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Maize crop nutrient input requirements for food security in sub-Saharan Africa

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ABSTRACT

Nutrient limitation is a major constraint in crop production in sub-Saharan Africa (SSA). Here, we propose a generic and simple equilibrium model to estimate minimum input requirements of nitrogen, phosphorus and potassium for target yields in cereal crops under highly efficient management. The model was combined with Global Yield Gap Atlas data to explore minimum input requirements for self-sufficiency in 2050 for maize in nine countries in SSA. We estimate that yields have to increase from the current ca. 20% of water-limited yield potential to approximately 50–75% of the potential depending on the scenario investigated. Minimum nutrient input requirements must rise disproportionately more, with N input increasing 9-fold or 15-fold, because current production largely relies on soil nutrient mining, which cannot be sustained into the future.

1. Introduction

Severe food insecurity at the global level has been rising in recent years, mainly due to increments in Africa and Latin America attributed to a range of factors including human conflict, adverse climate events, low prices of export commodities restricting public investments, and inequality in access to food (FAO et al., 2018). About 770 million people or close to 10% of the world population were exposed to severe food insecurity in 2017. At the regional level, values range from 1.4% in Northern America and Europe to almost 30% in Africa (FAO et al., 2018). By 2050, food demand is expected to increase by 60% worldwide compared to 2005/2007 (Alexandratos and Bruinsma, 2012), and by over 300% in sub-Saharan Africa (SSA) due to fast growth of the human population (Van Ittersum et al., 2016).

Cereals are the main staple crops in terms of calorie intake in SSA. Narrowing cereal yield gaps - i.e., the gap between actual farmers yield and water-limited yield potential - will therefore be essential to meet food demand in SSA without greater reliance on cereal imports and/or expansion of arable land (Van Ittersum et al., 2016). Maize is the most widely cultivated crop and is of great importance to food security and livelihoods of the people in SSA (Tesfaye et al., 2015). However, large yield gaps still exist. Country-average yields of rainfed maize over the 2007–2016 period ranged from 1.68 to 1.99 t/ha in SSA (FAOSTAT, 2018), representing 15–25% of country-mean water-limited yield potential for most countries.

One of the major constraints to higher crop productivity among smallholder farmers in SSA is low soil fertility related mainly to continuous cropping without replenishment of depleted nutrients (Breman and Debrah, 2003; Rusinamhodzi et al., 2011; Sanchez, 2015). Estimates of current nutrient use vary between studies but all are low, with most countries applying less than 10 kg of nutrients per ha – sum of nitrogen (N), phosphorus (P) and potassium (K) inputs - in organic and chemical fertilizers (Masso et al., 2017; Rurinda et al., 2013). Mean inorganic fertiliser use on arable land increased from 7.4 kg/ha in 1968–1972 to 12.9 kg/ha in the 2008–2012 period (fertiliser product mass basis) (AGRA, 2014). Increasing fertiliser input alone could close a

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large part of the yield gap in SSA before resorting to irrigation (Mueller et al., 2012), provided that good crop management practices such as weed and pest control are applied. Insufficient use of agricultural inputs, particularly N, has led not only to poor yields in terms of quantity but also in terms of nutritional value, and to soil fertility depletion. Hence, improved access to fertiliser N will be critical to ending poverty (Sustainable Development Goal – SDG - 1) and hunger (SDG 2) and improving health (SDG 3) in the region (Campbell et al., 2018).

In contrast, other parts of the world experience major environmental problems associated with excessive use of – notably N – fertilisers, beyond boundaries of sustainability (Rockström et al., 2009). In response, legislative measures are implemented to curb pollution of ground- and surface water bodies, as well as GHG emissions (Van Grinsven et al., 2012). Zhang et al. (2015) investigated such historical patterns of agricultural intensification and advocate that, when agriculture intensifies, the stage of excessive N use be prevented in the first place. They refer to this aim as 'tunnelling through the Environmental Kuznetz Curve'. Ex-ante assessment of nutrient requirements for target yields likely needed to ensure food self-sufficiency in coming decades must, therefore, be based on sustainable production methods and corresponding nutrient use efficiencies. Such estimates are important for a variety of reasons. First, to explore the size of the crop nutrient and fertiliser challenge in SSA to governments and industry. Second, to inform regional, continental and global integrated assessment studies (Stehfest et al., 2014; Keppo and van der Zwaan, 2012) with agronomically robust estimates of nutrient and fertiliser requirements. And third, as a starting point for experimental work to test and improve integrated soil fertility management to realise productivity gains in SSA.

The objective of this study was to explore minimum input rates of macro-nutrients (N, P and K) required to achieve full self-sufficiency in maize in nine countries (Burkina Faso, Ethiopia, Ghana, Kenya, Mali, Nigeria, Tanzania, Uganda, Zambia) in SSA by 2050. For this purpose we present a simple equilibrium model that relates nutrient use efficiency to relative target yield, taking water-limited yield potential as a reference, and accounts for long-term adjustment of soil fertility. The model is combined with the Global Yield Gap Atlas data (www.yieldgap.org; Grassini et al., 2015; Van Bussel et al., 2015) to express the geospatial distributions of model inputs and outputs. We compare our assumed nutrient use efficiencies with values assessed from SSA field trials documented in two large databases, and with findings reported in the literature. Among the three macro-nutrients our focus is on N as this is often the most limiting nutrient, and because this work was part of a larger study on climate-smart agriculture where climate impacts of intensification are dominated by N use besides land use change. The CO_2 footprint of N fertiliser is at least one order of magnitude larger than that of P and K. Our study relies partly on data and assumptions by Van Ittersum et al. (2016), and updates some of their findings.

2. Methods, data and concepts

2.1. Two scenarios of maize self-sufficiency in SSA by 2050

We explored the level of intensification of maize production needed to meet maize demand by 2050 in nine major maize growing countries in SSA, based on current maize area. Burkina Faso, Ghana, Mali, and Nigeria represented the region West-Africa; and Ethiopia, Kenya, Tanzania, Uganda, Zambia the region East-Africa. Two scenarios were defined with a focus on either the country or the region level (Table 1). Scenario I matches maize production with demand at the country level, by seeking per country the relative maize yield (this is the ratio of target yield, Y^T, to water-limited yield potential, Yw) that matches 2050 maize demand on current, 2015, cropland. Scenario II matches cereal production with cereal demand at regional level, and allows for extra maize production to make up for insufficient production of the other major cereals (millet, rice, sorghum, and wheat). The extra maize production in Scenario II comes exclusively from further intensification on current maize land, not from newly reclaimed land or from an increased share of maize area in total cropland area. Scenario II seeks, per region, the lowest single relative yield across all cereals that matches 2050 regional cereal demand. Whilst in Scenario II the same calculations were made for all cereals, outcomes are reported only for maize, which is the focus of this study. Scenario I was chosen to represent the simplest case of maize intensification on current maize land to match country maize demand. Scenario II aims to strike a balance between minimizing total N input for cereal production in the region, and limiting shifts in the volume proportions of the respective grain species produced.

Other factors are identical between the two scenarios. Domestic maize demand (2050 population * per capita maize demand) was divided by the maximum rainfed maize output (Yw * maize area) to obtain the relative target yield needed. Per capita maize and total cereal demands in 2050 were estimated by the IMPACT model (Robinson et al., 2015) that accounts for autonomous changes in diet. Demands were expressed in maize-equivalents to correct for unequal caloric per-kg values among the various cereal species (Food and Agriculture Organization (FAO) food balances, see faostat3.fao.org/home/E). Expected population in 2050 was based on a medium fertility population projection obtained from UN (2015). Current cultivated area per crop (FAO, 2015) and geospatial distribution of Yw per crop (Section 2.2; www.yieldgap.org) were presumed constant up to 2050. For countries with cropping intensity larger than 1 (multiple cycles of a crop per year; harvested area > cropland area) we used the mean Yw over the respective seasons. All per-ha results refer to harvested area. Resulting target yields were translated into minimum nutrient input requirements with the help of agronomic nutrient use efficiency coefficients (kg extra grain per kg nutrient input; 15.5% moisture in grain) as explained in Section 2.3.

2.2. Water-limited yield potential (Yw) in sub-Saharan Africa

Water-limited (i.e., rainfed) yield potential sets an upper limit to maize production and provides the reference for relative yield, our measure of production intensity. Yw was mapped for the nine SSA countries in the study, using the Global Yield Gap Atlas protocol (www.yieldgap.org; Grassini et al., 2015; Van Bussel et al., 2015). This implies (a) the use of location-specific data on climate, soils, and cropping systems in combination with (b) a robust spatial framework to aggregate results to a national scale, based on a climate zonation scheme (Van Wart et al., 2013), and (c) well-validated crop growth models to estimate water-limited yield potentials. The reported Yw values refer to currently cultivated maize area. For further details, see Van Ittersum et al. (2013, 2016). The main steps in the current study are summarised in Fig. 1.

