Can sub-Saharan Africa feed itself?

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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.

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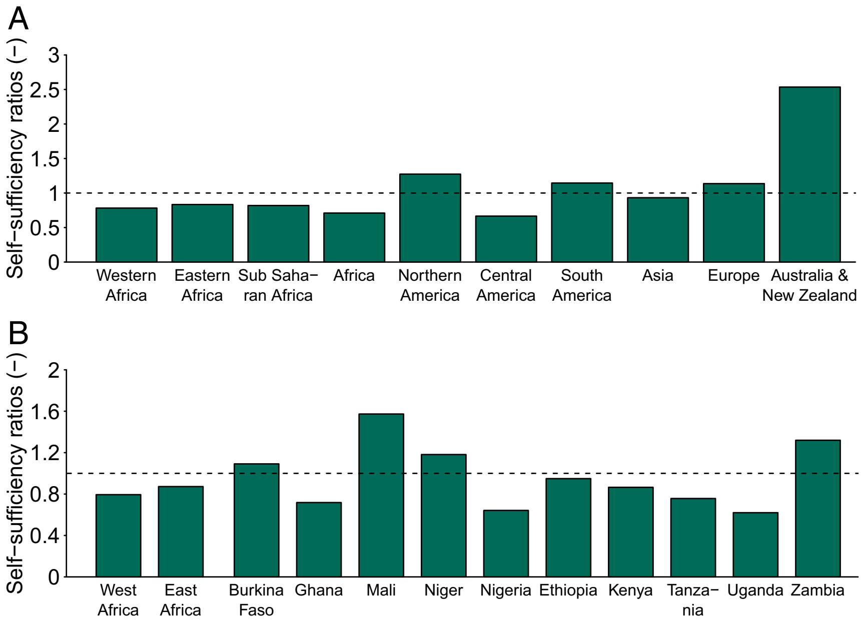

Fig. 1. Current (2010) self-sufficiency ratios for the five main cereals jointly. Major regions of the world based on FAO food balances (23) (*A*), and 10 sub-Saharan-African countries and the averages for the five countries in west and east SSA based on food demand calculated by IMPACT (22), actual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

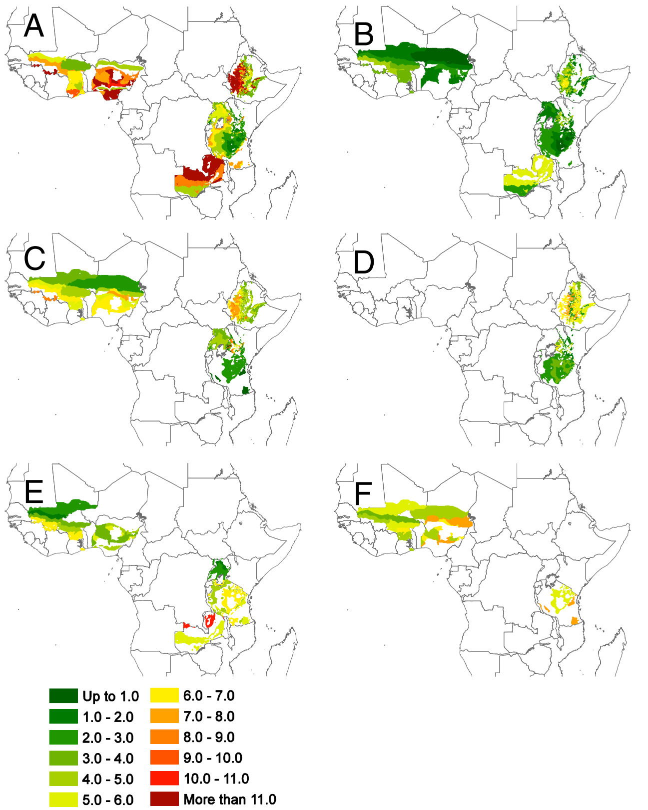

Fig. 2. Yield gaps (yield potential minus actual yields, t/ha harvested area) in the 10 sub-Saharan African countries. Rainfed maize (*A*), rainfed millet (*B*), rainfed sorghum (*C*), rainfed wheat (*D*), rainfed rice (*E*), irrigated rice (*F*). Source: www.yieldgap.org.

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.

