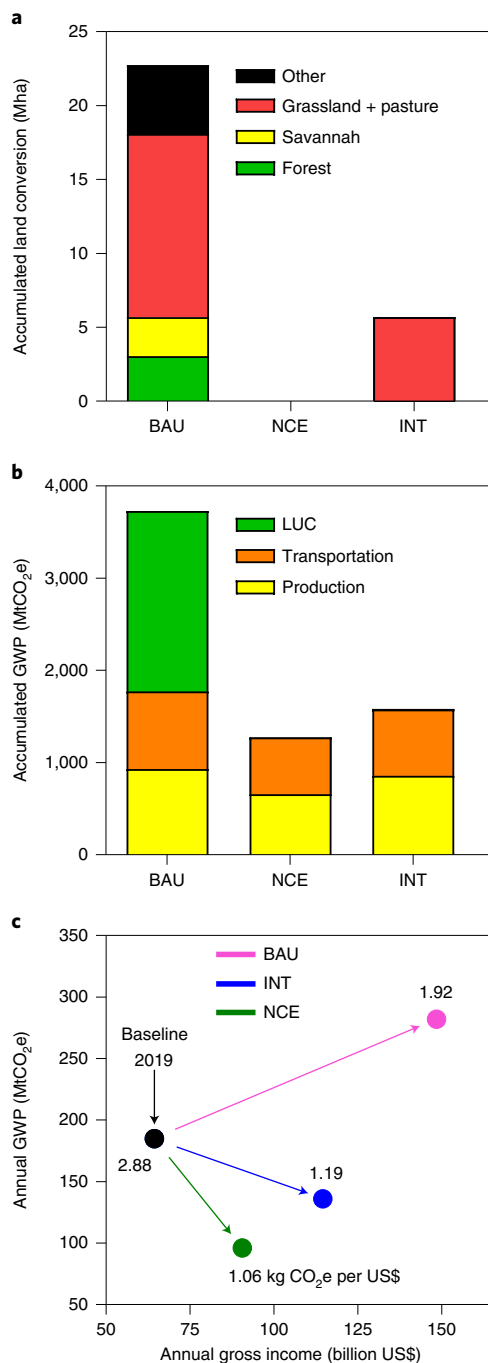## Production and land use change scenarios

We first explored a business-as-usual (BAU) scenario in which historical yield improvement and land use change patterns were projected to persist during the next 15 years (Figs. 3 and 4 and Supplementary Table 4). As an alternative pathway, we evaluated a scenario in which historical yield improvement continues over the next 15 years, but there is no cropland expansion (NCE) due to restrictions on converting new areas for soybean production and no expansion into pastures and grassland due to competition with livestock production (Figs. 3 and 4 and Supplementary Table 4). Finally, we assessed an intensification scenario (INT) to reduce the negative environmental impact of land conversion for soybean production while minimizing the negative economic impact (Figs. 3 and 4 and Supplementary Table 4). The INT scenario assumed a massive investment in AR&D so that the exploitable yield gap of soybean is narrowed by half in the Cerrado and the Amazon. Such a level of yield gap closure would require rates of yield improvement that would be two to three times larger than the historical rates in those

two regions, but comparable to those in the Pampa and the Atlantic Forest (Fig. 1). Because the current rates of yield improvement in the Pampa and the Atlantic Forest are already high, we assumed that yield gain rates in these two regions would remain the same, which allows full closure of the exploitable yield gap by 2035. In the case of second-crop maize, we assumed complete closure of the existing yield gaps, as the current rates are already high. Our INT scenario also assumed further adoption of second-crop maize on existing soybean area wherever the climate makes double-cropping possible. Additionally, we assumed a parallel intensification of the pasture-based livestock systems in the INT scenario so that part of the current pastureland and grassland is freed up for soybean production in all regions except the Amazon. We estimated that a roughly 12% increase in the stocking rate in current pasture-based livestock systems would be sufficient to meet the projected beef demand and free up 5.7 Mha of pastures and grassland for soybean production (Methods). Expansion at the expense of other food crop areas was not allowed in the INT scenario to avoid indirect land use change.

