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Prospect for increasing grain legume crop production in East Africa

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ABSTRACT

Agricultural production in East Africa (E-Afr) has to increase drastically to meet future food demand. Yield gap assessment provides important information on the degree to which production can be increased on existing cropland. Most research on yield gap analysis has focussed on cereal crops, while legumes have received less attention despite of their relatively large area, and their importance as source of protein in smallholder farming systems in E-Afr. The objectives of this study were to (i) estimate water-limited yield potential (Y_w) and yield gaps (Y_g) for major grain legume crops in E-Afr, and (ii) estimate how narrowing the current legume Y_g can contribute to food self-sufficiency by the year 2050. We focussed on Ethiopia, Kenya, and Tanzania, and five legumes crops including chickpea, common bean, cowpea, groundnut, and pigeonpea. A bottom-up approach which entails that local weather, soil and agronomic data was used as input for crop modelling (SSM-legumes) in a spatial framework, to estimate Y_w, actual on-farm yield (Y_a), and Y_g from local to regional scale. Future legume self-sufficiency was assessed for 2050 demand assuming different Y_g closure scenarios. On average, Y_a was 25% of Y_w across all legume-county combinations, being 15% for Kenya, 23% for Tanzania and 41% for Ethiopia. On average, common bean had the largest Y_g of 2.6 Mg ha^{-1}and chickpea the smallest (1.4 Mg ha^{-1}). Closure of the exploitable Y_g (i.e., 80% of Y_w) can help to meet future legume demand in both Kenya and Tanzania, while it seems not to be sufficient in Ethiopia.

1. Introduction

About 220 million people suffer from chronic hunger in sub-Saharan Africa (SSA) (United-Nations, 2016). East Africa (E-Afr) is the most populated region, accounting for around 42% of SSA population. Previous assessments on the potential to increase food production in E-Afr indicated that domestic grain demand is not met with current production, and food scarcity is expected to be exacerbated in the future, driven by high population growth and changes in diets (van Ittersum et al., 2016).

Yield potential (Y_p) is the yield achieved by a well-adapted cultivar without water and nutrient limitations and no yield reduction due to incidence of weeds, insect pests, and diseases (Cassman et al., 2003; Van Ittersum and Rabbinge, 1997). Y_p is determined by growth-defining factors, i.e. temperature, radiation, CO_2 and genetic traits of a crop cultivar. In rainfed conditions, water-limited yield potential (Y_w) is determined, next to growth-defining factors, by water supply amount and distribution, and by soil properties influencing the crop water balance, such as rootable soil depth, available water holding capacity, and terrain slope. Understanding how much extra food can be produced on existing (rainfed) cropland is the first step towards reducing the yield gap (Y_g), i.e., the difference between Y_w and average farmer yield (Y_a).

Most research on Y_g analysis in E-Afr (and elsewhere) has focussed on cereal crops (e.g. Gobbett et al., 2016; Kassie et al., 2014; van Ittersum et al., 2016), while grain legumes have received little attention (e.g. Aramburu-Merlos et al., 2015; Sinclair et al., 2014; Soltani et al., 2016), despite their relatively large area (ca. 20% of cropland area in

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Ethiopia, Kenya and Tanzania (FAO, 2018)) and their importance as source of protein, energy, vitamins, and minerals of poor farmers in SSA (Giller et al., 2013; Temba et al., 2016). Opportunities exist for intensifying grain legume crop production in E-Afr (Giller, 2001; Franke et al., 2017), because legumes fix atmospheric N and thereby also have benefits for other crops. For example, legume crops may enhance yield of cereal crops within the sequence by improving N nutrition of this subsequent crop (e.g. Franke et al., 2008, 2017; Giller, 2001; Kamanga et al., 2010; Ojiem et al., 2014; Sanginga, 2003). However, there is clearly a dearth of knowledge in relation with the potential for legume crops production increase in E-Afr.

The objectives of this study were to (i) calculate water-limited yield potential (Y_w) and yield gaps for major legume crops in E-Afr, and (ii) estimate how narrowing the current legume yield gap can contribute to food self-sufficiency in the region. We focussed here on three countries, Ethiopia, Kenya and Tanzania, and five legumes crops, chickpea (*Cicer arietinum* L.), common bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata (*L.*) Walp.*), groundnut (*Arachis hypogaea* L.) and pigeonpea (*Cajanus cajan (*L.*) Mill*sp.).

