Environmental Research Letters

LETTER • **OPEN ACCESS**

Rooting for food security in Sub-Saharan Africa

To cite this article: Nicolas Guilpart *et al* 2017 *Environ. Res. Lett.* **12** 114036

Environmental Research Letters

OPEN ACCESS

RECEIVED
3 July 2017

REVISED
31 August 2017

ACCEPTED FOR PUBLICATION
29 September 2017

PUBLISHED
17 November 2017

LETTER

Rooting for food security in Sub-Saharan Africa

Nicolas Guilpart[1,2], Patricio Grassini[1], Justin van Wart[1], Haishun Yang[1], Martin K van Ittersum[3], Lenny G J van Bussel[3,7], Joost Wolf[3], Lieven Claessens[4,5,8], Johan G B Leenaars[6] and Kenneth G Cassman[1,9]

[1] Department of Agronomy and Horticulture, University of Nebraska-Lincoln, PO Box 830915, Lincoln, NE 68583-0915, United States of America
[2] AgroParisTech, UMR Agronomie 211 INRA AgroParisTech Université Paris-Saclay, F-78850 Thiverval-Grignon, France
[3] Plant Production Systems, Wageningen University & Research, PO Box 430, 6700 AK, Wageningen, The Netherlands
[4] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), PO Box 39063, 00623 Nairobi, Kenya
[5] Soil Geography and Landscape Group, Wageningen University & Research, PO Box 47, 6700 AA Wageningen, The Netherlands
[6] ISRIC–World Soil Information, PO Box 353, 6700 AJ, Wageningen, The Netherlands
[7] Environmental Systems Analysis Group, Wageningen University & Research, PO Box 47, 6700 AA, Wageningen, The Netherlands
[8] International Institute of Tropical Agriculture (IITA), PO Box 10, Duluti, Arusha, Tanzania
[9] Author to whom any correspondence should be addressed.

E-mail: kcassman1@unl.edu

Keywords: food security, sub-saharan Africa, yield gap, maize, soil depth, water requirements

Supplementary material for this article is available online

Abstract

There is a persistent narrative about the potential of Sub-Saharan Africa (SSA) to be a ‘grain breadbasket’ because of large gaps between current low yields and yield potential with good management, and vast land resources with adequate rainfall. However, rigorous evaluation of the extent to which soils can support high, stable yields has been limited by lack of data on rootable soil depth of sufficient quality and spatial resolution. Here we use location-specific climate data, a robust spatial upscaling approach, and crop simulation to assess sensitivity of rainfed maize yields to root-zone water holding capacity. We find that SSA could produce a modest maize surplus but only if rootable soil depths are comparable to that of other major breadbaskets, such as the US Corn Belt and South American Pampas, which is unlikely based on currently available information. Otherwise, producing surplus grain for export will depend on expansion of crop area with the challenge of directing this expansion to regions where soil depth and rainfall are supportive of high and consistent yields, and where negative impacts on biodiversity are minimal.

Introduction

This paper provides a quantitative assessment of the degree to which major agricultural countries in west and east Sub-Saharan Africa (SSA) can join the ranks of the world most productive crop producing regions. Previous studies [1–4] and popular magazines like National Geographic [5] suggest that SSA, and especially the vast Guinea Savannah zone, could become a future world breadbasket. Breadbaskets are regions that produce a large and stable surplus of one or more major food crops (typically cereals and oilseeds) that not only meet local demand but also can make substantial contributions to food supply in other regions. By this definition, there are only a few major breadbaskets in the world: the US Corn Belt, Brazilian Cerrados, and Argentinean pampas for rainfed maize and soybean [6, 7], the lowland irrigated river basins and deltas of south and south-east Asia for rice [8], and the North China Plains, Indo-Gangetic Plains, central North American Plains, coastal belt of east, south, and western Australia, and central and northwest Europe for wheat [8, 9]. The potential for SSA to be another major breadbasket is suggested by the fact that most of the existing SSA cereal crop land (where nearly all grain is produced under rainfed—rather than irrigated—conditions) receives abundant precipitation (> 900 mm per year), equal to or greater than all existing breadbaskets except for the humid tropical lowland rice areas in Asia.

