12-27-2016

Can Sub-Saharan Africa Feed Itself?

Martin K. van Ittersum
Wageningen Agricultural University, martin.vanittersum@wur.nl

Lenny G. J. van Bussel
Wageningen Agricultural University

Joost Wolf
Wageningen Agricultural University

Patricio Grassini
University of Nebraska-Lincoln, pgrassini2@unl.edu

Justin van Wart
University of Nebraska-Lincoln, justin.vanwart@huskers.unl.edu

See next page for additional authors

Can sub-Saharan Africa feed itself?

Martin K. van Ittersum[a,1], Lenny G. J. van Bussel[a], Joost Wolf[a], Patricio Grassini[b], Justin van Wart[b], Nicolas Guilpart[b], Lieven Claessens[c], Hugo de Groot[d], Keith Wiebe[e], Daniel Mason-D'Croz[e], Haishun Yang[b], Hendrik Boogaard[d], Pepijn A. J. van Oort[f,g], Marloes P. van Loon[a], Kazuki Saito[f], Ochieng Adimo[h], Samuel Adjei-Nsiah[i], Alhassane Agali[j], Abdullahi Bala[k], Regis Chikowo[l], Kayuki Kaizzi[m], Mamoutou Kouressy[n], Joachim H. J. R. Makoi[o], Korodjouma Ouattara[p], Kindie Tesfaye[q], and Kenneth G. Cassman[b]

[a]Plant Production Systems Group, Wageningen University, 6700 AK Wageningen, The Netherlands; [b]Department of Agronomy and Horticulture, University of Nebraska, Lincoln, NE 68583-0915; [c]International Crops Research Institute for the Semi-Arid Tropics, 00623 Nairobi, Kenya; [d]Wageningen Environmental Research, Wageningen University & Research, 6700 AA, Wageningen, The Netherlands; [e]Environment and Production Technology Division, International Food Policy Research Institute, Washington, DC 20006-1002; [f]Africa Rice Center, Sustainable Productivity Enhancement Program, 01 BP 2031, Cotonou, Benin; [g]Centre for Crop Systems Analysis, Wageningen University, 6700 AK Wageningen, The Netherlands; [h]Jomo Kenyatta University of Agriculture and Technology, 00200 Nairobi, Kenya; [i]International Institute of Tropical Agriculture, Tamale, Ghana; [j]AGRHYMET Regional Centre, BP 11011 Niamey, Niger; [k]Department of Soil Science, Federal University of Technology Minna, P.M.B 65 Gidan-Kwano, Niger State, Nigeria; [l]Crop Science Department, University of Zimbabwe, MP167 Mount Pleasant, Harare, Zimbabwe; [m]National Agricultural Research Laboratories, Kampala Nabweru 7065, Uganda; [n]Institut d'Economie Rurale, BP 258 Bamako, Mali; [o]National Irrigation Commission, Ministry of Water and Irrigation, 14473 Dar es Salaam, The United Republic of Tanzania; [p]Institut de l'Environnement et de Recherches Agricoles, 04 BP: 8645 Ouagadougou 04, Ouagadougou, Burkina Faso; and [q]International Maize and Wheat Improvement Centre, Addis Ababa, Ethiopia

Edited by Robert John Scholes, University of the Witwatersrand, Wits, South Africa, and approved November 3, 2016 (received for review June 28, 2016)

Although global food demand is expected to increase 60% by 2050 compared with 2005/2007, the rise will be much greater in sub-Saharan Africa (SSA). Indeed, SSA is the region at greatest food security risk because by 2050 its population will increase 2.5-fold and demand for cereals approximately triple, whereas current levels of cereal consumption already depend on substantial imports. At issue is whether SSA can meet this vast increase in cereal demand without greater reliance on cereal imports or major expansion of agricultural area and associated biodiversity loss and greenhouse gas emissions. Recent studies indicate that the global increase in food demand by 2050 can be met through closing the gap between current farm yield and yield potential on existing cropland. Here, however, we estimate it will not be feasible to meet future SSA cereal demand on existing production area by yield gap closure alone. Our agronomically robust yield gap analysis for 10 countries in SSA using location-specific data and a spatial upscaling approach reveals that, in addition to yield gap closure, other more complex and uncertain components of intensification are also needed, i.e., increasing cropping intensity (the number of crops grown per 12 mo on the same field) and sustainable expansion of irrigated production area. If intensification is not successful and massive cropland land expansion is to be avoided, SSA will depend much more on imports of cereals than it does today.

yield gaps | food self-sufficiency | food security | food availability | cereals

Producing adequate food to meet global demand by 2050 is widely recognized as a major challenge (1, 2). Increased price volatility of major food crops (3, 4) and an abrupt surge in land area devoted to crop production since approximately 2002 (5) reflect the powerful forces underpinning this challenge. A number of studies argue it is possible to meet projected global food demand on existing agricultural land by narrowing gaps between actual farm yields and yield potential (3, 6–11). Yield potential assumes unconstrained crop growth and perfect management that avoids limitations from nutrient deficiencies and water stress, and reductions from weeds, pests, and diseases (12, 13). Yield potential is therefore location-specific and depends on solar radiation, temperature, and water supply during the crop growing season and can be calculated for both rainfed (water-limited yield potential) and irrigated conditions (12, 13). The difference between the yield potential and actual farm yield is called the yield gap.