2.3. Agronomic efficiency of applied nutrients in short and long term

Nutrient uptake requirement (U^T, $kg_{nutrient}$ ha^{-1}) is the amount of a nutrient (N, P or K) that must be absorbed in aboveground crop biomass to realise a certain target yield Y^T (kg ha^{-1}). In the short term, nutrient input requirement A^T ($kg_{nutrient}$ ha^{-1}) is the corresponding amount of nutrients that must be applied per season, supplementing soil nutrient supply. Accounting for local soil nutrient supply is highly relevant in fertiliser recommendations, as this supply varies widely in space and time. In contrast, strategic explorations on food security and intensification must account for the long-term response of soil fertility to changed input rates. Such feedback is relevant both under intensification (soil nutrient stocks increasing) and soil mining (stocks being depleted) conditions. We present, therefore, a simple equilibrium model that incorporates this feedback. It expresses long-term annual nutrient input requirement as:

Table 1
Characteristics of the two scenarios (year 2050) used to calculate maize target yields required for self-sufficiency (SS) in maize at country or regional level.

Parameter	Scenario I (SS at country-level)	Scenario II (SS at regional level)
Cereal demand	Not used	Per region, Robinson et al. (2015)
Maize demand	Per country, Robinson et al. (2015)	Per region, Robinson et al. (2015)
Cereal area	Not used	As per 2015 census, FAO, 2015
Maize area	As per 2015 census	As per 2015 census, FAO, 2015
Water limited yield potential of other cereals	Not used	Area-weighted mean per cereal per country
Water limited maize yield potential	Area-weighted mean per country	Area-weighted mean per country
Optimisation criterion to assess target yield	Match country maize production to country maize demand in 2050 by optimising a single relative maize yield per country	Match regional cereal production to regional cereal demand in 2050 by optimising a single relative cereal yield per region, same for all cereals
Cereal relative target yield	Not used	The outcome of optimisation is a single collective value for all cereals and across whole region
Maize relative target yield	The outcome of optimisation is a single value per country	Same value as cereal relative target yield of the region (above)

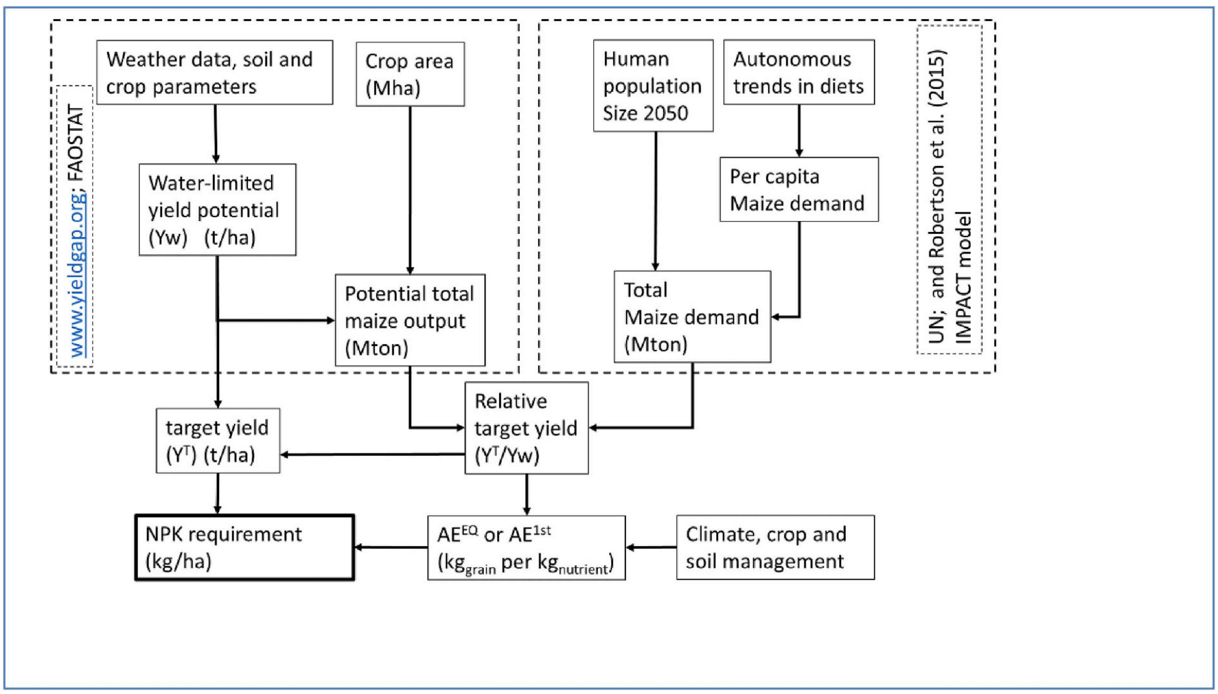

Fig. 1. Flow diagram representing the main components of the study. Coefficients AE^{1st} and AE^{EQ} refer to agronomic use efficiency of applied nutrients in the short and long term, respectively. Differences between scenarios are ignored here.

$$A^T = Y^T / AE^{EQ} \quad (1)$$

where AE^{EQ} (kg yield per kg nutrient applied) is the long-term agronomic use efficiency of the applied nutrient, achieved when soil nutrient supply is in steady state equilibrium with annual input rate. In addition, we define the short-term nutrient input requirement, for a soil that supports a yield Y_s in absence of nutrient inputs, as:

$$A^T = (Y^T\text{-}Y_s) / AE^{1st} \quad (2)$$

The superscript 1st refers to the yield response observed in the same year of fertiliser application. All our calculations on nutrient requirements for maize self-sufficiency in SSA are based on Eq. (1) or (2).

2.4. Components of agronomic efficiency

We need both the short-term and long-term variants of AE because all field data that we collected for maize in SSA refer to 1st-year fertiliser effects (Eq. (2)), while our scenarios on intensification of maize production in SSA have a long-term outlook (steady state equilibrium; Eq. (1)). Relations between the short-term and long-term variants are governed by the retention efficiency (^{RET}E, explanation later below) which regulates the development of soil fertility in the long run.

The short-term variant refers to increments in yield and uptake in response to fertiliser application, taking yield and uptake from just soil supply as externally defined baselines. AE^{1st} is the outcome of two component efficiencies:

$$AE^{1st} = RE^{1st} * IE^{1st} \quad (3)$$

where IE^{1st} is the extra yield per unit nutrient uptake (in aboveground crop biomass) from applied nutrients (kg_{yield} per $kg_{nutrient}$). The 'short-term recovery' RE^{1st} expresses extra nutrient uptake per unit nutrient applied ($kg_{nutrient}$ per $kg_{nutrient}$). Hence, AE^{1st} expresses extra yield per unit nutrient applied (kg_{yield} per $kg_{nutrient}$). In all of these, 'extra' refers to the increment above the 'soil-supplied' baseline.[1]

The equilibrium model, in contrast, incorporates soil supply as the long-term result of a given nutrient input rate, and ignores initial soil

[1] For nitrogen, IE^{1st}, RE^{1st} and AE^{1st} are identical to PE_N, RE_N and AE_N, respectively, as defined by Dobermann (2005); all refer to applied nutrient only, taking uptake and yield from soil supply as baseline.

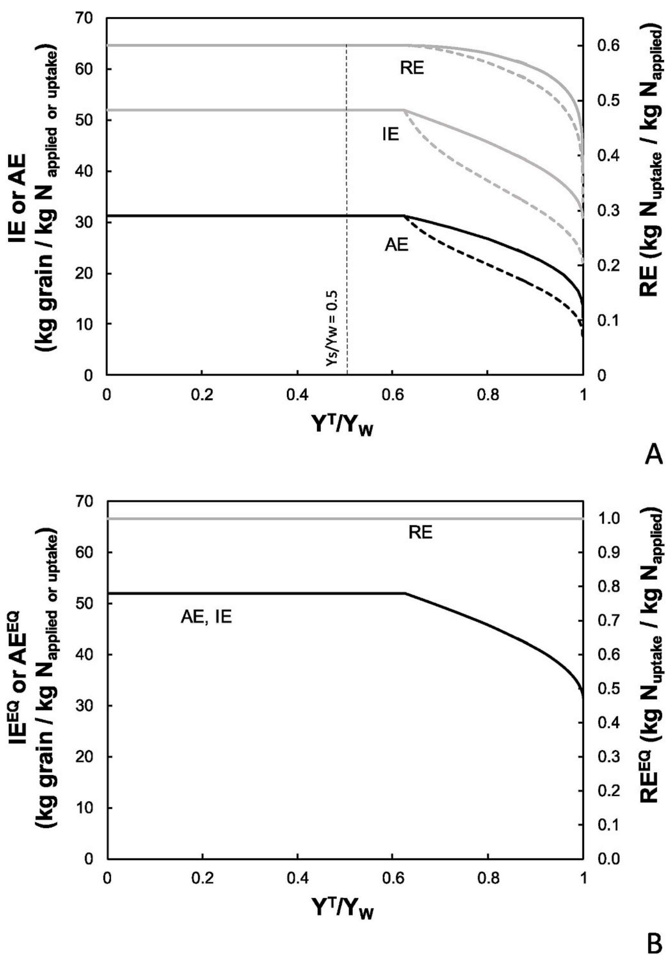

Fig. 2. Top (A): Generic Model for nutrient use efficiency indicators versus relative yield (Y^T/Y_w). Short-term agronomic efficiency (AE^{1st}; black curve, left-hand axis) and its two components (grey curves) internal efficiency (IE^{1st}; left-hand axis) and recovery efficiency (RE^{1st}; right-hand axis). All curves refer to an example for $RE^{1st} = 0.6$ at low to moderate yield (RE^{ini}, Section SI-2), $IE^{med} = 52$ and $IE^{acc} = 31$ kg_{grain}/kg_{uptake}. Solid curves for zero soil supply, broken line curves for a case with current (short term) soil N supply corresponding to Ys/Yw = 0.5 (vertical dotted line). Broken line curves start at Ys/Yw = 0.5 but are partly covered by solid curves. Solid curves also represent AE^{EQ} and IE^{EQ} (lefthand axis) and RE^{EQ} (right-hand axis) for a case with $RE^{ini} = 0.6$ and ${}^{RET}E = 0$, therefore $RE^{SP} = 0$. Bottom (B): Simplified Model with $RE^{EQ} = 1$. Solid lines: long term agronomic efficiency (AE^{EQ}, left-hand axis) and its two components internal efficiency IE^{EQ} (same curve as AE^{EQ}) and RE^{EQ} (right-hand axis). Further explanation in Sections 2.4 and 2.5, SI-1, SI-2.

