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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

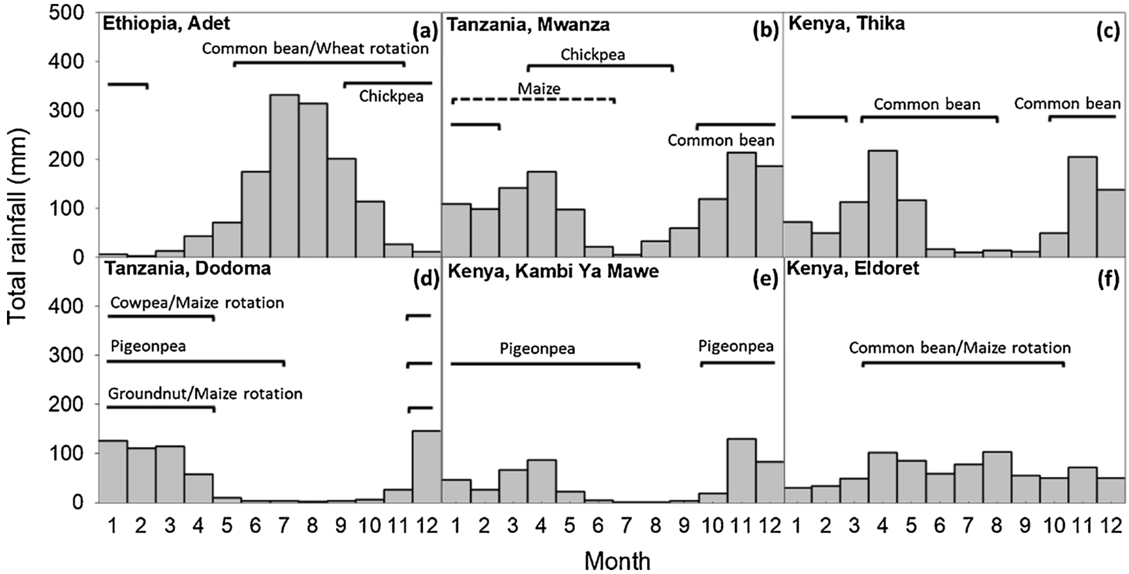

Fig. 1. Average (1998–2012) monthly total rainfall and dominant legume-based crop sequences in selected sites in East Africa. Horizontal solid lines and dashed lines represent the crop growth duration (i.e., from sowing until physiological maturity) for, respectively, each legume crop cycle and cereal crop cycle in each crop sequence.

(CSA-Ethiopia, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016); for Kenya a 5-year average centered on year 2005 was obtained from SPAM 2005 (You et al., 2014a, 2014b); and for Tanzania four years (2003, 2008, 2013, 2015) of district level data from the National Bureau of Statistics Tanzania were used (NBS-Tanzania, 2012, 2016a,b).

2.3. Simulation of legume crop yield potential

We considered Y_w as the relevant benchmark for estimating Y_g since legumes in E-SSA are mainly grown under rainfed conditions. Still, to understand the degree of limitation by water, we also simulated non-water limited Y_p. Y_p and Y_w were estimated using the generic crop growth model Simple Simulation Model for legumes (SSM-legumes) (Soltani and Sinclair, 2012; https://sites.google.com/site/cropmodeling/-7-ssm-soybean). The SSM model has been used to simulate growth and yield potential of a wide range of legume crops, including soybean (Sinclair et al., 2014, 2010), chickpea (Soltani and Sinclair, 2011; Vadez et al., 2013), common bean (Marrou et al., 2014), lentil (Ghanem et al., 2015), cowpea (Hissene et al., 2016), and groundnut (Halilou et al., 2016). Briefly, SSM-legumes is a simple, transparent, and mechanistic crop model structured in five modules informed with 57 parameters (including crop description, soil, and management) (Soltani and Sinclair, 2012). These five modules cover 1) development, based on cumulative photo-thermal days; 2) leaf area development, which is calculated from phyllochron and an exponential relation between leaf number on the main stem and total plant leaf area; 3) dry matter production; 4) dry matter allocation, as determined by N balance in the different plant organs, and 5) soil water balance, where transpiration is calculated as a function of daily dry matter production and daytime vapour pressure deficit using Sinclair et al. (1984) equation.