The degree to which crop water requirements are satisfied, however, also depends on evaporative demand (called reference evapotranspiration) and soil capacity to store water, which may be very different in SSA than in other breadbaskets. For example, US Corn

Table 1. Comparison of annual precipitation, annual reference evapotranspiration, and soil plant-available water-holding capacity in the US Corn Belt and Sub-Saharan Africa (SSA). West SSA: Burkina Faso, Ghana, Mali, Nigeria. East SSA: Ethiopia, Kenya, Tanzania, Uganda, Zambia. *Sources: US Corn Belt* [14] *and Global Yield Gap Atlas* (www.yieldgap.org) *for SSA*. For SSA, reported values refer to all locations selected following the Global Yield Gap Atlas protocols in the nine countries. A depth of 150 cm is specified for the US Corn Belt, which corresponds to the depth to which maize roots can grow in the absence of any soil physical or chemical constraint limiting root growth [15]. The range in values for water holding capacity reflects variation in soil texture to that depth. In contrast, with less reliable data on rootable soil depth for SSA, the range in values reflects differences in both rootable soil depth from 50 to 150 cm and the plant-available soil water holding capacity to that depth [16].

Parameter[a]	US CornBelt	West SSA	East SSA
Annual precipitation	600–1000	900–1400	900–1400
Plant-available water holding capacity in the root zone	200–300	20–140	25–130
Annual reference evapotranspiration	600–1000	2200–2900	2100–2400

[a] All values are expressed in mm of water.

Belt soils are deep and of recent origin, and young, laid down during the past 20 000 years, whereas soils in the Guinea Savannah region of SSA are much older and weathered from parent material dating back to the Precambrian era at least 540 million years ago [10]. Given the same soil particle size distribution (called soil texture), weathered tropical soils have water retention properties very different from younger temperate soils, behaving like a clay soil at high soil water content but resembling a sandy soil at low soil water content [11, 12]. Moreover, as described by Nye and Greenland in their seminal book on agricultural soils of west Africa [13]: 'over vast stretches of savannah, the rooting zone is often restricted by the presence of an indurated iron-oxide-cemented pan, often referred to as laterite, above the rotting rock'. As a consequence, despite greater precipitation, agricultural soils in SSA typically have much smaller capacity to store water in the rootable soil depth than US Corn Belt soils. Furthermore, evaporative demand as quantified by reference evapotranspiration is substantially larger in SSA, because of mostly tropical and sub-tropical climates (table 1).

The capacity of soils to store water determines the size of the water reservoir, which can support crop growth during periods of water deficit when rainfall does not meet evapotranspiration demand [17, 18]. The size of this reservoir depends on the depth to which roots can grow, as determined by soil physical and chemical properties, and on soil water holding capacity in that root zone, which is largely determined by soil texture. The degree to which soils can buffer against transient water deficits is of particular importance because plants are especially sensitive to short-term water deficits during specific growth stages, such as the period between silking and pollen shed in maize, called the anthesis-silking interval [19–21]. In addition to supporting higher average rainfed yield potential (the yield when crop growth is only limited by water supply), large soil water holding capacity in the root zone also confers greater yield stability due to smaller inter-annual yield variation arising from year-to-year variation in rainfall amount and timing. This is of great importance because yield stability has a large influence on farm income and the degree of risk associated with investments in inputs such as improved seed, fertilizer, and pest control measures. At regional and national scales, yield stability has a large influence on the potential to be self-sufficient in grain production or to be a dependable grain exporter.

Despite the importance of root zone water holding capacity in determining yield potential of rainfed crops and inter-annual yield variation [22], most previous estimates of SSA crop production potential have relied only on aboveground water balance (i.e. annual precipitation versus evapotranspiration) without considering root zone water holding capacity [1, 3]. In large part this omission reflects the paucity of data on rootable soil depth in agricultural soils of SSA [16]. The objective of this paper is to quantify the effect of uncertainty in rootable soil depth on crop production potential in SSA and the impact of rooting depth on capacity of SSA soils to support high and stable crop yields. To this end, we perform a sensitivity analysis of rainfed maize yield potential for major crop-producing countries of west and east Africa in relation to rootable soil depth to assess the likelihood that SSA could become a future maize breadbasket. Our analysis utilizes recent climate data and extends to 2050, a period in which the magnitude of climate change is projected to be modest compared to subsequent change to 2100 [23]. Likewise, the impact of climate change on SSA crop yields is thought to be mostly negative [24], so that achieving breadbasket status would be more difficult under climate change than as benchmarked in our study.

Methods

Maize production potential on existing maize land was evaluated in nine countries of SSA (west: Burkina Faso, Ghana, Mali and Nigeria, and east: Ethiopia, Kenya, Tanzania, Uganda, and Zambia) following protocols of the Global Yield Gap Atlas (www.yieldgap.org) established for estimating rainfed yield potential of major cereal crops [25, 26]. These nine countries represent 70% and 65% of total population in West Africa and East Africa, respectively, accounting for about the same proportions of total maize production area [27], and they contain most of the Guinea Savannah zone within their borders [1]. We focus on maize because of its increasing importance as a staple food crop in this region. For example, in the 2000–2013 period: (i) maize

