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The Brazilian case as a beacon to increase crop production in sub-Saharan Africa

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Abstract

Maize is one of the major agricultural commodities in the world, and a source of food in Africa, representing more than 40 million ha currently harvested on the continent. Despite sub-Saharan Africa's dependence on grain, the maize actual yield (Y_a) of the crop is low when compared to its potential yield. In Brazil, the yield-gap between Y_a and water-limited yield (Y_w) is approximately 50% of Y_w. The objective of this study was to carry out a case study, using upland maize as a reference to identify a set of agricultural areas with similar soil and climate in Brazil and sub-Saharan Africa (SSA). The climatic similarity between Brazil and SSA countries was verified, seeking homogeneous climatic zones that occur in both regions. The Y_a was determined including the data of at least the last three years of cultivation and were taken from the database of the national institutes of agricultural statistics. The climatic data showed that the SSA had well-distributed rainfall throughout the crop season, being higher than in Brazil, as well as the average air temperature. The average Y_w was 11.3 and 7.4 Mg/ha for Brazil and SSA, respectively. Maize Y_a in SSA was 1.4 Mg/ha, while in Brazil Y_a was 5.2 Mg/ha. Y_a represented approximately 9% of Y_w in the SSA. The low Y_a shows the large yield-gap found in SSA. With this, it is evident that the technologies used and the crop management are largely responsible for the yield differences between Brazil and SSA.

Introduction

Maize leads the global staple cereal in terms of annual production exceeding 1 billion tons in over 200 million ha, being on nearly 150 million ha in developing countries, corresponding to about 70% of the total maize area (FAOSTAT, 2022). Maize is an important source of food and nutritional security for millions of people in the developing world, also a key ingredient in animal feed, and it is used extensively in industrial products, including the production of biofuels.

With economic development, the consumption of animal-source foods and the need for renewable energy sources are accelerating and propelling the demand for maize. According to PRB (2020), the global population will reach almost 10 billion people in 2050, such increase will be more pronounced in developing countries, where more than 95% of the population growth will occur, and food production is expected to increase by 35% to 56% to meet such demand (Dijk *et al.*, 2021). This reflects concerns over the recent global food crisis and how to adequately provide for the growing global population while staying within planetary boundaries (Willett *et al.*, 2019). In this aspect, maize plays a diverse and dynamic role in global agri-food systems and food-nutrition security (Ranum *et al.*, 2014; Grote *et al.*, 2021; Poole *et al.*, 2021).

Producing adequate food to meet future global demand is a major challenge, therefore, it is important to understand the aspects that limit crop production. Yield potential (Y_p) assumes unconstrained crop growth and perfect management that avoids limitations from biotic and abiotic stress (Van Ittersum and Rabbinge, 1997; Evans and Fischer, 1999), being, therefore, location-specific and depends on solar radiation, temperature, and water supply over the crop growing season and can be estimated for both rainfed (water-limited yield potential) and under irrigated conditions. The difference between the Y_w and actual yield (Y_a) is known as the yield gap (Y_g) (Van Ittersum *et al.*, 2013). The Y_g analysis forms the cornerstone in pinpointing key crop, soil and management factors that currently restrict farm yields. By refining practices to bridge this disparity, it paves the way for enhanced agricultural productivity. Moreover, it facilitates strategic prioritization of research, development and interventions for maximum impact.

In Brazil, the Y_g is around 50% of Y_w (Marin *et al.*, 2022). Still, most tropical environments around the world are producing well below average potential, especially those located in sub-Saharan Africa (SSA) (Van Ittersum *et al.*, 2013). Maize is the principal staple crop in SSA, accounting for 30% of the total area under cereal production and over 30% of the total calories and protein consumed (Cairns *et al.*, 2013). According to Global Yield Gap Atlas (www.yieldgap.org), actual rainfed maize yields a range from 1.0 to 3.0 Mg/ha, which

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represents only 15–20% of the water-limited yield potential. In the eastern SSA, where the major maize-producing countries in Africa are located, the Y_g reaches 50% of Y_w in some countries such as Uganda (GYGA, 2022).

It might be challenging for SSA to feed itself, as projections indicate an increase in cereal imports in the coming decades (Pradhan *et al.*, 2015; Sulser *et al.*, 2015; Van Ittersum *et al.*, 2016). Many factors can lead to such stagnation in maize production in SSA such as low soil fertility, open-pollinated varieties and water stress, and therefore low crop yield (Sanchez, 2002; Stocking, 2003). While mineral fertilizers and irrigation practices may partially overcome the problem, rapid increases in world fertilizer prices and water scarcity have severely limited farmers' access to these technologies (Hargrove, 2008). Furthermore, opportunities for the expansion of cultivated land are limited due to restrictions on climate conditions and proper soils. Therefore, the improvement in maize production is highly dependent on yield gains through technological innovations that might reduce the Y_g.

Reducing the Y_g would reduce the dependence on cereal imports and avoid a vast expansion of rainfed cropland area, especially because the population in SSA is projected to grow almost 100% between 2050 and 2100 (Van Ittersum *et al.*, 2016). With fairly similar weather and soil conditions to SSA, Brazil has significantly reduced the Y_g in the past 40 years. Soil and climate similarities among countries can foster agricultural technology transfer (Cabral *et al.*, 2016). Therefore, Brazil might be used as a benchmark to improve SSA agricultural production by increasing the crop yield. Thus, we hypothesized that SSA can reach yield levels similar to Brazil in areas with equivalent soil and climate conditions, and identifying the main factors for the Y_g in the SSA would represent an increase of 3–4 Mg/ha, which would substantially improve food security in the region, reducing the dependence on imports.