In the BAU scenario, soybean area expands from 36 to 59 Mha, while the current yield increases from 3.1 to 3.6 Mg ha^{-1}, leading to a national soybean production of 212 MMT by 2035 (Figs. 3 and 4). However, the production increase in the BAU scenario would occur at the expense of converting 5.7 Mha of forests and savannah into soybean cultivation and an associated 1,955 MtCO$_2$e released to the atmosphere due to land conversion. In contrast, the NCE scenario avoids deforestation and reduces global warming potential (GWP), but it incurs a huge opportunity cost in terms of economic output (US$447 billion over the 15-year study period), leading to soybean production that falls short of that projected by year 2029[17] and 40% lower soybean and second-crop maize production compared with the BAU scenario. In the INT scenario, soybean average yield reaches 3.9 Mg ha^{-1} by 2035, while second-crop maize average yield attains 8.6 Mg ha^{-1}. Notably, the INT scenario achieves a reasonable balance between increasing agricultural output and reducing the negative environmental impact. Soybean production increases to 162 MMT by 2035, mitigating the opportunity cost associated with the NCE scenario. Indeed, the INT scenario achieves an aggregated gross income from soybean and second-crop maize that represents 85% of that in the BAU scenario. Because there is no deforestation, the total GWP decreases by 58% in the INT versus the BAU scenario, achieving a GWP intensity (that is, GWP per unit of gross income) that is comparable to that in the NCE scenario. Overall, the GWP reduction due to land saving is equivalent

Fig. 4 | Land conversion, GWP and gross income associated with different scenarios of intensification and land use change in soybean-based systems in Brazil. a, Accumulated area of forest, savannah, grasslands plus pastures and other land uses converted for soybean production. **b**, Accumulated GWP disaggregated by source: land use change (LUC), crop production and domestic grain transportation. **c**, Annual GWP and gross income in 2019 and for the three scenarios by year 2035. The arrows show the trajectory between 2019 and 2035 for each scenario, while the values show GWP intensity, expressed as GWP per unit of income (kg CO_2e per US$). Three scenarios are shown in all plots: BAU, NCE and INT.

to the total fossil fuel greenhouse gas (GHG) emissions at the national level in Brazil over four years.

Discussion

Brazil has made remarkable progress on fostering agricultural production during the past 50 years, becoming a major exporting country

of soybean, maize and beef. However, much of the increase in agricultural output has occurred from cropland expansion rather than cropland productivity (Fig. 1). Our analysis based on current available spatial data on land use in Brazil[16] shows that nearly one third of the recent soybean expansion in Brazil has occurred in the Amazon (Fig. 2), which is consistent with changes in carbon balance (from being a net CO_2 sink to a source) and record deforestation rates reported for this region[7,8]. Our study assessed the aggregated economic and environmental impacts of different trajectories in crop intensification and land use change at the national level, including assessing the potential for intensification in second-crop maize as well as allowing soybean expansion into pasture-based livestock areas (Figs. 3 and 4). On the one hand, the continuation of current trends in soybean area expansion (BAU scenario) would drive massive encroachment on the Amazon rainforest, biodiversity loss and increased global warming. On the other hand, imposing restrictions on expanding soybean area, without an explicit effort to accelerate historical rates of yield gain and intensify the pasture-based livestock sector (NCE scenario), would lead to a substantial negative economic impact due to lower national crop production. However, there is an alternative pathway that would balance out environmental and economic goals. We show here that Brazil can reverse current patterns of soybean expansion via a dual intensification of crop and livestock systems, coupled with land-use planning (INT scenario), without incurring substantial trade-offs between crop production and economic profit. 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.

We acknowledge that our study is subject to several uncertainties. For example, our yield gap and GWP estimates could be biased due to inaccuracies in underpinning weather, soil and management databases and emission factors. To the extent it was possible, we relied on the best sources of data that exist, giving preference to measured data at the finest level of spatial resolution and the most updated local emission factors published for Brazil. Our scenario assessment may also have limitations. For example, changes in yield potential because of potential expansion of irrigated area in Brazil, genetic improvement and climate change were not considered in our assessment. Given the relatively short timeframe of our scenario assessment (15 years), we do not expect these factors to influence yield potential substantially. Likewise, previous studies have shown that climate change effects on crop yields in Brazil can range from negative to positive and are relatively minor[18–20], with potential negative impacts likely to be mitigated via management practices[21–23]. We also assumed that new land converted for soybean production has the same yield potential as current cropland. If new land has lower yield potential, as has been shown to be the case in many instances[24], it will further emphasize the need to intensify production on existing cropland. Finally, our INT scenario assumes that the productivity of the pasture-based livestock sector increases, not only to meet the projected beef demand without needing to expand the livestock area but also to free up land for soybean production. Because of the difficulty of parsing out the portion of GHG emissions associated with each component, the emissions associated with the intensification of the livestock sector were not included in the calculation of GWP in our INT scenario, leading to some underestimation. However, we note that GHG emissions derived from intensification are likely to be relatively small compared with those from land conversion in the BAU scenario. Hence, we believe that the results from our study are robust and that the uncertainties and limitations associated with our methods will not modify the overall conclusions of our study.

