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Exploring avenues for tropical soybean intensification: how much water and nutrients are demanded to achieve exploitable yield?

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ABSTRACT: The world population is expected to rise by two billion in a few decades, boosting demand for soybean (*Glycine max* L.). Brazil has the world's largest tropical agricultural area, accounting for 40 % of the world's soybean output. This study was conducted to understand the potential and limitations of tropical soybean yield, estimate the amounts of main inputs (water and nutrients), and assess management to reach the crop yield potential (Y_P). We used CROPGRO-Soybean model, based on well-conducted experiments in different locations in Brazil. We generated estimates of Y_P and water-limited crop yield potential ($Y_{P\text{-}W}$), and explored long-term scenarios to evaluate the impact of sustainable practices on water management. Yield gap (Y_G) and agricultural efficiency (E_A) were computed based on simulations and actual yield. The total water and nutrients required to achieve the YP in Brazil were also calculated. According to our simulations, Y_P ranged from 3,952 to 6,084 kg ha^{-1}; $Y_{P\text{-}W}$ from 3,133 to 5,186 kg ha^{-1}, and YG from 589 to 4,401 kg ha^{-1}. On average, drought stress negatively affected 14 % of Y_P, while 42 % of Y_P was lost due to management failures. Irrigation was needed in 26 % of the soybean-planted areas in Brazil to mitigate the risks associated to seasonal rainfall variations. Our findings revealed that it was possible to save around 20 % of the water through conservative soil practices and 25.0 106 Mg of macronutrients (N = 356 kg ha^{-1}, P = 31 kg ha^{-1}, K = 104 kg ha^{-1}) annually is required to reach the exploitable soybean yield.

Keywords: agricultural efficiency, agricultural intensification, macronutrients, water management, yield gap

Introduction

Brazil is the world's largest soybean producer [*Glycine max* (L.) Merr] with a production of 163 million tons and a harvested area of 45.6 million ha (USDA, 2022). The vast majority (85 %) of the global increase in soybean production between 2002 and 2014 was due to the expansion of the harvested area, which offset the slower yield gains (Cassman and Grassini, 2020). These trends highlight the importance of research on the exploitable yield gap, considering the need to increase food production in the face of limited agricultural land (Marin et al., 2022).

The exploitable crop yield relies on effectively accessing essential water and nutrients from the soil and atmosphere (van Ittersum et al., 2013). Water scarcity poses as the most significant constraint to crop yields, and agriculture consumes 70 % of the world's freshwater resources (Armengot et al., 2021; Siyal et al., 2021). Thus, enhancements in water management could result in more efficient use of this resource, potentially improving the sustainability of agricultural systems in tropical environments (Silva et al., 2021a, 2022). Efficient management of fertilizers is also crucial to improve agricultural activities. In recent decades, fertilizers have significantly ensured high and consistent crop yields, accounting for 30-50 % of crop production globally (Chen et al., 2018; Dobermann et al., 2022).

In this sense, assessing the yield potential (Y_P), the water-limited crop yield potential ($Y_{P\text{-}W}$), and the yield gap (Y_G) of soybeans is a valuable means of exploring options to optimize agricultural practices and promote sustainability. In this study, we used the Cropping System Model (CSM)-CROPGRO-Soybean model (Boote et al., 2003; Hoogenboom et al., 2019) as a tool to quantify the effects of water use and crop management on plant growth and to estimate Y_P and $Y_{P\text{-}W}$.

Our study used a standardized protocol for field experiments, crop model simulations, and extrapolation of results to represent the entire soybean-producing region in Brazil. This study provides a novel and robust approach to computing and understanding of water and nutrient requirements to reach the soybean yield potential in tropical environments. The objectives were to estimate the soybean Y_P, $Y_{P\text{-}W}$ and yield gap and determine the water and nutrients required to reach the Y_P in tropical environments.

Materials and Methods

Calibration and evaluation of CROPGRO-Soybean and information on field experiments

The CROPGRO-Soybean model v.4.7 (Jones et al., 2003; Hoogenboom et al., 2019) was previously calibrated and evaluated. The authors used a robust dataset collected in 13 well-managed field experiments with consistent protocol [(see experimental design and management information in Silva et al. (2023) and Setubal et al. (2023)], representing thoroughly the soybean production system in tropical environments in Brazil.

The authors obtained an excellent agreement between simulated and observed values for leaf area index [index of agreement (D-statistics) between 0.92 to 0.99, and root-mean-square error (RMSE) between 0.21 to 0.82], leaf dry matter (D-statistics between 0.87 to 0.99, and RMSE between 43 to 528 kg ha^{-1}), stem dry matter (D-statistics between 0.87 to 0.98, and RMSE between 156 to 650 kg ha^{-1}), grain weight (D-statistics between 0.96 to 0.99, and RMSE between 48 to 650 kg ha^{-1}), aboveground dry matter (D-statistics between 0.93 to 0.99, and RMSE between 232 to 1,536 kg ha^{-1}), crop yield (bias between −611 to 348 kg ha^{-1}), and grain protein (bias −1 to 3 %) and oil concentration (bias −6 to 5 %) for all cultivars. For instance, the crop yield prediction showed an average bias of −120 kg ha^{-1} (or −3 %) (Silva et al., 2023). The cultivar traits obtained were used in the simulations (Table 1). In this study, we applied these well-evaluated cultivar traits for the first time to simulate Y_P and Y_{P-W} using CROPGRO-Soybean.