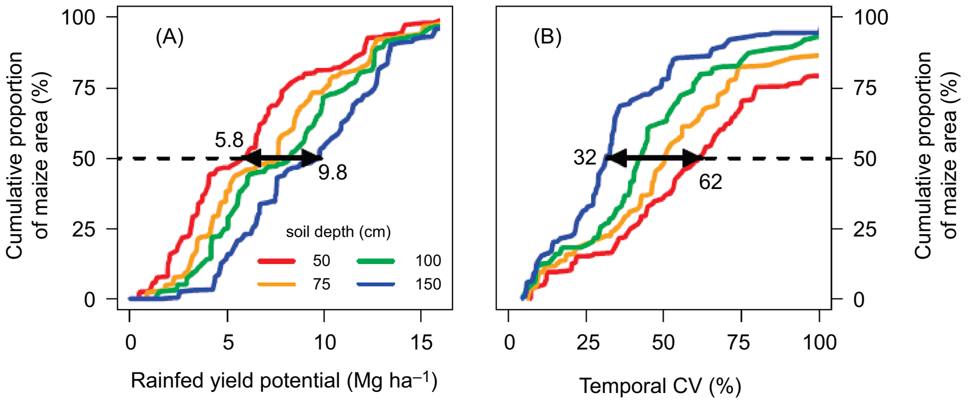

Figure 1. Effect of rootable soil depth on (*a*) frequency distribution of water-limited yield potential and (*b*) inter-annual variation expressed as the temporal coefficient of variation (CV). The arrows and black bold numbers indicate the range in the 50th percentile (50% of maize area) across different rootable soil depths. For each rootable soil depth, the frequency distribution includes 5815 simulated yields across 105 locations, 1–3 crop sequences, and 3–5 soil types at each location over, at least, 15 recent years.

production area increased by 75% in West Africa and 50% in East Africa [27] and this trend is expected to continue [6], (ii) maize accounted for 8% (West Africa) and 24% (East Africa) of dietary calories [27], and (iii) maize use for livestock feed is expected to increase more than four-fold by 2050 compared to 2005 [28]. Likewise, the SSA population will more than double during the same time period [29], driving a dramatic increase in food demand [30].

Rainfed yield potential was simulated with a well-validated biophysical crop model [17, 31, 32] at 105 locations in major maize producing regions of these nine countries (figure S1) using local weather, soil, and cropping system data as the basis for simulations. This model has been rigorously evaluated on its ability to reproduce measured maize yields, across a diverse range of production environments where yields ranged from complete failure up to 18 t ha^{-1} [17, 31, 32]. At least 15 recent years of weather data were utilized for simulations at each location to allow estimation of yield stability, as quantified by the temporal coefficient of variation for yield, due to normal inter-annual variation in weather. Taken together, these 105 locations are representative of 70% of total maize area within the nine countries (table S1) as delineated by climate zones within the geospatial framework of the Global Yield Gap Atlas [26]. Separate simulations were performed at each location for: (i) the dominant maize-based crop sequences (typically one or two), and (ii) the dominant soil types on which maize is grown (typically 3–5). Aggregate estimates for each location were based on weighting for proportion of maize production area with each crop sequence and soil type [26, 33]. Location-specific results were then aggregated to climate zone and national spatial scales following an upscaling approach based on the current distribution of harvested maize area [26, 33]. National maize production capacity was assumed to be 80% of rainfed yield potential [14, 34, 35] on existing maize production area. Details about methods and sources of data are described in the supplementary materials methods section available at stacks.iop.org/ERL/12/114036/mmedia.

Separate sets of simulations were performed with soil depth specified at 50, 75, 100 and 150 cm across all locations, and with a recently completed map of root zone plant available water holding capacity for SSA, which represents the best available data on rootable soil depth in SSA [16]. This recent soil depth database has a number of weaknesses, however, due to lack of adequate underpinning data for key soil properties at sufficient spatial resolution, which makes the estimated rooting depths highly uncertain. Thus, the analysis presented here is crucial for assessing the importance of soil depth in estimating rainfed yield potential and its stability at national to regional spatial scales.