The objective of this study is to use rainfed maize as a case study to identify cropland grown on similar soil and climate in Brazil and SSA where a comparable response to a given set of technologies would be expected. Moreover, to understand the Y_g levels in the SSA by analysing the climate and soils of both regions, comparatively analysing the influence of climate, soil and management on maize yield in SSA and Brazil.

Materials and methods

Region comparison and study sites

The checking for climate compatibility between Brazil and SSA countries was based on the approach of homogenous agro-climate zones (CZs) described by Van Bussel *et al.* (2015), searching for CZs occurring in both regions, using CZs data at weather station (WS) spatial level available in the GYGA platform (www.yieldgap.org). This protocol builds on the spatial framework developed by Van Wart *et al.* (2013), which consists of delineating agro-climatic zones based on three climate variables that influence crop yield and its variability: growing degree days, temperature seasonality and aridity index.

As the CZs have a broad spatial scale, we added a second criterion for selecting the analogous regions in Brazil and SSA by using the simulated water-limited yield (Y_w), as we evaluated the rainfed maize as a study case. We used the estimated Y_w from the GYGA project (www.yieldgap.org) as described in the next section, by selecting from the GYGA database, for each similar CZz, the values of Y_w provided for the same soil types and rooting depths or choosing the closest as possible values considering soil and rooting depth. As the Hybrid-Maize crop model was used for simulating Y_w both in Brazil and SSA, and the model uncertainty was reported as root mean squared error (RMSE) of 1.2 t/ha in harsh environments (Yang *et al.*, 2017), and so we assumed such value as the maximum acceptable difference as the criterion for selecting the pairs of locations to be studied herein. For those selected pairs of sites, we averaged at a monthly scale the data of maximum and minimum temperature, rainfall, grass reference evapotranspiration (ETo) calculated according to Allen *et al.* (1998), and incoming solar radiation (Supplementary Material A). As the maize crop cycle of each CZs varied according to the location and cropping systems from 95 to 120 days, we selected the first 3 months of the cycle for these comparisons, as this period would cover the more sensitive crop phases, avoid comparisons between periods that are not similar between CZs, and exclude the late crop phase (maturation) from the comparisons as the crop became relatively insensitive to the weather. The agreement between the weather of the regions was evaluated by the root mean-squared error (RMSE, Equation 1), and mean absolute error (MAE, Equation 2).

$$RMSE = \sqrt{\frac{\sum (v_{B,i,j} - v_{SSA,i,j})^2}{n}} \tag{1}$$

$$MAE = \frac{\sum (v_{B,i,j} - v_{SSA,i,j})}{n} \tag{2}$$

where v_B is the average of climate variables in Brazil for a month i and site j and v_{SSA} is the average of climate variables in SSA countries for a month i and site j, and n is the number of sites-months (i^*j) evaluated.

Simulations of rainfed maize yield

Water-limited yield estimates (Y_w) were performed with Hybrid-Maize in Brazil and SSA (Yang *et al.*, 2004, 2017), and simulations were based on local weather, soil and key management practices influencing Y_w, such as sowing date and cultivar maturity, which were collected following the tier approach for selection of best available data sources described by Grassini *et al.* (2015a). For all sites, management practices for each reference weather stations (RWS) buffer zone, used for model setup, were retrieved from the local agronomists. Separate simulations were performed for Y_w and potential yield (Y_p) and both assumed no limitations to crop growth by nutrients.

Weather and soil data used for crop model simulations

Brazil

In Brazil, long-term (15+ years) daily weather data were retrieved from the Brazilian Institute of Meteorology (INMET, https://portal.inmet.gov.br/) and include daily maximum and minimum temperature, and rainfall. Quality control and filling-correction of the weather data was performed based on the propagation technique developed by Van Wart *et al.* (2013). Solar radiation was estimated using the Bristow and Campbell (1984) method, with locally calibrated coefficients (Marin *et al.*, 2022). Based on crop harvested area distribution and the CZs defined

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by Van Wart *et al.* (2013), many RWS were selected to represent the maximum cropped area of rainfed maize in the country using as little RWS as possible, such an approach was used in Brazil and SSA countries. In this study, we considered the simulations made for maize as the major crop during the summer season in Brazil, assuming an average of 1623 (°C days^{-1}) growing degree-days (GDD) and base temperature of 10°C.

The two–three dominant soil series were identified for each RWS buffer based on data from the Radambrasil project (Cooper *et al.*, 2005). Rooting depth was set at 1.0 m to reflect the limitation to maize root growth in deep soils due to low pH and the different sensitivity of crop variety to this factor. Calibrated pedo-transference functions for tropical soils were used to derive soil water limits (Tomasella *et al.*, 2000). For each RWS, each soil type combination was simulated, and then weighted by their relative proportion to retrieve an average Y_w at the level of the RWS buffer zone. Simulations assumed no limitations to crop growth by nutrients and no incidence of biotic stresses such as weeds, insect pests and pathogens.