Fostering an intensification of Brazilian agriculture will require strategic investments in AR&D programmes in both the crop and livestock sectors. Our detailed yield-gap analysis identifies areas with the largest yield gaps, providing a roadmap to orient AR&D programmes. For example, our study shows that yield gaps are larger in the relatively

new soybean areas across the Cerrado and the Amazon than in the traditional soybean area in southern Brazil (Fig. 2). Given favourable soil and weather endowments and adequate farmer access to markets, inputs and extension services, we are optimistic about reaching the desired level of crop intensification in these new regions within a relatively short time via a targeted investment in AR&D programmes. The specific interventions needed to close the current yield gap include the judicious choice of sowing dates and cultivars, the application of nutrient fertilizer, better crop protection, improved soil and water management and the use of cover crops[25–28]. We note that the required practices will have a negligible impact on biodiversity (for example, changes in sowing dates, improved plant nutrition and integrated pest management). Perhaps more importantly, their impact is substantially smaller than that associated with the conversion of forest and savannah for soybean production. Intensification would also benefit from a cropping-system perspective, rather than one focusing on individual crops, to optimize the productivity of the whole crop sequence. For example, using early-maturing soybean cultivars may reduce soybean yield but would allow earlier maize sowing and higher yield, leading to higher annual productivity and profit for the whole cropping system. Regarding pasture-based livestock systems, previous studies have shown that ample room exists for intensification, considering that the current productivity represents only 20–30% of the potential[29–35]. Hence, our assumption of a modest 12% increase in stocking rates leading to land sparing for soybean production, while meeting projected beef demand, is reasonable and feasible to achieve within a relatively short period.

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 the local level[36,37], showing that intensification can help achieve a reasonable balance between crop production and the 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 programmes can help protect fragile ecosystems from conversion[15,38]. However, recent examples in Brazil and other countries have shown that these programmes fall short in protecting forests in countries that depend heavily on crop commodity exports, especially when the socio-economic and policy context is favourable for converting natural ecosystems to agricultural production (for example, high crop prices, poor enforcement of deforestation actions and regularization of illegally grabbed public lands)[7,39–41]. Intensification can complement these other approaches to protect fragile ecosystems, providing a means to reconcile economic and environmental goals. For example, intensification can mitigate the usually large opportunity cost associated with programmes that prevent land conversion for agriculture by fostering higher production on existing cropland. A key message from our study is that, without an emphasis on intensifying crop production within the existing agricultural area, coupled with strong institutions and policies that prevent deforestation in frontier agricultural areas, it would be difficult to protect the last bastions of forests and biodiversity on the planet while being sensitive to the economic aspirations of countries to develop.

Methods

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: the Pampa, the Atlantic Forest, the Cerrado and the Amazon (Supplementary Section 1). Soybean production is negligible in the Pantanal and the 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 September–October, and maize is sown right after the soybean harvest in late January–February. Single soybean is common in the Pampa, where the drier climate does not allow double cropping. In contrast, higher precipitation allows double cropping in the Amazon, the Cerrado and most of the Atlantic Forest (Supplementary 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 (Fig. 1 and Extended Data Fig. 1). Land use change arising from soybean expansion was estimated using data from the MapBiomas project (v.5.0)[10] (Supplementary Table 1). Our estimation of land use change accounted for the time lag between land conversion and the beginning of soybean production, which can include transitional stages such as the cultivation of upland rice or short-term pasture-based livestock systems[42]. To account for this, we looked at the new land brought into soybean production during the 2008–2019 period, and we analysed how much of this land was under a different land use type (forest, savannah, grassland, pasture or other crops) in 2000 (Extended Data Fig. 2).