Results and discussion

Soil root-zone depth and maize yield potential

Results from this sensitivity analysis showed that median rainfed yield potential with 50 cm rooting depth was only 60% of the yield potential with 150 cm depth (figure 1(*a*)). Even with a relatively deep soil profile of 100 cm, median yield decreased by 15% compared to the typical rooting depth of 150 cm found in most of the US Corn Belt, Argentinean pampas, and northwest Europe wheat belt. Most notable, however, is the sensitivity of maize yield stability to rootable soil depth in these SSA countries. Across all soil depths, the median coefficient of variation ranged from 32% to 62% (figure 1(*b*)). This degree of inter-annual yield variation is comparable to that of harsh, rainfed environments as found, for example, in the driest areas of the western US Corn Belt (figure 2), where 50% of maize area is irrigated to provide stability to annual grain production [36]. In contrast, regions considered breadbaskets for rainfed maize, such as the central US Corn Belt states of Illinois and Iowa, and the Argentinean Pampas, have coefficients of variation in yield less than 25%. Even

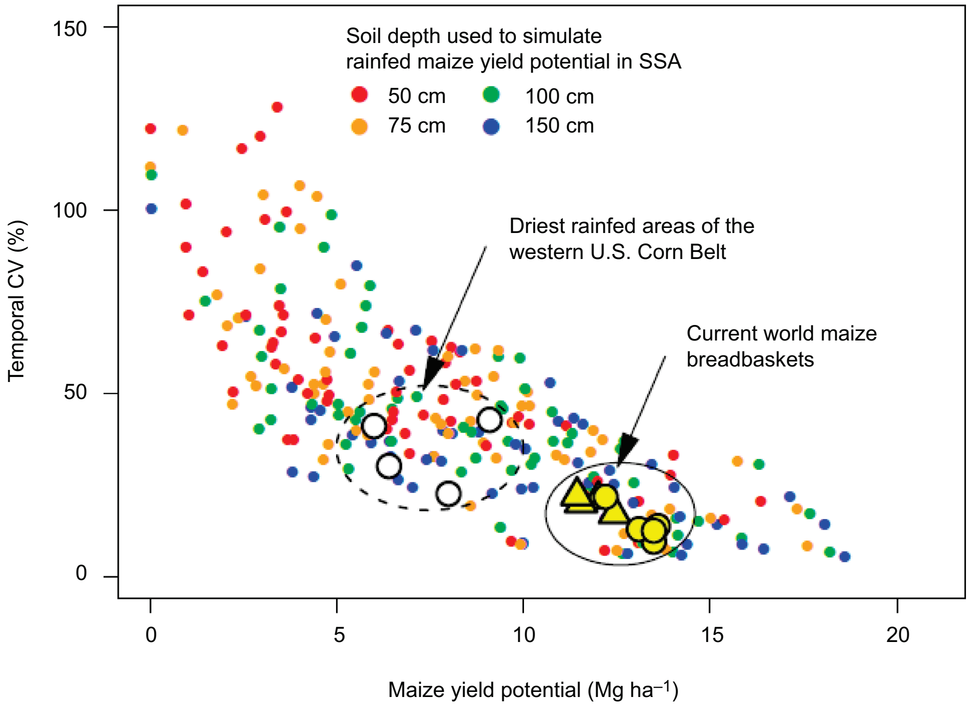

Figure 2. Relationship between simulated rainfed maize yield potential and its variability over years (temporal CV) in Sub-Saharan Africa and comparison with rainfed maize yield potential and its stability (*i*) in two current maize breadbaskets: Argentina and the US Corn Belt, and (*ii*) in the driest rainfed areas of the western US Corn Belt. Each data point represents a climate zone of the Global Yield Gap Atlas (see table S2 for a list of these climate zones, and figure S2 for a map of their locations). White circles: driest areas of the western US Corn Belt. Yellow circles: favorable rainfed areas of the central US Corn Belt. Yellow triangles: favorable rainfed areas of the Argentinean pampas. All yields are simulated rainfed maize yield potential. Current world breadbaskets included in the figure all have average rainfed maize yield potential >11 Mg ha^{-1} and a CV <25%. *Source: Global Yield Gap Atlas* (www.yieldgap.org).

with the deepest soil profile evaluated (150 cm), only 30% of maize production area in the nine SSA countries have yield and yield stability comparable to those of regions considered breadbaskets for rainfed maize (figure 2), and this proportion decreased to 15% with a rooting depth of 100 cm.

Rootable soil depth has a large influence on the simulated maize yields in SSA through the probability of water stress occurring during the sensitive anthesis-silking interval (figure 3(*a*)), which is a critical stage for yield formation in maize [19– 21]. Indeed, water stress intensity around flowering explained *ca.* 60% of variation in rainfed yield potential across the 105 SSA locations and the four rootable soil depths (figure 3(*b*)). Average water stress index (WSI[10]) during this period more than doubled when soil depth decreased from 150 cm (WSI = 0.14) to 50 cm (WSI = 0.30), highlighting the importance of water storage capacity in the root zone to mitigate yield loss in the tropical wet-dry climates that exist in much of SSA with relatively large total annual rainfall.

The next breadbasket?