Ghana

Weather datasets with at least 10 years of daily data were collected from the Ghana Meteorology Agency (GMet, https://www.meteo.gov.gh/gmet/). NASA-POWER (http://power.larc.nasa.gov/) was used as a source of incident solar radiation (Table 1). Years in which more than 20 consecutive days (10 consecutive days for precipitation) and/or more than 20% of the days are missing are left out, and linear interpolation was used to fill missing data. Soil data were derived from the Africa Soil Information Service (Leenars *et al.*, 2018) (Table 1), and the three dominant soil mapping units for the growth simulations per crop type, based on their crop-specific cropped area within each buffer zone around each RWS. For all African countries, for each RWS, each maize–soil type combination was simulated, and then weighted by their relative proportion to retrieve an average Y_w at the level of the RWS buffer zone. Simulations assumed no limitations to crop growth by nutrients and no incidence of biotic stresses such as weeds, insect pests and pathogens.

Nigeria

Historical daily weather data sets were collected from the Nigerian Meteorological Agency (NiMet, https://nimet.gov.ng/). Weather datasets are available for 39 locations in Nigeria and contain ten or more years of data. Weather data are derived from both historical weather data sets, propagated weather data and NASA-POWER. Linear interpolation was used to fill missing data in historical weather data sets. Soil data were derived from Africa Soil Information Service (Leenars *et al.*, 2018) (Table 2), which provided data on root zone depth and water-holding capacity. In Nigeria, soil classes were selected until achieving 50% area coverage of crop harvested area within RWS buffer zones, with at least three dominant soil classes. Then, Y_w was simulated for all selected soil classes.

Kenya

Daily weather data sets collected from the Kenya Meteorological Department (KMD, https://meteo.go.ke/). Weather sets are available for 31 locations in Kenya and contain ten or more years of data available. Weather data are derived mainly from weather propagation (based on historical measured weather data) and NASA-POWER. The sowing days used for the simulations are determined as the first day within the sowing window when the cumulative rainfall exceeds 20 mm (counting starts on the first day of the sowing window). Soil data have the same source as for Nigeria, as well as the procedures for selecting soil classes and the Y_w simulations. Soil data were derived from Africa Soil Information Service (Leenars *et al.*, 2018) (Table 2).

Ethiopia

Daily weather data sets were collected from the National Meteorology Agency of Ethiopia (NMA, http://www.ethiomet.gov.et/). Weather datasets are available for 80 locations in Ethiopia and contain 10 or more years of data. Weather data are derived mainly with support of weather propagation based on at least three years of actual measured data. Soil data have the same source as for Nigeria, as well as the procedures for selecting soil classes and the Y_w simulations.

Uganda

Daily weather data sets were collected from the Uganda Department of Meteorology (UNMA, https://www.unma.go.ug/). Weather datasets are available for 30 locations in Uganda and contain ten or more years of data. Weather data are derived from weather propagation based on historical weather data, and from NASA-POWER. Based on crop harvested area distribution and the climate zones defined for Uganda (Van Wart *et al.*, 2013) under rainfed maize, 13 RWS were selected for representing 63% of the total country-producing area. Soil data have the same source as for Nigeria, as well as the procedures for selecting soil classes and the Y_w simulations.

Zambia

Historical daily weather data sets were collected from the Zambia Meteorological Department (ZMD, https://www.mgee.gov.zm/?page_id=1181). Weather datasets are available for 25 locations in Zambia and contain ten or more years of data. Weather data are derived from weather propagation based on historical weather data, and from NASA-POWER. Soil data have the same source as for Nigeria, as well as the procedures for selecting soil classes and the Y_w simulations. The number of RWS and coverage percentage of total rainfed maize per country, given by the sum of area covered by each RWS, for all the study sites, are shown in Table 2.

Actual yields from reported observations

The Y_a was determined by including the last three years of data to account for weather variability while avoiding the trend bias due to technology or climate change (Calviño and Sadras, 2002; van Ittersum *et al.*, 2013; Grassini *et al.*, 2015b). In all cases, Y_a was estimated with at least three recent years of yield data, as follows this procedure: (a) determine per district the dominant climate zone; (b) calculate the average yield per buffer zone (by weighted averaging) based on the actual yields in districts that first, have a dominant climate which is similar to the climate of the buffer zone and second, are at least partly within the buffer zone.

For Brazil, district-level data on crop harvested area and average yields for each crop was retrieved from the IBGE (Brazilian Institute of Geography and Statistic). Statistics from the most recent five cropping seasons (2006–2010) were used to calculate crop area and average yields. For Ghana, Nigeria, Kenya, Ethiopia, Uganda and Zambia, district-level data on annual actual yields were retrieved from their respective national bureau of statistics. As mentioned, data from the last three years were used to estimate average actual yields per buffer zone in Africa. Harvested

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Table 1. Sources of data to simulate water-limited maize potential yield and estimate yield gaps for African countries

Country	Sowing window	Daily weather data	Cultivar thermal time requirement (GDD)[a]	Plant available water (mm)[b]	Soil root zone (cm) [b]	Actual yield[c] (Mg/ha)
Ethiopia	15-Apr to 10-Jun	Measured and propagated data[d]	1400	45	38	2.8
Ghana	15-Apr and 15-Jun	Measured and propagated data	1900	25	29	1.8
Kenya	15-Apr to 31-May	Propagated data	1450	56	48	2.8
Nigeria	15-Apr to 10-Jun	Measured and propagated data	1785	24	28	2.0
Uganda	15-Apr and 15-Sept	Propagated data	1470	44	54	1.2
Zambia	15-Dec	Measured and propagated data	1671	33	50	3.0