Estimation of yield potential and yield gaps

We used results on yield potential for Brazil that we generated through the Global Yield Gap Atlas project[43] using well-validated process-based crop models and the best available sources of weather, soil and management data. Briefly, we selected 32 sites to portray the distribution of the soybean harvested area within the country, following protocols that ensure representativeness and a reasonable coverage of the national crop area[44]. The 32 sites collectively accounted for half of the soybean harvested area in Brazil. These sites were located within agro-climatic zones accounting for 86% of the national soybean production and accounted for 72–92% of the soybean area in each region. Following protocols that gave preference to measured data at a high level of spatial and temporal resolution[45], we collected databases on weather, soil, management and crop yields for soybean for each site, and also for second-crop maize at those sites where double-cropping is practised (Supplementary Tables 2 and 3 and Supplementary Section 3).

Yield potential was simulated for widespread cultivars in each region using the CROPGRO soybean model embedded in DSSAT v.4.5[46] and the Hybrid-Maize model[47]. Both models simulate crop growth and development on a daily time step. Growth rates are determined by simulating both CO_2 assimilation and respiration, with partitioning coefficients to different organs dependent on developmental stage. The model phenological coefficients were calibrated to portray the crop cycle of the most dominant cultivars in each region in Brazil. We used generic default coefficients for growth-related model internal parameters such as photosynthesis, respiration, leaf area expansion, light interception, biomass partitioning and grain filling. In all cases, simulations of yield potential assumed the absence of insect pests, weeds and diseases and no nutrient limitations. In simulating yield potential, both models account for solar radiation, photoperiod, temperature, and the timing and amount of rainfall as well as soil properties influencing crop water balance.

We first evaluated the CROPGRO and Hybrid-Maize models on the ability to reproduce measured phenology and yields across 40 well-managed experiments located across the four regions. The models showed satisfactory performance at reproducing the measured values (Extended Data Fig. 3). We then simulated soybean yield potential for the dominant agricultural soils at each site (usually two or three), as determined from the soil maps generated by the Radambrasil project[48]. The simulations were based on long-term (1999–2018) measured daily weather data retrieved from the Brazilian Institute of Meteorology[49]. Soybean yield potential was simulated for each year of the time series. We also simulated yield potential for second-crop maize for those sites

where double-cropping is practised. To do so, we used sowing dates and cultivar maturities that maximize the overall productivity of the soybean–maize system; these sowing dates and cultivar maturities are within the current ranges in each region[21,28]. To estimate the average yield potential for each site, we weighted the simulated values for each soil type by soil area fraction at each site. In all cases, the simulations assumed no limitations to crop growth due to nutrient deficiencies or incidence of biotic stresses such as weeds, insect pests and pathogens. The results were upscaled from site to region and then to country following van Bussel et al.[44]. Briefly, the average yield potential for each region was estimated by averaging the 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 the national level. Details on crop modelling, data sources and upscaling are provided in Supplementary Section 3.

The average farmer yield was calculated separately for soybean and second-crop maize on the basis of the average yield reported over the 2012–2017 period for the municipalities that overlap with each site, weighing municipalities on the basis of 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 the 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 Section 2).

Assessing scenarios of intensification and land use change

We explored three scenarios with different soybean and maize yields and areas by 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 closing 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 BAU scenario, historical (2007–2019) trends of soybean and second-crop maize area and yield (Extended Data Fig. 1) remain unchanged in all regions between the baseline year (2019) and the final year (2035). Likewise, soybean area expands following the same pattern of land use change observed during 2008–2019 (Extended Data Fig. 2).

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

Finally, we explored a third scenario of intensification plus target area expansion (INT), in which identical yield gain rates and the adoption of double-cropping equivalent to those in the NCE scenario were assumed, but with physical expansion of the soybean–maize system allowed in low-C ecosystems (that is, pastures and grasslands). In this scenario, soybean expansion is limited to 5% of existing pastures and grasslands in the Pampa, the Atlantic Forest and the Cerrado (total of 5.7 Mha) as a result of a parallel intensification in the pasture-based livestock sector that frees up land for soybean production. The latter would require an increase of current stocking rates, not only for freeing up 5% of the area for soybean cultivation but also to meet the projected 7% beef production increase during the study period (2020–2035)[17]. Hence, an overall 12% increase in stocking rates would be required within our 15-year timeframe, which is a reasonable target as reported in previous studies and based on current trends in stocking rates[16,29,32,33].