Aggregated for all nine countries, total annual maize production capacity decreased from 96 Mt to 76 Mt (21% reduction) when rootable soil depth decreased from 150 cm to 75 cm (figure 4, table S3). This reduction represents maize supply for 214 million people and is comparable to the difference in projected total annual maize demand in 2050 for the high (95 Mt) and low (78 Mt) fertility variants of the United Nations (U.N.) population scenarios [29] and per capita maize demand projections from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) [37] (table S4). Using the best available data on soil depth in SSA [16], total annual maize production capacity is estimated to be 6% greater than projected 2050 maize demand of 86 Mt based on the medium U.N. population projection, and suggests an average rootable soil depth, weighted by current maize production area, of about 120 cm. If, however, average rooting depth is 100 cm or 75 cm, then production capacity falls to 97% and 88% of projected demand, respectively (figure 4). And while the 150 cm rooting depth scenario projects an annual surplus of 10 Mt, the magnitude of this projected surplus is considerably smaller than current annual exports of 40 and 16 Mt from the US and Argentina, respectively (5 yr average, 2009–2013). The high degree of sensitivity in SSA maize production capacity to rootable soil depth highlights the need for accurate maps of rootable soil depth of sufficient spatial resolution to evaluate food security scenarios with an acceptable degree of accuracy [38].

---

[10] WSI = 1-(AT/PT), where AT and PT are the simulated water-limited and non-water limited transpiration, respectively.

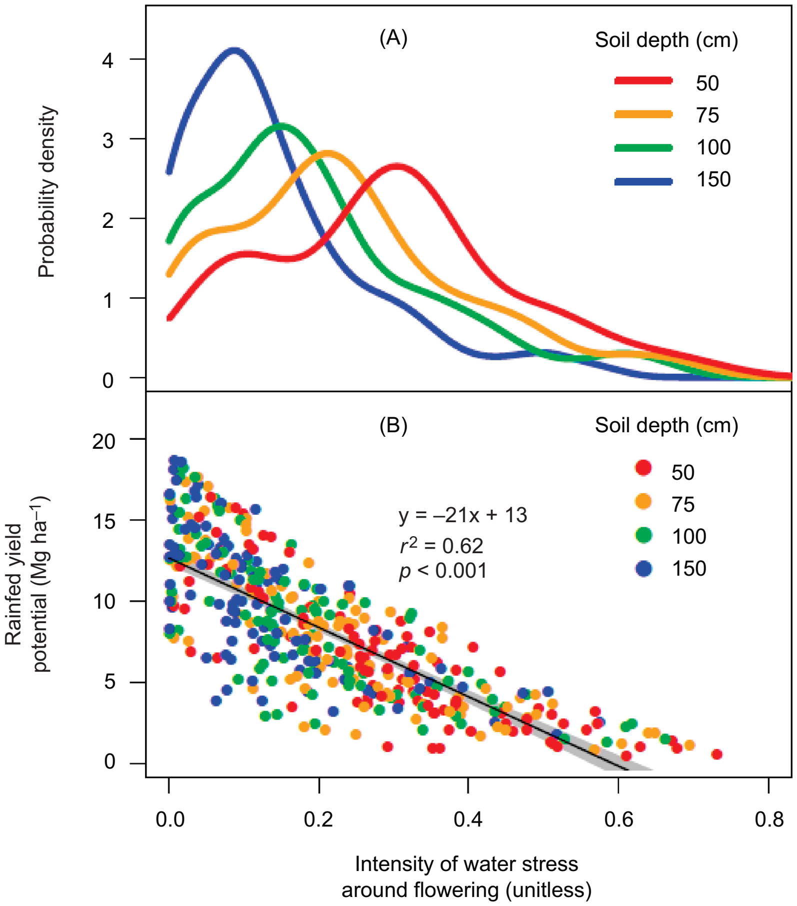

Figure 3. Relationship between rootable soil depth, water stress intensity around flowering (± 10 d), and rainfed yield potential. (*a*) Effect of rootable soil depth on probability of water stress around flowering. Water stress intensity reflects the water stress index (WSI) as simulated by the Hybrid-Maize model [31,32], which ranges from 0 (no stress) to 1 (maximum stress), indicating the degree to which daily crop water requirements are met by the available water supply from plant-available water reserves in the rootable soil volume and rainfall during the ±10 day period centered on flowering. (*b*) Relationship between rainfed yield potential and water stress intensity around flowering for different rootable soil depths. Each data point corresponds to the mean rainfed yield potential for a specific location. Grey shadow represents the 95% confidence interval of the linear regression.