We collected the value of general plant parameters from previous model applications (Sinclair et al., 2010, 2014; Soltani and Sinclair, 2011; Vadez et al., 2013; Marrou et al., 2014; Ricaurte et al., 2016; Guiguitant et al., 2017). In each of these studies, genotypes have been sampled to represent the diversity of genotypes used in each study environment, covering temperate, dry tropical, and humid tropical climates. Most plant parameters are known from preceding studies not to vary significantly within species. For the crop specific parameters, phenology and photoperiod sensitivity, we calculated them to portray the varieties grown in E-Afr, by using the parameter values of genotypes of the same variety in preceding studies, or calculating them from the phenology reported by local agronomists. The list of crop parameters is provided for each crop in Table S1.

Selected plant densities for the simulations were 50 (chickpea, common bean, and pigeonpea), 40 (cowpea), and 30 (groundnut) plants m^{-2}. These densities compared well with the range of plant densities used in field experiments that aimed to maximize legume yields in different regions (Dapaah et al., 2014; Halilou et al., 2016; Mligo and Craufurd, 2007; Soltani et al., 2016). Our simulations also assumed that, in each year, sowing was triggered when cumulative rainfall was > 20 mm within 7 consecutive days in the sowing window as defined for each buffer by the local agronomist (Dobor et al., 2016; Wolf et al., 2015) (Table S2).

As for soil variables, the soil albedo (degree of soil reflectance depending on soil colour and moisture) was calculated following the method of Soltani and Sinclair (2012). Soil curve numbers were estimated based on field slope and drainage class reported for each soil (Yang et al., 2016). Chickpea, known by its deep and prolific root system, is typically grown in Vertisols during the dry season in Ethiopia and Tanzania (Fig. 1a); due to the specific soil structure, these soil types can hold more water than other soils, which allows chickpea to complete its crop cycle relying on residual soil water from the wet season (Woldeab, 1988). In order to simulate these characteristics, we changed both soil depth (830–1270 mm originally) and maximum effective depth of water extraction from soil by roots (1000 mm originally) parameter to 1500 mm for chickpea in Ethiopia, and the maximum soil depth to 2000 mm (Woldeab, 1988). Besides, we set the volumetric soil water content available for extraction by crop roots at 0.15 (0.111–0.134 originally) to reflect the effect of vertisols on chickpea growth in Ethiopia. Since legume crops (except chickpea) are mostly grown during the wet season and no crop is planted during dry season (Fig. 1), we assumed that there was a 6 month fallow period before sowing and initiated the water balance module at that time with 50% of extractable soil water. An exception was chickpea in Ethiopia, which is sown at the end of the wet season; here, the soil water balance was initiated one week before sowing assuming a fully recharged soil profile.

2.4. Estimation of yield gaps for legume crops and data analysis

For each buffer, Y_w was simulated for each of three dominant soil types. Average Y_w was calculated for each buffer using a weighted average based on the proportion of soils within the buffer. Y_g was calculated as the difference between long-term average Y_w and Y_a. Relative yield gap (ReY_g; expressed as percentage of Y_w) was calculated as one minus the ratio between Y_a and Y_w times 100. Results were upscaled from buffer to CZ and from CZ to country level using the bottom-up approach described by van Bussel et al. (2015). In short, the weighted average of the yields per soil type was taken to obtain the yield per crop cycle for a buffer. In case of multiple crop cycles per year the average was taken to obtain the yield per crop (Van Bussel et al., 2015). Finally, the average of all years was calculated to obtain the yield per bufferzone. We upscaled the potential yield, actual yield and yield gap from buffer zone to CZ. This was done by taking per CZ the harvested area-weighted average yields of the included bufferzones. The CZ yields were further upscaled to country level by taking the harvested area-weighted average yield per CZ (Van Bussel et al., 2015).

Two parameters were used to assess the degree of crop water limitation: crop water availability (CWA), which was derived from the simulated crop evapotranspiration, and the water limitation index (WLI, in %), which was calculated as one minus the ratio between Y_w and Y_p times 100. Quantile regression was used to derive a boundary function for the relationship between simulated Y_w and CWA based on the 95th percentile. The boundary function used an x-intercept (*i.e.*, minimum soil evaporation) that corresponds to the 5th percentile of simulated soil evaporation for each individual crop across country-years-sites. Analysis was performed using the "quantreg" package in R (R Core Team, 2018). Water-use efficiency derived from the slope of the boundary functions fitted to simulated data were compared against maximum water-use efficiency reported in the literature (Halilou et al., 2015; Miriti et al., 2012; Ramírez Builes, 2011; Zhang et al., 2000; Connor et al., 2011), except for pigeon pea for which we are not aware of robust estimates of water-use efficiency.

