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Quantifying Yield Potential and Yield Gaps of Faba Bean in Ethiopia

Wondafrash Mulugeta[1], Kindie Tesfaye[2], Mezegebu Getnet[3], Seid Ahmed[4], Amsalu Nebiyu[1], and Fasil Mekuanint[5]

[1]*Jimma University College of Agriculture and Veterinary Medicine (JUCAVM) Jimma, Ethiopia.*
[2]*International Wheat and Maize Research Center (CIMMYT), Addis Ababa, Ethiopia*
[3] *International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), Addis Ababa, Ethiopia*
[4] *International Centre for Agricultural Research in Dry Areas (ICARDA), Rabat, Morocco.*
[5] *Ethiopian Institute of Agricultural Research (EIAR)*

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ኢትዮጵያ ባቄላ በዓለም አቀፍ ደረጃ በዋናነት ከሚመረትበቻው አገሮች አንዶ ናት። ነገር ግን የባቄላ ምርታማነትን በአገር አቀፍ ደረጃ በአማካይ በሄክታር ከ 2 ቶን አይበልጥም። ለዚህም ዝቅተኛ የዝራያዎች ምርታማነት ፣ ኋላ ቀር የሰብል ጥበቃና አያያዝ ፣ እንዲሁም የአፈር ለምነት መቀነስ እንደ ምክንያት ይጠቀሳሉ ። የዚህ ምርምር ጥናት ዓላማ የሰብል ዕድገት ሞዴልን በመጠቀም የባቄላን ከፍተኛ ምርታማነትን ካለምንም ማነቆዎች እና በዝናብ ዕጥረት ሁኔታ ያለውን ምርታማነት በመለየት ከአርሶ አደሩ ምርታማነት ጋር ያለውን ከፍተት ማወቅ ነው ። ለዚህም በኢትዮጵያ ሁኔታ ተስማሚነቱ የተሞከረ Decision Support System for Agrotechnology Transfer(DSSAT)- CROPGRO-faba bean የተባለውን ሞዴል ተጠቅመናል። ይህም ከመሥክ በተገኘ መረጃ በንፅፅርና በማረጋገጥ ስሌት የተደገፈ ሲሆን የአርሶ አደሩን ምርታማነት ከተፃፉ መዛግብት ወስደናል። የጥናቱ ውጤት እንደሚያሳየው የባቄላ ምርታማነት ካለምንም ማነቆዎችና በዝናብ ዕጥረት ሁኔታ የምርታማነት ከፍተት በዋና ባቄላ አምራች ዞኖች ከፍተኛ ነው። በአሁኑ ወቅት በዋና ባቄላ አምራች ዞኖች የሚገኙ አርሶ አደሮች በዝናብ ዕጥረት ሁኔታ ከሚገኘው ምርታማነት በ40 % ያነሰ ምርት ያገኛሉ። የምርምር ጥናቱ ግኝት እንደሚያመለክተው ከፍተኛ ዝናብ የሚያገኙ ቦታዎች ከፍተኛ የምርታማነት ከፍተት ያሳያሉ ።በተጨማሪ የምርታማነት ከፍተት ደረጃ ምርታማነት አቅምን ለመለየት በምንጠቀምባቸው ዝርያዎች ዓይነት ይወሰናል። በአጠቃላይ የጥናቱ ግኝት እንደሚያመለክተው የሰብል አያያዝን ትክክለኛና ወቅቱን የጠበቀ የሰብል ጥበቃ በሥራ ላይ በማዋል የባቄላ ምርታማነት ከ 100-300 % መጨመር ይቻላል።

Abstract

Ethiopia is one of the major faba bean growing countries in the world but with a low average national yield (≤ 2 t ha^{-1}) compared to yield levels in other countries. The objective of this study was to determine potential yield (Yp), water-limited potential yield (Yw) and yield gaps (Yg) of faba bean across the faba bean growing regions of Ethiopia. Potential yields were obtained from simulation of crop growth using the CROPGRO-faba bean model, which was calibrated and evaluated using field experiment data while faba bean actual yields were obtained from a secondary source. Results show that both Yp and Yw and respective yield gaps were very high across the major faba bean growing zones in Ethiopia. Farmers are currently getting less than 40% of the water limited yield penitential of faba bean in all major growing areas. Findings of this study show that areas located in the high rainfall areas constitute the highest faba bean yield gap. It is also found that the level of yield gap could vary depending on the type of crop varieties used in the estimation of potential yields. The results indicated the possibility of increasing faba bean yield by 100 - 300% to achieve attainable yields through the application of precision agronomy and appropriate and timely crop protection measures.