Long-term simulations for Y_P, Y_{P-W}, and computation of Y_G under tropical conditions

For long-term simulations, we utilized the 16 agroclimatic zones (CZ) defined by Silva et al. (2021b) to represent the soybean production area in Brazil [see Figure 1 from Silva et al. (2021b)]. To define the CZ, we used official statistical data on soybean harvested area in Brazil provided by the Instituto Brasileiro de Geografia e Estatística (IBGE, 2022) and followed the protocol described by van Wart et al. (2013), based on three factors: crop degree days, annual dryness index, and seasonality of air temperature. To account for the total area of each CZ, we made minor modifications: we considered the harvested area of the last five harvests (2017-2022). We selected only municipalities with an average harvested area greater than 600 ha as criteria to identify consolidated soybean production areas. Approximately 98 % of the soybean production area in Brazil was covered to achieve these criteria.

To set up CROPGRO-Soybean for Y_P and Y_{P-W} simulations for each CZ, the following steps were taken: (i) weather data for each CZ from 1990 to 2021 was acquired from NASA POWER (Sparks, 2018) on a daily basis (Table 2); (ii) the soil file was created by merging data on soil extraction from the Brazilian Soil Map (EMBRAPA, 2022) with information from the WISE (World Inventory

Table 1 – Calibrated values for cultivar coefficients for soybean cultivars (TMG 7062, TMG7063, NS7901, 65i65RSF, 8579RSF) used in this study. Source: Silva et al. (2021b).

Traits[1]	TMG 7062	TMG 7063	NS7901	65i65RSF	8579RSF
CSDL	12.58	12.33	12.07	12.58	12.07
PPSEN	0.311	0.320	0.330	0.311	0.001
EM-FL	25.5	20.5	26.7	25.1	19.7
FL-SH	11.5	9.8	10.5	8.0	9.1
FL-SD	15.3	15.2	16.3	13.5	14.9
SD-PM	33.0	36.2	34.2	36.6	32.1
FL-LF	18.8	18.0	18.0	18.8	34.0
LFMAX	1.30	1.03	1.03	1.30	1.40
SLAVR	400	495	435	400	400
SIZLF	180	210	180	180	190
XFRT	1	1	1	1	1
WTPSD	0.18	0.18	0.18	0.18	0.19
SFDUR	26	23	23	26	21
SDPDV	2.40	2.05	2.05	2.4	2.30
PODUR	10	10	10	10	10
THRSH	78	78	78	78	77
SDPRO	0.408	0.400	0.400	0.360	0.315
SDLIP	0.180	0.200	0.200	0.170	0.210

[1]Definition of each trait can be found in Boote et al. (2003).

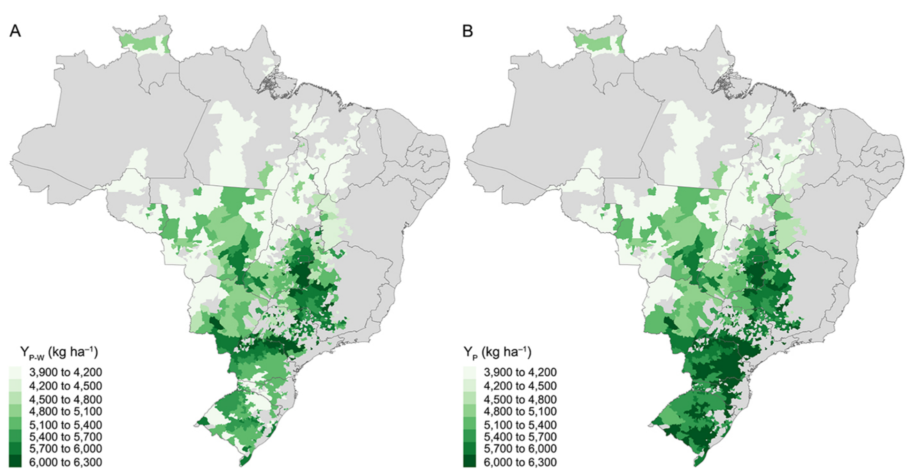

Figure 1 – A) Long-term simulations (1990-2021) for average water-limited crop yield potential [Y_{P-W}] and B) average crop yield potential [Y_P] in Brazil.

Table 2 – The weather station used to represent each agroclimatic zone (CZs), official sowing window, soil profile, long-term annual average temperature and total annual rainfall, and cultivar calibration selected for CROPGRO-Soybean simulations. Source: Silva et al. (2021b adapted).