We investigated opportunities for Y_g closure by identifying sites with (i) large relative yield gap (ReY_g), (ii) large harvested area, and (iii) low yield risk (Van Oort et al., 2017). We used the inter-annual coefficient of variation (CV, %) of Y_w as a proxy to yield risk.

2.5. Extra production potential due to intensification of existing legume cropping systems

Current domestic grain legume demand was calculated for each legume and country as the product of 2010-population (United-Nations, 2015) and the legume demand per capita derived from the IMPACT model (Robinson et al., 2015). In order to compute a total legume demand that aggregates the demand of all legumes in this study, the domestic demand of each legume was expressed as common bean equivalent (Ceq) using the crop-specific grain caloric contents (FAO food balances) as follows:

$$D_i = \sum D_{ij}\, x\, Ceq_j \quad (1)$$

where D represents total domestic legume demand, *i* represents either current or future scenarios, and *j* represents the legume crop. Future legume demand per capita was estimated based on IMPACT (Robinson et al., 2015) and the projected 2050 population established for the medium fertility variant of United Nations (2015).

Following van Ittersum et al. (2016), legume self-sufficiency ratio (SS) was calculated as:

$$SS_i = \frac{P_i}{D_i} \quad (2)$$

Which is the quotient of total domestic legume production (P) and demand (D) for current (2010) and future (2050) scenarios, where *i* represents either current or future scenarios of legume production. Future production scenarios include (1) legume yield is equal to current production (Y_a), (2) legume yield equals 50% of Y_w, and (3) legume yield equals 80% of Y_w (exploitable Y_g). Data from previous studies showed that 80% of Y_w is a reasonable maximum goal in commercial, intensive legume cropping systems (Rattalino Edreira et al., 2018).

Current legume production was calculated per country as the product of mean actual crop yield and the 2010-harvested area per crop (FAO, 2018). Future legume production was estimated for the three production scenarios assuming no future changes in legume area. Note, that we do not include the effects of climate change in our study, because of the large uncertainty in the degree and impact of climate change in E-Afr, as discussed in van Ittersum et al. (2016).

3. Results

3.1. Yield potential of legume crops in East Africa

Y_w varies across countries and legumes (Table 1). The highest average (area-weighted average across legumes in a country) Y_w was found in Kenya, i.e. 3.3 Mg ha^{-1}, which was 18% and 8% higher than that in Ethiopia and Tanzania, respectively (Table 1). Of all simulated legumes in East Africa, highest Y_w's were found for common bean (3.3 Mg ha^{-1}) and cowpea (3.2 Mg ha^{-1}) and these two crops also exhibited the lowest year-to-year yield variation as measured using the coefficient of variation (CV of respectively 5 and 7%). Groundnut exhibited the lowest Y_w, with a CV of 14%. For dry season crops such as chickpea, the average Y_w was 2.6 Mg ha^{-1}, with a CV three times higher than that in common bean, indicating unstable yields across years. Although pigeonpea has the longest growth duration in our study (Fig. 1 d,e), the Y_w of pigeonpea was 17% less than that of common bean, and the CV was highest (27%). Y_w varied across countries, i.e., Y_w for common bean and pigeonpea was respectively 12% and 14% higher in Kenya than in Tanzania, and Y_w for chickpea was 22% higher in Ethiopia than in Tanzania.

A negative relationship was found between Y_w and WLI ($r^2 = 0.68$, $p < 0.05$). Legumes with a high Y_w, such as common bean and cowpea, had the smallest limitation by water (WLI = 8%). For common bean, WLI in Ethiopia and Tanzania was even less than 5%, revealing common bean growth experiences hardly any water limitation in those countries. In contrast, legumes with a low Y_w such as chickpea, groundnut, and pigeonpea had substantially higher WLI (range: 37%–64%).

3.2. Average farmer yield and yield gaps of legume crops in East Africa

The highest, area-weighted, average actual legume yield was 1.2 Mg ha^{-1} in Ethiopia, two times larger than that in Tanzania and Kenya (Table 1). Across different legume species, Y_a of chickpea was 1.2 Mg ha^{-1}, which was around twice the Y_a of common bean, cowpea and groundnut, and three-fold greater than that of pigeonpea. Contrary to Y_w, the variation of Y_a across countries was greater than that across species.

Our results showed a large legume yield gap in East Africa (E-Afr), i.e. the relative yield gap (ReY_g) was on average 76% for all the legumes across the three countries, ranging from 49 to 88% for the different crop-country combinations. Comparing ReY_g across countries, ReY_g decreased in this order: Kenya, Tanzania, and Ethiopia (ReY_g: 82%, 77%, and 59%, respectively). Pigeonpea and cowpea had the highest ReY_g (82%), followed by common bean (79%) and groundnut (71%). ReY_g for chickpea was 80% in Tanzania and 49% in Ethiopia. Except for chickpea in Ethiopia, ReY_g for all legume-country combinations was higher than 50%, (68–88%).