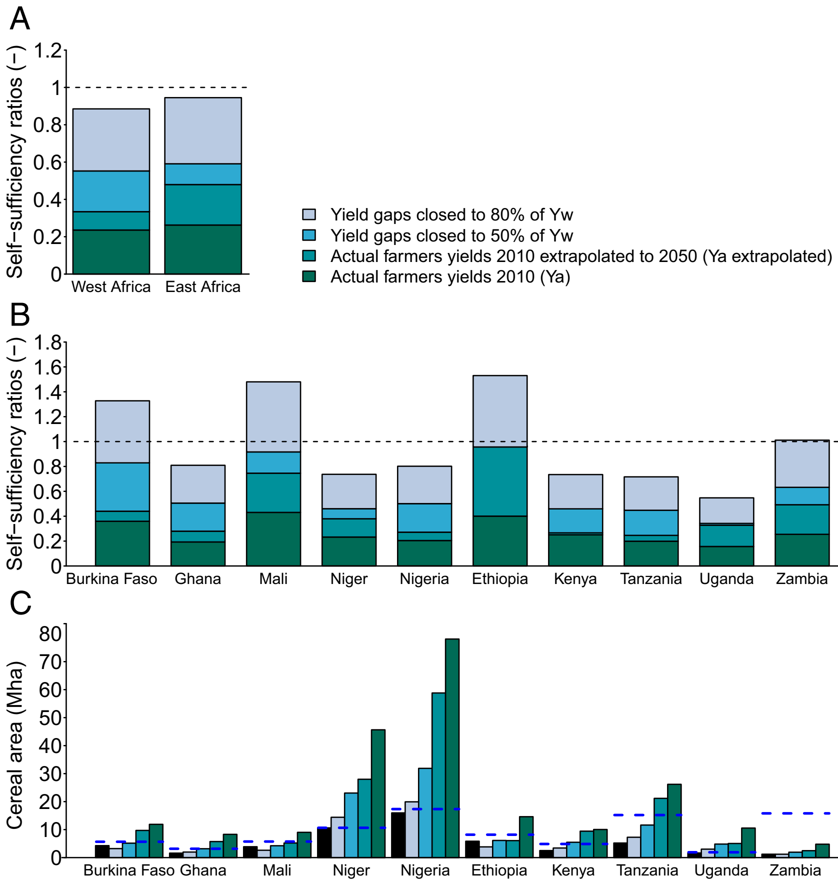

Fig. 3. Self-sufficiency ratios by 2050 based on various yield increase scenarios and required cereal area expansion to realize self-sufficiency by 2050. Yield scenarios are as follows: 2010 actual farmers' yields (Ya), actual yield increase 1991–2014 extrapolated to 2050 (Ya extrapolated), yield gaps 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*.

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AGRICULTURAL SCIENCES

SUSTAINABILITY SCIENCE

Supporting Information

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SI Materials and Methods

Current (2010) Cereal Demand and Production. Current total cereal demands (consumption) per country were calculated as the product of current population size (Table 1; from UN population prospects, ref. 14; see https://esa.un.org/unpd/wpp/) and cereal demand per capita based on IMPACT (22, 23) (Table S2). Current cereal demand per capita was derived from the total annual consumption (including grain use for livestock feed and other purposes—the latter includes cereals for processing such as sorghum for beer, biofuel, and losses and wastages) of the five cereals per capita per country in 2010. 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 Food and Agriculture Organization (FAO) food balances, see faostat3.fao.org/home/E). Per capita cereal demand around year 2010 differs widely between countries (Table S2). For instance, demand for the five cereal crops analyzed in the present study is low in Ghana, Uganda, and Ethiopia because of the substantial contribution of tuber and root crops and bananas to diets in Ghana and Uganda, and teff in Ethiopia.

Current (approximately year 2010) domestic grain production per cereal crop (maize, wheat, rice, sorghum, and millet) per country was calculated as the mean actual crop yield (2003–2012) as estimated in GYGA (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). Our estimations of actual crop yields were close to those from FAOSTAT, but we were able to disaggregate rainfed and irrigated yields.