CZs	Weather Station	Sowing date window		Soil profile	Average temperature and annual rainfall	Cultivar
6801	Cascavel - PR	8 Sept	31 Dec	Ultisols	18.2 °C 1,822 mm	TMG 7062
6901	Dom Pedrito - RS	17 Sept	31 Dec	Entisols	18.5 °C 1,313 mm	65i65 RSF
7501	Unaí - MG	7 Oct	31 Dec	Oxisols	23.5 °C 1,275 mm	TMG 7063
7601	Cristalina - GO	27 Sept	31 Dec	Oxisols	20.1 °C 1,422 mm	TMG 7063
7701	Jataí - GO	27 Sept	31 Dec	Oxisols	23.3 °C 1,541 mm	TMG 7063
7801	Primavera do Leste - MT	27 Sept	31 Dec	Ultisols	22.0 °C 1,784 mm	NS 7901
7802	São Borja - RS	27 Oct	31 Dec	Oxisols	20.5 °C 1,567 mm	65i65 RSF
7901	Palmeira das Missões - RS	17 Sept	31 Dec	Oxisols	18.7 °C 1,838 mm	65i65 RSF
8401	Formosa do Rio Preto - BA	17 Oct	31 Jan	Oxisols	24.3 °C 902 mm	NS 7901
8501	Barreiras - BA	17 Oct	31 Jan	Entisols	24.9 °C 1,045 mm	NS 7901
8601	Canarana - MT	30 Sept	25 Dec	Oxisols	24.8 °C 1,541 mm	NS 7901
8701	Sorriso - MT	30 Sept	25 Dec	Oxisols	25.0 °C 1,883 mm	NS 7901
8801	Nova Mutum - MT	30 Sept	25 Dec	Entisols	25.2 °C 958 mm	NS 7901
9301	Bom Jesus - PI	6 Nov	9 Feb	Entisols	26.7 °C 1,002 mm	8579RSF
9501	Balsas - MA	17 Oct	20Jan	Entisols	26.4 °C 1,190 mm	8579RSF
9701	Lagoa da Confusão - TO	8 Oct	1 Mar	Inceptisols	27.2 °C 1,882 mm	8579RSF

PR = state of Paraná; RS = state of Rio Grande do Sul; MG = state of Minas Gerais; GO = state of Goiás; MT = state of Mato Grosso; BA = state of Bahia; PI = state of Piauí; MA = state of Maranhão; TO = state of Tocantins.

of Soil Emission Potentials) database, available at the International Soil Reference and Information Centre (ISRIC - http://www.isric.org). For the dominant soil type in each CZ (Table 2), data on soil holding characteristics, curve number, infiltration, and runoff was from these database; (iii) the sowing interval data was obtained using the sowing window recommended by the Ministério da Agricultura, Pecuária e Abastecimento (MAPA, 2022), with 5-day intervals between simulations (Table 2); (iv) Y_P and $Y_{P\text{-}W}$ were simulated for each soybean cultivar (Table 1) and, after simulations, we selected the cultivar with the highest averaged Y_P (Table 2); (v) the FAO-56 Penman-Monteith potential evapotranspiration method (Allen et al., 1998) combined with the Ritchie Two-Stage soil water evaporation method (Ritchie, 1972) was used, as it showed a better performance to simulate crop evapotranspiration under tropical conditions (Silva et al., 2022); (vi) the soil organic matter method used was Century, as described by Gijsman et al. (2002); (vii) soil water balance was initiated with 50 % of the available soil water content 30 days before sowing.

For Y_P simulations, water and nitrogen (N) options were turned off in CROPGRO-Soybean, and for $Y_{P\text{-}W}$ we only kept on water options to assess the effects of water on crop yield. The Y_G was determined by subtracting the average Y_P from the crop yield. For Y_A, we used the IBGE (2022) database to calculate the average soybean yield in each municipality of each CZ for the last five seasons (2017-2022). We treated this as a sample of mean yield at farms, accounting for multiple soils, cultivars, and sowing dates. Agricultural efficiency (E_A) was calculated as the ratio between Y_G and $Y_{P\text{-}W}$. We conducted approximately 19,200 simulations, accounting for site-year interactions (1990 to 2021 for 16 CZ), to obtain Y_P and $Y_{P\text{-}W}$. Based on these simulations, we estimated the long-term scenarios for: yield average, yield lower limit (here defined as average less one standard deviation), and yield upper limit (here defined as average add one standard deviation).

Simulations of long-term water management scenarios

After simulating Y_P and $Y_{P\text{-}W}$, we carried out a seasonal analysis using what-if scenarios to explore water management practices in each CZ where the ratio between $Y_{P\text{-}W}$ and Y_P exceeded 0.90 (eight CZ). This threshold was established because it is unlikely that a farmer-producer uses irrigation to boost crop yield by less than 10 %. Or, from a risk analysis viewpoint, we are selecting areas to irrigate where the risk is not reaching Y_P due to seasonal rainfall variation higher than 10 %. The aim of these hypothetical scenarios (Tsuji et al., 1998; Thornton and Hoogenboom, 1994; Silva et al., 2021a, 2022, 2023) was to identify water management strategies that could enhance water use efficiency.

We applied the following long-term water management scenarios: (i) CT = conventional tillage practices with the original soil root growth factor (SRGF); (ii) NT = no-tillage practices with 8,500 kg ha^{-1} of crop surface residue (maize) under the initial conditions, with no changes in SRGF; (iii) NT + SRGF = no-tillage practices with 8,500 kg ha^{-1} of crop surface residue (maize) under the initial conditions, and soil root growth factor changed; and (iv) irrigation application under scenarios CT, NT, and NT + SRGF.

In CROPGRO-Soybean, the SRGF is a critical soil-plant parameter because it influences the maximum amount of soil water content that roots can extract (Wang et al., 2003; Mulazzani et al., 2022). We changed the SRGF factor based on values obtained by Battisti and Sentelhas (2017), which used the proportional soybean root length density distribution observed in high-yield fields in Brazil. We also followed the recommendation of Silva et al. (2021a) for tropical environments to trigger irrigation when soil water availability at the top 0.30 m of the soil profile falls to 60 %. Additionally, we calculated the amount of irrigation applied per season by multiplying the total soybean harvest area (municipality level) with the average of the last five seasons (2017-2022) provided by IBGE (2022).