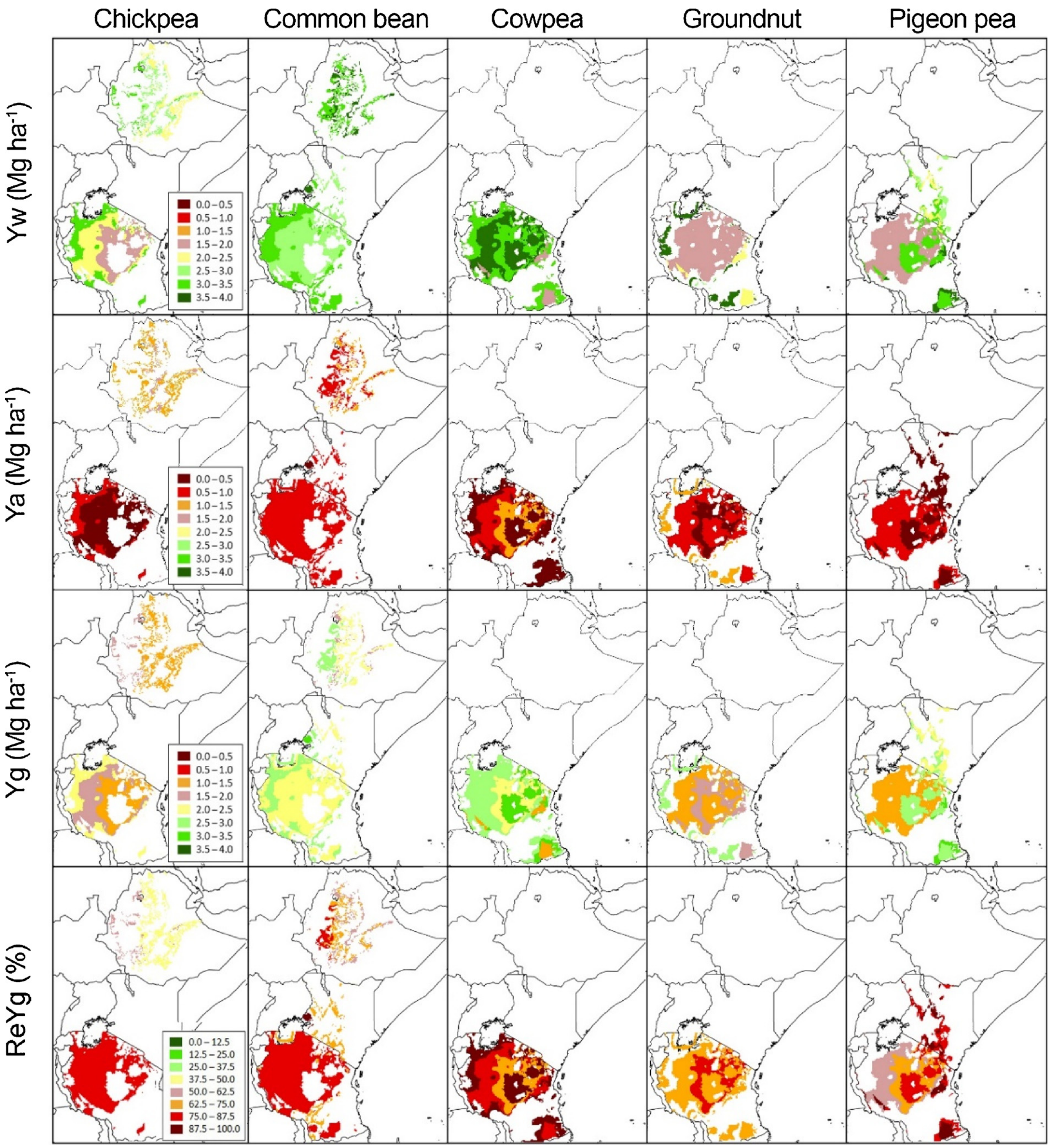

Fig. 2. Water-limited yield potential ($Y_{w)}$, average farmer yield (Y_a), yield gap (Y_g), and relative yield gap (ReY_g) for the selected climate zones in East Africa for the five legume crops.