Although meeting the increased global demand may be possible, a more pressing question is whether and how different regions of the world can meet their respective demands for staple food crops. More specifically, although sub-Saharan Africa's current self-sufficiency ratio in staple cereals is just above 0.8 (Fig. 1*A*), it is among the (sub) continents with the lowest cereal self-sufficiency ratio while it has the greatest projected increase in population (14, 15). Self-sufficiency is defined here as the ratio between domestic production and total consumption (or demand); the latter is assumed to be equal to the domestic production plus net imports. While recognizing that food self-sufficiency is not an essential precondition for food security, self-sufficiency for low-income developing countries is of great concern because many lack adequate foreign exchange reserves to pay for food imports and infrastructure to store and distribute it efficiently. Substantial reliance on food imports is only possible if economic development is sufficient to afford them, and economic development of low-income countries to support such imports does not occur without strong agricultural development (16, 17). Apart from city states such as Singapore, there are no examples of low income countries that successfully industrialized in the second half of the 20th century while importing major shares of their food supply. Essentially, all success stories started with an economic revolution in the agricultural sector. Indeed, the African Development Bank explicitly highlights self-sufficiency in food production as a principal

Significance

The question whether sub-Saharan Africa (SSA) can be self-sufficient in cereals by 2050 is of global relevance. Currently, SSA is amongst the (sub)continents with the largest gap between cereal consumption and production, whereas its projected tripling demand between 2010 and 2050 is much greater than in other continents. We show that nearly complete closure of the gap between current farm yields and yield potential is needed to maintain the current level of cereal self-sufficiency (approximately 80%) by 2050. For all countries, such yield gap closure requires a large, abrupt acceleration in rate of yield increase. If this acceleration is not achieved, massive cropland expansion with attendant biodiversity loss and greenhouse gas emissions or vast import dependency are to be expected.

Author contributions: M.K.v.I., L.G.J.v.B., J.W., P.G., and K.G.C. designed research; M.K.v.I., L.G.J.v.B., J.W., P.G., J.v.W., N.G., L.C., H.d.G., K.W., H.Y., H.B., P.A.J.v.O., K.S., and K.G.C. performed research; M.K.v.I., L.G.J.v.B., J.W., J.v.W., N.G., H.d.G., D.M.-D., P.A.J.v.O., M.P.v.L., O.A., S.A.-N., A.A., A.B., R.C., K.K., M.K., J.H.J.R.M., K.O., and K.T. analyzed data and results; M.K.v.I., P.G., and K.G.C. wrote the paper; H.d.G. database and visualization; and O.A., S.A.-N., A.A., A.B., R.C., K.K., M.K., J.H.J.R.M., K.O., and K.T. collected data.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

[1]To whom correspondence should be addressed. Email: martin.vanittersum@wur.nl.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1610359113/-/DCSupplemental.

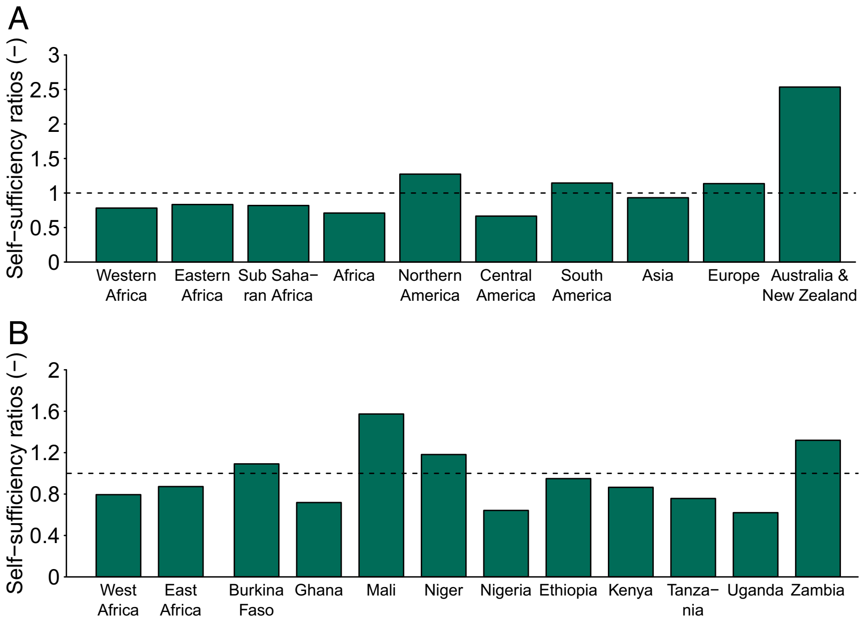

Fig. 1. Current (2010) self-sufficiency ratios for the five main cereals jointly. Major regions of the world based on FAO food balances (23) (*A*), and 10 sub-Saharan-African countries and the averages for the five countries in west and east SSA based on food demand calculated by IMPACT (22), actual yields taken from www.yieldgap.org, and crop areas from FAOSTAT (23) (*B*).

goal of its Action Plan for an African agricultural transformation (18). Hence, a key question is whether Africa, and in particular sub-Saharan Africa (SSA), can be food self-sufficient by 2050—and whether this can be achieved on existing agricultural land through yield increase or will rely on continued crop area expansion as has occurred in the past four decades (19). Although growth in total factor productivity has become the most important source of growth in global agricultural production in the past two decades, in SSA this metric grew by less than 1% per year over that period, even while it faces the world's highest population growth rates (20). A recent global study (11), based on the use of gridded spatial analysis and coarse global datasets, suggests it will be challenging for Africa to feed itself, whereas other global and continental analyses (15, 21) project that cereal imports will increase in SSA in the coming decades.