fertility. Here, AE^{EQ} expresses yield – as achieved in steady state equilibrium - per unit nutrient annually applied (kg_{yield} per $kg_{nutrient}$). AE^{EQ} depends again on its component efficiencies:

$$AE^{EQ} = RE^{EQ} * IE^{EQ} \tag{4}$$

where IE^{EQ} refers to total yield per unit total nutrient uptake (kg_{yield} per $kg_{nutrient}$), and RE^{EQ} to total uptake per unit nutrient applied ($kg_{nutrient}$ per $kg_{nutrient}$). (We use 'total' to mark the contrast with just the increments in yield and uptake considered in Eq. (3)). AE^{EQ} and AE^{1st} and their components are not fixed but decline as relative yield exceeds a certain threshold. For N, their values and dependence on relative yield are illustrated in Fig. 2A. For P and K we presumed constant AE^{EQ} values of 416 and 78 kg grain per kg nutrient applied, based on Janssen et al. (1990). The ensuing nutrient ratios (N:P:K) meet the balanced nutrition condition proposed by Janssen (1998, 2011). See SI-1 section for further details.

Part of the nutrients that become available for crop uptake annually (from annual input and the soil) is exported with the harvested yield. The remainder is not taken up or is in crop residues. We define retention efficiency ${}^{RET}E$ as the fraction of this remainder that is captured into the soil nutrient pool, to be released in later years ($kg_{nutrient}$ per $kg_{nutrient}$). In governing long-term soil supply, ${}^{RET}E$ also links the short-term and long-term variants of IE, RE and AE. The long-term recovery efficiency of applied nutrients is given as:

$$RE^{EQ} = RE^{1st} + RE^{SP} \tag{5}$$

where RE^{SP} is annual nutrient uptake from the (equilibrated) soil pool, expressed as fraction of annual input rate. This 'retarded recovery' can be written as:

$$RE^{SP} = \{ {}^{RET}E * R_S (1 - H*RE^{1st})\} / \{1 - {}^{RET}E (1 - H*R_S)\} \tag{6}$$

where the nutrient harvest index H is the fraction of crop uptake exported in harvest, and R_S is the fraction recovered – by the crop - of nutrients released annually from the soil pool.[2] ${}^{RET}E$ can be optimised by management practices, such as the use of catch crops and residue management. The relation between short-term and retarded recoveries as governed by ${}^{RET}E$ is illustrated in the SI-3 section. The underlying mechanisms and relations supporting Eqs. (3)–(6) and Fig. 2A and B are further documented in the SI-1 and SI-3 sections, along with their numerical parameterisation based on the literature (which includes the work by B.H. Janssen and colleagues on the QUEFTS model, from which important elements are used here.)

In steady state equilibrium, the nutrient surplus S is the sum of losses by all pathways (see SI-3 section) and is related to the agronomic parameters in Eq. (6) as:

$$S = (1 - {}^{RET}E) * (1 - H*RE^{EQ} + RE^{SP}/R_S) * A^T \tag{7}$$

Nutrient surplus is the difference between nutrient input (I, here A^T) and nutrient offtake in harvest (O), and therefore closely related to the O/I ratio, a common indicator of nutrient use efficiency (Zhang et al., 2015; Oenema, 2015; Lassaletta et al., 2016; Brentrup and Lammel, 2016):

$$O/I = 1 - S/A^T \tag{8}$$

The above expressions show how – in equilibrium state - the O/I ratio depends on the respective agronomic parameters (RE^{1st}, Rs, H, ${}^{RET}E$, IE^{EQ}). Eqs. (7) and (8) are used to validate our approach to long-term minimum requirements against O/I or S reported in the literature (Section 4.4).

2.5. The equilibrium model simplified

As stated, AE^{EQ} is the basis for our calculations of long-term nutrient requirements. Of its two constituents, IE^{EQ} and RE^{EQ}, only the first is well documented[3] for maize in SSA for each of the macro-nutrients (N, P, K). To our knowledge, no direct observations exist of AE^{EQ}, RE^{EQ} or RE^{SP} for maize in SSA, for any of the nutrients. The parameters that affect RE^{EQ} at given relative yield (RE^{1st}, ${}^{RET}E$, H, R_s) likely depend on environmental and management conditions, and all except ${}^{RET}E$ will depend on genotype. Given the large uncertainties in these parameters, estimates of actual nutrient input requirements for given target yield across the wide range of conditions in SSA will remain highly speculative. Therefore we introduce the concept of *minimum nutrient input requirements*, postulating that - even under favourable conditions - the value of RE^{EQ} will not exceed 1. Our projections are restricted to *minimum nutrient input requirements*, and presume that RE^{EQ} equals 1,

[2] All recovery coefficients (RE^{1st}, RE^{SP}, RE^{EQ}, R_S) refer to uptake in above-ground whole-crop biomass.

[3] In contrast to RE^{EQ} and AE^{EQ}, IE^{EQ} can be measured in absence of equilibrium because it refers to total yield and total uptake, irrespective of the source of nutrient supply, i.e., soil or fertiliser.

Table 2
Key characteristics for current (2015) maize production in selected sub-Saharan countries. Maize area (FAO, 2015) refers to harvested area, accounting for cropping intensities of 1.26 (Ghana), 1.25 (Kenya), 1.91 (Uganda) and 1.00 (other countries). Mean (2003–2012) actual crop yield (Ya), water-limited yield potential of currently cultivated maize land (Yw), and actual mineral fertiliser (N, P, K) input are based on the Global Yield Gap Atlas (www.yieldgap.org; Grassini et al., 2015; Van Bussel et al., 2015). Yw for Kenya and Tanzania was updated relative to Van Ittersum et al. (2016). Maize output potential is the product of Yw and maize area.

Country	Maize area (Mha)	Current maize output at Y = Ya (Mt)	Maize output potential at Y = Yw (Mt)	Yw (t/ha)	Ya (t/ha)	Ya/Yw	Current nutrient input (kg/ha)		
							N	P	K
Burkina F.	0.86	1.27	5.3	6.3	1.5	0.24	8.4	1.6	3.3
Ethiopia	2.11	4.71	26.4	12.5	2.2	0.18	9.7	3.2	0.1
Ghana	0.88	1.49	7.6	8.6	1.7	0.20	7.2	2.2	2.3
Kenya	2.10	4.04	16.5	7.9	1.9	0.24	21.0	1.4	1.7
Mali	0.90	1.70	8.7	9.7	1.9	0.20	18.5	2.3	4.0
Nigeria	6.77	11.10	72.9	10.8	1.6	0.15	5.2	0.4	0.6
Tanzania	3.79	4.36	22.6	6.0	1.2	0.19	4.9	0.9	0.6
Uganda	1.13	1.81	7.7	6.9	1.6	0.23	0.8	0.3	0.3
Zambia	0.86	2.00	9.8	11.3	2.3	0.20	43.2	4.5	1.7
West-Africa	9.41	15.56	94.6	10.1	1.7	0.16	6.9	0.9	1.3
East-Africa	9.99	16.92	82.9	8.3	1.7	0.20	12.1	1.7	0.8
SSA_9[a]	19.39	32.47	177.5	9.2	1.7	0.18	9.6	1.3	1.0

[a] Total for the nine countries listed.

thus setting AE^{EQ} numerically[4] equal to IE^{EQ} (Eq. (4); Fig. 2B). For a given Y^T, annual nutrient input A^T is then equal to the uptake (U^T) of that nutrient in total crop biomass. This input rate is at least required to sustain Y^T over longer periods, under favourable environmental conditions and management tailored to achieve high efficiency.