3.3. Legume yield differences in different regions within a country

Yield gaps differed across regions within a country (Table S2). For example, in Ethiopia, chickpea cropping area is mainly situated in the central and north-western part of the country, and Y_w and Y_a of chickpea was higher in the north-western region than in the central region (Fig. 2). ReY_g in the north-west was approx. 57%, and in the centre it was 48% or lower (Fig. 2). For common bean, ReY_g was 20–30% lower in the central than in the north-western region. This is because Y_w was the highest in the north-west, while Y_a was higher in the central region. In Tanzania, a relatively high Y_w was found in the north-western region for chickpea, common bean and groundnut, and in the central region for pigeonpea and cowpea. In Kenya, for common bean the highest Y_w and lowest Y_a was found in southwest Kenya near the rift valley, resulting in a higher yield gap than in other regions. For pigeonpea, Y_w had a small range of 2.5–3.1 Mg ha^{-1}, while the average Y_a was less than 0.4 Mg ha^{-1}. Therefore, a large ReY_g (86–92%) was found. Differences in Y_g and Y_w across regions within a country likely reflect differences in the biophysical environments as well as farmers' access to inputs, markets and extension.

Yield-gap analysis performed for the five legume crops can help identifying country-crop combinations with greatest potential for crop intensification based on the size of the gap (REYg%), risk levels (CV) and harvested area (Fig. 3). Common bean in Tanzania has the largest harvested area, with a relatively high ReYg (79%) and low CV (4%) (Table 1 and Fig. 3). In contrast, chickpea in Ethiopia had a relatively high CV (23%) and low ReYg (49%), with a small harvested area (Table 1 and Fig. 3). The CV of chickpea is relatively high, because of

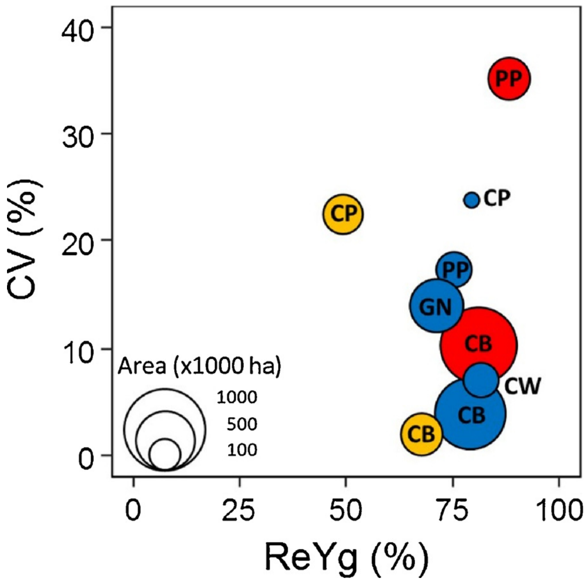

Fig. 3. Relative yield gap (ReY_g) versus coefficient of variation of Yw (CV) for chickpea (CP), common bean (CB), cowpea (CW), groundnut (GN), and pigeonpea (PP) of Ethiopia (yellow symbols), Kenya (red symbols), and Tanzania (blue symbols). Size of the symbols indicates the size of the harvested area of the crop. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the large variability in rainfall across years during the dry season. Pigeonpea had the highest CV (35%), which is mainly due to the low temperatures within the season and regions it is growing and therefore it has a long and variable growth duration.

3.4. Relationships between crop water availability and yield among different legume crops

There was large variation in CWA across countries, sites, and years for all legumes (Fig. 4). The 5th and 95th percentiles for CWA were, in the same order, 260 and 460 mm (chickpea), 400 and 820 mm (common bean), 450 and 730 mm (cowpea), 470 and 860 mm (groundnut), and 380 and 830 (pigeonpea). Highest yields were linearly related to CWA, as illustrated by the boundary functions fitted across countries and years separately for each crop (Fig. 4a–e). The slope of those boundaries represents the upper limit of water-use efficiency, which varied from 13 to 21.5 Mg ha^{-1} mm^{-1} for groundnut and common bean, respectively. For any level of CWA, there was a wide variation in Y_w for all crops and regions. Boundary functions fitted to simulated Y_w and CWA were (chickpea) or were not (cowpea and groundnut) in reasonable agreement with boundary functions derived from the literature (Fig. 4a–e). No boundary function was fitted between Y_a and CWA, as there was no significant relationship ($p > 0.25$ for all crops except common bean [$p = 0.02$]).