In this paper, we focus on 10 countries in SSA and use local, agronomically relevant data and a spatial upscaling protocol to estimate food production capacity with greater (compared with global and continental studies mentioned above) spatial resolution. We assess whether Burkina Faso, Ghana, Mali, Niger, Nigeria, Ethiopia, Kenya, Tanzania, Uganda, and Zambia can achieve self-sufficiency in the five main cereals (maize, millet, rice, sorghum, and wheat) by 2050, and whether this can be realized on existing cropland area or, instead, will require cropland expansion and food imports. The focus on cereals recognizes their central food security role, accounting for approximately 50% of caloric intake and total crop area in SSA (22, 23). The 10 countries jointly account for 54% of the 2010 population and 58% of the 2010 arable land area in SSA. Details of our analytical approach and sources of data are described in *SI Materials and Methods*. Briefly, 2050 cereal demand is estimated from projected population increase (medium fertility variant of the United Nations (UN) population projections; ref. 14), and per capita consumption as influenced by the projected income growth resulting in additional cereal demand for use as livestock feed and other purposes, using the partial equilibrium model for the agricultural sector IMPACT (15, 22). All five cereals are expressed in maize equivalents by conversion of each grain's specific caloric content. Then we estimate cereal production capacity on existing crop land through various degrees of yield gap closure, based on recently completed yield gap analyses for the 10 countries as published in the Global Yield Gap Atlas (www.yieldgap.org; Fig. 2 and refs. 24–26). Several 2050 supply-demand scenarios are evaluated based on degree of yield gap closure and other strategic options (e.g., expanded irrigation area, increased cropping intensity, and crop area expansion). Self-sufficiency is calculated as the ratio between cereal production and cereal demand, and we evaluate self-sufficiency ratios of each country and also for quasiregional zones that include five countries each for west and east Africa. The regional analysis indicates cereal self-sufficiency potential assuming open trade within these zones.

Results and Discussion

Current Cereal Self-Sufficiency and Trends. Today (2010), the self-sufficiency ratio for the five main cereals (maize, millet, rice, sorghum, and wheat) is 0.82 for sub-Saharan Africa as a whole (Fig. 1*A*), which is similar to the average value (0.83; Fig. 1*B*) for the 10 SSA countries evaluated in detail in this paper. Population in these countries is projected to increase two- to more than fourfold between 2010 and 2050 (Table 1). Trends show that all countries except Ethiopia and Zambia (23, 27) have cereal yields growing more slowly than population and demand (Fig. S1), whereas total cropland area has increased 14% in just the past 10 years (Table 1). Much of the increase in area took place in Ethiopia and Tanzania. National statistics in these two countries (28, 29) indicate that the additional crop land came from deforestation, conversion of marginal grazing land, and recultivation, using better technologies, of crop land that had previously been abandoned.

Future Cereal Self-Sufficiency. Estimated cereal demand by 2050 for the 10 countries is 335% of that in 2010 under the medium population projections and projected per capita demand from IMPACT (Table 1). Population growth alone accounts for approximately three-quarters of this increase and is thus much more important than per capita increase in demand due to dietary changes (Table 1 and Fig. S2). Demand increases vary substantially among countries in response to demographic trends and dietary shifts.

Actual rainfed maize yields (the dominant crop in SSA) during the period 2003–2012 range from 1.2 to 2.2 t/ha (Table 1 and ref. 24), which represents only 15–27% of the water-limited yield potential (Fig. 2). Rainfed maize has the greatest yield potential and largest yield gaps, whereas millet has the smallest potential and gaps (www.yieldgap.org). There is a similar spatial pattern for all rainfed crops with largest gaps in more favorable (higher rainfall) regions of the savannahs and cooler highlands of Ethiopia and the northern Zambia plain (Fig. 2).

AGRICULTURAL SCIENCES

SUSTAINABILITY SCIENCE

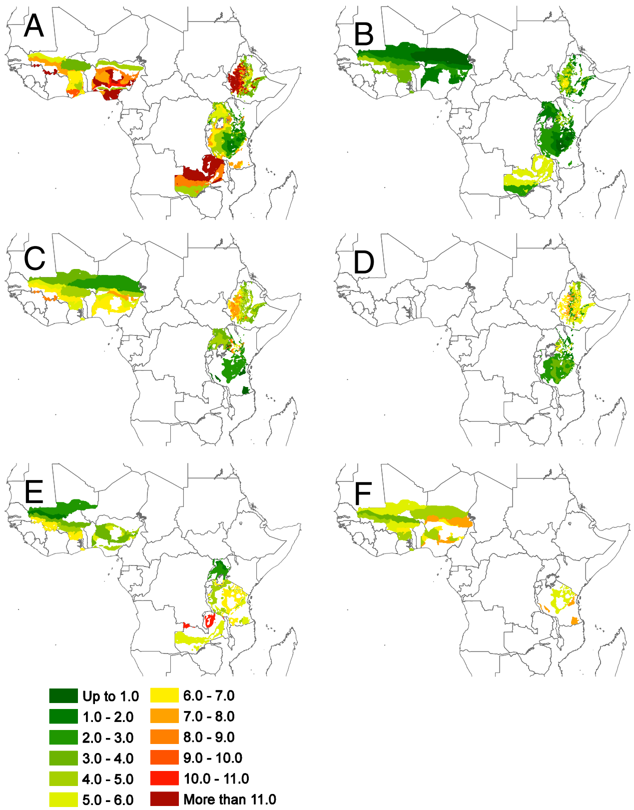

Fig. 2. Yield gaps (yield potential minus actual yields, t/ha harvested area) in the 10 sub-Saharan African countries. Rainfed maize (*A*), rainfed millet (*B*), rainfed sorghum (*C*), rainfed wheat (*D*), rainfed rice (*E*), irrigated rice (*F*). Source: www.yieldgap.org.

Assuming extrapolation of yield increase rates from 1991–2014 to 2050 without expansion of cereal area, cereal self-sufficiency decreases from 0.79 and 0.87 in 2010, to 0.33 and 0.48 in 2050, respectively, for the countries in west and east SSA (Fig. 3*A*). If by 2050 rainfed crop yields were lifted to 50% of the water-limited potential, self-sufficiency becomes 0.55 (west SSA) and 0.59 (east SSA), with a range of 0.34–0.96 among the 10 countries (Fig. 3*B*). Considering technical and economic feasibility and environmental concerns, it is generally accepted that 80% of yield potential represents an upper limit of attainable yield because of diminishing returns and greater inefficiencies from further investments in yield-enhancing inputs and labor (26, 30). Whereas Burkina Faso, Mali, and Ethiopia could become net exporters when reaching this 80% of yield potential by 2050, cereal self-sufficiency levels in Uganda and Tanzania would remain well below 0.75 (Fig. 3*B*). Aggregate cereal self-sufficiency levels for the west and east SSA countries are still <1.0 (Fig. 3*A*), suggesting that regional trade alone among these five countries within west or east SSA does not lead to self-sufficiency.