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 the Amazon to prevent 'leaking' effects and the impact of road development on land clearing[50,51]. Similarly, the conversion of area cultivated with food crops for soybean production was not allowed to avoid the negative impact of indirect land use change[52].

Estimation of GWP and gross income

We estimated GHG emissions, 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, NCE and INT). GHG_{LUC} includes emissions associated with changes in C stocks from aboveground and belowground biomass when land is converted for soybean production (GHG_{BIO}), as well as GHG emissions derived from changes in soil organic C (GHG_{SOC}). For each land use type, annual GHG_{BIO} was estimated on the basis of the difference between C stocks of 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[53–55]:

$$GHG_{BIO} = \sum(TDM_i - TDM_{crop}) \times A_i \qquad (1)$$

where i is the land cover type, TDM is the total dry matter (tC ha^{-1}) in land cover type i and in cropland (crop), and A_i is the annual area converted from land use type i for soybean cultivation (Supplementary Table 4). C stocks for single soybean and soybean–second-crop maize systems were assumed at 2 and 5 tC ha^{-1}, respectively[53–55]. Changes in SOC stocks were estimated following the Intergovernmental Panel on Climate Change 2019 guidelines[54], available country-specific emission factors[56] and the SOC values estimated for each region[57,58]:

$$GHG_{SOC} = \sum(SOC_{REF,i} \times F_{LU}) \times A_i \qquad (2)$$

where SOC_{REF} is the SOC stock for mineral soils in the upper 30 cm for the reference condition (tC ha^{-1})[57] in land cover type i (Supplementary Table 5), and F_{LU} is the stock change factor for SOC land-use systems for a particular land use (Supplementary Table 4). Because no-till is the predominant soil management strategy in Brazil[59], we used $F_{LU} = 0.96$ for natural vegetation converted to no-till annual crop production, and $F_{LU} = 1.16$ for pasture and grassland converted to no-till annual crop production[56]. Because we wanted to assess the full impact of the three scenarios (BAU, NCE and INT) on GWP, we assigned all GHG_{BIO} and GHG_{SOC} derived from land conversion to the first year after land conversion and expressed them 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, soil N_2O emissions derived from the application of nitrogen (N) fertilizer, and domestic grain transportation. For the baseline year (2019), annual GHG emissions from N, phosphorous (P) and potassium (K) fertilizers and other inputs (lime, pesticides and fuel) were calculated on the basis of 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 and Supplementary Section 3.4). To calculate GHG emissions associated with manufacturing, packaging and transportation of N, P and K fertilizers and lime, we used specific updated emissions factors for South America[60], 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 in converted areas. Emission factors associated with seed production, pesticides and diesel were derived from ref. [61]. Soil N_2O emissions derived from N fertilizer application were calculated assuming an N_2O emission factor of 1% of the applied N fertilizer on the basis of the country-specific emission factor[62]. Emissions derived from domestic grain transportation for each region were estimated using the GHGs per ton of grain as reported by previous studies for each region[63]. We assumed that inputs other than nutrient fertilizer will not change relative to the baseline in the BAU scenario. In the INT scenario, applied inputs were calculated on the basis of those reported for current high-yield fields where the yield gap is small. We estimated fertilizer nutrient rates for the three scenarios following a nutrient-balance approach that depends on the projected yield for each scenario (Supplementary Table 6 and Supplementary Section 3.4).

GHG$_{PROD}$ in the baseline year (2019) and for the three scenarios in 2035 (BAU, NCE and INT) was estimated for each region by multiplying the emissions per unit of area by the annual soybean harvested area, summing them to estimate GHG emissions at the national level. Overall 100-year GWP was estimated as the sum of GHG$_{LUC}$ and GHG$_{PROD}$, both expressed as CO_2e 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 a per mass basis, respectively. The gross income was estimated for each scenario by multiplying the annual crop production by the average price for soybean and maize grain during the past ten years (US$453 and US$184 per t for soybean and maize, respectively[1]). Finally, to combine the environmental and economic impacts into one metric, we calculated the GWP intensity as the ratio between GWP and gross income.

Reporting summary
Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
The data on yield potential and yield gaps that support the findings of this study are publicly available via the Global Yield Gap Atlas website (www.yieldgap.org). The data that support the findings of this study are also available from the corresponding author upon request. Source data are provided with this paper.