2. Material and methods

2.1. Description of legume cropping systems in East Africa

We performed yield-gap analysis for five grain legume crops (chickpea, common bean, cowpea, groundnut, and pigeonpea) for three countries in E-Afr (Ethiopia, Kenya, and Tanzania), considering, for each crop, only countries with an annual harvested area ≥50,000 ha. These three countries account for 50% and 16% of area sown with these five crops in E-Afr and SSA, respectively. Selected crop-country combinations included common bean (Ethiopia, Kenya, and Tanzania), chickpea (Ethiopia and Tanzania), pigeonpea (Kenya and Tanzania), cowpea (Tanzania), and groundnut (Tanzania) (Table 1). Overall, common bean is the most important legume crop in the region with *ca.* 2 million ha across the three countries (FAO, 2018). We focus on bush bean only, as this is the main common bean variety sown in E-Afr. Chickpea is mainly grown in north-west and central Ethiopia and in some regions in north Tanzania, while groundnuts, pigeonpea, and cowpea are mostly grown in Tanzania and/or Kenya (Fig. S1). To illustrate the legume cropping system in E-Afr, Fig. 1 shows dominant legume-based crop sequences at six selected locations in Ethiopia, Tanzania, and Kenya. In most cases, legume crops are rotated with cereal crops (*e.g.*, teff, maize, sorghum, and rice) and are grown during the wet season for a period of 4–5 months. An exception is chickpea, which is commonly sown by the end of the wet season, growing mostly during the dry season and relying on the residual soil water (Fig. 1a). Another exception is pigeonpea in Kenya, where it is sown all year round, with a crop cycle ranging from 8 to 10 months (Fig. 1e).

2.2. Site selection and data sources

We followed the protocols of the Global Yield Gap Atlas (www.yieldgap.org) to determine Y_w and Y_g for legume crops in Ethiopia, Kenya, and Tanzania (Grassini et al., 2015b; van Bussel et al., 2015). Briefly, we selected sites for each crop-country combination based on (i) a climate zone (CZ) scheme that accounts for variation in growing degree days, temperature seasonality, and aridity index (Van Wart et al., 2013), (ii) distribution of crop area as reported by SPAM 2005 maps (You et al., 2014a, 2014b), and (iii) availability of meteorological stations with daily weather data. Within each country, CZs with > 5% of total national harvested area for each crop were selected. Within each CZ, a 100-km radius 'buffer' surrounding each weather station was created and clipped by the borders of the CZ to ensure that the buffer zone is located within a unique CZ. Buffer zones were sequentially selected based on their contribution to national crop harvested area until ca. 50% national crop area coverage was achieved. If needed, additional buffers were added to include regions with high crop area density but without a weather station. In our set of 3 countries, there were 14, 22, 11, 10 and 13 buffers selected for, in the same order, chickpea, common bean, cowpea, groundnut and pigeonpea. In turn, these buffers were located in, respectively, 6, 11, 7, 6, and 6 different climate zones, which, overall, accounted for respectively 52, 43, 75, 89, and 70% of E-Afr harvested area with these crops.

In the selected buffers, long-term (1998–2012) daily weather data were retrieved from the National Meteorology Agency of Ethiopia (NMA, 1998), Tanzania Meteorological Agency (TMA, 1998-2012; TMA, 1998), and Kenya Meteorological Department (KMD, 1998-, 2012KMD, 1998KMD, 1998-, 2012). Since 52% of the buffers had less than 10 years of weather data but at least 3 years, long weather data records were generated using the method described by Van Wart et al. (2015). In short, this method corrects long-term daily gridded NASA-POWER maximum and minimum temperature based on correlations between measured and gridded weather and uses uncorrected NASA-POWER solar radiation and TRMM rainfall to generate long-term synthetic weather files. Finally, for buffer zones without any measured weather data (48% of total buffers), we used uncorrected gridded weather data from NASA-POWER.

Within each buffer zone, up to three dominant soil types were selected, based on the distribution of the harvested area of the target crop within the buffer.

Soil data were retrieved from both AfSIS-GYGA functional soil information of sub-Saharan Africa database (maximum effective depth of water extraction from soil by roots, maximum soil depth, volumetric soil water content available for extraction by crop roots) (Leenaars et al., 2015, 2018) and ISRIC-World soil information, WISE international soil profile dataset (drainage) (Batjes, 2012). Information about dominant legume-based cropping systems in each buffer (*e.g.*, sowing and harvest windows, plant density) was provided by local agronomists. Average on-farm yield (Y_a) for Ethiopia was based on nine year district level data obtained from the Central Statistical Agency Ethiopia

Table 1
Total harvested area, average water-limited potential yield (Y_w,), temporal variation of Y_w ($CV_{temporal}$), average farmer yield (Y_a), relative yield gap (ReY_g, i.e., [1-Y_a/Y_w] x 100), yield potential (Y_p), water limitation index (WLI) for each crop-country combination.

Country	Crop	Harvested area (1000 ha)	Y_w (Mg ha^{-1})	CV (%)	Y_a (Mg ha^{-1})	ReY_g (%)	Y_p (Mg ha^{-1})	WLI (%)
Ethiopia	Chickpea	197	2.7	23	1.4	49	5.7	52
	Common bean	215	3.4	2	1.1	68	3.4	1
Kenya	Common bean	944	3.4	10	0.6	81	4.0	13
	Pigeonpea	190	2.9	35	0.3	88	5.6	49
Tanzania	Chickpea	65	2.2	24	0.5	80	5.2	57
	Common bean	859	3.1	4	0.6	79	3.2	4
	Cowpea	155	3.2	7	0.6	82	3.5	8
	Groundnut	421	2.3	14	0.7	71	3.7	37
	Pigeonpea	155	2.5	17	0.6	75	7.1	64