From yield and nutrient gaps to assessing future food self-sufficiency in SSA

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Africa is a vast content will relatively few inhabitants, due to its old and strongly weathered landscapes that are prevalent in many places that provided little soil fertility to support a large human population. The African Rift valley and the large river deltas are an exception, here fertile soils developed on relatively young volcanic or river deposits. In these areas, the population density is far higher than in other parts of the continent. Soil fertility constraints are most prevalent in the savannas and the tropical regions. But also in the drier areas towards the Sahelian climate zone, nutrients are limiting. In these zones, soil fertility constraints are strongly exacerbated by lack of soil water (Breman *et al.*, 2001) and temporal mismatches between crop demand and soil nutrient supply.

Options for irrigation are limited in most parts of the continent. Yet, seasonal rainfall is abundant in many parts with high rainfed yield potentials. For example, the tropical rainforest and guinea savannah climate zones cover a large area and have long seasons and often support long season crops. Overall, it has been shown for many decades that rainfall is less frequently limiting yields when compared to nutrients. For most countries in SSA, yield gaps are very large, and generally, farmers are achieving only 20 to 40% of the rainfed potential yield (van Ittersum *et al.*, 2016). The yield gaps are mainly due to a nutrient gap (ten Berge *et al.*, 2019), although efficiency and technology gaps are also important (Silva *et al.*, 2021). African soils have long been mined with negative soil nutrient balances (Stoorvogel and Smaling, 1998), also evidenced by the extremely high N use efficiency reported for some countries in SSA (Lassaletta *et al.*, 2014). The green revolution did not yet transform African agriculture (Frankema, 2014) which resulted in small yield increases over the last decades, estimated at about 30 kg ha^{-1} y^{-1} for cereals in SSA (Grassini *et al.*, 2013; van Ittersum *et al.*, 2016).

There are limited opportunities to address these nutrient deficiencies with organic manures and other organic sources. There is no excess biomass available in the system. Wood is needed for construction and cooking while crop residues are often required for feed. Livestock manure availability is restricted in many regions due to small and low productive herds and used for multiple purposes besides fertilisation, including energy and plastering. If available, quality is typically low and manure use often limited to areas around the homestead (Tittonell *et al.*, 2005; Rowe *et al.*, 2006). Use of mineral fertilizers is still very limited, despite strong pledges by African and international politicians. Local production increased more strongly than agricultural demand, while there is hardly any K fertilizer production in Africa (FAO, 2022). However, the agricultural use of N and P far exceeds production in SSA (Chianu *et al.*, 2012). Markets for inputs and products function poorly, due to a raft of reasons (Holden, 2018). There are large challenges in the supply chain related to the large distances between farms and supply markets but also the extensive distribution network needed to reach smallholder farmers. Hence, distributors focus on simple, one-size-fits all solutions without tailoring to the local needs. Subsidy programs often do not serve their purpose of enhancing the access to fertilizers by smallholders (Jayne *et al.*, 2018).

The legacy of animal manures is reflected in large differences in soil P and K contents (Njoroge *et al.*, 2017, 2019). The use of animal manures on selected fields created a patchwork of soil fertility in African landscapes, similar to the historical situation in north-western Europe (Breman *et al.*, 2008). Concentrating manures on the best fields is the best strategy for farmers (Rowe *et al.*, 2006), yet also mines other fields that consequently have a poor yield response to standard (N or NP) fertilizer. For these fields with strongly depleted soil nutrient pools, larger investments are needed with animal manures (Zingore *et al.*, 2008) and/or a balanced fertilizer applied during 2-3 seasons (Njoroge, 2019) for a good yield response. These less fertile fields are further more often managed by poor farmers who have limited access to animal manures and lack financial resources (Tittonell and Giller, 2013). Hence, investments in these fields is risky and counterintuitive for farmers. The majority of smallholders are very risk averse and not willing to invest in agriculture because prices of products strongly fluctuate and seasons strongly vary (Jindo *et al.*, 2020). Increasing yields may not be economically rational, due to labour productivity limitations (Silva *et al.*, 2019). Many smallholder farmers are food insecure and are net food consumers (Frelat *et al.*, 2016), and may be farmer for lack of other options (Giller *et al.*, 2021b). About 40-70% of the food secure smallholders in SSA are just "hanging in", while only 11-13% are "stepping up" and investing in intensification (Thornton *et al.*, 2018). An important factor enabling farmers to step up is credit availability. For example, the One Acre Fund is popular as they provide a standard package including hybrid maize seeds, one 50 kg bag of di-ammonium phosphate (DAP) and calcium ammonium nitrate (CAN) per acre on credit. Credit needs to be repaid only after the season when the crop has been harvested. However, commercial viability of such initiatives is highly problematic and such initiatives strongly depend on donor funds to support costs of staff.