Literature review for nutrient uptake during soybeans season and long-term scenarios for nutrient demand

A systematic literature review was carried out to provide the necessary knowledge on research about macronutrient uptake for soybean crop systems. The data was extracted from scientific articles published (2012-2022) and indexed in the Scopus and Web of Science databases. The keywords used were "soybean", "nutrient uptake", "nutrient extraction", and "macronutrient". We only considered studies that computed the amount of nutrient uptake by a whole plant (seed + stover), and when the study had more than one treatment, we used the means of the treatments.

We considered literature on macronutrient accumulation by crop yield, and then, we obtained the average of each nutrient uptake during soybean seasons (Table 3): (i) = 69.81 g kg^{-1} of N in grains, (ii) = 7.50 g kg^{-1} of P in grains, (iii) = 40.17 g kg^{-1} of K in grains, (iv) = 24.80 g kg^{-1} of Ca in grains, (v) = 10.86 g kg^{-1} of Mg in grains, and (vi) = 3.64 g kg^{-1} of S in grains. Finally, the total amount of each nutrient needed to reach Y_P was computed by multiplying Y_P by soybean harvested area (IBGE, 2022) and nutrient accumulation per kg of grain for each CZ. For the final calculation of macronutrient demand, we considered the exploitable yield, which is 80 % of Y_P (van Wart et al., 2013).

Table 3 – Total nutrient uptake in soybean grain, compiled from selected nutrient accumulation studies from 2012 to 2022.

Reference	N	P	K	Ca	Mg	S
			g kg^{-1}			
Kumawat et al. (2021)	85.06	8.73	46.54	---	---	---
Barth et al. (2018)	73.45	5.82	30.30	17.12	7.36	3.25
Gaspar et al. (2017)	---	6.56	35.54	---	---	---
Caires et al. (2017)	46.69	5.43	53.08	---	---	---
Monsefi et al. (2016)	82.49	10.86	55.00	---	---	---
Chander et al. (2015)	59.06	3.98	22.01	---	---	2.23
Bender et al. (2015)	79.02	6.03	40.80	32.47	14.36	5.45
Aulakh et al. (2012)	63.13	9.84	---	---	---	---
Patil et al. (2012)	69.63	10.20	38.06	---	---	---
Devi et al. (2012)	---	7.49	---	---	---	---
Average	69.81	7.50	40.17	24.80	10.86	3.64

Results

Using different simulated sowing dates, cultivars, and soil types, we obtained an average $Y_{P\text{-}W}$ of 4,684 kg ha^{-1} and 5,441 kg ha^{-1} for Y_P (Figure 1A and B), with an average Y_A of 3,092 kg ha^{-1} under 16 CZ. Our results demonstrated a robust correlation between Y_P (or $Y_{P\text{-}W}$) and the sowing date.

The lower limit of long-term scenarios for crop yield (Figure 2A and B) revealed that unfavorable sowing dates might lead to a Y_P of 4,800 kg ha^{-1} (641 kg ha^{-1} lower than the average Y_P) and a $Y_{P\text{-}W}$ of 4,353 kg ha^{-1} (331 kg ha^{-1} lower than the average $Y_{P\text{-}W}$). The sowing dates associated to unfavorable conditions are typically at the end of Dec for Y_P and mid-Oct for $Y_{P\text{-}W}$.

However, the best sowing dates presented in our long-term scenarios for the upper limit yield (Figure 2D and C) could result in a Y_P of 5,854 kg ha^{-1} (413 kg ha^{-1} greater than the average Y_P) and a $Y_{P\text{-}W}$ of 5,186 kg ha^{-1} (502 kg ha^{-1} higher than the average $Y_{P\text{-}W}$). These optimal sowing dates, in general, are observed at the beginning of Oct for Y_P and mid-Sept for $Y_{P\text{-}W}$.

The computed Y_G averaged 2,349 kg ha^{-1}, ranging between 589 and 4,401 kg ha^{-1} (Figure 3A). Our results exhibited a marginal increase of up to 1 % in crop yield when comparing CT and NT practices. A more significant increase ranging from 2 to 5 % was observed when NT combined changes in the SRGF parameter. The computed E_A averaged 50 % with range values between 26 and 87 % (Figure 3B). The highest values of E_A were obtained in some regions of the Brazilian Amazon (states of Amazonas, Pará, Rondônia, and north of Mato Grosso), which have the highest E_A values with an average of 77 %, primarily due to the cultivation of soybean in pastures converted from natural vegetation for cattle production, leading to relatively low Y_P values (approximately 4,010 kg ha^{-1}, Figures 2B, 3A and B). On the other hand, São Paulo State has the lowest E_A values (averaged 43 %), where soybean is generally sown in sugarcane fields without applying low inputs, as reported by Souza and Seabra (2013) and Longati et al. (2020).

According to our findings, the water amount needed for the long-term scenario with conventional tillage in the selected areas (considering CZs 6801, 6901, 7801, 8401, and 9301) was 9,597.94 Mm^3 (Figures 4 and 5A). However, when using conservative soil practices, such as no-till combined with better conditions for root growth, the total water amount required decreased to 7,665 Mm³ (20.14 %) (Figures 4 and 5B).