3.5. Yield gap closure and potential impact on food self-sufficiency

Currently, Ethiopia and Kenya are self-sufficient in legumes, and Tanzania is almost self-sufficient (Fig. 5a). However, population is expected to double in both Ethiopia and Kenya, and to triple in Tanzania by the year 2050 compared with 2010, and the per capita domestic grain legume demand is expected to increase by 62% (Ethiopia), 13% (Kenya), and 33% (Tanzania) (Table 2). If actual yields do not increase, the legume self-sufficiency would be only ca. 0.4 in the three countries in 2050 (Fig. 5b). If legume yields would increase up to 50% of Y_w, Kenya will be almost self-sufficient, while Tanzania and Ethiopia will still not be self-sufficient in legume production. If legume yields increase up to 80% of Y_w, Tanzania will also be self-sufficient in legumes and Ethiopia will still not be self-sufficient (Fig. 5b). Compared with cereal self-sufficiency (van Ittersum et al., 2016), Ethiopia had lower

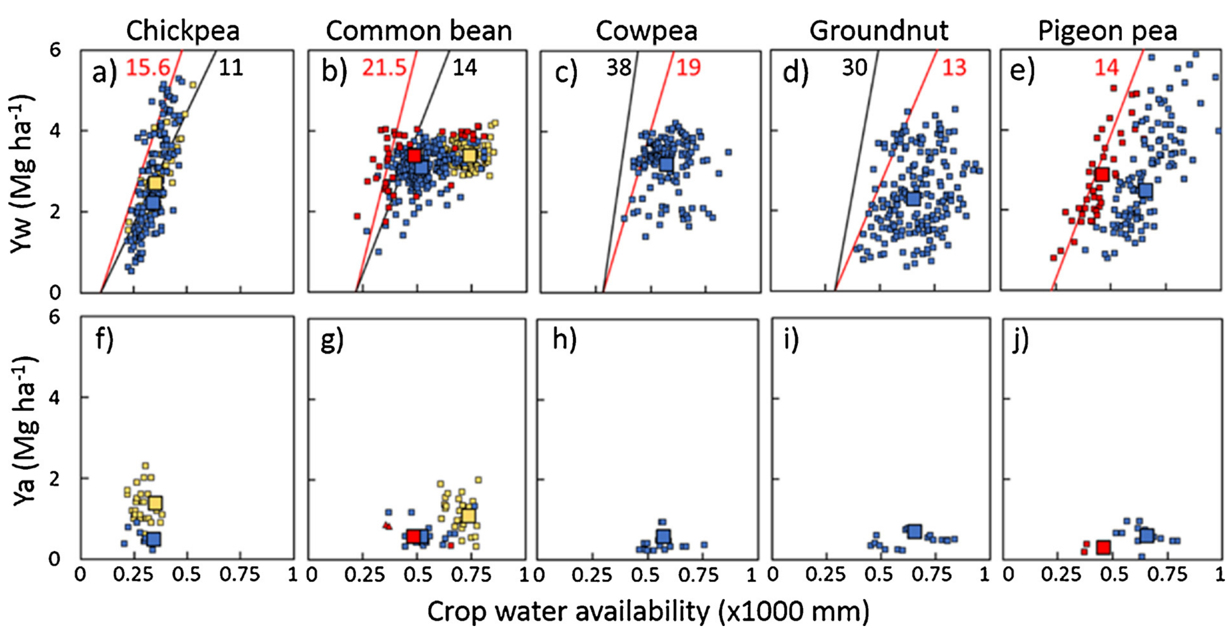

Fig. 4. Water-limited yield potential (Y_w, a – e) and average farm yield (Y_a, f – *j*) plotted against seasonal crop water availability for Ethiopia (yellow), Kenya (red) and Tanzania (blue) for the five legume crops. Y_w and Y_a for each buffer-year combination are shown (small symbols) as well as Y_w and Y_a averages for each crop-country combination (large symbols). In all panels, solid lines represent potential water-use efficiency from literature (black line) and estimated by quantile regression analysis of simulated data based on 95th percentile (red lines), with minimum soil evaporation set for each individual crop at the 5th percentile of simulated soil evaporation across country-years-sites (chickpea: 93 mm; common bean: 218 mm; cowpea: 284 mm; groundnut: 292 mm; pigeon pea: 229 mm). Slopes of potential water-use efficiency are shown next to reference lines and expressed as kg ha^{-1} mm^{-1} (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