Future (2050) Demands of Cereals Using IMPACT. Total annual cereal demand per capita, for each of the five cereals and each country, in 2050 were retrieved from IMPACT modeling results (22, 56). For this purpose, the SSP2 (no climate change; ref. 51) from the IPCC's fifth assessment was used. Per capita cereal demand includes cereals directly consumed by humans or used as feed for livestock production and use of cereals for other purposes (including brewing and bio-energy). Postharvest losses and food waste were accounted. Total annual per capita demands for the five cereals were again aggregated to maize equivalents (see above). Increase in per capita demand between 2050 and 2010 varied between 9 and 80% (Table S2). Total cereal demand per country in 2050 was calculated based on projected 2050 population (medium fertility variant of UN population prospects, ref. 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.

Future (2050) Cereal Production for Different Scenarios Using GYGA. Food production can be increased by intensifying crop production on existing cropland area (by narrowing existing yield gaps, increasing cropping intensity, and increasing the proportion of crop production area that is irrigated), expanding rainfed cropland area, or both. We first calculated self-sufficiency ratios for year 2050 assuming the above-mentioned intensification interventions 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). We used FAOSTAT (23) for current arable land areas (year 2010) (Table 1). 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 from the Global Agro-ecological Zones study (GAEZ) from International Institute for Applied Systems Analysis and FAO (52, 53) and from the World Bank (57). We took the potentially available cropland areas including forest land, not accounting for profitability to exploit the new land, from this recent study (34), which implies that the numbers should be regarded as optimistic. 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). Thus, under the scenario of cereal area expansion, areas of all other food crops, e.g., root and tuber crops, could increase by the same proportion.

Before calculating the effects of yield gap closure, we estimated a business as usual scenario, i.e., by extrapolating historical annual yield increases (i.e., between year 1991 and 2014) to the year 2050; if the average annual yield change was nonsignificant or negative, we used a zero yield increase for extrapolation. Potential (i.e., irrigated; Yp) and water-limited potential (i.e., rainfed; Yw) yields for cropping systems were calculated for the main cropping areas per cereal crop (i.e., areas from the SPAM database for 2005; ref. 58) in the 10 African countries within the GYGA project (24, 25). Crop yield was simulated by using crop area-specific sets of historical weather data, main soil types, and main cropping systems and their management (cultivars and sowing dates). Crop growth models Hybrid-maize (59), ORYZA2000 (60, 61), and WOFOST version 7.1.3 (release March 2011) (62, 63) were used for simulation of, respectively, maize, rice, wheat, sorghum, and millet. For each country, models were calibrated and evaluated with country-specific experimental data (www.yieldgap.org; ref. 24). Maps with computed crop yields and yield gaps, and all underpinning data, are available on www.yieldgap.org. Long-term (12–20 y) weather data were used to portray current weather variability and, particularly, rainfall variability across years. For irrigated cereal cultivation—rare in SSA apart from rice cultivation—Yp is the benchmark for yield gaps (Yg); for rainfed cereal cultivation, Yw is the benchmark for Yg. Mean location-specific Yp, Yw, and Yg were aggregated to the climate zone (64) in which crop yield is assumed to be similar, and next to the national scale for the different cereal crop-country combinations, using a crop area-weighted scaling procedure (25). We calculated national cereal production for 2050 for four yield scenarios: (*i*) actual farmers' yields do not change until 2050 (Ya); (*ii*) historical annual yield increases extrapolated to 2050 (Ya extrapolated); (*iii*) yields in 2050 are 50% of Yp or Yw (labeled 50% of Yw as the great majority of the land is rainfed), or (*iv*) in 2050 yields are 85% of Yp or 80% of Yw (labeled 80% of Yw).

For current harvested area, actual cropping intensity (www.yieldgap.org) was used, as estimated by local experts. We also estimated the mean maximum cropping intensity (i.e., cropping intensity potential, which is the maximum number of crops grown per year) per country for all rain-fed cereal crops on the basis of GAEZ data (52, 53) (see webarchive.iiasa.ac.at/Research/LUC/SAEZ/index.html). We assumed the maximum cropping intensity to be one, two, or three per grid cell if the length of the growing season is at least 90, 210, and 330 d, with the mean cropping intensity potential per country being the average of the maximum crop intensities for all grid cells with cropping in that country (Table S1). Length of the growing season was defined as the period during the year when both moisture availability and temperature allow crop growth—for details, see GAEZ (52, 53).