Required Yield and Crop Area Increases. In the 1991–2014 period, maize yield increase averaged only 27 and 34 $kg \cdot ha^{-1} \cdot y^{-1}$ in the five west and east SSA countries, respectively (Fig. S1 and Table 1). Narrowing yield gaps from the present approximately 20% to 50% of water-limited maize yield potential in 2050 requires accelerated yield increase rates of 72 (west SSA) and 64 (east SSA) $kg \cdot ha^{-1} \cdot y^{-1}$, and approximately double those rates to attain the 80% threshold. Such high rates are feasible in both developed and developing countries where farmers have access to markets and to the seed, fertilizer, and pest management inputs required to support higher yields (5, 31). To date, however, such conditions have been elusive in the majority of countries in SSA (32, 33), although recent maize yield increases in Mali, Ethiopia, Uganda, and Zambia hold promise (Table 1 and Fig. S1).

If yield gaps do not close, the projected 2050 production deficit for cereal self-sufficiency will need to be compensated by crop area expansion, greater cereal imports, or both. For example, if 1991–2014 yield growth rates continue, an additional 97 Mha (+185%) of cereal production area would be needed to achieve cereal self-sufficiency (Fig. 3*C*). Under this scenario, and assuming the share of land requirements for each of the cereals and other crops remains constant, 7 of the 10 countries do not have enough suitable land area (34) to support this expansion (Fig. 3*C*). Achieving 50% of yield potential lifts only Mali and Ethiopia to self-sufficiency, whereas an additional 44 Mha (+84%) cereals is needed for the other eight countries, with at least four countries still facing a shortage of suitable land area (Fig. 3*C*). In these area expansion scenarios, we assume

Table 1. Cereal demand increase by 2050 and recent developments in cereal production and cropland area in SSA

Country	Population 2050 (million) (and as % of 2010 population)	Cereal demand 2050 as % of that in 2010	Cereal area as % of total current cropland	Actual maize yields (2003–2012) used in GYGA, $t\,harvested\,ha^{-1}$	Annual maize yield increase (1991–2014), $kg \cdot ha^{-1} \cdot yr^{-1}$	Cropland area 2010, Mha	Increase in cropland area (2004–2013), Mha
Burkina Faso	43 (275)	304	74	1.5	9	5.8	1.6*
Ghana	50 (206)	372	34	1.7	16*	4.6	0.7*
Mali	45 (325)	365	60	1.9	60*	6.4	1.4*
Niger	72 (454)	508	70	0.8†	6	15.2	1.8*
Nigeria	399 (250)	314	48	1.6	31*	33.0	–1.0
Ethiopia	188 (216)	237	40	2.2	86*	14.6	2.8*
Kenya	96 (233)	346	45	1.9	–4	5.5	0.5*
Tanzania	137 (305)	381	44	1.2	–9	11.9	4.0*
Uganda	102 (300)	396	25	1.6	51*	6.7	1.0*
Zambia	43 (325)	519	35	2.3	55*	3.5	0.8*
Total	1,175 (261)	335	49	1.9	30*	107.0	13.6*

Medium fertility population projection in 10 sub-Saharan African countries by 2050, cereal demand 2050 versus 2010 [based on IMPACT (22) and UN medium fertility population projection (14)], cereal area as a percentage of cropland (%), actual (2003–2012) and progress (1991–2014) in maize yields (the former estimated in GYGA, the latter based on FAOSTAT; ref. 23), cropland area (2010 based on FAOSTAT; ref. 23) and trend in cropland area (2004–2013 based on FAOSTAT; ref. 23).

*Significant trend ($P < 0.05$).

†Maize area in Niger was too small to include in GYGA; average yield is taken from FAOSTAT.