The total amounts of macronutrients demanded for all CZs to reach exploitable yield ranged from 544 to 838 kg ha^{-1}, with an average of 725 kg ha^{-1} (Figure 6). The average demand of each macronutrient was: 356 kg ha^{-1} for N, 31 kg ha^{-1} for P, 168 ha^{-1} for K, 104 kg ha^{-1} for Ca, 46 kg ha^{-1} for Mg, and 15 kg ha^{-1} for S. Our estimates of macronutrient demand showed an amount of 31.2 10^6 Mg required to reach the Y_P for all

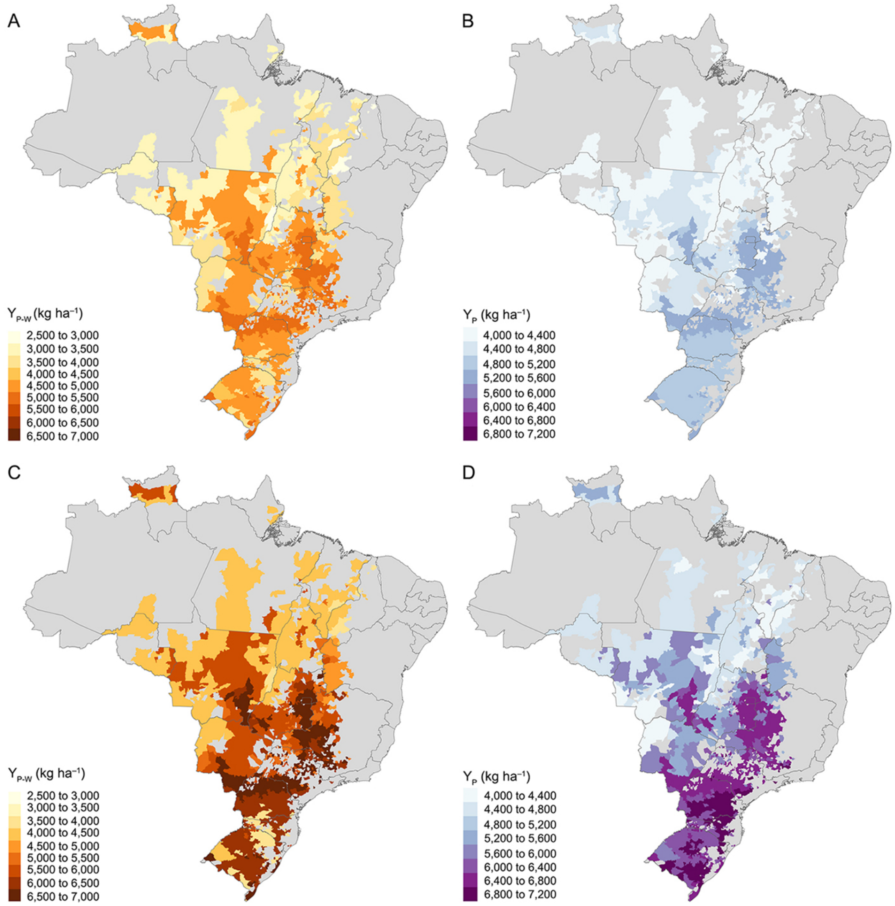

Figure 2 – Long-term scenarios (1990-2019) for water-limited crop yield potential (YP-W) lower limit (A) and upper limit (C); and yield potential (Y_P) lower limit (B) and upper limit (D) in Brazil.

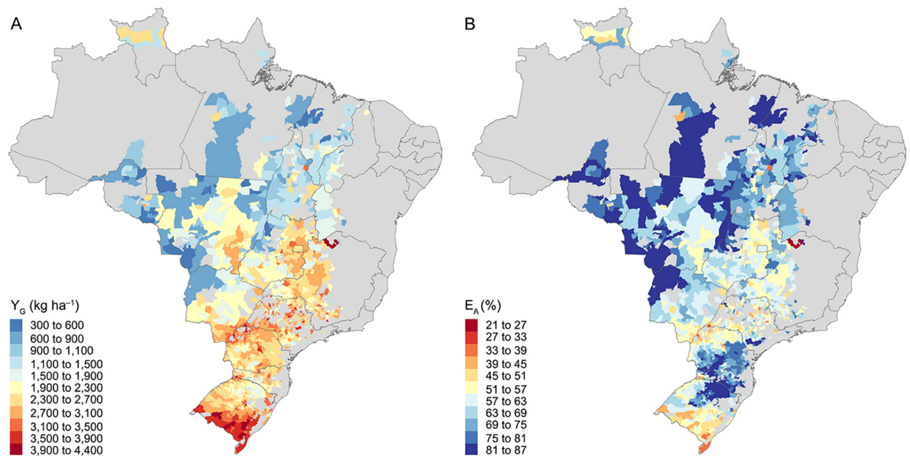

Figure 3 – A) Soybean yield gap (Y_G) computed as the difference between average yield potential (1990-2021) and average actual soybean crop yield (2017-2022) in Brazil, and B) agricultural efficiency (E_A) calculated as the ratio of the actual yield to the yield potential under water-limited conditions.

soybean areas in Brazil (Figure 7A and B). This amount was separated by nutrient, with 24.1 10^6 Mg of primary macronutrients [N, P, K (Figure 7A and C)] and 7.1 10^6 Mg of secondary macronutrients [Ca, Mg, S (Figure 7D-F)]. The total demand for macronutrients was 25.0 10^6 Mg to reach the exploitable yield.