Fulfilling the boundary condition $RE^{EQ} = 1$ - which is equivalent to the condition $A^T = U^T$ - requires rather stringent values for the parameters in Eq. (6). It can be shown (SI-3 section), for example, that at example values of 0.60 for RE^{1st}, 0.5 for Rs and 0.65 for H (all reflecting high efficiency), 70% of the amount of N that is annually available to the crop (from fertiliser and soil supply) but is not removed in the season's harvest, must be retained in the soil pool ($^{RET}E = 0.7$). In the equilibrium state, the loss fraction S (Eq. (6)) is then 35% of annual N input, namely the fraction (1-H) retained in the crop residues. This shows that the condition $RE^{EQ} = 1$ should not be confused with a short-term recovery (RE^{1st}) of 1. Upper limits to RE^{1st} are well documented (references in Section 4.3) and range between 0.5 and 0.7 in cereals, depending on environmental factors. Maintaining the above boundary condition over longer periods is only possible due to recycling and re-use by the crop of non-harvested N. Note that RE^{EQ} is in theory not restricted to values smaller than 1 (but the product $H*RE^{EQ}$ is). While RE^{EQ} exceeding 1 seems unrealistic for N, values well above 1 would seem possible for P and K as these nutrients are less prone to losses. Relations governing nutrient flows are further documented in the SI-3 section.

2.6. Short-term minimum N input requirement

Minimum N input requirement for target yield Y^T in the presence of current soil nutrient supply was calculated with the help of Eq. (2), using for Ys the country-mean yield level supported by soil supply alone. This soil-supported yield was inferred from country-mean actual yield and N use (Table 2), assuming that N inputs today are used at a first-year agronomic efficiency (AE^{1st}) equal to the SSA mean derived from a large number of trials (Sections 2.7 and 3.2). Subsequently, the minimum N input requirement under highly efficient management was calculated from Eq. (2) applying an initial AE^{1st} value of 30 kg kg^{-1}. ('Initial' refers here to low and moderate relative yield, where AE is constant as illustrated in Fig. 2.) This value implies a first-year recovery of about 0.6 kg kg^{-1} for low to modest yield, declining steeply as yields approach the yield ceiling (Fig. 2A).

No short-term minimum requirements were estimated for P and K, for lack of reliable estimates of 'efficient' AE^{1st} values and supposedly large relative uncertainties in current P and K use (Table 2), which would propagate in short-term A^T estimates for these nutrients.

2.7. Assessment of actual AE^{1st} in SSA countries

A prerequisite for our minimum nutrient requirements to have practical relevance is optimal agronomic management. That means, among others, good cultivar and seed quality, the control of weeds, pest and diseases; and optimal planting and harvesting dates, such that Yw can be achieved under sufficient supply of macro-nutrients (N, P, and K). In reality, management may be suboptimal and limit yield to levels below Yw. That would result in lower than anticipated values of AE^{1st} and its constituents, IE^{1st} and RE^{1st}. We explored values of AE^{1st} for maize from short-term nutrient response trials across different locations in sub-Saharan Africa as aggregated by OFRA (OFRA, 2017). In addition, we analysed primary data from on-farm nutrient omission trials by the TAMASA project (http://www.tamasa.cimmyt.org; Shehu et al., 2018).

Depending on experimental set-up, AE^{1st} for nutrients N, P or K was calculated in two different ways. The OFRA database holds data on fertiliser trials with different crops across countries in SSA. While these data refer mostly to published results, the original experiments share no common design. Data from 403 trials (locations) with maize in seven countries (Ghana, Kenya, Malawi, Niger, Nigeria, Tanzania and Zambia) were found suitable to analyse AE^{1st} for N. These trials contain pairs of treatments differing only in the amount of N applied. AE^{1st} was calculated as the difference in maize grain yield between a treatment where N was applied (Y_N, kg ha^{-1}) and another without N application (Y_s), divided by the dose of N applied (A, kg N ha^{-1}), denoted Method 1:

$$AE^{1st} = (Y_N - Y_s) / A \tag{9}$$

Method 1 allows for estimation of AE^{1st} per experiment (location and year), but variation in these estimates actually reflects both variation in response between locations and random plot-level (i.e. residual) variation (Vanlauwe et al. 2016). The TAMASA trials were implemented in Ethiopia, Tanzania and Nigeria and share, within each country, a common experimental setup that allows for the assessment of AE^{1st} for each of the nutrients N, P and K. Data were analysed for 2015 (Ethiopia and Nigeria) and 2016 (Tanzania), covering a total of 468 trials (locations) in the three countries, each trial with six treatments (control, NK, NP, PK, NPK, and NPK plus micro-nutrients). Input rates of N, P and K depended on local Yw estimate, and were 100, 30 and

[4] Their dimensions remain different, of course.

30 kg/ha of N, P and K for low yield potential (Yw smaller than 6 t/ha); 120, 40 and 40 kg/ha for medium potential (6 < Yw < 8 t/ha); and 140, 50 and 50 kg/ha for high potential (Yw > 8 t/ha). Whereas treatments were replicated in many of the OFRA trials, the TAMASA trials are based on single implementation (single plot) of each treatment per location. For the TAMASA data, the presence of five treatments with varying combinations of N, P and/or K application allows for estimation of AE^{1st} by estimating yield effects of each nutrient via linear regression (Method 2) based on multiple treatments per site. Assuming the absence of location-specific nutrient interactions, the mean nutrient responses, two-way interactions and location-specific nutrient responses are estimated by a mixed model, where the location-specific responses are taken as random effects to obtain a direct measure of response variation across locations (See SI-4). For the TAMASA trial data, both the observed location-level variation and the best linear unbiased estimates of AE^{1st} were calculated for N, P and K, respectively.

2.8. Climate change

Climate change may deteriorate crop production conditions across SSA, and thereby affect our projections. Climate variability and extremes are already a key driver behind the recent rise in global hunger (FAO et al., 2018). Whilst projected target yields and presumed nutrient use efficiencies will constitute enormous challenges by themselves, climate change may render them well beyond reach. At the same, there will likely be genetic progress in 30 years' time in yield potential, which may partly compensate for negative impacts of climate change. In this study we ignored both processes because of the large uncertainties associated with them.

3. Results

3.1. Target yield and minimum nutrient requirements for SSA in 2050

Characteristics of current maize production in nine SSA countries are listed in Table 2. Yw differs by a factor of roughly two between countries (Table 2), and varies over a much wider range between climate zones within and across countries. (Map in SI-5 section). Actual yields are about 20% of Yw, and current country-mean N input is about 10 kg/ha or less, except for Mali, Kenya, Zambia with N-input varying between 18 and 43 kg/ha. Current country-mean P and K inputs are also only few kg ha^{-1} (Table 2).

Country-level maize demands projected for 2050 under both scenarios are given in Table 3. Totals for the nine countries collectively are 86.3 (Scenario I) and 132.4 (Scenario II) Mt of maize grain. Total cereal demands as used in Scenario II are 93.3 and 128.0 Mt of grain for West and East Africa, respectively.

Table 3
Maize demand by 2050 according to Scenarios I and II. The value for Scenario I is identical with 2050 maize demand as given by the IMPACT model (Robinson et al., 2015). Scenario-I matches maize production and demand at country level, and maize does not compensate for shortfall in yield potential of non-maize cereals. Scenario-II matches total cereal production and demand at regional level (West or East Africa) and extra maize production compensates for shortfall in yield potential of non-maize cereals.

Country	Maize demand (Mt y^{-1})	
	Scenario-I	Scenario-II
Burkina F.	2.2	3.8
Ethiopia	8.9	20.6
Ghana	7.0	5.4
Kenya	11.2	12.9
Mali	2.3	6.2
Nigeria	24.6	52.2
Tanzania	17.3	17.6
Uganda	5.3	6.0
Zambia	7.6	7.6
West-SSA	36.1	67.7
East-SSA	50.3	64.8
SSA_9	86.3	132.4

Table 4 lists the country and regional means of relative and absolute per-ha maize yields needed to meet self-sufficiency, and corresponding maize yield increment ratios under the two scenarios. Variation in these target yields between countries largely reflects variation in Yw, but differences in intensity (relative yield Y^T/Yw) occur too. The yield levels (t/ha) and total maize output at SSA level increase by a factor of 2.7 in Scenario I, with higher values for East than for West Africa. Scenario II shows a steeper yield increment, a factor 4.1 for SSA (Table 4). Overall, required SSA production increases from a total of 32.5 Mt maize grain today to 86.3 (Scenario I) and 132.5 (Scenario II) Mt maize grain for the nine countries. These production levels correspond to maize relative yields of 0.38 (West Africa), 0.61 (East Africa) and 0.49 (SSA) for Scenario I, or 3.83, 5.03 and 4.45 t ha^{-1}, respectively. The relative cereal yields under Scenario II are 0.72, 0.78, and 0.75 for the three regions, corresponding to maize yields of 7.20, 6.49 and 6.83 t ha^{-1}. Scenario II pushes production closer to its water-limited ceiling, with maize compensating for insufficient yield potential in other cereals (see Yw map in SI-5 section).