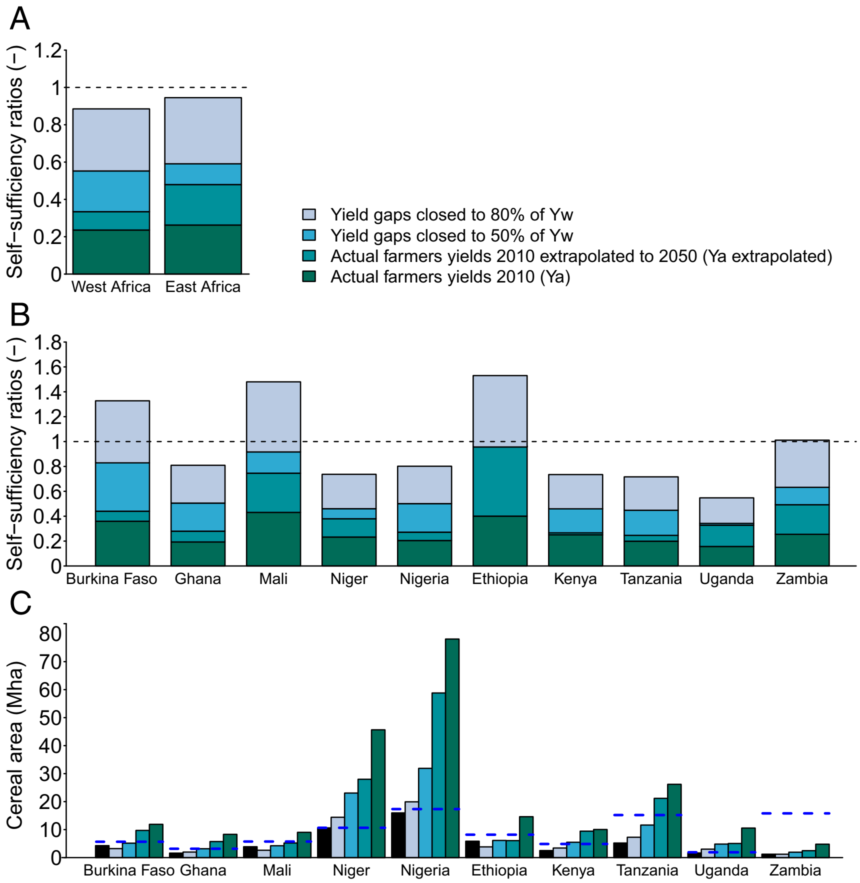

Fig. 3. Self-sufficiency ratios by 2050 based on various yield increase scenarios and required cereal area expansion to realize self-sufficiency by 2050. Yield scenarios are as follows: 2010 actual farmers' yields (Ya), actual yield increase 1991–2014 extrapolated to 2050 (Ya extrapolated), yield gaps closed to 50% or 80% of their water-limited potential (50% or 80% of Yw). (*A*) Regional self-sufficiency ratios by 2050 for the five western and eastern countries in SSA and current cereal areas. (*B*) Ratios for the 10 countries in SSA by 2050 and current cereal areas. (*C*) Cereal area required to achieve a self-sufficiency of 1 by 2050; black bars indicate current cereal area, and blue dashed lines indicate total potentially available cereal area (including today's cereal area) (34).

productivity of new and existing land to be the same, which is optimistic because the best quality farm land is likely already under cultivation and recent experience of crop land expansion in Ethiopia and Tanzania shows that a substantial portion of new crop land comes from marginal land (28, 29).

Other Important Factors. Our analysis does not account for several factors that might be important for future agricultural productivity. First, the assumption of maximum attainable yields at a level of 80% of water-limited yield potential in harsh rainfed regions with large year-to-year variation in rainfall is probably too optimistic. At the same time, our calculations are too pessimistic if genetic progress in yield potentials is achieved. Historically, genetic progress in yield potential has contributed to progress in farm yields (31) although the magnitude of this contribution is sometimes difficult to measure (35). Progress in elevating yield potential of the major cereals would imply, however, that even larger yield gaps need to be overcome than the already large gaps reported herein.

Second, although we included current climate variability in our analysis, we opted not to evaluate effects of long-term climate change because of large uncertainty in the degree of climate change impacts at local scales (in particular precipitation for east SSA) and because climate change impacts by 2050 are projected to be relatively small compared with the large yield gaps in SSA (36, 37). For example, recent analyses project that climate change to 2050 is likely to have a negative effect on major cereal crops in SSA, varying between a slightly positive impact (up to 10%) in high elevation regions of east SSA to negative impact up to approximately 20% elsewhere (36, 37). Although adaptation (in particular cultivar maturity and sowing date adjustment) may partly offset negative effects, climate change is likely to result in greater temporal variability of production (36, 38). Indeed, present climate variability in SSA, aggravated by climate change, will make the challenge even greater and may be a valid reason to target national or regional self-sufficiency ratios greater than 1.

Third, we assume no change in shares of areas of different crops within countries, either due to changes in diet or changes in cropping systems driven by profit motive. Trends of the past two decades, for example, indicate a substantial increase in maize area at the expense of sorghum and other staple food crops (23). If this trend continues, our estimates of cereal self-sufficiency would be somewhat pessimistic because maize is generally more productive than other cereal crops (31). At the same time, greater production of high value cash crops, such as cotton, cocoa, coffee, and oilseed crops may generate income for cereal imports but will also compete for land with cereals, resulting in a more pessimistic cereal self-sufficiency outlook.

Finally, apart from intensification through yield gap closure on existing farm land, cropping intensity may increase (i.e., more crop cycles per year on the same field) and the amount of irrigated crop area can increase where water resources allow it (Table S1). Based on best available data (*SI Materials and Methods*), we estimate the combined impact of these two factors across the three yield-growth scenarios. Results give a more optimistic outlook to achieve self-sufficiency on existing cereal production area, with potential for cereal exports under scenarios with accelerated yield growth to 80% of yield potential (Fig. S3). We emphasize, however, there are large uncertainties associated with the coarse data available for this additional analysis, and uncertainties associated with underpinning economic and environmental assumptions regarding intensifying cropping systems and irrigation expansion. Note, for instance, the large ranges in estimated potentials for increasing irrigated areas (39, 40).

Implications of This Assessment. Although recent positive trends in cereal yields in Ethiopia (18), and several other SSA countries (refs.

41 and 42 and Fig. S1) hold promise, for some of these countries, yield improvements follow a period of stagnant to sluggish yield increase in the 1980s and 1990s (43). However, it is clear that with improved cultivars, hybrids, and seed, coupled with increased use of fertilizers, modern pest management practices, and good agronomy, it is possible to achieve accelerated rates of yield gain (27, 42). It is also generally agreed that accelerated intensification will require greater investment in research and development (R & D) in both public and private sectors (44–46). This investment is needed now, and even more so under future climate change (27–29).

We emphasize that our study addresses only the biophysical opportunities and limitations to increase production, whereas many socio-economic and institutional factors need to be attuned to allow for production increases. R & D investments in agriculture must be matched by supportive policies and public finance for improved transport and communication, market infrastructure, credit, insurance, and improved land entitlements (21, 45–47). Targeted measures to stabilize markets (which may imply some degree of import tariffs) for smallholder farming seem essential (3, 48). Because smallholder farming is so prominent in SSA relative to commercial scale farming, creating off-farm employment opportunities is probably equally important as targeting agricultural productivity and yield gap closure to allow for upscaling of farming (33). Finally, anticipating and avoiding negative environmental impacts of intensification will be important, and especially a period of excess use of nutrients and pesticides such as in Europe and China. Indeed, a direct transition from an agriculture that mines the soil to one based on high resource use efficiency and conservation of natural resources is necessary (49, 50), requiring anticipatory R & D focused on the dual goals of increasing yields and protecting environmental quality.