Discussion

Our Y_P estimates were like those of Sentelhas et al. (2015). The authors reported 5,332 kg ha^{-1}. However, our $Y_{P\text{-}W}$ estimate was 27 % higher, at 3,866 kg ha^{-1}. Sentelhas et al. (2015) used the empirical FAO model, which requires only total soil holding capacity, while CROPGRO-Soybean uses a tipping bucket and curve number approach to simulate soil water movement, infiltration, and runoff, which may have contributed to the differences for the $Y_{P\text{-}W}$ estimates. Battisti et al. (2018) estimated higher values of $Y_{P\text{-}W}$ (ranged from 5,442 to 11,296 kg ha^{-1}) and Y_P (ranged from 7,595 to 13,378 kg ha^{-1}) using a database from soybean contest areas that are not representative of real areas of farmers and without standardization for the data collected. In a study conducted in the Cerrado biome, Y_P was estimated between 11,075 and 12,078 kg ha^{-1}, and $Y_{P\text{-}W}$ ranged from 5,552 to 8,271 kg ha^{-1} (Santos et al., 2021). For both estimations (Battisti et al., 2018; Santos et al., 2021), the values seem overrated in comparison with other studies conducted in areas of more solar energy availability combined with non-limiting temperatures (higher yield potential) under temperate environments (e.g., Grassini et al., 2014; Rizzo et al., 2021).

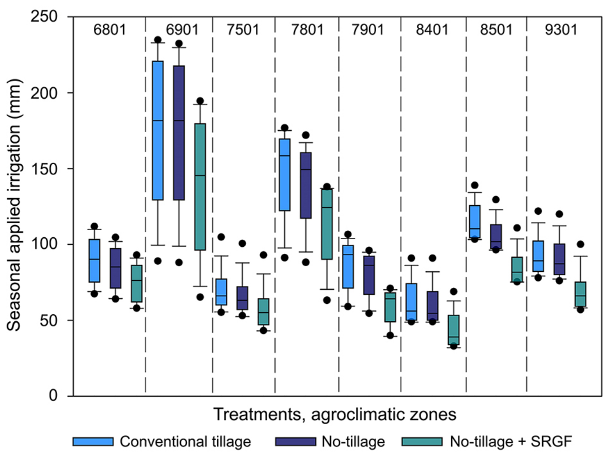

Figure 4 – Long-term scenarios (1990-2019) for seasonally applied irrigation under conventional tillage, no-tillage, or no-tillage practices with changes in the SRGF (soil root growth factor) parameter under agroclimatic zones (CZs).

Upon comparing the ratio between the averages of Y_P and $Y_{P\text{-}W}$, our research findings have indicated that, in 74 % (25.4 M ha) of soybean production areas in Brazil, the degree of water limitation responded to less than 10 % losses in crop yield. The Y_P was penalized by drought stress from 3 to 32 % (14 % on average) in all CZs. Overall, the soybean production areas in Brazil exhibited a good average $Y_{P\text{-}W}$, with relatively small losses due to drought in most areas. This stands in contrast to studies conducted in other countries, where the soybean Y_P depletion by drought stress varied from 5 to 61 % in Mississippi, the United Sates (Zhang et al., 2016), up to 50 % in Uruguay (Rizzo et al., 2021), and 10 to 28 % in India (Bhatia et al., 2008). Nevertheless, 26 % of the soybean area in Brazil (CZs: 6801, 6901, 7501, 7801, 7901, 8401, 8501, and 9301) require improvements in agricultural water management to increase the yield level.

The sowing dates played a crucial role in determining the Y_P by affecting the crop cycle duration, which, in turn, was influenced by solar radiation and air temperature. This observation is consistent with the findings of similar studies conducted in the United States (Grassini et al., 2014; Edreira et al., 2017) and Argentina (Vitantonio-Mazzini et al., 2021) on soybean crops.

In the case of rainfed soybeans (i.e., $Y_{P\text{-}W}$ at drought losses), predicting the ideal sowing date is more challenging due to the need to balance the effects of water stress and the reduced energy availability (solar radiation). Given the various factors contributing to rainfall uncertainty, accurate long-term rainfall forecasts remain challenge (Asnaashari et al., 2015; Ni et al., 2020;

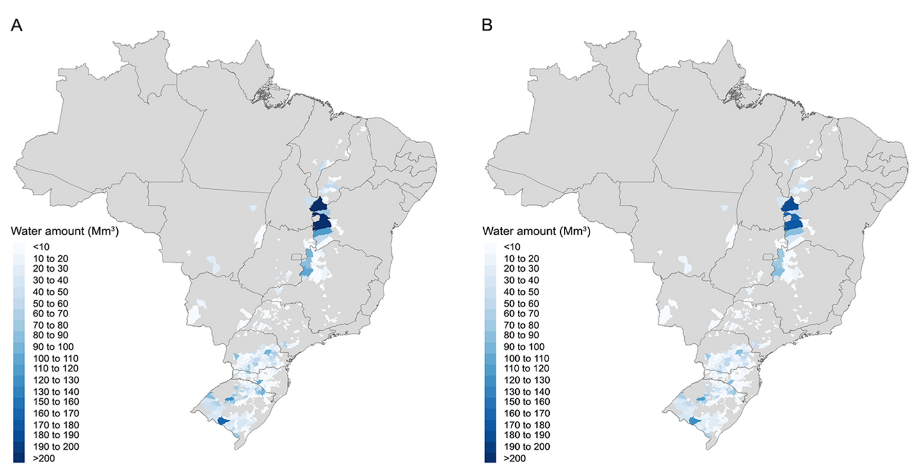

Figure 5 – Average of long-term scenarios (1990-2019) for total seasonal irrigation applied in soybean, under treatments with conventional tillage (A), and no-tillage with changes in the SRGF (soil root growth factor) parameter (B). We use the average harvested area under five last seasons (2017-2022) reported by IBGE (2022).