The geographical distributions of long-term minimum N, P and K input requirements for the two scenarios of maize self-sufficiency in 2050 are presented in Fig. 3, and country means in Table 4. Area-weighted values for SSA are 91.0 (N), 10.7 (P) and 57.1 (K) kg ha^{-1} in Scenario I, and 143.2 (N), 16.4 (P) and 87.6 (K) kg ha^{-1} in Scenario II. Corresponding yields are then 4.45 and 6.83 t ha^{-1}. Fig. 4 summarizes these projections and compares them against current inputs and yields for the two regions. Minimum N input requirements estimated for the short term (Section 2.6) are 21% (Scenario I) and 42% (Scenario II) larger than the equilibrium values (Table 4; Fig. 4). This is because soil-supplied nutrient uptake is fixed – in the short term estimates - at current levels (20–40 kg N ha^{-1} for the different countries, by the procedure in Section 2.6), whereas it would increase under sustained higher N input, provided a high degree of nutrient conservation (^{RET}E). Table 4 and Fig. 4 also indicate the amount of N that would be required for the target yields if N inputs were used against the low mean AE^{1st} value of 14.3 kg kg^{-1} reported in Section 3.2, and if it were possible to attain those yields by just nutrient application. Both conditions are very unlikely to hold true.

In short, even by our lowest estimates, N inputs in SSA must increase 9-fold (Scenario I) and 15-fold (Scenario II) to sustain the target yields, with similar increments for P and K inputs. Total inputs for the nine countries then amount to 1764 and 2777 million kg of N, 208 and 318 million kg P, and 1107 and 1698 million kg K for the two scenarios, respectively. Projected increases in nutrient inputs are far steeper than the yield increment ratios, not only because target yields are in the non-linear domain (for N; Fig. 2), but also because at higher yields a larger share of nutrient supply must come from external inputs (rather than from soil supply) if further exhaustion of soil fertility is to be curbed. Such exhaustion is a widespread cause of soil degradation in SSA today.

3.2. Observed values of agronomic efficiency in sub-Saharan Africa

Results on current agronomic nutrient use efficiency (AE^{1st}, kg additional yield per kg nutrient applied) inferred from field experiments in SSA countries are presented for N in Fig. 5 for the six countries in the OFRA database; and for N, P and K (Fig. 6) for the TAMASA trials. Mean observed AE^{1st} values were 14.4 (OFRA, Table 5) and 14.3 kg additional grain yield per kg N applied (TAMASA, Table 6), and 23.9 kg additional grain yield per kg P applied (TAMASA, Table 6). For TAMASA, there was little variation in AE^{1st} for N or P between countries. Country values for N were more variable in the OFRA set. No significant K response was found in any of the three countries (TAMASA, Table 6).

In both data sets, variation in observed AE^{1st} for N is large with most

Table 4
Total maize production per country and per region in sub-Saharan Africa for maize self-sufficiency in 2050, and related variables: Yw (water-limited maize yield potential), Y^T (target maize yield; 15.5% moisture), relative maize yield (Y^T/Yw), yield increment ratio (Y^T/Ya), long-term minimum input requirements of nitrogen (N), phosphorus (P) and potassium (K), short-term minimum N requirement; and equivalent N input at AE^{1st} = 14.3 kg kg^{-1} (explanation in main text). All variables are area-weighted means per country or region. Scenario-I matches maize production and demand at country level, and maize does not compensate for shortfall in yield potential of non-maize cereals. Scenario-II matches total cereal production and demand at regional level (West or East Africa) and extra maize production compensates for shortfall in yield potential of non-maize cereals. Total cereal demand in 2050 (used only in Scenario II) is 93.3 Mt (East Africa) and 128.0 Mt (West Africa). Further explanation of scenarios in main text and Table 1.

Country	Yw t/ha	Maize output (Mt)	Y^T t/ha	Y^T/Yw	Y^T/Ya	Minimum input requirement (kg/ha)				Equivalent Input at AE^{1st} = 14.3 kg/kg (kg/ha)
						Long-term			Short term	
						N	P	K	N	N
Scenario I										
Burkina Faso	6.25	2.15	2.51	0.40	1.69	48.3	6.0	32.2	38.3	80.3
Ethiopia	12.49	8.90	4.22	0.34	1.89	81.1	10.1	54.1	70.8	148.6
Ghana	8.64	7.01	7.97	0.92	4.72	199.1	19.1	102.1	328.9	446.1
Kenya	7.86	11.16	5.32	0.68	2.76	105.9	12.8	68.2	132.0	258.4
Mali	9.68	2.28	2.53	0.26	1.34	48.7	6.1	32.4	30.2	63.4
Nigeria	10.77	24.62	3.64	0.34	2.22	69.9	8.7	46.6	69.0	144.8
Tanzania	5.96	17.34	4.58	0.77	3.98	97.4	11.0	58.7	137.5	244.5
Uganda	6.85	5.28	4.69	0.68	2.92	93.9	11.3	60.1	112.1	216.6
Zambia	11.33	7.59	8.79	0.78	3.80	188.3	21.1	112.7	279.6	495.8
West-Africa	10.06	36.06	3.83	0.38	2.32	78.0	9.2	49.1	86.8	159.4
East-Africa	8.31	50.27	5.03	0.61	2.97	103.2	12.1	64.5	131.7	245.7
SSA_9	9.16	86.33	4.45	0.49	2.66	91.0	10.7	57.1	109.9	203.8
Scenario II										
Burkina Faso	6.25	3.82	4.47	0.72	3.01	91.5	10.8	57.3	116.0	217.3
Ethiopia	12.49	20.59	9.75	0.78	4.37	209.7	23.4	125.0	305.2	535.4
Ghana	8.64	5.44	6.18	0.72	3.66	126.4	14.9	79.2	170.3	321.2
Kenya	7.86	12.88	6.14	0.78	3.19	132.1	14.8	78.7	182.0	315.9
Mali	9.68	6.23	6.92	0.72	3.67	141.6	16.6	88.8	196.0	370.7
Nigeria	10.77	52.18	7.71	0.72	4.70	157.6	18.5	98.8	226.1	429.5
Tanzania	5.96	17.64	4.66	0.78	4.05	100.2	11.2	59.7	143.0	250.1
Uganda	6.85	6.02	5.35	0.78	3.33	115.0	12.9	68.6	152.5	262.6
Zambia	11.33	7.64	8.84	0.78	3.82	190.2	21.3	113.4	283.5	499.7
West-Africa	10.06	67.68	7.20	0.72	4.35	147.2	17.3	92.2	208.0	394.4
East-Africa	8.31	64.77	6.49	0.78	3.83	139.5	15.6	83.2	198.7	347.2
SSA_9	9.16	132.44	6.83	0.75	4.08	143.2	16.4	87.6	203.2	370.1

values ranging between −30 and + 70 kg for OFRA (Fig. 5), and between −20 and + 50 for TAMASA (Fig. 6a, red shaded area) datasets. As most of the trials did not contain replicates of treatments within the location, a large part of this variation is probably caused by plot-level error. When accounting for plot-level errors (Section 2.7), the variation in TAMASA outcomes reduces, with AE^{1st} for N ranging between −10 and 40 kg kg^{-1}, and for P between −10 and + 65 kg kg^{-1} (Fig. 6a,b green shaded area).

After correction for plot-level error, the mean response of maize yield to K application was still not significantly different from zero (Fig. 6c, green area; and Table 6). Neither did we find a significant yield response to micronutrients supplemented on top of N, P and K (16.7 kg/ha additional yield on average, with standard error of 74 kg/ha). Absence of these responses does not necessarily imply that yield effects might not occur in specific locations, or that K or micronutrients can be omitted on the longer term.

4. Discussion

We are not aware of other explicit attempts to estimate future nutrient requirements for self-sufficiency in specific crops in Africa, using agronomic principles in a long-term equilibrium approach. Global and regional integrated assessment models use either econometric methods to estimate future fertiliser requirements (Alexandratos and Bruinsma, 2012; Britz et al., 2012; Robinson et al., 2015), or use fixed output/input ratios (see Eq. (8)) to assess nutrient input requirements A^T for projected yields (cf. Lassaletta et al., 2016; Zhang et al., 2015). In the following we discuss our outcomes on food security and minimum nutrient requirements, and compare our assumptions on nutrient use efficiency against other sources.