Introduction

Ethiopia is one of the major faba bean (*Vicia faba* L.) producing countries in the world (FAO, 2015). It is the fourth largest faba bean exporting country next to France, Australia, and the United Kingdom (FAO, 2016). Faba bean takes the largest share of area (443,966 ha) and production (848655 tones) of the pulses grown in Ethiopia (CSA, 2015). Faba bean plays a key role in improving food and feed security of smallholder farmers and soil fertility. The crop usually grows in Nitisol and Vertisol dominated areas of Ethiopia mixed with cereals and field peas. The average national yield of faba bean is about 2.1 t ha^{-1} (CSA, 2018) which is very low compared to the average yield of 3.7 t ha^{-1} in major producer countries (FAOSTAT, 2017).

The major factors that are usually mentioned for the low yield of faba bean in Ethiopia include climatic, edaphic, biotic (diseases, pests and weeds) factors, and poor agronomic practices. On the other hand, the on- farm average yield of released faba bean varieties reaches up to 3.5 t ha^{-1} (National Planning Commission, 2016) indicating the existence of considerable yield gap between farmer managed and researcher managed plots.

Moreover, there is a need to qualify the potential yield of faba bean under different conditions in order to estimate the magnitude of the exploitable gap for designing policies that can help improve productivity and ensure closing of yield gaps and thereby contribute to food security (Cassman et al., 2003). According to the production–ecological approach (Van Ittersum and Rabbinge, 1997), there are three yield levels of crop yield, namely, potential (Yp), water limited (Yw) and actual yields (Ya) that explains potential, water limited and actual production levels as function of yield defining, yield limiting and yield reducing factors, respectively. Yp is a theoretical yield obtained under yield defining factors (radiation, temperature, carbon dioxide and crop characteristics) of a given physical environment where water and nutrients are supplied optimally, and pests and diseases are fully controlled. Yw is defined as the maximum yield that can be obtained from a crop cultivar in a specific rainfed location without any nutritional and biotic limitations (van Ittersum et al., 2013). Both Yp and Yw are estimated for optimum or recommended sowing dates, planting density and variety (Van Ittersum et al., 2013). Ya is determined by the degree to which a crop is exposed to yield reducing factors (weeds, diseases and pests) together with the effects from yield defining and yield limiting factors. Thus, Ya is influenced by the actual climatic, soil and biotic factors and crop management practices and it represents the average yield obtained by farmers. There is no quantified information that gives the different yield levels and associated yield gaps of faba bean in Ethiopia. Therefore, the objective of this study was to quantify the yield potential and yield gaps of faba bean across the major growing areas using a calibrated and evaluated crop model for Ethiopian conditions.

Materials and Methods

The study areas

Seventeen major faba bean-producing areas were selected in three regions for this study (Table 1). The sites were selected based on representation of major faba bean production areas and availability of long-term good quality weather and soil data. The sites have an altitude range of 1800 and 3000 meters above sea level with annual rainfall ranging between 700 to 1550 mm. The sites also have different monthly distribution (Fig. 1).