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Author contributions

F.R.M., P.G. and A.J.Z. conceived the project. E.H.F.M.S., G.L.R., L.A.S.A., B.S.M.R.R. and G.G.R. collected the data and ran the

Competing interests

The authors declare no competing interests.

Additional information

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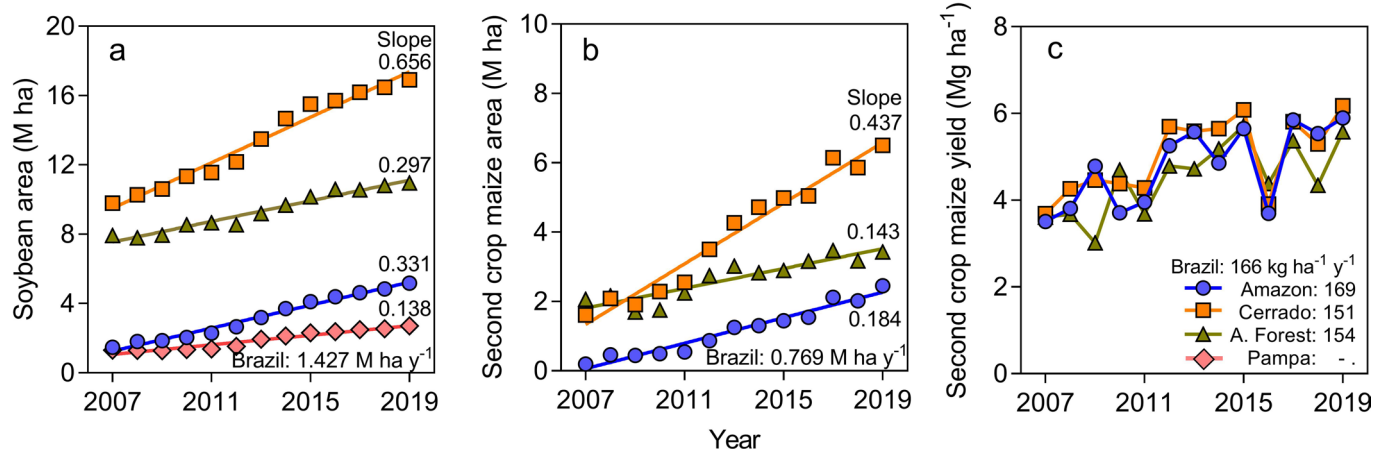
Extended Data Fig. 1 | Historical trends of yield and harvested area for soybean and second-crop maize in Brazil. Fitted models are shown in (a) and (b), but not in (c) to avoid overlapping. Slopes of the fitted linear regression models are shown. Slopes were statistically different from zero in all cases as evaluated using double-tailed, t-tests: P < 0.0001 for all slopes in (a) and (b) and P = 0.0075 (Amazon), P = 0.0113 (Cerrado), and P = 0.0057 (A. Forest) for slopes in panel (c). Data on yield and crop area was retrieved from IGBE[16].