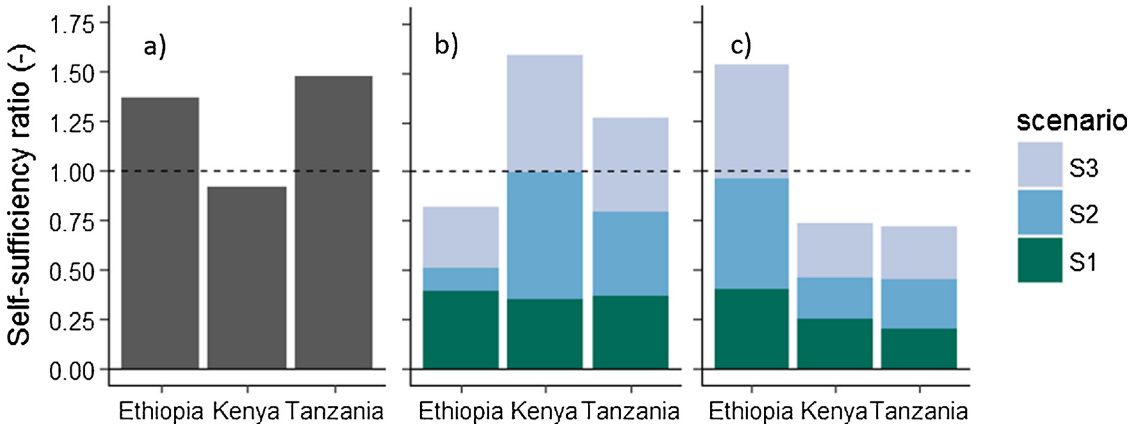

Fig. 5. Grain legume self-sufficiency on existing legume area for the legumes jointly per country for a) 2010 and b) for the different scenarios in 2050: scenario 1 (S1), no change in yield in 2050 compared to 2010; scenario 2 (S2), yields in 2050 will be 50% of water-limited yield; scenario 3 (S3), yields in 2050 will be 80% of water-limited yield; c) compared with cereal self-sufficiency for the same scenarios and countries (van Ittersum et al., 2016).

Table 2
Increase in population and per capita legume demand from 2010 to 2050 for Ethiopia, Kenya and Tanzania.

Country	Population 2050 (% of 2010)	Per capita legume demand 2050 (% of 2010)
Ethiopia	216	162
Kenya	233	113
Tanzania	305	133

self-sufficiency ratio in legumes than in cereals, while Kenya and Tanzania had higher self-sufficiency ratio in legumes than in cereals (Fig. 5b,c). While Ethiopia cannot meet legume demand in S3, Kenya can meet legume demand in S3 and S2 and Tanzania can meet the demand only in S3.

4. Discussion

4.1. Data on benchmarking legume production in SSA

This study was the first to assess, at a regional level, the yield gaps (Y_g) of legume crops in East Africa (E-Afr), and to investigate opportunities of different levels of yield gap closure to achieve future (2050) legume self-sufficiency on existing cropland. We followed the protocols of the Global Yield Gap Atlas to map Y_g in an agronomically robust and reproducible manner, based on a bottom-up approach using local data as input and involving local experts to evaluate model results. For a robust analysis, one of the requirements is that all input data meets the minimum quality standards at the appropriate spatial scale (Grassini et al., 2015a). Given the known data limitations in SSA, our assessment helps in identifying priority data gaps that need attention. In particular actual yield estimates for Kenya are highly uncertain, since they are based on only one year data, obtained from SPAM 2005 (You et al., 2014a,b), as national statistical data were not available. Second, while parameterization of the phenological parameters of the SSM-legumes model resulted in good reproduction of observed phenology and spatial yield variation as reported by local agronomists, model evaluation based on experiments was challenging. Our review of the existing literature indicated a very few experiments carried out under (rainfed) potential conditions for legumes crops in E-Afr (Tesfaye et al., 2006). There was also very little information in the literature on potential water use efficiency of legume crops (except for soybean) in SSA and elsewhere. Our results presented in Fig. 4 should therefore be seen as a first attempt to benchmark such values. Differences in potential water-use efficiency between our results and those reported in literature (Fig. 4) might be attributable to (i) different evaporative demands, soil evaporation, crop evapotranspiration after flowering, and intensity of water stress around flowering that all affect potential water-use efficiency (Rattalino Edreira et al., 2018), but (ii) also to the fact that we are comparing boundary functions derived from simulations for potential growth under rainfed conditions while data from literature are from field experiments that might have been affected also by other limitations or reducing factors (*i.e.*, deficient nutrition, poor weed management, insect and disease damage). The latter may (partly) explain why we simulated higher water-use efficiencies for chickpea and common bean than found in experiments results reported in the literature; it can however not explain that we found lower potential water-use efficiencies for cowpea and groundnut than reported in literature. Finally, to estimate potential legume yields we assumed sole cropping, despite the substantial but unknown legume area under intercropping (Muthoni Andriatsitohaina et al., 2015). Better data on the shares of legumes grown as sole crop and intercrop (well characterized) will be helpful. Once this is known, it may also be of interest to estimate the consequences of growing legumes as a sole or intercrop (Gou et al., 2017), if the necessary model complexity and experimental data to simulate legume intercropping is available (Probert et al., 1998).