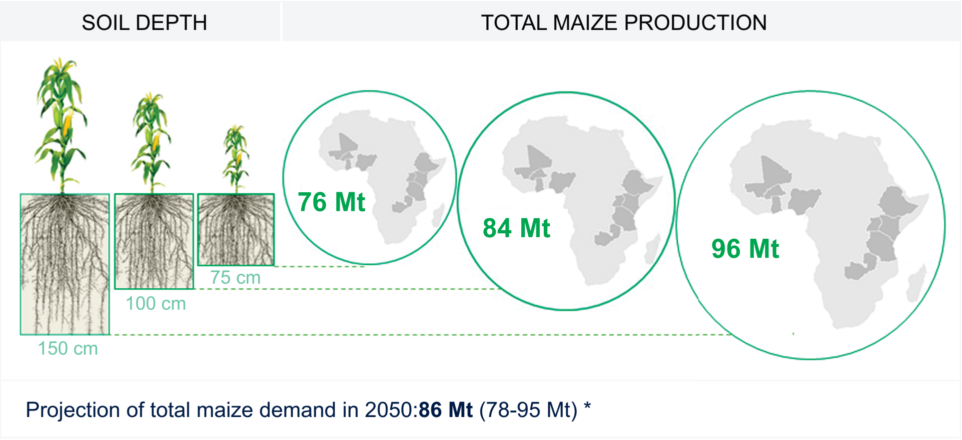

Figure 4. Effect of rootable soil depth on attainable total annual maize production on existing maize area in nine countries in Sub-Saharan Africa, which are indicated in dark grey in the maps. Estimates of attainable total maize production are based on 80% of simulated rainfed yield potential for major maize producing climate zones in each country and current maize harvested area. Note that circles areas are not strictly proportional to maize production totals. *Projection of total maize demand in 2050 is based on per capita maize demand projections from the IMPACT model [37] and the United Nations population projections [29] using the medium (in bold) or the low and high (values in parenthesis) fertility variants.

Given these projections, and the goal of food self-sufficiency for SSA as proposed by the World Bank [39], the analysis presented here confirms the need for substantial acceleration in yield gains and some expansion of both rainfed and irrigated production area to meet cereal demand by mid-century [30]. Annual gain in maize yield of 133 kg ha^{-1} $year^{-1}$ is required to support a yield increase from 1.7 Mg ha^{-1} in 2015 to 6.3 Mg ha^{-1} in 2050, which is 80% of the average rainfed yield potential with 100 cm rootable soil depth in the studied countries. Although such rapid rates of gain were achieved for some cereal crops in several countries during the green revolution in the last half of the 20th century [35], it would require more than a four-fold acceleration in the current (2004–2014) rate of maize yield gain in many of these nine SSA countries, with the exception of Ethiopia that achieved an annual gain in maize yield of 160 kg ha^{-1} yr^{-1} during this recent 10 yr period [27]. And it is notable these high rates of yield increase occurred in favorable environments for rainfed crop production over a period of several decades (e.g. Argentina and central US Corn Belt). Thus, the challenge for SSA is to increase yields at annual rates similar to those achieved in environments with favorable climate and deep soils, but with the disadvantage of having harsher climatic conditions and reduced water storage capacity in the root zone.

The need for accurate data on root-zone depth

While estimates of grain production capacity are necessary to evaluate food security scenarios for SSA, they are not sufficient and must be augmented by analysis of economic, social, environmental and policy constraints for effective prioritization of research and development investments. The analysis presented here focuses on rainfed yield potential, and thus on water as the main limiting factor to crop yields. It assumes that other limiting factors can be overcome with currently available technologies, such as fertilizers to overcome soil fertility constraints, which are recognized as one of the main factors currently limiting crop yields in SSA [40, 41], and adoption of improved crop varieties [6]. But overcoming these constraints will still come up short with respect to attaining food self-sufficiency if rootable soil depth is less than 100 cm. Moreover, even with soil depth greater than 100 cm, the high degree of yield instability adds substantial risk to investment in these critical inputs. Therefore, estimation of rainfed yield potential and its stability based on realistic assumptions about rootable soil depth is crucial to assess whether SSA can become a breadbasket, self-sufficient, or a major importer of grain, and also to identify regions with greatest opportunities for crop intensification. Such insight would better inform policies and priorities for investment in agricultural research to support agricultural development and to minimize potential negative impact on habitat to maintain biodiversity. It would also help identify current rainfed crop production areas that would benefit most from the development of irrigation, assuming a sustainable supply of irrigation water is available. With concerns about climate change and increasing variability in rainfall amount and timing [42], irrigated crop production is likely to play an increasingly important role, which would contribute to higher and more stable crop yields [38, 43].