Conclusions

This study provides insight about the challenge in meeting the projected tripled cereal demand by 2050 due to expected population growth and modest changes in diets in 10 SSA countries, through scenarios of yield gap closure. Together these 10 countries represent 54% of total population and 58% of the arable land area in SSA, making it unlikely that the situation is more optimistic for the rest of the region. Results reveal that although yield gap closure on existing cropland and a large acceleration in yield growth rates are essential to achieve cereal self-sufficiency, they are most likely not sufficient. For instance, increasing maize yields from the approximately 20% of yield potential in 2010 to 50% by 2050 implies a doubling of annual yield increases compared with the past decades. Even then, cereal areas must increase by more than 80% to realize self-sufficiency in the 10 countries. Therefore, the path to self-sufficiency will likely require, in addition to yield gap closure, increased cropping intensity and expansion of irrigated production area in regions that can support these options in a sustainable manner. Failure to achieve these intensification options will result in increasing dependence on cereal imports and vast expansion of rainfed cropland area, especially because population in SSA is projected to further increase between 2050 and 2100 by a factor 1.9 and anticipated climate change will make the situation even more challenging. In highlighting the need for intensification through accelerated yield growth, greater cropping intensity, and increased irrigated area, we emphasize the importance of adequate R & D investments by the public and private sectors, accompanied by facilitating government policies to meet this challenge and to ensure intensification without negative environmental consequences.

Materials and Methods

We first computed current (2010) national demand (assumed equal to the 2010 consumption) and the 2010 production of the five main cereal crops (i.e., maize, millet, rice, sorghum, and wheat) to estimate 2010 self-sufficiency ratios in the 10 countries included in this study. Most of these countries have a large number of rural poor farmers living in high density rural areas, combined with large and growing market potential, making them a priority for private and public sector investments in SSA. Current total cereal demands per country were calculated as the product of current population size (Table 1; from UN population prospects, see ref. 14; see https://esa.un.org/unpd/wpp) and cereal demand per capita based on IMPACT (22, 23) (Table S2). The annual per capita demand for the five cereals was next expressed in maize yield equivalents by using the crop-specific grain caloric contents (with caloric contents based on FAO food balances, see faostat3.fao.org/home/E). Current (approximately year 2010) domestic grain production per cereal crop per country was calculated as mean actual crop yield (2003–2012) as estimated in the Global Yield Gap Atlas (Table 1; www.yieldgap.org; refs. 24 and 25) times the 2010 harvested area per crop (FAOSTAT; ref. 23: (faostat3.fao.org/home/E) (Table S1). Note, we expressed production and demand data at standard moisture content (15.5% for maize; 14% for rice, sorghum, and millet; 13.5% for wheat).

Total future (2050) annual cereal demand per capita, for each of the five cereals and each country, was retrieved from IMPACT modeling results (22). For this purpose, the Shared Socioeconomic Pathway (SSP2, no climate change; ref. 51) from the Intergovernmental Panel on Climate Change (IPCC) fifth assessment was used. Total cereal demand per country in 2050 was calculated based on projected 2050 population (medium fertility variant of UN population prospects (14), see https://esa.un.org/unpd/wpp; see Table 1 for medium fertility population projection) multiplied by the per capita cereal demand in 2050 from the SSP2 scenario.

Opportunities to increase cereal production by 2050 on current cereal land were estimated through extrapolation of 1991–2014 increases in actual yields and different levels (50% and 80%) of yield gap closure derived from the Global Yield Gap Atlas (GYGA) (www.yieldgap.org; refs. 24 and 25). The yield gap is calculated by the difference between current farm yield and yield potential when the crop is grown by using competent management that avoids yield loss from insect pests, disease, weeds, and nutrient deficiencies (26, 30). With much coarser data, we also estimated the possibilities of increasing cropping intensity (i.e., the number of crops grown in the same piece of land within a 12-mo time period), and expansion of irrigated area (*SI Materials and Methods*). These future cereal production data were compared against projections for the 2050 demand for cereals. We first calculated self-sufficiency ratios for year 2050 assuming the above-mentioned yield gap closures and with no expansion of rainfed cropland and no change in areas for each of the cereals. If the food self-sufficiency ratio by 2050 was <1, we calculated how much additional arable land area would be needed to reach self-sufficiency. For example, a self-sufficiency ratio of 0.5 would require the cropland area to be doubled assuming that the new land brought into crop production has the same productivity as current land (which is an optimistic assumption). Maximum land areas suitable for high-input rainfed cereal production (Table S1) were taken from a recent study (34) that concluded that the potential for profitable smallholder-based cropland expansion in many African countries is likely to be smaller than previous estimations (52, 53). We assumed the share of cereal land in total cropland will remain the same as today (Table S1) and corrected potentially available cropland for cereals accordingly (shown in Fig. 3*C* by dashed lines).

Note, that although the IMPACT model simulates both the supply and demand side of agricultural commodities, it was used in this analysis only for the per capita demand side. IMPACT includes the livestock and feed demand and incorporates interactions between agricultural sectors, but not with nonagricultural sectors. We opted to assess future supply based on different degrees of yield gap closure as derived from GYGA. Yield gap analysis, i.e., assessing the difference between yield potential and actual farm yield in a given location, is now widely used in literature to assess opportunities for sustainable intensification (6, 9, 11, 26, 30, 54, 55). The advantage of using yield gap analysis is that ultimate opportunities and limitations of technological progress are revealed, whereas in economic models, technological progress is simulated with economic feedbacks and at much lower temporal and spatial resolution. Our analysis thus provides the biophysical limits to become self-sufficient in cereals. GYGA uses a global protocol that relies on location-specific data on climate, soils, and cropping systems combined with a robust spatial framework to aggregate results to a national scale, and well-validated crop growth models to estimate potential yields (24–26). The database includes a unique collection of measured weather data, a recently completed map for SSA on Root Zone Plant Available Water Holding Capacity (www.isric.org/content/afsis-gyga-functional-soil-information-sub-saharan-africa-rz-pawhc-ssa) and location-specific information on cropping systems from country agronomists. Crop models were calibrated and evaluated by using the best available experiments. Simulations therefore provide estimations of yield gaps with agronomic rigor and a finer level of spatial resolution than previous studies. Cereal production in SSA is largely rainfed; hence, we use the water-limited yield potential as a benchmark for estimating yield gaps except for irrigated areas (mainly rice growing areas) where yield potential is unconstrained by water limitation (26).