To calculate additional cereal production from increased cropping intensity, shares of land used for the total of the five cereals and each of the five cereals were kept the same as current (Table S1). For irrigated crops, the cropping intensity potential was set to 2.0 in all countries except for Uganda where it was set to 2.5 (because it is already 2 for irrigated land). We calculated cereal production in 2050 based on: (*i*) current (2010) cropping intensities, and (*ii*) maximum cropping intensities (i.e., actual harvested areas multiplied by the ratio of potential cropping intensity to current cropping intensity). Note, that in case of higher cropping intensities, we assumed the same potential productivity of the additional crop(s) as that of the current crop, which is optimistic because yields of individual crops generally decrease when cropping intensity increases because of shorter crop cycle duration.

Current irrigated cereal area in sub-Saharan countries is small (Table S1) and mainly used for rice cultivation. The maximum possible increase in irrigated area per country was derived from AQUASTAT data (40) (see Table S1 and www.fao.org/nr/water/aquastat/data). Typically, these estimates are based on availability of water resources without explicit attention to soil properties, topography, and whether use of irrigation is sustainable (withdrawal rates similar to recharge rates) or economically feasible (e.g., depth of groundwater and associated pumping costs). Thus, these estimates likely overestimate the potential area where irrigation is possible. Because no area expansion of the five cereals was assumed under the irrigation expansion scenario, newly irrigated land for the cereals comes at the expense of rainfed cultivation of these cereals. Because it is likely that newly irrigated land also will be used for crops other than cereals, we assumed the current fraction of cereals of total arable land (Table S1) to derive the maximum irrigated area for rice, maize, and wheat (millet and sorghum were not considered viable crops for irrigation). We calculated the food supply for 2050 based on (*i*) current irrigated areas and (*ii*) maximum irrigated cereal area per country and with maximum yield gap closure level of 85% of Yp as found for other irrigated systems where producers have access to inputs, markets, and extension education (see US irrigated maize on www.yieldgap.org).

Current and Future Cereal Self-Sufficiency Ratios. The degree of cereal self-sufficiency in 2010 and for the different scenarios by year 2050 was calculated as the ratio between national cereal production and cereal demand, either per country or for the five countries in west and east SSA.

Sensitivity Analyses for Future (2050) Cereal Demand. The increase in cereal demand is largely determined by the increase in population growth for the 10 countries; the per capita increase in cereal demand due to an increased consumption of livestock products is only a modest part of the total increase in demand (Fig. S2). Given the importance of population growth, cereal demand was also calculated for the low and high fertility variants of UN population projections (14). Implications of these different projections are shown in Fig. S3*A*, which indicate our cereal self-sufficiency estimations are fairly robust.

Second, we estimated future food demand per capita by using an alternative approach, i.e., per capita food demand was assumed to depend on the gross domestic product (GDP) per capita based on the relationship between per capita caloric intake and per capita GDP derived by Tilman et al. (7). Mean GDP per capita per country in year 2050 was calculated from the GDP per capita in 2010 (from World Bank data) and three (inflation-corrected) rates of GDP increase per year per capita, i.e., 2%, 4%, and 6% per year. The resulting GDP per capita-values for 2050 were next incorporated into the Tilman et al. relationship to derive total future caloric demands per capita. Note that the rapid increase in caloric demand with GDP increase per capita according to the Tilman et al. (7) approach is mainly caused by increasing consumption of dairy and animal products and the low conversion efficiency of feed cereals to animal products. Note also, that the Tilman et al. approach estimates total food demand (not just cereals), but through use of the relative change in food demand between 2010 and 2050, we can use this approach for the purpose of this study to calculate 2050 cereal demand. The increases in demand estimated with the approach derived from Tilman et al., assuming an average 4% annual economic growth rate, were similar to the ones based on IMPACT (Table S2), which again suggests that our estimations of future demand are fairly robust.