[a] Calculated based on sowing, flowering and maturity timing information provided by the country agronomist (CA) using weather data and cardinal temperatures. Base temperature of 10°C.
[b] Average data of the last 3 years extracted from Africa Soil Information Service available at: https://www.isric.org/projects/afsis-gyga-functional-soil-information-sub-saharan-africa-rz-pawhc-ssa. Accessed on 2024-05-15 (Leenars *et al.*, 2018).
[c] Available at https://www.fao.org/faostat/en/#data. Accessed on 2024-04-08.
[d] Details are in Van Wart *et al.* (2015).

areas were retrieved from the HarvestChoice SPAM crop distribution maps (You *et al.*, 2006, 2009).

Description of rainfed maize cropping systems

Maize is grown in practically the whole of Brazil, and the most typical maize crop systems in Brazil were the two-year soybean–maize (rotation system) and one-year-soybean–maize (known as second season, off-season maize). In the first, the yields are usually higher as the crop was well fertilized and managed and grows under high temperatures and solar radiation with well-distributed and abundant rainfall over the crop cycle. In the second cropping system, short cycle soybean is planted with the onset of rains and matures in late January, February or early March. Maize is then sown after soybean harvest with very low (if any) fertilizer application. As the rainy season ends right before maize maturity, which experiences terminal drought, which explains the lower yield levels observed in such cropping systems. In both systems, most of the areas are entirely mechanized and the decision on which cropping system to use each year is predominantly based on the international soybean and maize prices.

Maize is one of the main staple crops in all SSA countries considered in this paper, and it is grown once or twice a year as a single crop or in annual double-crop systems such as maize–maize, maize–cowpea and groundnut–maize, as some of the countries have a bimodal rainfall pattern. The lack of crop rotation due to the cropland restriction, a significant deficiency in fertilization, inadequate return of crop residues (with a majority being diverted to animal feed), and poor management of animal manures resulting in minimal return has led to a decline of soil fertility and grain yield, and that may explain part of the low yields as those observed in Uganda (1–2 Mg/ha). There is no mechanization in most of the maize areas in SSA countries and their agriculture is predominantly on a smallholder basis (Fig. 1).

Table 2. Number of selected reference weather stations (RWS) and coverage percentage of total rainfed maize per country

Country	Number of RWS	Coverage (%)
Brazil	25	70
Ghana	6	69
Kenya	8	26
Uganda	13	63
Ethiopia	24	38
Zambia	11	36

Results

Selection of comparable sites in Brazil and SSA

Regarding the 11 CZs occurring both in SSA and Brazil, there were 11 pairs of sites under similar soils (Table 2), for which simulated Y_w ranged from 5.3 to 18.6 Mg/ha in Brazil and from 5.2 to 11 Mg/ha for SSA countries, averaging 11.3 and 7.4 Mg/ha for Brazil and SSA, respectively. The comparison site by site of simulated Y_w values revealed four sites in which yield difference was lower than the crop model uncertainty (1.2 Mg/ha) (Fig. 2, site-pairs e, f, i and j in Table 2). In these four pairs of sites, simulated Y_w ranged from 5.2 to 18.5 Mg/ha and were included in CZs 7701, 8501, 7601 and 9701 as defined by Van Wart *et al.* (2013). These CZz are all characterized by having, during the cropping seasons, well-distributed rainfall with minimum amounts of 135 mm/month, minimum temperature always above 19.5°C, and average solar radiation of 18.6 MJ/m^2/d (Table 3).

The CZ 7601 (c,d,e), is composed of one Brazilian city and four cities in SSA. The soil of Paracatu (Brazil), is clay and presents the most superficial root depth (1 m). The cities of Arua, Kasama and Kisumu (belonging to Uganda, Zambia and Kenya, respectively) have silty soils and the root system in these places was 1.5, 1.15 and 1.15 m, respectively. The Brazilian city presented the same Y_w and Y_a of 6.4 Mg/ha, while in the SSA region, the Y_w ranged from 5.3 to 18.5 Mg/ha and Y_a from 1.0 (Kenya) to 2.8 Mg/ha (Zambia) representing Y_g of 81 and 85% of Y_w.

The CZ 7701 (f, g), composed of Bambui (Brazil), Kakamega (Kenya) and Ayira (Ethiopia) showed crop root depths of 1.0, 1.5 and 1.5 m, respectively. Kakamega (Kenya) presented Y_g of 5.9 Mg/ha (73% of Y_w), and Bambui (Brazil) with 3.4 Mg/ha (38% of Y_w). Besides the similar soil texture to the Brazilian site (clay soil), the highest Y_g was found in Ayira (Ethiopia), with 15.9 Mg/ha or 89% (Table 3).

Votuporanga (Brazil) and Lira (Uganda), belonging to CZ 8501 (i), presented similar root system depths of 1 and 1.15 m, respectively. The estimated values of Y_w were similar (about 8 Mg/ha). However, the Y_a for Lira was only 0.8 Mg/ha, resulting in a Y_g of 7.0 Mg/ha (90% of Y_w). While the Y_g of Votuporanga was 4 Mg/ha (49% of Y_w).