Our analysis covers the 2010–2050 time period, and we note that year 2050 is often used as the target in evaluations of future food supply-demand projections. This 40-y period is long enough to envision the possibility of closing the current, large yield gaps given what has occurred in 30–40 y in many other parts of the world (e.g., Asia and Europe; ref. 31). It is a compromise between a timeframe that is long enough for changes in policies, investments, and technologies to have substantial impact, yet not so long that uncertainties overwhelm the analysis. As explained in *Results and Discussion*, we opted not to include climate change in our assessment.

Details of estimating current and future cereal demand and production (including sensitivity analysis for future cereal demand) are provided in *SI Materials and Methods*.

ACKNOWLEDGMENTS. We thank J. Chamberlin for providing potentially available cropland areas and K. E. Giller for comments on an earlier version of the manuscript. This research was performed in the context of the GYGA project (www.yieldgap.org) supported by the Bill & Melinda Gates Foundation, the Robert B. Daugherty Water for Food Institute at the University of Nebraska-Lincoln, and Wageningen University & Research (The Netherlands). Research conducted with the International Food Policy Research Institute's (IFPRI) IMPACT model was supported by the CGIAR Research Program on Policies, Institutions, and Markets (PIM) and the Bill & Melinda Gates Foundation. We also acknowledge the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS).