4.2. Scope to increase legume production and achieve self-sufficiency

This paper shows the substantial potential to increase rainfed legume production on existing cropland area in E-Afr. Actual farmers yields were very low (i.e., on average across all crops and countries 0.7 Mg ha^{-1}, equivalent to only 25% of Y_w), with lowest Y_a in Kenya (15% of Y_w), then Tanzania (23% of Y_w), and highest in Ethiopia (41% of Y_w). These findings are consistent with relative yield reported for cereal crops in E-Afr (i.e., on average 26%) (Global Yield Gap Atlas, www.yieldgap.org; Van Ittersum et al., 2016), but substantially lower than relative yields reported for soybean in the USA (ca. 80%; Edreira et al., 2017; Grassini et al., 2015a), Argentina (ca. 70%; Aramburu Merlos et al. 2015), India (ca. 40%; Bhatia et al., 2009, 2008) and chickpea in Iran (ca. 47%; Ahmadi et al., 2014; Soltani et al., 2016).

The inter-annual coefficient of variation (CV) of Y_w was lower for the legumes in E-Afr (i.e., on average 15%) compared with that of legumes in Argentina and India, to chickpea in Iran, and to cereals in E-Afr (respectively, on average 22, 29, 46 and 23%). This suggests that legume crops are relatively interesting crops for strategic investments in E-Afr (Van Oort et al., 2017), as they are relatively secure crops in terms of yield variability due to variation in weather while relatively large yield gains can be made.

Recent research suggests large opportunities for closing the legume Y_g. In particular for common bean there is experimental evidence that improved management increases yields highly (Checa et al., 2006;

Ronner et al., 2017). We showed that this crop is hardly limited by water during the growing season, and a large yield increase may be obtained by alleviating other limiting factors such as nutrients, and biotic stress, e.g. by increasing P fertilizer use and use of inoculants (Rurangwa et al., 2017). There also exists a large potential for closure of cowpea Y_g; also this crop is hardly limited by water during the growing season. This contrasts with pigeonpea and groundnut, which are more water-limited and, consequently, have lower Y_w. Chickpea on the other hand, has the advantage that it can enhance legume production in the dry season without competing for crop area with other major legumes; it has the highest water use efficiency of all crops considered in this study. The increase of common bean production could have major implications for human nutrition in E-Afr, as common bean is the major legume crop in the region (Katungi et al., 2010). This is especially true for Kenya and to a lesser extent for Tanzania and Ethiopia because of the large area of this crop in Kenya.

Our analysis revealed that in Kenya and Tanzania closure of the exploitable Y_g (80% of Y_w) is needed to fulfil future (2050) legume demand as a result of the expected large population increase and to achieve self-sufficiency. In contrast, intensification of legume production is not enough to obtain self-sufficiency on existing cropland in Ethiopia. This finding is clearly different than that for cereal crops as reported by (van Ittersum et al., 2016), who found that closure of the exploitable Y_g for cereal crops would lead to cereal self-sufficiency in Ethiopia, and not in Kenya and Tanzania (Fig. 5c). Obviously, legume areas are currently only small in Ethiopia. The relatively favourable potentials to achieve cereal self-sufficiency in Ethiopia (van Ittersum et al., 2016) suggest there may be scope to increase the legume areas in this country, either at the expense of cereals or combined with cereal in intercropping systems.

5. Conclusions

To our knowledge, this is the first assessment of yield gaps of the main grain legume crops in East sub-Saharan Africa. Results reveal substantial legume yield gaps, i.e., largest in Kenya, then Tanzania and finally Ethiopia. There is thus large room for improvement of legume production on existing cropland, in particular for common bean. Furthermore, it was shown that closing the exploitable legume yield gaps on existing cropland is necessary to fulfil the future (2050) legume demand, which is projected to increase a lot due to the expected large population growth and increased per capita consumption. Self-sufficiency may be achievable in both Kenya and Tanzania through yield gap closure on existing cropland, but in Ethiopia yield gap closure on existing cropland alone would not be enough to obtain legume self-sufficiency by 2050.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2018.09.004.

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