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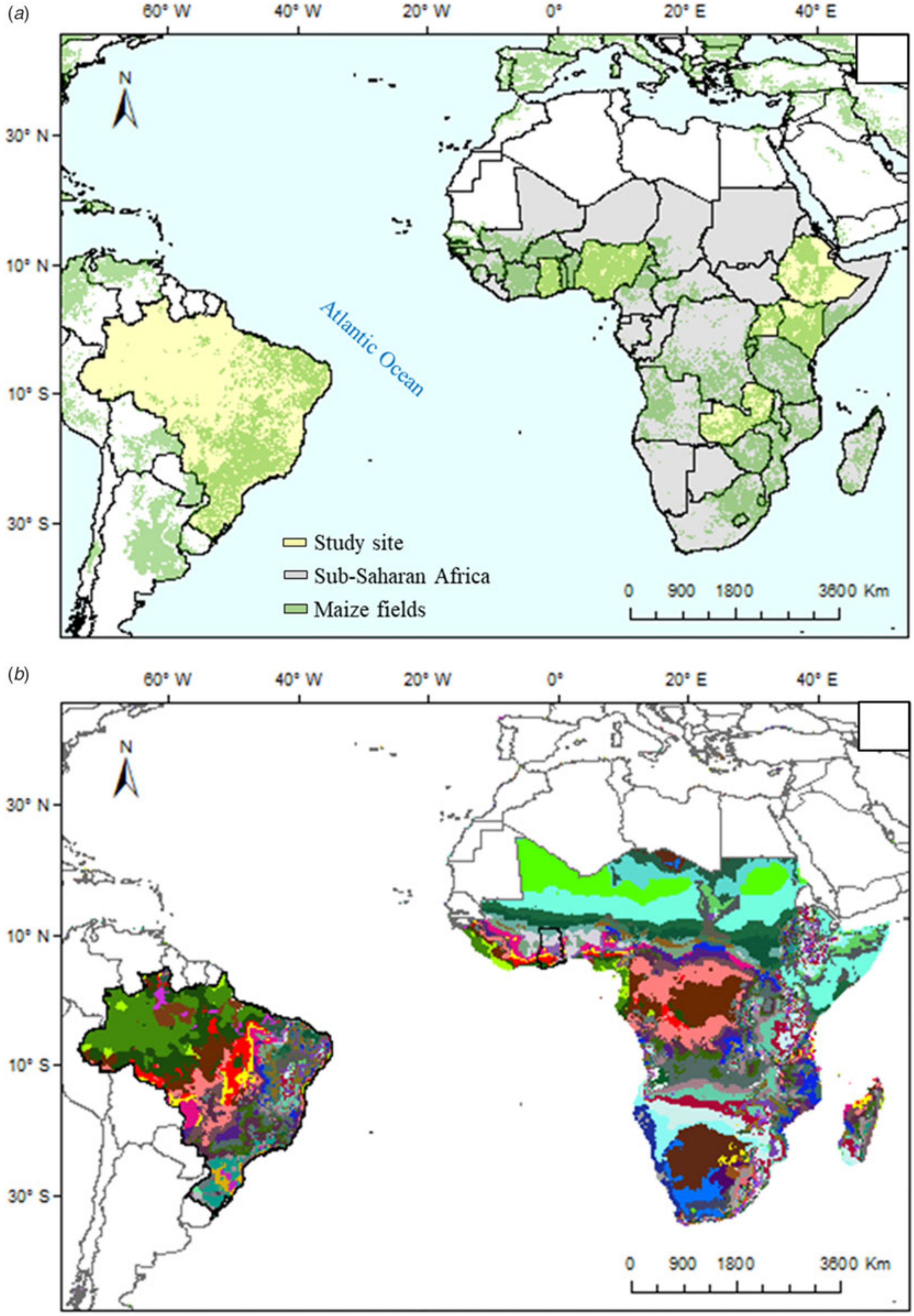

Figure 1. Area cultivated with maize in Brazil and SSA (A). Polygons with the same colour represent the same climate zone, found both in Brazil and SSA (B).

The CZ 9701 (a, b) is represented by São J. Rio Claro (Brazil), Sefwi-Bekwai (Ghana) and Akure (Nigeria), which have similar clay soils, and the root system depth was 1.5, 1.0 and 1.15 m, respectively. The sites presented Y_w ranging from 7.4 to 9.8 Mg/ha, with the lowest value for the Brazilian city and the highest value for Akure (Nigeria). However, despite the highest Y_w, the African regions presented low Y_a (from 1.8 to 2.1 Mg/ha) and, consequently, the highest Y_g, being 6.8 and 7.7 Mg/ha for Ghana and Nigeria, respectively, or Y_g of 79% for both sites.