4.1. Minimum crop nutrient requirements for maize self-sufficiency in 2050

This study assesses scenarios of self-sufficiency by the year of 2050. While self-sufficiency is not a necessary condition to achieve food security, self-sufficiency is relevant for low-income developing countries because many lack adequate foreign exchange reserves to afford massive food imports and infrastructure to store and distribute it efficiently. Substantial reliance on food imports is only possible if allowed by economic development and this, in low-income countries, requires agricultural development first (Johnston and Mellor, 1961; Chang, 2009). Van Ittersum et al. (2016) found that cereal self-sufficiency for SSA in 2050 could not be fully achieved on the 2010 cereal area used in their assessment. In the present study we used the 2015 cereal area which has increased by 7% relative to 2010, including a 25% increase in maize area (FAO, 2015). We also updated Yw estimates for some areas in Kenya and Tanzania (www.yieldgap.org), which are now slightly higher. Finally, in contrast to the cited study, we ignored Niger because of its insignificant maize area. The combined impact of these adjustments is that full cereal self-sufficiency now turns out possible on current (2015) cereal area, albeit that our relative yields (Table 4, Scenario II) are near the practical feasibility limit of 80% proposed by

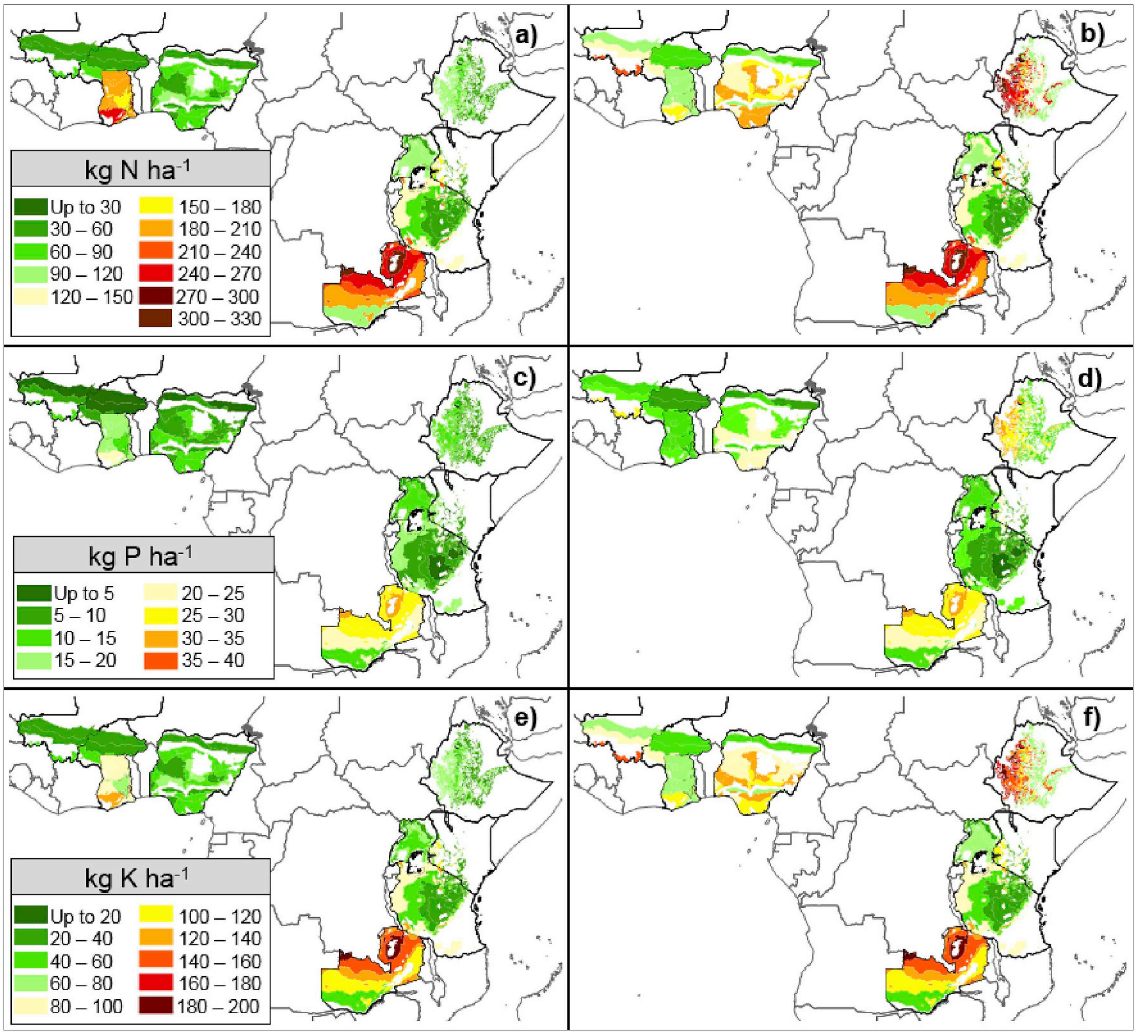

Fig. 3. Long-term minimum N (a,b), P (c,d) and K (e,f) input requirements for maize in 2050 in climate zones with current maize land; expressed in kg per ha of harvested area. Left for Scenario-I (matching maize production and demand at country level; maize does not compensate for shortfall in non-maize cereals). Right for Scenario-II (matching total cereal production and demand at regional level (West or East Africa); maize compensates for shortfall in non-maize cereals). Area cultivated to each cereal species remains constant (equal to 2015 areas) in both scenarios. Source: www.yieldgap.org.

Van Ittersum et al. (2016).

Uncertainty in population growth propagates into our projections of food demand. Low and high growth scenarios predict populations that are 9.4% lower or 9.8% higher in 2050 than by the medium course we assumed (UN, 2015). For maize demand this means, especially under Scenario II, margins somewhat larger than ± 10% due to maize compensating for other cereals. Uncertainty in P and K requirements would be proportional to these; for N, however, uncertainty is still larger as relative yields are in the non-linear response domain, under Scenario II.

Maize production in SSA (Table 4) is higher under Scenario II (132.4 Mt) than under Scenario I (86.3 Mt), because maize compensates here for insufficient production in other cereals that have smaller yield potential. Maize outputs in both scenarios are produced from the same (current) maize area, hence their difference is due to production intensity only. Scenario I outcomes reveal which countries, within each region, are likely to become importers or exporters of maize. Ghana, for example, could import maize from Burkina Faso, thus reducing the need to push its domestic production to its limit. Most of the yield increments in Scenario II versus I, however, arise from the need to compensate for limited production in the other cereals, either within the same country or elsewhere in the region.

Our projected nutrient input requirements (Table 4) are based on high efficiency (AE^{EQ} and AE^{1st}) values and are therefore called *minimum* requirements and do not reflect mean or expected nutrient input requirements. Such high efficiency is currently not common in SSA, and is difficult to attain in general. Nevertheless, our long-term estimates are consistent with high nutrient output/input (O/I) ratios proposed by several other studies (Section 4.4). Moreover, various SSA field studies have shown that efficiencies can be drastically improved by proper management, so that high values are feasible in SSA, too (Section 4.3).

Minimum K requirements (Table 4) are considered excessive by local agronomists, a view supported by the insignificant mean yield response to K found in the TAMASA trials ($AE^{1st,K}$, Table 6). We attribute such absence of yield response to a currently sufficient K supply from the soil. In the long run, however, soil stocks must be replenished, and our estimates account for this.

We do not propose that all nutrients come as mineral fertilisers. Optimal nutrient management involves balanced crop nutrition (with secondary and micronutrients inputs besides N, P and K), but also using the best blends of locally available nutrient sources (manures; green manures; crop residues; composts and household waste) besides mineral fertilisers. While vast increments in mineral fertiliser use will be unavoidable to meet the stated target yields, the use of available organic sources should be maximised to improve and sustain soil quality, a precondition for good crop growth. The locally optimised use of all

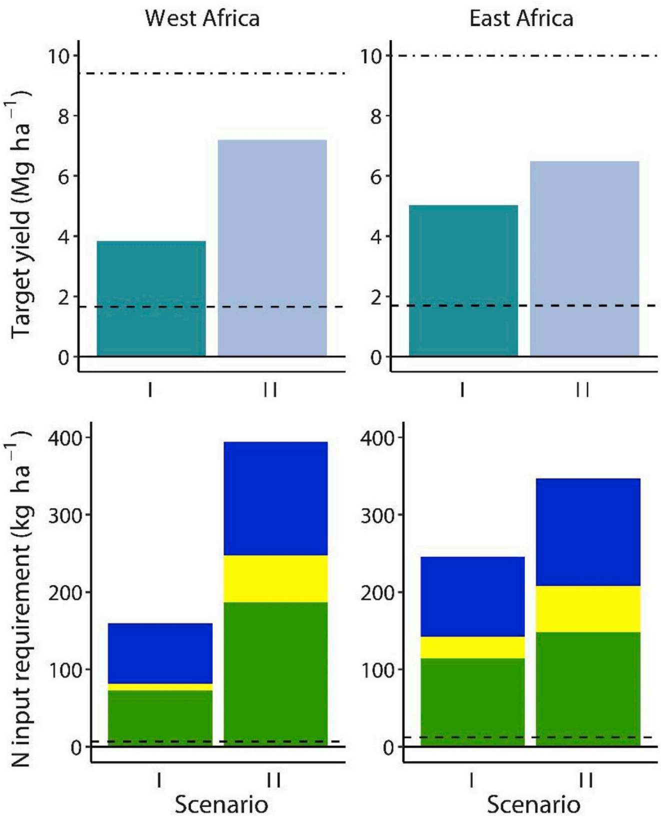

Fig. 4. Maize target yield (top) and corresponding minimum N input requirements (bottom) for Scenario I (matching maize supply and demand at country level; maize does not compensate for shortfall in non-maize cereals) and Scenario II (matching total cereal supply and demand at regional level; maize compensates for shortfall in non-maize cereals), for selected countries in West Africa (Burkina Faso, Ghana, Mali, Nigeria) and in East Africa (Ethiopia, Kenya, Tanzania, Uganda, Zambia). Dotted lines refer to mean actual (2003–2012) yield (top) and N use (bottom). The upper broken line in the top graphs indicates the water-limited yield potential. Minimum N input requirement refers to highly efficient management after equilibration of soil N supply to increased N input rate ('long term', based on Eq. (1); green columns), or to highly efficient management on soil with current mean soil N supply ('short term', Eq. (2); green plus yellow columns). Blue columns express the amount of extra N needed per ha under the hypothetical conditions that agronomic N use efficiency will not improve from today's mean value (AE^{1st} = 14.3 kg extra grain per kg N applied) and that this value can be maintained up to the stated target yields. In reality, the low AE^{1st} value itself may reflect that current yield ceilings are far below water-limited yield (Yw) due to a range of factors (See discussion). N input rates in the blue-marked domain should be regarded as wasteful. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

nutrient and carbon sources is referred to as Integrated Soil Fertility Management (ISFM), and has been extensively documented (e.g., Vanlauwe et al., 2011, 2015). ISFM is an indispensable cornerstone of sustainable intensification.