Source of soybean new area (2008-2019)
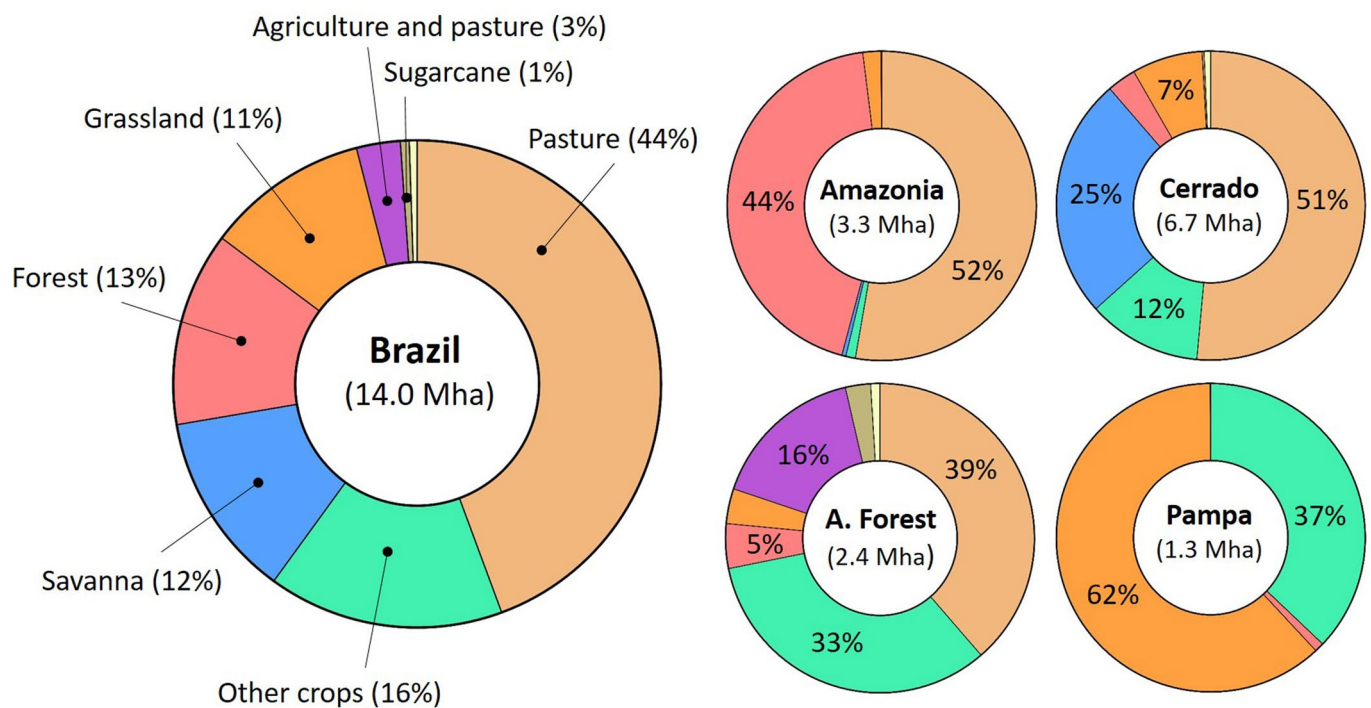
Extended Data Fig. 2 | Land use change driven by soybean production in Brazil. Proportion of land type by year 2000 that was converted for soybean production during the 2008-2019 period as estimated from the MAPBIOMAS Project – Collection 5.0[10]. Separate pie charts are shown for the whole Brazil and for each of the soybean producing regions. See Supplementary Information for details on calculations of land-use change.
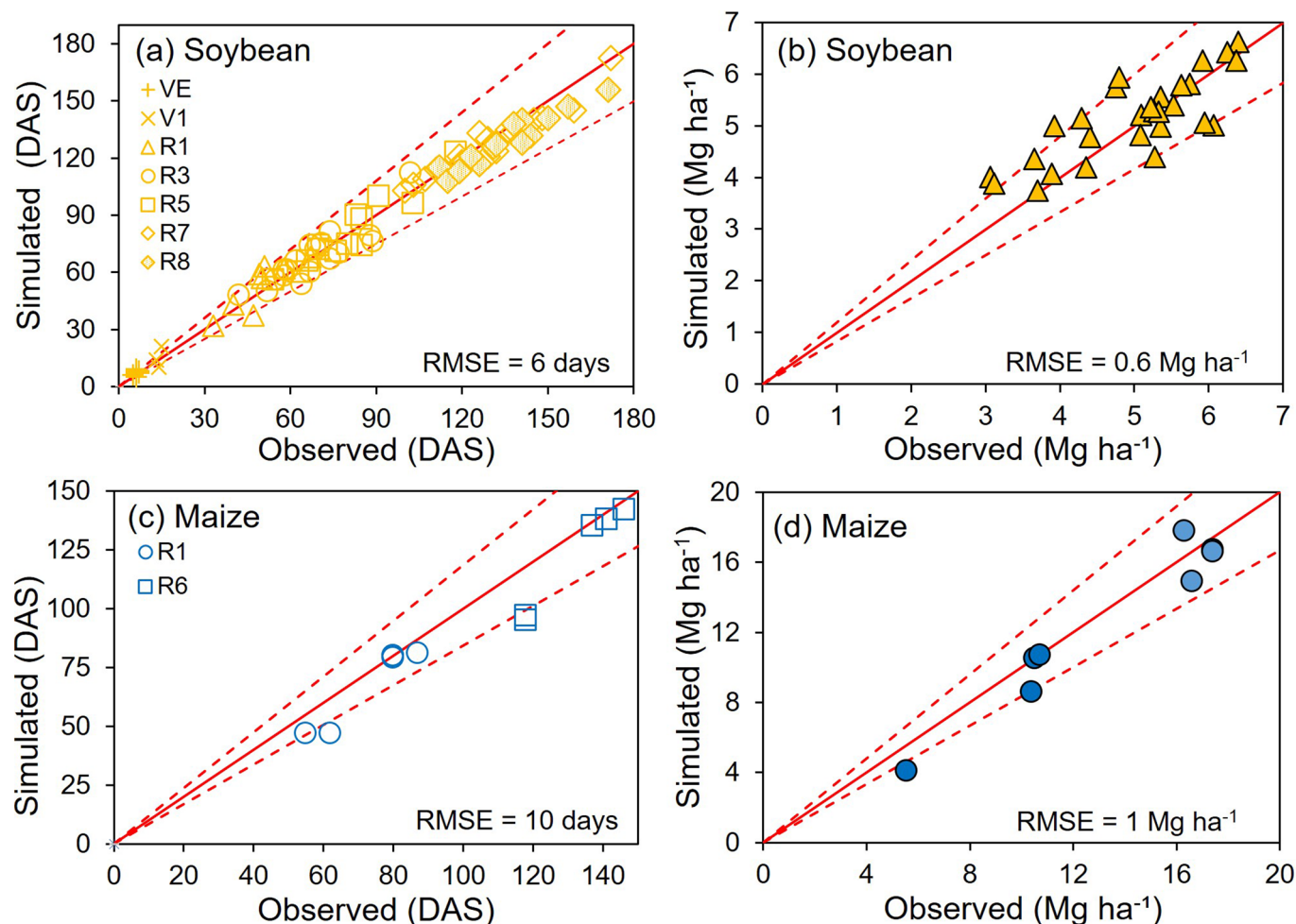
Extended Data Fig. 3 | Evaluation of crop models used for estimation of yield potential for maize and soybean in Brazil. Comparison of simulated and observed phenology (left) and grain yields (right) for soybean (upper panels) and maize (bottom panel) based on well-managed experiments conducted across main producing regions in Brazil, where crops were grown without nutrient limitations and kept free from incidence of biotic stresses such as weeds, insect pests, and pathogens. Phenological stages for soybean and maize based on Fehr and Caviness[65] and Ritchie et al.[66], respectively, are shown. In the case of soybean, stages are emergence (VE), unifoliate leaves (V1), first open flower (R2), beginning pod setting (R3), beginning seed filling (R5), physiological maturity (R7) and harvest maturity (R8). In the case of maize, stages are silking (R1) and physiological maturity (R6). In all cases, stages are reported based on their date of occurrence after sowing (DAS). The solid red line represents y = x and the dashed red lines represent ± 20% deviation from the y = x line. The latter is considered a good threshold to assess accuracy in model prediction. The root mean square error is shown in absolute terms (RMSE).