To this end, a key question is how to design a soil sampling plan for SSA to collect data in areas most relevant to current and future crop production, and where data are lacking or most uncertain. Global databases and spatial frameworks such as those developed in the Global Yield Gap Atlas [25, 26] and AfSIS [16] provide a point of departure to design such a cost-efficient sampling plan by identifying the smallest number of locations required to achieve adequate spatial resolution to cover current SSA crop production area. As shown by previous studies, one cannot assume that other underpinning data used in our analysis, in addition to soil depth, are free of uncertainty (e.g. see [44] regarding weather data). Hence, while we recognize there is room and need for improvement of the underpinning data [25], the results from our study utilize the best available data and provide strong evidence that rootable soil depth is a major determinant of cereal production capacity in SSA and stability of that production over time due to year-to-year variation in weather.

Acknowledgments

Support for this research was provided by the Bill and Melinda Gates Foundation and the Daugherty Water for Food Global Institute at University of Nebraska-Lincoln (UNL). We thank other members of the Global Yield Gap Atlas team who have been involved in the project: H de Groot and H Boogaard (Wageningen Environmental Research). We thank the country agronomists that contributed to the Global Yield Gap Atlas for their respective countries including: Dr Korodjouma Ouattara (Institut de l'Environnement et de Recherches agricoles, Burkina Faso), Dr Mamoutou Kouressy (Institute of Rural Economy, Mali), Dr Abdullahi Bala (Federal University of Technology, Minna, Nigeria), Dr Samuel Adjei-Nsiah (University of Ghana, Ghana), Dr Kindie Tesfaye (CIMMYT, Ethiopia), Dr Ochieng Adimo (Jomo Kenyatta University of Agriculture and Technology, Kenya), Dr Joachim Makoi (Ministry of Agriculture Food Security and Cooperatives, Tanzania), Dr Kayuki Kaizzi (National Agriculture Research Laboratories, Uganda), and Dr Regis Chikowo (University of Zimbabwe, Zimbabwe).

ORCID iDs

Nicolas Guilpart https://orcid.org/0000-0003-3804-0211

References

[1] Morris M L, Binswanger-Mikhize H P and Byerlee D 2009 *Awakening Africa's Sleeping Giant: Prospects for Commercial Agriculture in the Guinea Savanah Zone and Beyond* (World Bank Publications)

[2] Sanchez P A 2010 Tripling crop yields in tropical Africa *Nat. Geosci.* **3** 299–300

[3] Mueller N D *et al* 2013 Closing yield gaps through nutrient and water management *Nature* **490** 254–7

[4] Nkonya E, Johnson T, Kwon H Y and Kato E 2016 Economics of land degradation in Sub-Saharan Africa *Economics of Land Degradation and Improvement—A Global Assessment for Sustainable Development* (Springer) pp 215–59 (https://doi.org/10.1007/978-3-319-19168-3)

[5] Bourne J K Jr 2014 The next breadbasket *Nat. Geogr.* **226** 46–77

[6] Shiferaw B, Prasanna B M, Hellin J and Bänziger M 2011 Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security *Food Sec.* **3** 307–27

[7] Hartman G L, West E D and Herman T K 2011 Crops that feed the world 2. Soybean-worldwide production, use, and constraints caused by pathogens and pests *Food Sec.* **3** 5–17

[8] Cassman K G 1999 Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture *Proc. Natl Acad. Sci. USA* **96** 5952–9

[9] Boogaard H, Wolf J, Supit I, Niemeyer S and Van Ittersum M K 2013 A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union *Field Crops Res.* **143** 130–42

[10] Sanchez P A and Buol S W 1975 Soils of the tropics and the world food crisis *Science* **188** 598–603

[11] Sharma M L and Uehara G 1968 Influence of soil structure in water relations in a low humic latossol: I. Water retention *Soi Sci. Soc. Am. J.* **32** 765–70

[12] Sanchez P A 1976 *Properties and management of soils in the tropics* (New York: Wiley)

[13] Nye P and Greenland D 1960 *The Soil Under Shifting Cultivation* (Harpenden: Commonwealth Bureau of Soils)

[14] Van Wart J, Kersebaum K C, Peng S, Milner M and Cassman K G 2013 Estimating crop yield potential at regional to national scales *Field Crops Res.* **143** 34–43

[15] Dardanelli J L, Bachmeier O A, Sereno R and Gil R 1997 Rooting depth and soil water extraction patterns of different crops in a silty loam haplustoll *Field Crops Res.* **54** 29–38

[16] Leenaars J G B *et al* 2015 Root Zone Plant-Available Water Holding Capacity of Sub-Saharan Africa soils, version 1.0. Gridded functional soil information (dataset RZ-PAWHC SSA v. 1.0). *ISRIC Report* 2015/02. Collaboration project of Africa Soil Information Service (AfSIS) and Global Yield Gap and Water Productivity Atlas (GYGA). ISRIC–World Soil Information, Wageningen, the Netherlands (www.isric.org/documents/document-type/isric-report-201502-root-zone-plant-available-water-holding-capacity-sub)