Statistical differences based on *t*-test between monthly averaged climate variables and the four pairs of sites revealed that all the SSA sites had lower rainfall, and maximum and minimum

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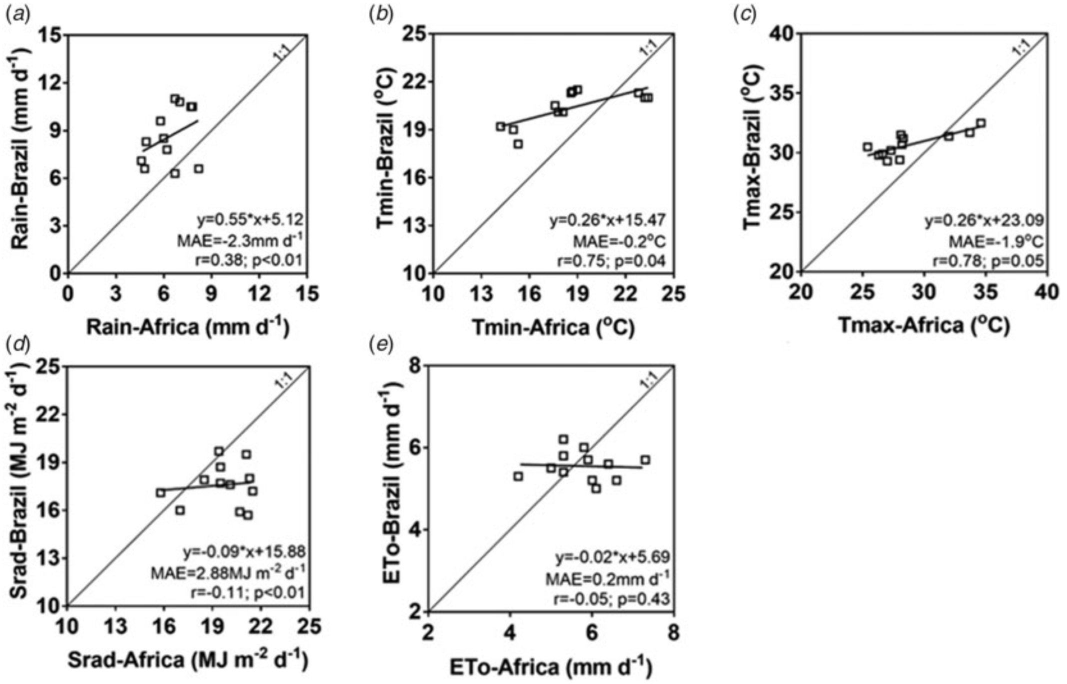

Figure 2. Relation between monthly average along the crop cycle of rainfall (rain, (a), minimum (T_{min}, (b) and maximum (T_{max}, (c) temperatures, incoming solar radiation (S_{rad}, d) and grass reference evapotranspiration (ETo, e), of selected sites under same climate zones and similar water-limited yield in Brazil and SSA countries.

air temperature (Figs 2a, 2b, and 2c) over the crop cycle compared to Brazilian sites, however, lowers values for net radiation was observed in Brazil (Figs 2d). The MAE values were equal to 2.3 mm/d for rainfall, −0.2°C and −1.9°C for minimum and maximum temperature, respectively, and 2.9 MJ/m^2/d for net radiation. The *t*-test for ETo did not show significance at 5% ($P = 0.43$). Still, the data remained close to the 1:1 line (Fig. 2e), with an MAE of 0.2 mm/d.

Potential, actual and yield gap

As the model uncertainty is 1.2 Mg/ha, so we assumed such value as the maximum acceptable difference as the criterion for selecting the sites as described before. Based on this criterion, we found four climate zones where the Y_w agreed well between Brazil and Africa (Fig. 3), being the CZ 7601 (Kenya), 7701 (Kenya), 9701 (Uganda) and 8501 (Ghana). We observed Y_w for Brazil was 2.1% greater than SSA sites, with an overall average of 7.7 and 7.4 Mg/ha for Brazil and SSA, respectively (Fig. 3a).

The Y_a in Brazil, however, was more than three times higher than in SSA (Fig. 3b). The average Y_a for the sites in SSA was 1.4 Mg/ha, which represented only 19% of the Y_w and stayed much below the 5.2 Mg/ha found in Brazil. Such low average yields in SSA also accounted for the larger Y_g found for SSA (6.0 Mg/ha), which was nearly double that in Brazil (2.6 Mg/ha) (Fig. 3c).

Discussion

The four sites with very similar Y_w are located within the tropical zone. Some of them are closer to the Equator line, but at high altitudes, well compared with others in higher latitudes but in low altitudes to sea level (Table 3). The Brazil sites had higher rainfall during the crop cycle, representing around 70 mm/month more than in SSA, which might compensate for the soil limitations. The greater solar radiation levels in Africa, even the minimum values found in the selected sites were enough to ensure high maize potential yield (Cooper, 1979). Considering this together with rainfall and temperature would ensure that the SSA sites, based on a biophysical perspective, could produce as much as in Brazil, as revealed in field trials carried out with good hybrids, high N fertilization, and higher plant population (Jumbo *et al.*, 2017). Although rainfed maize yield levels are usually strongly related to seasonal rainfall constraints (Kassie *et al.*, 2014), the assessment of other climate variables, especially when water deficit is not so accentuated, can be used in the understanding and management planning of yield gaps.

Average maize grain yields in SSA varied between 0.9 and 2.0 Mg/ha (+121%) for the period 1961–2016, while in Brazil it increased from 1.2 to 4.3 Mg/ha (+226%) during the same period (FAOSTAT, 2022). Such yield increase observed for Brazil would be higher if prices were worth it for farmers as a large fraction of maize production in Brazil is from high-yielding modern cultivars in commercial agriculture (Jones and Thornton, 2003). Maize grain yields could reach 4 Mg/ha in the fertilized homestead plots, which are usually less than 10% of the farmland (Mueller *et al.*, 2012). Besides the lack of sufficient nutrient inputs (which would include P and K as well), low soil pH and the lack of high potential germplasm, and/or pests and diseases are also listed as the causes of low maize yields (Vanlauwe *et al.*, 2013). Rainfed maize has one of the greatest Y_p among common crops and the largest Y_g in SSA, being the larger Y_g found in the most favourable (higher rainfall) regions of the savannahs and cooler highlands of the northern Zambia plain (Van Ittersum *et al.*, 2016).