To illustrate the grand challenge of keeping up with the enormous increases in food demand, let us take the cereals. Cereals play a central role in food security in sub-Saharan Africa (SSA) and account for approximately 50% of caloric intake and total crop area. Cereal demand in the region is projected to nearly triple between 2015 and 2050 due to rapid population growth and to a lesser extent dietary change (van Ittersum et al. 2016). As indicated above, increases in cereal yields are very slow in most SSA countries, at current rates it takes more than 30 years to achieve a 1 t/ha maize yield increase (Van Ittersum et al., 2016; FAOSTAT). Until now, increase in SSA food production resulted largely from area expansion (Giller *et al.*, 2021a). In the short term, agricultural area expansion remains an important means to keep up with the growing food demand, causing losses of forests or grasslands, thereby reducing carbon stocks and accelerating loss of biodiversity

Sustainable intensification is urgently needed to limit this area expansion. To assess what is possible, four different intensification scenarios were evaluated for ten selected countries who make up more than half of the population and cropland of SSA (Van Ittersum et al., 2016): 1) In 2050, per-ha cereal yields are the same as today (the year 2015); 2) Cereal yield trends over the period 1991-2014 are extrapolated to 2050; 3) In 2050, cereal yields are 50% of water-limited potential yield (Yw); 4) In 2050, cereal yields are 80% of current Yw. Estimation of Yw does not include expected impacts of on-going climate change. While for some countries (Mali and Ethiopia) current trends in cereal yields would suffice to achieve self-sufficiency in 2050, most countries will not be self-sufficient by 2050 even if farmers achieve 80% of the yield potential. Under the scenario with the highest intensification, cereal self-sufficiency for the whole SSA region in 2050 is possible with the current cereal area, but only just so. Current yields of ca. 20-40% of yield potential will have to increase to ca. 80% of the potential, the latter being even more than in Europe, USA and China, and requires an unprecedented steep and continuous increase in production for rainfed systems. The different potentials of different countries emphasizes that food trade between countries within West, Central and East Africa will be essential for regional food security. This is even more true considering the fact that relatively land abundant and less populated countries in especially central Africa have a larger scope for area expansion (Chamberlin *et al.*, 2014; Giller *et al.*, 2022).

Sustaining 2015 average yields into the future will require at least three times more N and P input than the amounts currently reported by FAOSTAT to prevent further soil depletion. To increase yields to 50% or even 80% of Yw requires large inputs of all macronutrients. It is estimated that minimum nitrogen requirements for maize crops with ca. 80% of rainfed yield potential will be ca. 140 kg N/ha, while current average fertilizer inputs are ca. 10 kg N/ha (www.yieldgap.org; Ten Berge et al., 2019). This minimum N requirement assumes that other nutrients in the soil are not limiting. However, amounts of P and occasionally K are often far below desired levels and require substantial inputs. Current phosphorus and potassium inputs are on average very low to negligible (less than 5 kg/ha). The required amounts to reach optimal soil fertility levels are so large, that the strategy to fertilize the soil as used in developed countries is unlikely to succeed. Fertilizing the plant (Njoroge, 2019) with balanced fertilizer applications including N, P and K ensures a good agronomic efficiency (Schut and Giller, 2020a) and will build up soil pools steadily.