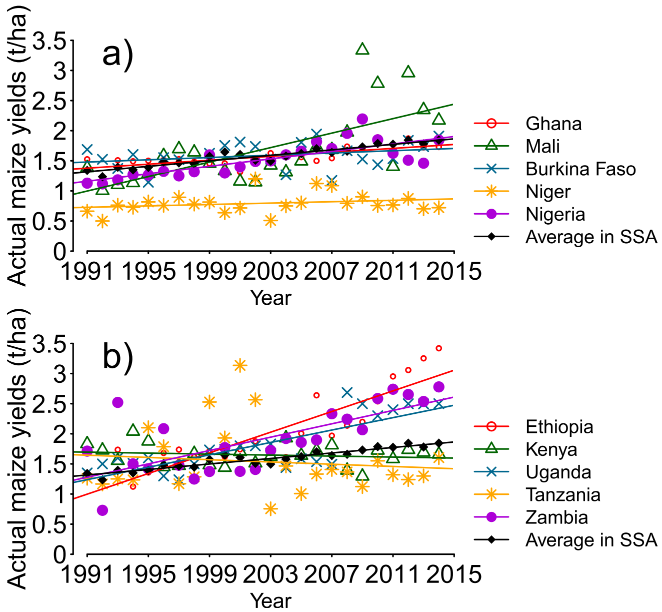

Fig. S1. Evolution of maize yields in the five western (*A*) and five eastern (*B*) sub-Saharan African (SSA) countries over the 1991–2014 period (23); in both figures also averages for SSA have been given. Trendlines have been added (for annual yield progress and significance, see Table 1).

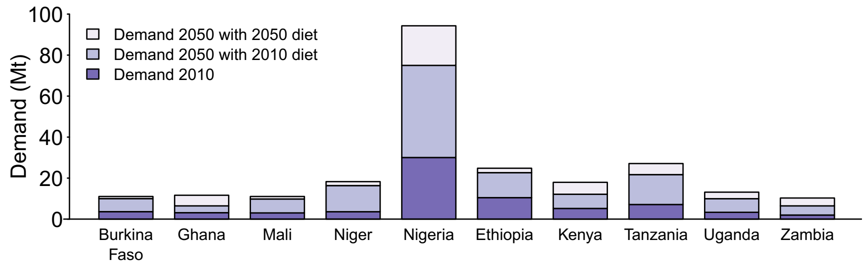

Fig. S2. National demand for the five main cereals for 2010 and 2050. Demand for 2050 has been split into the part due to population growth (maintaining 2010 diets), and the part due to changes in diets as projected for 2050 based on IMPACT modeling results (22).

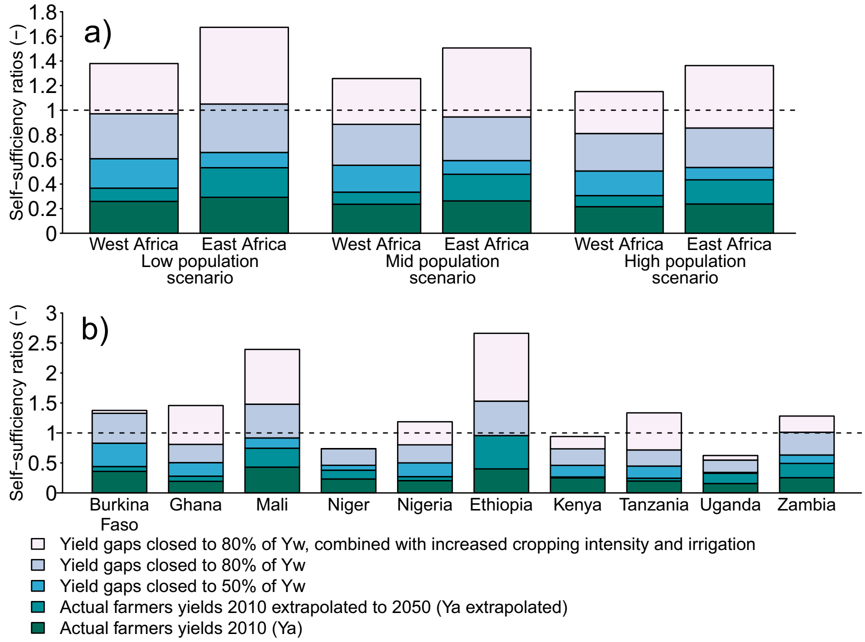

Fig. S3. Self-sufficiency ratios in 2050 for west and east SSA and the 10 countries separately. Current cereal areas apply and yield scenarios including the following: 2010 actual farmers' yields (Ya), actual yield increase 1991–2014 extrapolated to 2050 (Ya extrapolated), yield gaps closed to 50% or 80% of their water-limited potential (50% or 80% of Yw), and yield gaps closed to 80% of Yw plus increased cropping intensities and expanded irrigated areas (for irrigated crops 85% of the potential yield (Yp) was used as maximum yield gap closure). Regional self-sufficiency ratios by 2050 for the five western and eastern countries in SSA and low, medium, and high fertility UN population projections (*A*) and ratios for the 10 countries in SSA by 2050 and medium fertility UN population projections (*B*).