The increase of Y_a in SSA towards attainable yield would reflect the economic circumstances of the crop in the region,

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Table 3. Climate zones (CZ) occurring in Brazil and SSA, including site description, reference weather stations (RWS), soil texture, root depth, sowing month and crop model used for simulating water-limited (Y_w) and potential yield (Y_p), as well as the actual yield (Y_a), yield gap (Y_w-Y_a) and Y_g (%)

CZ	Country	RWS	Lat	Long	Elevation	Site pair	Soil texture	Root depth	Sowing	Y_p	Y_w	Y_a	Y_w-Y_a	Y_g (%)
–	–	–	–	–	m	–	–	m	month	Mg/ha				
	Brazil	Cruz Alta	−28.6	−53.6	464	a, b	Sandy clay loam	1.0	Aug	14.6	5.2	4.6	0.6	12
6801	Kenya	Kisii	−0.7	34.8	1171	a	Sandy loam	1.5	Aug	14.5	9.1	2	7.1	78
	Ethiopia	Jimma	7.8	36.4	1750	b	Sandy clay loam	1.5	Apr	16.2	15.7	2	13.7	87
	Brazil	Paracatu	−17.2	−46.9	711	c, d, e	Clay loam	1.0	Oct	12.3	6.4	6.4	0	0
7601	Uganda	Arua	3.1	30.9	1211	c	Silt loam	1.5	Aug	13.6	8.4	1.7	6.7	80
	Zambia	Kasama	−10.2	31.1	1384	d	Silt loam	1.15	Nov	18.7	18.5	2.8	15.7	85
	Kenya	Kisumu	−0.1	34.7	1146	e	Silt loam	1.15	Aug	19.4	5.3	1	4.3	81
	Brazil	Bambuí	−19.9	−46.1	661	f, g	Clay	1.0	Oct	10.6	9.0	5.6	3.4	38
7701	Kenya	Kakamega	0.2	34.5	1530	f	Sandy loam	1.5	Aug	14.8	8.1	2.2	5.9	73
	Ethiopia	Ayira	9.1	35.3	1700	g	Clay loam	1.5	Apr	18.6	18.2	2.3	15.9	87
7801	Brazil	Araxá	−19.6	−46.9	1004	h	Clay	1.0	Oct	13	11	6	5	45
	Ethiopia	Gore	8	35.5	1880	h	Clay loam	1.5	Apr	15.3	15.3	2.1	13.2	86
8501	Brazil	Votuporanga	−20.4	−50	502.5	i	Sandy clay loam	1.0	Oct	11.2	8.1	4.1	4.0	49
	Uganda	Lira	2.4	32.9	1091	i	Silt loam	1.15	Mar	14.5	7.8	0.8	7.0	90
	Brazil	São J. Rio Claro	−13.4	−56.7	350	j, k	Clay loam	1.5	Apr	15.5	7.4	4.0	3.4	46
9701	Ghana	Sefwi-Bekwai	6.2	−2.3	172	j	Clay	1.0	Oct	10.8	8.6	1.8	6.8	79
	Nigeria	Akure	7.2	5.3	335	k	Clay loam	1.15	Apr	13.7	9.8	2.1	7.7	79

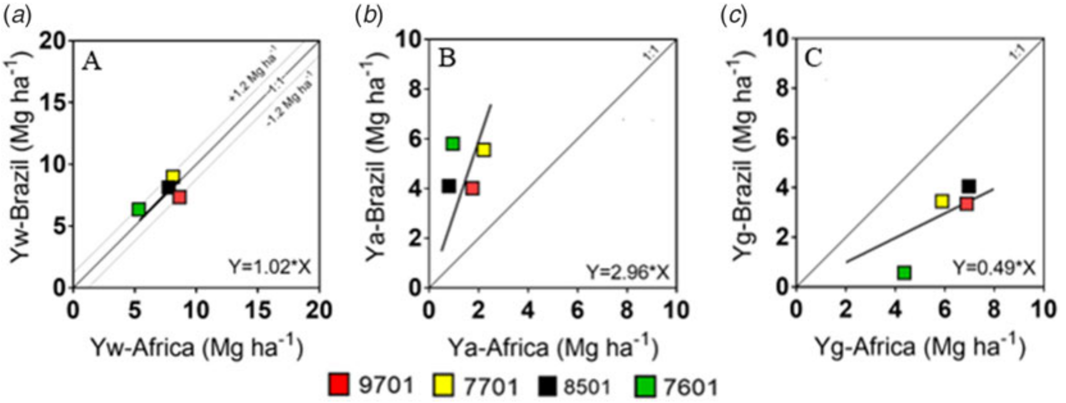

Figure 3. Relation between potential water-limited yield (Y_w), actual yield (Y_a) and yield gap (Y_g) for sites under the same climate zones in Brazil and SSA. Colours identify each climate zone as described in Table 2.

particularly grain prices relative to input costs, all measured at the farm gate. Although it is not easy to establish an appropriate attainable yield, general experience suggests that it will be approximately 20–30% below Y_p in situations where world prices and reasonable transport costs operate (van Ittersum *et al.*, 2013). Where this does not occur, for example, in much of SSA where infrastructure and institutions are weak, attainable yield may be much lower due to low investment in technology and management or access to financial instruments for loans. Alternatively, where inputs and grain prices are heavily subsidized, it could more closely approach Y_w (Fisher *et al.*, 2014).