Greenhouse gas (GHG) emissions in crop production are mostly caused by the use of peatlands (Leifeld and Menichetti, 2018; Lin *et al.*, 2022) and by the conversion of forest and grassland to cropland (area expansion) which results in a net loss of carbon stocks in soil and vegetation. Also fossil-fuel CO_2 emissions from production and N_2O emissions from use of N (intensification) is a major GHG source. The lack of other nutrients causes low agronomic efficiency of N (Kihara *et al.*, 2016), resulting in relatively large GHG emissions per kg of food. At the same time the Paris Conference of the Parties (COP21) Agreement aims to keep global warming below 2 °C or even 1.5 °C by 2100. SSA has already seen a continuous increase in emissions from agriculture-driven deforestation between 1990 and 2015. Yet, intensification, i.e. higher yields per hectare with sufficient and judicious use of inputs, will also lead to higher emissions per unit area because of the required fertiliser use. Estimations suggest that intensification of cereal production with sufficient and efficient use of fertilizers will lead to lowest GHG emissions (van Loon *et al.*, 2019), but requires excellent agronomy, including the use of well-adapted cultivars, proper planting densities, good nutrient management and crop protection against weeds, pests and diseases (Vanlauwe *et al.*, 2015).

Several additional factors ought to be considered in the above analysis. First, the assumption of maximum attainable yields at a level of 80% of water-limited yield potential in harsh rainfed regions with substantial large year-to-year variation in rainfall is probably too optimistic. At the same time, it is likely there will be further genetic progress in yield potentials in the decades to come which would lead to more optimistic assessments. Second, the required yield increments are extremely difficult to achieve across the agricultural landscape. With a small proportion of farmers willing to invest, the highly variable yield responses to standard inputs that do not match the crop needs and the larger investments needed for fields with a poor fertility means that required yield increases will probably only be realised on a small proportion of the land that is currently in use. Third, climate change is likely to affect future yields and their variability. However, it is estimated that such effects are relatively modest until 2050 and adaptation of cultivars and growing seasons may mitigate negative yield effects. Yet, present climate variability, aggravated by climate change with changes of average conditions but also more frequent extreme events, is a valid reason to target self-sufficiency ratios greater than 1 to be on the safe side. Given the above, a scenario of ***intensive agricultural growth*** without land expansion seems highly unlikely.

As indicated, there are still ample opportunities for more food production in the SSA region with intensification of existing farmland. There are ample opportunities with tropical crops common in the area, such as banana, cassava, sweet potato or yams (Schut and Giller, 2020b). Especially cassava has a large yield potential but low actual yields (Adiele *et al.*, 2020; Adiele *et al.*, 2021). However some agricultural land use expansion will be needed. In every case, good agronomy will be essential to realise production targets and to keep (*e.g.* GHG) emissions manageable. Development of extension services, but also targeted fertilizer subsidy programs combined with credit, insurance and market regulation programmes are needed to support local food production. Subsidy programs should ensure balanced fertilizer use, hence focus on P and K and maybe S and Mg to ensure that N is effectively used. The N fertilizers are already widely used and available. Yet, the required yield increments to feed the quickly growing urban area from existing farmland far exceed scenarios for yield increases that are realistic given these challenges. Some of the required food may need to be produced on well managed larger farms (Schut and Giller, 2020b), that have access to credit and can use mechanised equipment with direct yield benefits (Aune *et al.*, 2017; Aune *et al.*, 2019). These consolidated farms do not have to be very large or be owned by a single farmer. For example, younger farmers with an entrepreneurial attitude may be able to rent land from other farms and produce for markets (Holden and Tilahun, 2021).

Extensive agricultural expansion driven by land exhaustion may result in strong environmental degradation, for example as a result of the economic collapse of Zimbabwe (Chagumaira *et al.*, 2015) and is a worse-case scenario with undesired outcomes for food self-sufficiency, loss of biodiversity and large GHG emissions from land conversions. However, the points above do underpin why it is unlikely that yield increments alone can keep pace with population growth. Policies which are good for food security and for the climate must therefore seek to strike an optimum balance between intensification and controlled expansion. When incentives to produce are strong, farmers may also start using less suited land with low productivity and land erosion and degradation as a consequence, as observed for example in Malawi (Li *et al.*, 2021). Hence, policies to support agriculture need to be combined with environmental policies to protect natural reserves, quality of land, air and water.

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