Table S1. Area and cropping intensity data

Country	Area fraction in 2010					Area fraction cereal crops in 2010*	Cropland 2010,† Mha	Potentially available cropland in addition to 2010 area,‡ Mha	Irrigated cereal crop areas according to SPAM2005,§ 10^4 ha	Potentially irrigated area,¶ 10^4 ha	Cropping intensity rainfed crops in 2010	Potential cropping intensity rainfed crops
	Maize	Sorghum	Millet	Wheat	Rice							
Burkina Faso	0.19	0.47	0.32	0.00	0.03	0.74	5.8	1.9	2.1	17.5	1.0	1.0
Ghana	0.61	0.16	0.11	0.00	0.11	0.35	4.6	4.5	1.3	189	1.2	1.7
Mali	0.13	0.31	0.38	0.00	0.18	0.62	6.4	3.1	30.5	201	1.0	1.0
Niger	0.00	0.31	0.69	0.00	0.00	0.70	15.2#	0.0#	0.2	17.8	1.0	1.0
Nigeria	0.26	0.31	0.27	0.00	0.15	0.48	33.0	2.8	8.4	136	1.0	1.4
Ethiopia	0.34	0.33	0.07	0.27	0.00	0.40	14.6	5.8	5.0	241	1.0	1.5
Kenya	0.81	0.09	0.04	0.06	0.00	0.45	5.5	5.2	1.7	24.3	1.2	1.5
Tanzania	0.59	0.12	0.07	0.01	0.22	0.45	11.9	22.9	0.2	194	1.0	1.4
Uganda	0.63	0.22	0.10	0.00	0.05	0.24	6.7	1.0	1.0	3.1	1.9	2.1
Zambia	0.93	0.00	0.04	0.00	0.03	0.34	3.5	42.1	2.0	26.7	1.0	1.1

Area fractions for the main cereal crops in 2010, the area fraction of arable land used for the grain crops, the arable land area in 2010, estimated potentially available cropland area, irrigated area in 2010 and maximum irrigated area, and 2010 cropping intensity and potential cropping intensity for rainfed crops.
*Total area of the five cereal crops divided by the total arable land area per country in 2010 (FAOSTAT) (23).
†Cropland area (ha) per country in 2010 (FAOSTAT; ref. 23).
‡Potentially available cropland as derived from ref. 34.
§Currently irrigated areas (ha) with cereal crops, which consists mainly of rice cultivation (58).
¶Potentially irrigated areas (ha) as based on AQUASTAT estimates from ref. 40.
#Maximum cropland area in Niger is lower than the actual cropland area; much of the present cropland in Niger falls in a lower suitability class than used for future estimations (34, 52, 53).

Table S2. Two approaches for estimating annual cereal demand per capita

Country	Annual cereal demand per capita IMPACT, kg air-dry maize grain		Relative increase in cereal demand 2050–2010 IMPACT	Annual food demand per capita Tilman et al. (assuming 4% growth in GDP), kcal		Relative increase in demand 2050–2010, Tilman et al. (4% GDP)
	2010	2050		2010	2050	
Burkina Faso	233.7	257.8	1.10	2,174	2,818	1.30
Ghana	128.8	232.2	1.80	2,387	3,761	1.58
Mali	215.9	243.0	1.13	2,198	2,925	1.33
Niger	226.3	253.1	1.12	2,106	2,502	1.19
Nigeria	188.1	236.6	1.26	2,663	4,893	1.84
Ethiopia	120.2	131.6	1.09	2,099	2,471	1.18
Kenya	126.8	187.7	1.48	2,233	3,082	1.38
Tanzania	158.2	197.6	1.25	2,154	2,726	1.27
Uganda	97.7	129.1	1.32	2,139	2,655	1.24
Zambia	150.0	239.3	1.59	2,358	3,635	1.54

Annual per capita cereal demand (kg maize equivalents) in 2010 and 2050 based on the IMPACT model (22), and the annual food demand per capita (in kilocalories) in 2010 and 2050, estimated based on the Tilman et al. (7) approach assuming 4% growth in GDP per year. For both methods, the relative increase in demand between 2050 and 2010 is also provided.