Table1. Location and climate conditions of faba bean growing sites used for the study

Region	Zone	Site	Latitude (N)	Longitude (E)	Altitude (m)	Annual rainfall (mm)	T min (^{0}C)	T max (^{0}C)	Soil type
Amhara	North Gondar	Debark	13.156	37.883	2706	728	16	29	Vertisols
	North Wollo	Sirinka	11.750	39.050	1850	963	10	23	Vertisols
	South Gondar	Debre Tabor	11.850	38.017	2706	1118	16	28	Nitisols
		Nefas Mewcha	11.733	38.467	3000	1187	8	20	Nitisols
	West Gojam	Adet	11.276	37.492	2240	1251	11	24	Nitisols
		Gergera	11.167	37.667	2650	1027	12	24	Nitisols
	Waghimra	Sekota	12.631	39.035	1850	747	8	20	Nitisols
Oromiya	Arsi	Bekoji	7.544	39.256	2780	1020	9	22	Nitisols
		Meraro	7.408	39.249	2940	993	8	22	Nitisols
		Kulumsa	8.019	39.153	2200	799	12	26	Nitisols
		Arsi-Robe	7.884	39.628	2420	1059	11	24	Vertisols
	Bale	Agarfa	7.283	39.817	2550	1046	7	22	Vertisols
		Gasera	7.367	40.300	2320	1062	11	25	Vertisols
		Sinana	7.143	40.350	2400	1009	14	27	Nitisols
	Southwest Shewa	Adadi	8.633	38.013	2383	1105	10	23	Nitisols
	West Arsi	Kofle	7.074	38.795	2660	1330	9	23	Vertisols
	West Shewa	Ambo	8.966	37.859	2130	1170	10	25	Vertisols
		Ginchi	9.033	38.150	2200	1221	9	21	Vertisols
		Kuyu	9.800	38.400	2400	1468	9	21	Vertisols
		Holetta	9.070	38.496	2400	1045	8	21	Nitisols
SNNP	Gedio	Bulle	6.300	38.417	2860	1478	10	24	Nitisols
	Hadiya	Hosena	7.568	37.856	2306	1028	11	25	Nitisols
	Kembata Tembaro	Angacha	7.333	37.850	2381	1077	11	26	Nitisols
	Wolayta	Kokate	6.822	37.749	2161	1552	9	23	Nitisols

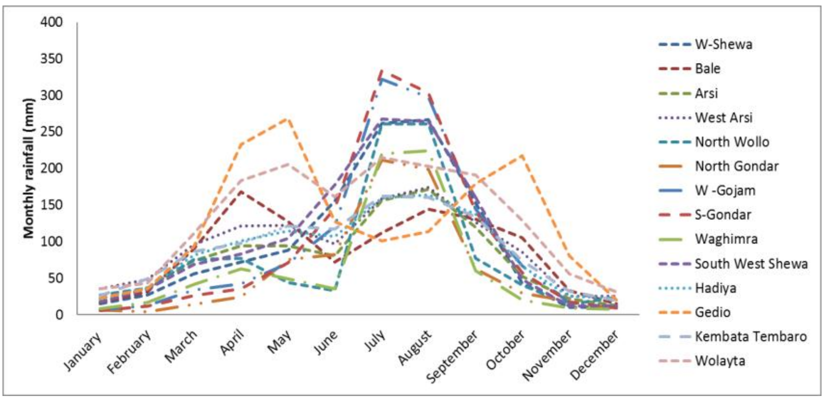

Figure 1 Monthly distribution of rainfall in representative stations of faba bean production zones.

Data collection

Daily weather and soil data

Daily weather data of maximum and minimum temperatures and rainfall for the period 1980 to 2009 were obtained from National Meteorological Agency of Ethiopia for the selected sites. Daily solar radiation was taken from the National Aeronautics and Space Administration for Climatology Resource for Agro-climatology (NASA POWER) (Stackhouse, 2010, http://power.larc.nasa.gov). Soil profile data were obtained from secondary sources (Mesfin, 1998; Tolosa, 2006; Sahlemedhin and Abayneh, 2003) for sites used for model parametrization (Table 2), and from the Africa Soil Profiles Database (Leenaars, 2012) for the rest of the sites studied.