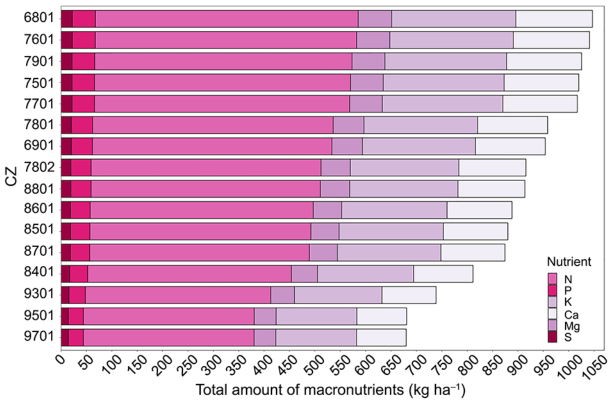

Figure 6 – Total amount of macronutrients required to reach the average crop yield potential for each agroclimatic zone (CZ). The bars show the amount of each macronutrient: nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S).

Raval et al., 2021). Therefore, soybean crops grown under a well-managed irrigated system could benefit from an additional yield increase by appropriately selecting the sowing date rather than avoiding drought stress.

Our estimation of Y_G contrasts with the findings of Nóia Júnior and Sentelhas (2020), who reported a lower average Y_G of 1,641 kg ha^{-1}. However, their study employed only one cultivar (BRS 284-maturity group 6.5) calibrated by Battisti and Sentelhas (2017) using experiments conducted in Southern Brazil to simulate crop yield potential for the entire country. The simplification by employing a single maturity group is inadequate to realistically represent the complex soybean crop systems in Brazil. It may explain the underestimation of Y_G obtained by Nóia Júnior and Sentelhas (2020) compared to our results. In contrast, the soybean yield gap in Rio Grande do Sul (RS), the southernmost state of Brazil, found a Y_G ranging from 4,150 to 4,800 kg ha^{-1} (Tagliapietra et al., 2021). Our estimates of Y_G for Rio Grande do Sul State ranged from 1,628 to 4,157 kg ha^{-1}, reflecting the higher Y_G in the southern region due to the more significant losses caused by the water deficit (Figures 1A and 3A).

The computed E_A indicated that nearly half of the potential soybean production in Brazil is lost due to inadequate crop management practices such as inappropriate sowing date, suboptimal seeding rate, improper cultivar selection, unsuitable tillage method, limited nutrient availability, and inadequate control of biotic stress factors, such as insects, diseases, and weeds. Thus, our findings highlight the need to implement more effective crop management practices in Brazil to increase the efficiency of rainfed soybean production and minimize the yield gap.

This increase is primarily attributed to the positive effects of SRGF on soil and crop management, particularly on root growth, which has been previously established by Battisti and Sentelhas (2017). Moreover, our findings show that NT + SRGF can lead to substantial water savings compared to CT practices, with water savings ranging from 16 to 30 %, and averaging 20 %. Conversely, the difference in water use efficiency between CT and NT practices was relatively minor, ranging from 1 to 5 % (Figure 4). These results indicate that implementing sustainable practices, such as NT + SRGF in water-limited areas, can enhance crop yield while minimizing water usage, thereby promoting the sustainability of agricultural systems. Keeping soil mulch through appropriate soil management practices can reduce the amount of water required, minimizing soil water evaporation (Silva et al., 2021a, 2022). The CROPGRO-Soybean considers the potential root water uptake from each soil layer, which is determined by the water fraction that can be extracted from that layer and the SRGF, or soil-root growth factor. It aligns with field studies that reported increasing water uptake promoted by optimal conditions to root depth elongation (Rellán-Álvarez et al., 2016; He et al., 2019; Bossolani et al., 2021). Therefore, by incorporating the effects of root growth and depth on water uptake into the model, the study can accurately simulate the relationship between soil moisture and plant growth.

Estimates of the macronutrients required to reach exploitable soybean yield in Brazilian agricultural systems were divided by primary and secondary nutrients. This value is 19.3 10^6 Mg of primary nutrients and 5.7 10^6 Mg of secondary nutrients. Notably, these quantities are based on the total plant requirements and not the total amount of macronutrients to be applied via fertilizers. In high-yielding soybean fields, the removal of 75 and 40 % average of primary and secondary nutrients was identified, respectively (Barth et al., 2018). The high nutrient removal values must impact the nutrient demand; thus, an adequate fertilizer supply and improvements on N biological fixation may be vital in reaching high soybean yields. Furthermore, sustainable practices discussed previously, such as no-tillage, combined with root growth improvement, may increase nutrient availability in the soil (Williams and Weil, 2004; Mazzafera et al., 2021).