1. Alexandratos N, Bruinsma J (2012) *World Agriculture Towards 2030/2050: The 2012 Revision* (Food Agri Org United Nations, Rome).
2. Godfray HC, et al. (2010) Food security: The challenge of feeding 9 billion people. *Science* 327(5967):812–818.
3. Koning NBJ, et al. (2008) Long-term global availability of food: Continued abundance or new scarcity? *NJAS Wagening J Life Sci* 55(3):229–292.
4. Lagi M, Bertrand KZ, Bar-Yam Y (2011) The food crises and political instability in North Africa and the Middle East. SSRN:10.2139/ssm.1910031.
5. Grassini P, Eskridge KM, Cassman KG (2013) Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nat Commun* 4(2918):2918.
6. Mueller ND, et al. (2012) Closing yield gaps through nutrient and water management. *Nature* 490(7419):254–257.
7. Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci USA* 108(50):20260–20264.
8. Foley JA, et al. (2011) Solutions for a cultivated planet. *Nature* 478(7369):337–342.
9. Erb K-H, et al. (2016) Exploring the biophysical option space for feeding the world without deforestation. *Nat Commun* 7:11382.
10. Mauser W, et al. (2015) Global biomass production potentials exceed expected future demand without the need for cropland expansion. *Nat Commun* 6:8946.
11. Pradhan P, Fischer G, van Velthuizen H, Reusser DE, Kropp JP (2015) Closing yield gaps: How sustainable can we be? *PLoS One* 10(6):e0129487.
12. Evans LT, Fischer RA (1999) Yield potential: Its definition, measurement, and significance. *Crop Sci* 39(6):1544–1551.
13. Van Ittersum MK, Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Res* 52:197–208.
14. United Nations - Department of Economic and Social Affairs (2015) *World Population Prospects, the 2015 Revision* (United Nations, New York).
15. Sulser TB, Mason-D'Croz D, Islam SRS, Wiebe K, Rosegrant MW (2015) Africa in the global agricultural economy in 2030 and 2050. *Beyond a Middle Income Africa: Transforming African Economies for Sustained Growth with Rising Employment and Incomes. ReSAKSS Annual Trends and Outlook Report 2014*, eds Badiane O, Makombe T (Int Food Policy Res Inst, Washington, DC).
16. Johnston BF, Mellor JW (1961) The role of agriculture in economic development. *Am Econ Rev* 51(4):566–593.
17. Chang H-J (2009) *Rethinking Public Policy in Agriculture: Lessons from Distant and Recent History* (Food Agric Organ United Nations, Rome).
18. African Development Bank (2015) *Feeding Africa: An Action Plan for African Agricultural Transformation* (African Development Bank, Abidjan, Cote d'Ivoire).
19. Brink AB, Eva HD (2009) Monitoring 25 years of land cover change dynamics in Africa: a sample based remote sensing approach. *Appl Geogr* 29:501–512.
20. Fuglie KO, Wang SL, Ball VE, eds (2012) *Productivity Growth in Agriculture: An International Perspective* (CABI, Wallingford, UK).
21. OECD/FAO (2016) *OECD-FAO Agricultural Outlook 2016-2025* (OECD Publishing, Paris).
22. Robinson S, et al. (2015) *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT); Model Description for Version 3, IFPRI Discussion Paper* (Int Food Policy Res Inst, Washington, DC).
23. Food and Agriculture Organization of the United Nations (2015) *Production/Crops and Resource/Fertilizer* (FAOSTAT Database Collections, Rome).
24. 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.
25. Van Bussel LGJ, et al. (2015) From field to atlas: Upscaling of location-specific yield gap estimates. *Field Crops Res* 177:98–108.
26. Van Ittersum MK, et al. (2013) Yield gap analysis with local to global relevance—A review. *Field Crops Res* 143:4–17.
27. Abate T, et al. (2015) Factors that transformed maize productivity in Ethiopia. *Food Secur* 7(5):965–981.
28. CSA (2015) Report on Area and Production of Crops (Private Peasant Holdings, Meher Season). Agricultural Sample Survey 2014/2015 (2007 E.C.). *Statistical Bulletin 578* (Central Stat Agency, Addis Ababa, Ethiopia), Vol I.
29. AGSTATS (2013) The 2012/13 Preliminary Food Crop Production Forecast for 2013/14 Food Security. *AGSTATS for Food Security* (Ministry of Agric Food Secur Cooperatives, Dar es Salaam, Tanzania).
30. Lobell DB, Cassman KG, Field CB (2009) Crop yield gaps: Their importance, magnitudes, and causes. *Annu Rev Environ Resour* 34:179–204.
31. Fischer T, Byerlee D, Edmeades G (2014) *Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World?* (Aust Centre Int Agric Res, Canberra) pp XXI, 634.
32. Tittonell P, Giller KE (2013) When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Res* 143:76–90.
33. Frelat R, et al. (2016) Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proc Natl Acad Sci USA* 113(2):458–463.
34. Chamberlin J, Jayne TS, Headey D (2014) Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. *Food Policy* 48:51–65.
35. Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu Rev Environ Resour* 28:315–358.
36. Niang I, et al. (2014) *Africa. 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*, eds Barros VR, et al. (Cambridge Univ Press, Cambridge, UK), pp 1199–1265.
37. Porter JR, et al. (2014) *Food Security and Food Production Systems. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Field CB, et al. (Cambridge Univ Press, Cambridge, UK), pp 485–533.
38. Lesk C, Rowhani P, Ramankutty N (2016) Influence of extreme weather disasters on global crop production. *Nature* 529(7584):84–87.
39. You L, et al. (2011) What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy* 36(6):770–782.
40. Food and Agriculture Organization of the United Nations (2015) AQUASTAT. Available at www.fao.org/nr/water/aquastat/data. Accessed November 22, 2016.
41. The Economist (March 12, 2016) Briefing African Agriculture – A Green Evolution. *The Economist*, 19–22.
42. Sanchez PA (2015) En route to plentiful food production in Africa. *Nat Plants* 1:14014.
43. Nin-Pratt A, Johnson M, Yu B (2012) *Improved Performance of Agriculture in Africa South of the Sahara: Taking Off or Bouncing Back. IFPRI Discussion Paper No. 01224.* (Int Food Policy Res Inst, Washington, DC), p 32.
44. Pardey PG, Alston JM, Chan-Kang C (2013) Public agricultural R&D over the past half century: An emerging new world order. *Agric Econ* 44(s1):103–113.
45. World Bank (2009) *Awakening Africa's Sleeping Giant Prospects for Commercial Agriculture in the Guinea Savannah Zone and Beyond* (World Bank, Washington, DC), p 4.
46. World Bank (2013) *Growing Africa: Unlocking the Potential of Agribusiness* (World Bank, Washington, DC), p 162.
47. Smale M, Byerlee D, Jayne T (2013) Maize revolutions in Sub-Saharan Africa. *An African Green Revolution: Finding Ways to Boost Productivity on Small Farms*, eds Otsuka K, Larson DF (Springer, Dordrecht), pp 168–196.
48. Koning N, van Ittersum MK (2009) Will the world have enough to eat? *Curr Opin Environ Sustain* 1(1):77–82.
49. Cassman KG (1999) Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proc Natl Acad Sci USA* 96(11):5952–5959.
50. Zhang X, et al. (2015) Managing nitrogen for sustainable development. *Nature* 528(7580):51–59.
51. O'Neill B, et al. (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim Change* 122(3):387–400.
52. Fischer G, van Velthuizen H, Shah M, Nachtergaele F (2002) *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results* (IIASA, Laxenburg, Austria, and Food Agric Org United Nations, Rome).
53. IIASA/FAO (2012) *Global Agro-ecological Zones (GAEZ v3.0)* (IIASA, Laxenburg, Austria, and Food Agric Org United Nations, Rome).
54. Sumberg J (2012) Mind the (yield) gap(s). *Food Secur* 4(4):509–518.
55. Van Oort PAJ, et al. Can yield gap anlaysis be used to inform R&D prioritisation? *Glob Food Secur*, in press.
56. Wiebe K, et al. (2015) Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environ Res Lett* 10(8):085010.
57. Deininger K, Byerlee D (2011) *Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits?* (World Bank Publications, Washington, DC).
58. You L, et al. (2014) Generating global crop distribution maps: From census to grid. *Agric Syst* 127:53–60.
59. Yang H, Dobermann A, Cassman KG, Walters DT (2006) Features, applications, and limitations of the hybrid-maize simulation model. *Agron J* 98(3):737–748.
60. Bouman BAM, et al. (2001) *ORYZA2000: Modeling Lowland Rice* (IRRI, Los Baños, The Philippines), p 235.
61. van Oort PAJ, de Vries ME, Yoshida H, Saito K (2015) Improved climate risk simulations for rice in arid environments. *PLoS One* 10(3):e0118114.
62. Supit I, et al. (2012) Assessing climate change effects on European crop yields using the Crop Growth Monitoring System and a weather generator. *Agric Meteorol* 164:96–111.
63. Wolf J, et al. (2011) Modeling winter wheat production over Europe with WOFOST – the effect of two new zonations and two newly calibrated model parameter sets. *Methods of Introducing System Models into Agricultural Research. Advances in Agricultural Systems Modeling 2: Trans-disciplinary Research, Synthesis, and Applications*, eds Ahuja LR, Ma L (ASA-CSSA-SSSA, Madison, WI), pp 297–326.
64. Van Wart J, et al. (2013) Use of agro-climatic zones to upscale simulated crop yield potential. *Field Crops Res* 143:44–55.