Lobell *et al.* (2009) reported a typical variation of 0.2–0.8 for Y_a/Y_w in the main world cropping systems (wheat, rice and maize), both rainfed and irrigated. Specifically for maize, the values ranged from 0.16 (SSA) to 0.56 (USA). These authors argued that values above 0.70 are common in wheat and rice, due to the strong association of this crop with rainfall variability, ultimately also affecting crop management. In the present study, the mean Y_a/Y_w ranged from approximately 0.66 (Brazil) to 0.17 (SSA). These relatively low Y_a/Y_w in SSA may be related to the management carried out in the area since the Y_w values of Brazil and SSA are similar. The higher values of Y_a/Y_w in the present study may also be an indication that, in these scenarios, average yields are relatively close to reaching a plateau (70–80% of Y_w, as indicated by Lobell *et al.*, 2009) and will likely remain close to these levels for years to come. Y_p and Y_w are unlikely to change quickly, as the main drivers of average yields at national scales depend on crop genetic improvements (conventional breeding and genetic engineering), soil fertility and crop management, as well as social, economic and environmental issues, even though the improved varieties and fertilization and technologies have not been adapted yet at farmer level in SSA.

In the past few decades, maize has been hailed as a crop poised to revolutionize agriculture in SSA (Gilbert *et al.*, 1993; Smale, 1995; Byerlee and Eicher, 1997; Howard and Mungoma, 1997). This perception largely stems from the significant yield gains attributed to the adoption of improved seeds and fertilizers, particularly heightened during the 1980s. This surge was fuelled partly by the incorporation of proprietary technologies and partly by state policies that incentivized their utilization through market mechanisms and support prices (Smale *et al.*, 2013).

Despite past successes, continued investment in maize productivity remains crucial for agricultural growth and food security. For example, investment in maize research is needed to produce improved cultivars that would better adapt to SSA's production conditions. Beyond merely securing adequate seeds, the implementation of diversified maize cropping systems alongside enhanced crop management practices becomes imperative for soil recovery and subsequent yield enhancement. Central to this endeavour is the maintenance of soil fertility, predominantly through strategic fertilization with N, P and K, as well as pH adjustment via liming. These practices play a pivotal role in bolstering crop growth, plant health and increasing yield and stress resilience by fostering robust root development, better soil structure and higher water retention. The establishment of more fertile soil profiles in a broad sense emerges as a linchpin in maximizing crop yields and fostering sustainable agricultural practices. To ensure adoption in the continent's heterogeneous production environments, farmers will need combinations of inputs and practices, diffused through pluralistic systems of seed supply and advice. The expansion of markets in densely populated areas with small-scale farms will require different approaches to areas with good potential, dispersed populations, and less intensive land use. Designing interventions to support market development will require monitoring ongoing policy experiences (Smale *et al.*, 2013). The use of insecticides or pest-resistant varieties as well as fertilization is crucial for higher maize yields (Bempomaa and de-Graft Acquah, 2014; Oppong *et al.*, 2016; Awunyo-Vitor *et al.*, 2016).

Furthermore, the use of improved seeds can increase crop yields by up to 9 Mg/ha (van Loon *et al.*, 2019), although the use of these seeds is scarce due to high prices and farmers' lack of money to invest in these seeds. In most cases, producers tend to use seeds produced and stored (incorrectly) on their farms, which would not represent a real problem if the variety is open-pollinated and if seed germinability is assured. Brazilian agricultural sector grew at formidable rates from 1950 to 1980, because of two major factors: (a) the rapid occupation of idle areas of the enormous national territory and (b) the dynamic incorporation of new and more productive technologies (Buainain and Silveira, 2002), in particular during the 1970s. In the 1980s, Brazil started to adopt liberal and market-oriented policies, which significantly impacted the performance of its food and agriculture sector (Chaddad and Jank, 2006), the way grain production almost tripled from 1980 to 2016 (FAOSTAT, 2022). Consistently internal demand expansion together with export

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increase assured the markets for staple crops such as maize, while external markets were the destination of the variable surplus of the other agricultural products (Buanain & Silveira, 2002). During the 1990s, the Brazilian economy underwent a series of structural and institutional reforms that deeply affected the Brazilian agribusiness sector and fostered changes regarding cost-efficient technology use and yield increase (Buanain & Silveira, 2002).

Conclusion

Eleven climatic zones were found that occur in Africa and Brazil, of which only four presented Y_g lower than the uncertainty of the model, and Y_w average was 11.3 and 7.4 Mg/ha for Brazil and SSA, respectively;

Based on the methods and sources used, solar radiation was greater in SSA when compared to Brazil, demonstrating the high productive capacity in SSA. The SSA minimum and maximum rainfall and air temperature were lower when compared to data from Brazil for the same period.

The productive areas of SSA are generally in the hands of small producers, who have low income for investment in technologies, which leads to higher Yg;

The lack of investment in management and technology can be the main factor increasing the Y_a of the SSA areas.

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