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Study description	We followed a data-rich spatial approach, consisting of crop modeling coupled with the best available sources of weather, soil, and production data, to determine the available room for increasing soybean and maize production on existing cropland area in Brazil. We estimated potential environmental benefits, in terms of land savings and climate change mitigation, and discussed the required interventions and policies to promote intensification. See Methods section & Supplementary Information for more details.
Research sample	We estimated the scope for crop intensification across sites representative of the soybean production area in Brazil. See Methods section & Supplementary Information for more details.
Sampling strategy	We followed the protocols of the Global Yield Gap Atlas to select representative sites under soybean production in Brazil using a "stratified sampling" approach. Selected sites accounted for most of national soybean area. See Methods section and Supplementary Information for more details.
Data collection	Complete databases on long-term weather, soil properties, and management and productivity data from soybean-based cropping systems were collected across the selected sites. See Methods section & Supplementary Information for more details.
Timing and spatial scale	To account for yield variation due to weather variability, simulations were based on long-term weather data. Results were upscaled from the selected sites to regional and national levels. See Methods section & Supplementary Information for more details.
Data exclusions	No data were excluded from the analysis.
Reproducibility	Raw data inputs used for model simulations and other analyses are available upon reasonable request and data used for figures are provided as Source Data files.
Randomization	Not applicable as we did not conduct field experiments.
Blinding	Not applicable.

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