4.2. Sustainable intensification

Intensification of maize production in SSA – and that of other cereals in parallel – will have to occur in a short time span to avoid enormous exposure to food insecurity, given population development. Such time span is very brief compared to past intensification trajectories elsewhere (Van Ittersum et al., 2016). To realise this on current arable land, as presumed in this study, presents formidable challenges in different domains. These include the development of both physical and financial infrastructure for markets to ensure widespread availability of farm inputs at affordable cost. Extension efforts must be drastically intensified to improve all aspects of crop and soil management, and associated risk management. Adapted genotypes and sanitised seed, timely soil preparation and proper seed rate should enable sound crop establishment in the first place, and must be accompanied by weed control and protection of crops from pest and diseases. Harvest and post-harvest technology and grain storage facilities must be developed alongside, to prevent wastage or forced selling at dump prices. All of this requires focussed development efforts supported by adequate policies.

While low marginal profitability caused by a high fertiliser prices and low yield responses are widely recognised as a major hurdle to sustainable intensification in SSA (Jayne and Rashid, 2013), underlying barriers are often poorly understood. This holds in particular for the causes of low responsiveness in extremely exhausted soils (Tittonell and Giller, 2013). Intensification pathways are therefore uncertain and risky (Tadele, 2017; Holden, 2018). Where intensification succeeds, it is likely to come with substantial increases of nutrient losses to the environment, including emissions of N_2O with impacts on global warming. However, failure to succeed in increasing per-hectare productivity of cropland will most probably lead to further degradation of farmland and widespread crop area expansion to satisfy food demand.

Given the above recent trend in SSA cropland area, cropland is likely to expand further in coming decades. This would reduce target yield levels needed to meet maize demand, and associated per-ha nutrient requirements. The reduction for P and K would be proportional to yield. For N, the reduction would be slightly steeper than proportional, especially in Scenario II where target yields (Table 4) are in the nonlinear response domain (Fig. 2). Actual nutrient requirements would also depend on the initial fertility of newly reclaimed lands, at least for some period. Cropland expansion, however, would come at the cost of biodiversity loss and habitat loss, and likely a much larger impact on climate as compared to intensification, provided the latter is accompanied by effective policies on nature conservation (Van Loon et al., 2018).

4.3. Presumed AE^{EQ} versus AE^{1st} observed in SSA field trials

Our long-term model presumes high values of nutrient uptake efficiency (recovery), internal (physiological) efficiency, and retention of nutrients beyond the growing season. The resulting long-term agronomic efficiency (AE^{EQ}) in our calculations ranges from 31 to 52 kg grain per kg N, depending on relative yield (see Fig. 2B). For P and K, as stated earlier, we used AE^{EQ} values of 416 and 78 kg grain per kg nutrient applied, respectively. The mean first-year N, P and K agronomic efficiencies (AE^{1st}) derived from the large TAMASA and OFRA datasets appear very low, not only when compared to our assumed AE^{EQ} values, but also – for N – in comparison to our assumed AE^{1st} (30 kg kg^{-1} for low to modest relative yield). The low yield responses to fertilisers in the TAMASA and OFRA trials suggest that crop performance in a majority of the 871 locations was limited by other factors than water, N, P and K.

In spite of the above, clear evidence exists - here and in previous studies, see below - that high AE^{1st} values are possible under good conditions, also in SSA. The TAMASA trials do include locations with AE^{1st} up to 40 kg kg^{-1} (Fig. 6, green area). Brentrup et al. (2016) found a mean of 28 kg kg^{-1} from 15 on-farm trials in Tanzania (5 locations * 3 years), but reported locations (Welela and Kichiwa) with three-year averages of 43 and 38 kg kg^{-1}, respectively. Similarly, Kurwakumire et al. (2015) reported high AE^{1st} (38 kg kg^{-1}) from a trial in Zimbabwe. Such values exceed the average of about 29 kg kg^{-1} reported for grain maize trials in the United States (Ciampitti and Vyn, 2012). Vanlauwe et al. (2011) extensively studied AE^{1st} for maize in SSA. Their average was also modest (19 kg kg^{-1}) under farmer-led management, but increased to 32 or 34 kg kg^{-1} when combined with improved practices, including improved varieties. Some uncertainty remains, however,

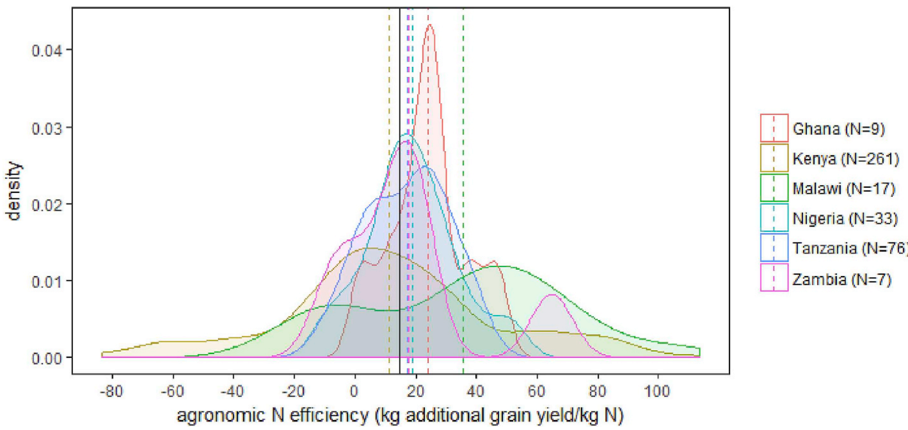

Fig. 5. Frequency distributions of observed agronomic N use efficiency ($AE^{1st,N}$; kg extra grain per kg N applied) values across six countries in sub-Saharan Africa (OFRA database, OFRA (2017)). Vertical lines represent country-means. Solid vertical line represents grand mean value of agronomic N use efficiency.

whether P and K applications in those trials were the same for treatments with and without N application. Nonetheless, the almost doubling of $AE^{1st,N}$ values under improved management does show the potential to raise AE^{1st}. Another study by Kamanga et al. (2014) in Malawi - without confounding P and K effects - found high AE^{1st}, up to 57 kg kg^{-1}. Their mean AE^{1st} increased from 19 to 39 kg kg^{-1} by weeding the plots twice instead of once per season, showing that simple measures may raise AE^{1st} substantially.

Achieving and sustaining projected yield levels (Y^T) at nutrient input rates equal to our long-term minimum input requirements (Table 4) implies closing the gap between observed AE^{1st} and presumed AE^{EQ}. This requires, in the first place, balanced nutrition and agronomic practices that enable high first-year recovery (RE^{1st}) values, near 0.6 as can be achieved elsewhere (e.g., Stecker et al., 1993; Barbieri et al., 2003; Dobermann, 2005). Such value (0.6) would correspond, with IE^{1st} about 50 kg kg^{-1}, to a value of 30 kg kg^{-1} for AE^{1st}, the value assumed in our short-term model. Practices to improve RE^{1st} are documented by Xia et al. (2017). Second, additional agronomic practices (catch crops and careful retention of crop residues) would be needed to close the gap between RE^{1st} and 1, that is, to increase nutrient retention in the soil (^{RET}E) and retarded recovery (RE^{SP}). This is – especially for N - increasingly difficult at higher relative yield where RE^{1st} is lower (Figs. 1A and 2), and is likely not possible everywhere. Our estimates (Table 4) may therefore underestimate the minimum requirements especially at high relative yield.

The mean AE^{1st} for P in TAMASA (23.9 kg kg^{-1}, Table 6) can be used to estimate fertiliser P recovery ($RE^{1st,P}$), dividing $AE^{1st,P}$ by the internal use efficiency $IE^{1st,P}$ (Eq. (3)). Until TAMASA nutrient uptake values are available to assess $IE^{1st,P}$, we resort to the 'medium' (IE^{med}) and 'accumulated' (IE^{acc}) values for P by Janssen et al. (1990) (416 and 208 kg kg^{-1}, respectively; details in SI-1 section), and then arrive at RE^{1st} for P of 6% or 11%, respectively. These are similar to values for P recovery by others: 0–15% (Tittonell et al., 2008), a maximum of 14% (Saidu et al., 2003), and a default of 10% recommended by Smaling and Janssen (1993) for use in their QUEFTS model.