Our study provided important insights into the water-limited crop yield potential and yield gaps of soybean production in Brazil. Our estimates reveal that water-limited crop yield potential ranged from 4,353 to 5,186 kg ha^{-1}, yield potential range from 4,800 to 5,854 kg ha^{-1}, yield gap averaged 3,092 kg ha^{-1}, and agricultural efficiency averaged 50 %. Notably, our simulations highlighted that drought and agricultural mismanagement result in a loss of around 14 and 42 % of soybean potential yield, respectively. Furthermore, we found that supplementary irrigation is needed for 26 % of soybean production areas in Brazil. Areas with conventional tillage practices required an average water volume of 9,598 Mm³, while no-tillage combined with root growth improvement practices reduced water demand to 7,665 Mm³. Lastly, we determined the total macronutrient demand for soybean yield potential, which amounted to 31 10^6 Mg, with N accounting for approximately 50 % of the total nutrient requirement.

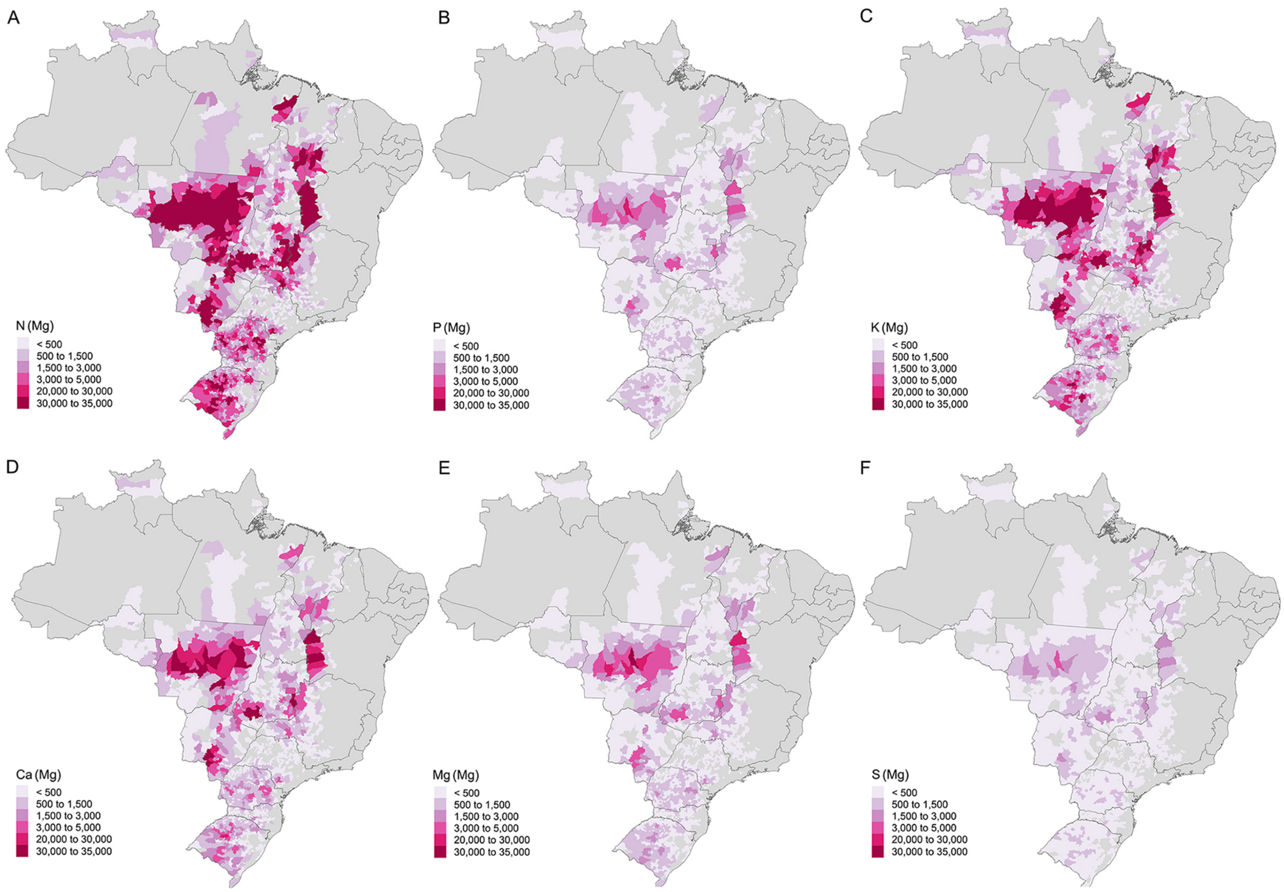

Figure 7 – Total of macronutrients demanded to reach an average of long-term simulations (1990-2019) for soybean yield potential in Brazil. Macronutrients: A) Nitrogen; B) phosphorus; C) potassium; D) calcium; E) magnesium; and F) sulfur.

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Authors' Contributions

Conceptualization: Silva EHFM, Marin FR. **Data curation:** Silva EHFM, Fattori Junior IM. **Formal analysis:** Silva EHFM, Fattori Junior IM. **Funding acquisition:** Silva EHFM, Marin FR. **Investigation:** Silva EHFM, Vieira Junior NA. **Methodology:** Silva EHFM. **Project administration:** Silva EHFM, Marin FR. **Resources:** Silva EHFM, Marin FR. **Supervision:** Marin FR. **Writing-original draft:** Silva EHFM, Vieira Junior NA. **Writing-review & editing:** Silva EHFM, Marin FR, Fattori Junior IM.

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