[17] Grassini P, Yang H and Cassman K G 2009 Limits to maize productivity in Western Corn-Belt: a simulation analysis for fully irrigated and rainfed conditions *Agric. Forest Meteorol.* **149** 1254–65

[18] Passioura J and Angus J 2010 Improving productivity of crops in water-limited environments *Adv. Agron.* **106** 37–76

[19] Otegui M E and Bonhomme R 1998 Grain yield components in maize I. Ear growth and kernel set *Field Crops Res.* **56** 247–56

[20] Hall A J, Vilella F, Trapani N and Chimenti C 1982 The effects of water stress and genotype on the dynamics of pollen-shedding and silking in maize *Field Crops Res.* **5** 349–63

[21] Andrade F H *et al* 1999 Kernel number determination in maize *Crop Sci.* **39** 453–9

[22] Van Ittersum M K *et al* 2013 Yield gap analysis with local to global relevance–a review *Field Crops Res.* **143** 4–17

[23] Meyer L A 2014 Climate change 2014: synthesis report *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* Core Writing Team ed R K Pachauri and L A Meyer (Geneva: IPCC) pp 151

[24] Schlenker W and Lobell D B 2010 Robust negative impacts of climate change on African agriculture *Environ. Res. Lett.* **5** 014010

[25] Grassini P *et al* 2015 How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis *Field Crops Res.* **177** 49–63

[26] Van Bussel L G J *et al* 2015 From field to atlas: upscaling of location-specific yield gap estimates *Field Crops Res.* **177** 98–108

[27] Food and Agriculture Organization of the United Nations FAOSTAT Database Collections (http://faostat.fao.org/default.aspx) (Accessed: March 2016)

[28] The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (http://impact-model.ifpri.org/#scenario/SSP2_NoCC/map//qlxagg/agg_subcontinent/maiz) (Accessed: March 2016)

[29] United Nations–Department of Economic and Social Affairs World Population Prospects, the 2015 Revision (http://esa.un.org/wpp/) (Accessed: March 2016)

[30] Van Ittersum M K *et al* 2016 Can sub-saharan Africa feed itself? *Proc. Natl Acad Sci.* **113** 14964–9

[31] Yang H *et al* 2004 Hybrid-Maize—a maize simulation model that combines two crop modeling approaches *Field Crops Res.* **87** 131–54

[32] Yang H, Grassini P, Cassman K G, Aiken R M and Coyne P I 2017 Improvements to the Hybrid-Maize model for simulating maize yields in harsh rainfed environments *Field Crops Res.* **204** 180–90

[33] Van Wart J *et al* 2013 Use of agro-climatic zones to upscale simulated crop yield potential *Field Crops Res.* **143** 44–55

[34] Cassman K G, Dobermann A, Walters D T and Yang H 2003 Meeting cereal demand while protecting natural resources and improving environmental quality *Ann. Rev. Environ. Res.* **28** 315–58

[35] Grassini P, Eskridge K M and Cassman K G 2013 Distinguishing between yield advances and yield plateaus in historical crop production trends *Nat. Commun.* **4** 2918

[36] Grassini P, Specht J, Tollenaar M, Ciampitti I and Cassman K G 2014 High-yield maize–soybean cropping systems in the US corn belt *Crop Physiology—Applications for Genetic Improvement and Agronomy* (Netherlands: Elsevier)

[37] Robinson S *et al* 2015 *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)* (Washington, DC: IFPRI Discussion paper, International Food Policy Research Institute)

[38] Cassman K G and Grassini P 2013 Can there be a green revolution in Sub-Saharan Africa without large expansion of irrigated crop production? *Glob. Food Secur.* **2** 203–9

[39] Deininger K and Byerlee D 2011 *Rising Global Interest in Farmland: Can It Yield Sustainable and Equitable Benefits?* (Washington, DC: World Bank Publications)

[40] Sanchez P A 2002 Soil fertility and hunger in Africa *Science* **295** 2019–20

[41] Gonzalez-Dugo V, Durand J-L and Gastal F 2010 Water deficit and nitrogen nutrition of crops. A review *Agron. Sust. Dev.* **30** 529–44

[42] Niang I, Ruppel O C, Abdrabo M A, Essel A, Lennard C, Padgham J and Urquhart P 2014 Africa. in: Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed V R Barros *et al* (Cambridge: Cambridge University Press) pp 1199–265

[43] Xie H, You L, Wielgosz B and Ringler C 2014 Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa *Agric. Water Manage.* **131** 183–93

[44] van Wart J, Grassini P and Cassman K G 2013 Impact of derived global weather data on simulated crop yields *Glob. Change Biol.* **19** 3822–34