4.4. N use efficiency, N surplus and O/I ratio – evidence from the global literature

We are not aware of direct observations of ^{RET}E to validate our

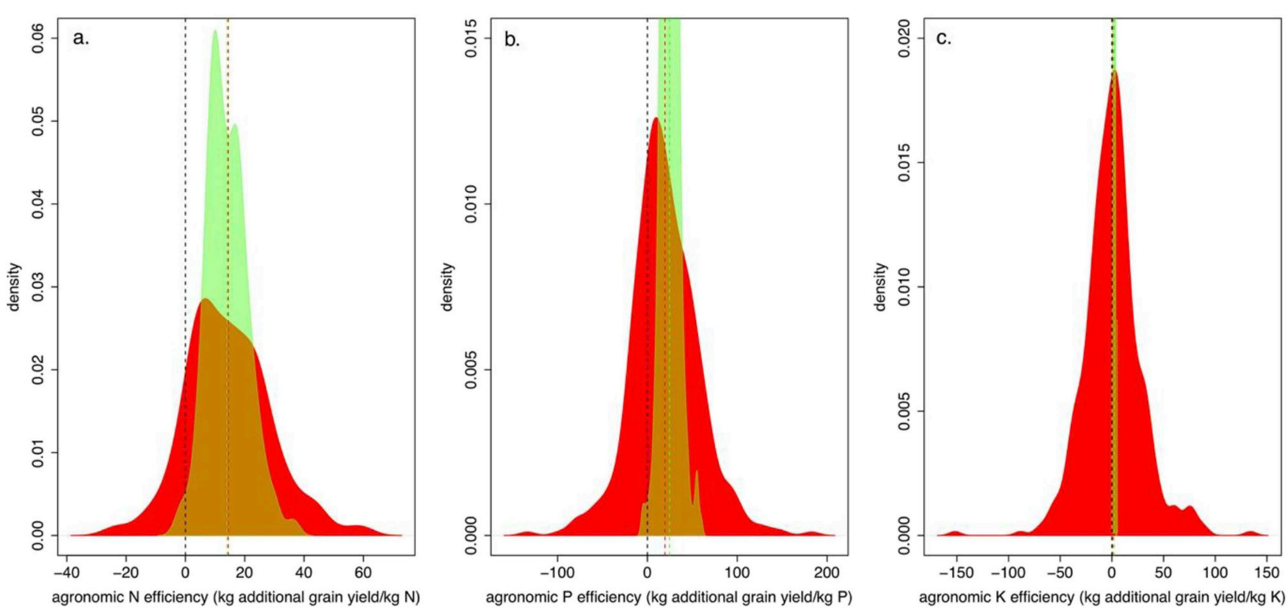

Fig. 6. Frequency distributions of observed (red) and predicted (BLUPs, green/orange) field level responses to the three crop macro-nutrients N, P and K. Black, red and green vertical lines mark 0, the observed means and the marginal model means (best linear unbiased estimates, BLUEs). TAMASA nutrient omission trials (NOTs) in Ethiopia (n = 82), Tanzania (n = 202), and Nigeria (n = 167). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Mean first-year agronomic nitrogen use efficiency ($AE^{1st,N}$) and 95% confidence interval per country for six countries in sub-Saharan Africa, with mean N rate, mean maize grain yield observed, and 95% confidence interval (CI) of mean $AE^{1st,N}$. Data from short-term experiments, OFRA database (OFRA, 2017).

Country	N (#)	mean N rate in treatments with N applied (kg N/ha)	mean grain yield in treatments with N applied (t/ha)	mean $AE^{1st,N}$ (kg additional yield/ kg N)	95% CI of mean $AE^{1st,N}$
Ghana	(9)	45.0	3.7	24.0	20.3
Kenya	(261)	29.6	4.3	11.4	3.8
Malawi	(17)	24.5	3.1	35.4	14.8
Nigeria	(33)	41.2	2.2	18.7	10.6
Tanzania	(76)	60.0	4.0	17.1	7.0
Zambia	(7)	41.6	4.0	17.7	23.0
All	(403)	36.6	4.0	14.4	3.1

approach; instead our calculated nutrient surpluses can be compared with values found elsewhere. Two types of references may serve this purpose: (i) regional or global studies where errors in loss estimates due to un-equilibrated soil supply are averaged out to some extent; and (ii) long-term trials where an equilibrium is approached between annual input, soil supply, offtake and surplus. Short-term trials are unsuitable for this purpose as they tend to show an inverted picture with low surplus on soils with high nutrient supply, and vice versa (Ten Berge et al., 2007).

We focus again on N. In our long-term approach with boundary condition $RE^{EQ} = 1$, the N output/input ratio (O/I) is equal to the N harvest index (H). The latter is 0.60–0.75 for grain maize. Surplus by our approach is then 25%–40% of annual N input (A^T) (Section 2.5). These numbers compare well with the target O/I ratio of 0.7 proposed by Zhang et al. (2015) for N in maize in SSA in 2050; and with the global O/I value (all cropping systems lumped) in the early 1960's of 0.68, which deteriorated with increased N inputs to the current 0.47 (Lassaletta et al., 2016). Van Grinsven et al. (2012) calculated an N surplus of 36% of total N input (O/I = 0.64) for EU27 over 2005–2008 (all cropping systems lumped), based on Eurostat (2012).

For the long-term (160 years) Continuous Wheat treatment in the Broadbalk Wheat Experiment (UK), where both grain and straw were harvested, Brentrup and Lammel (2016) reported N surplus (S) values of 39%–50% depending on N rate, well above the 25–40% (depending on harvest index) implied in our equilibrium model. This means that our estimates of minimum N requirement would be too low to sustain the yields attained in the trial. Nevertheless, the trial confirms our concept of long-term soil fertility building, also under a regime of mineral fertilisers. The long-term fertiliser-induced increment in annual crop N uptake from the soil was 30 kg N ha^{-1} at a fertiliser rate of 144 kg N/ha, and half of annual mineralisation was originally derived from fertiliser (Glendining et al., 1996). Similarly, Schröder et al. (2005; 2007a,b) estimated, in their analysis of allowable N inputs on silage maize in the Netherlands, that N retention from manures, crop residues and non-recovered fertiliser is about 60%. Based on this value, their model predicts an N loss fraction of 39% for grain maize (at presumed H of 0.7) of annual N input including atmospheric N deposition. This is again close to the equilibrium surplus implied in our model (Section 2.5).

5. Conclusions

We presented a generic approach to assess minimum nutrient (N, P and K) input requirements for given target yields of crops, and applied it to future maize production in sub-Saharan Africa. The intensity of maize production, currently around 20% of water-limited yield potential in both West and East Africa, must rise to 38% or 61% under Scenario I and to 72% or 78% under Scenario II in West or East Africa, respectively, in order to attain complete maize (Scenario I) or cereal (Scenario II) self-sufficiency in 2050. At the level of SSA (nine countries), this amounts to intensities of 49% (Scenario I) and 75% (Scenario II) of water-limited maize yield potential, which is respectively 2.7 and 4.1 times higher than today's values. Whilst these are steep increments to realise future yields averaging 4.5 or 6.8 t ha^{-1} for SSA in the two scenarios, minimum nutrient input requirements must rise disproportionately more, by factors of 9 or 15 for N, and 8 or 12 for P under the respective scenarios, compared to today. The disproportionality is because current production largely relies on soil nutrient mining, which cannot be sustained into the future.

Sustainable intensification of agriculture in SSA will be a balancing act between increasing nutrient inputs while avoiding unnecessary nutrient losses to the environment. This study shows that current levels of agronomic nutrient use efficiency achieved in on-farm trials are far too low to support this goal. Raising nutrient inputs while failing to address the causes of low yield responses is inefficient and uneconomical, and might worsen the impact of agricultural intensification on climate and environment.

Table 6
Estimated means by the linear mixed model (Section 2.7 and SI-4) for first-year agronomic nitrogen ($AE^{1st,N}$), phosphorus ($AE^{1st,P}$) and potassium ($AE^{1st,K}$) efficiencies for Tanzania, Ethiopia and Nigeria, with standard error. n is the number of NOT trials. Data from short term experiments, TAMASA database (http://www.tamasa.cimmyt.org).

Country	n	Country-mean[d] application rate (kg N, P or K ha^{-1})			Y_{NPK} (t/ha)	Mean agronomic nutrient use efficiency (kg additional yield per kg N, P or K applied)		
		N[a]	P[b]	K[c]		$AE^{1st,N}$	$AE^{1st,P}$	$AE^{1st,K}$
Ethiopia	82	120	40	40	6.4	16.0 (± 1.5)	23.4 (± 3.9)	5.4 (± 3.4)
Nigeria	167	138	49	49	5.1	15.7 (± 0.9)	26.4 (± 2.0)	0.9 (± 1.8)
Tanzania	202	126	43	43	4.2	11.2 (± 1.0)	21.8 (± 2.4)	3.4 (± 2.1)
All	451	127	44	44	4.4	14.3 (± 0.8)	23.9 (± 2.1)	3.2 (± 1.8)

[a] The N rate refers to NP, NK and NPK treatments.
[b] The P rate refers to NP, PK and NPK treatments.
[c] The K rate refers to NK, PK and NPK treatments.
[d] Country-mean N,P,K rates in the trials resulted from the TAMASA fertiliser recommendations depending on local yield potential at the trial location (low, medium or high, See Section 2.7).

Declaration of interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2019.02.001.

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