Crop data

Crop phenological and yield data for model calibration and evaluation were obtained from field experiments conducted at four sites (see Table 2) during the Meher seasons of 2014/15 and 2015/16. Two improved faba bean cultivars, namely, Gora (EH91026-8-2 X BPL44-1), and Gebelcho (ILB4726 X 75TA26026-1-2) were planted at Holeta and Kulumsa on Nitisols while Dagem (Grar Jarso 89-8) and Walki (ILB4726 X 75TA26026-1-2) were planted at Ambo and Kuyu on Vertisols. The varieties were grown in a plot size of 100 m^2 (10 m x 10 m) using 30 cm spacing between rows and 10 cm spacing between plants. The experiment at Holetta was repeated in the small rainy season (February-April) under supplemental irrigation. The experiments were managed under optimum management practices to avoid stresses from nutrients, weeds, insect pests, and diseases. The minimum crop data set required for model calibration and evaluation (phenology, dry biomass at regular intervals until harvest, yield components, and yield at harvest) were collected following standard breeding trails sampling methods for the crop.

Modeling Faba Bean

Model description

The cropping system model (CSM) used for this study was the CROPGRO-faba bean model (Boote et al., 2002), which is embedded in the Decision Support System for Agro-technology Transfer (DSSAT), Version 4.6 (Hoogenboom et al., 2015). The CSM-CROPGRO-Faba bean model simulates phenological development, leaf development and senescence, dry matter production and partitioning, plant nitrogen balance, yield formation and soil water balance. Responses of crop processes to environmental factors of solar radiation, photoperiod, temperature, nitrogen and water availability, and genotype differences were included in the model. The model uses a daily time step and readily available weather and soil information, and it has been tested in different environments (Hassanein et al., 2007; Dallacort et al., 2011).

Model calibration and validation

The CROPGRO-faba bean model was calibrated and validated using data collected from the field experiments two soil types (Nitisols and Vertisols) mentioned above. First season experimental data were used for model calibration while the second season data were used for model evaluation. The genotype coefficient calculator (GenCalc) of DSSAT-CSM version 4.6 (Hoogenboom et al., 2015) was used in the first estimation of variety coefficients needed for the model. Then the cultivar coefficients were adjusted estimated iteratively until a close match between simulated and observed phenology, growth, and yield was obtained for the four cultivars studied.

Table. 2 Example of soil profile data used for model input at representative sites

Depth (cm)	DUL* (cm^3)	LL (cm^3)	SAT (cm^3)	pH (H_2O)	BD (g/m^3)	CEC (mol/kg)	K (ppm)	P (ppm)
Ambo								
13	0.189	0.092	0.468	6.2	1.36	1.0	15	0.96
45	0.148	0.077	0.477	6.5	1.33	0.56	14.2	0.97
78	0.163	0.084	0.48	6.8	1.37	0.29	11.7	1.03
110	0.177	0.088	0.483	6.8	1.48	0.15	13.6	1.18
153	0.157	0.085	0.46	7.1	1.56	0.07	9.8	1.25
187	0.155	0.109	0.474	7.2	1.59	0.03	10.7	1.48
200	0.155	0.109	0.471	7.1	1.52	0.024	12.2	1.47
Holetta								
20	0.339	0.13	0.45	5.4	1.36	0.82	29.9	328
40	0.347	0.13	0.45	6	1.6	0.55	31.4	250
80	0.345	0.13	0.44	6	1.26	0.30	25	438
120	0.332	0.13	0.43	6.0	1.26	0.07	24.7	344
Kulumsa								
25	0.409	0.20	0.52	5.9	1.16	0.79	31.4	2.03
45	0.426	0.22	0.53	6.4	1.15	0.50	32.6	1.41
70	0.469	0.26	0.54	6.4	1.13	0.32	37.4	1.38
115	0.529	0.31	0.55	7.0	1.10	0.16	39.0	1.56
145	0.529	0.31	0.55	7.4	1.10	0.07	39.2	1.69
185	0.369	0.17	0.51	7.8	1.19	0.04	46.6	2.19
Kuyu								
17	0.438	0.137	0.518	5.3	1.28	0.84	52.3	1.04
41	0.459	0.349	0.533	5.7	1.24	0.55	64.2	1.07
94	0.458	0.349	0.538	6.3	1.23	0.26	65.9	1.03
129	0.46	0.349	0.531	6.9	1.24	0.12	70.4	0.10
188	0.457	0.457	0.542	6.5	1.21	0.042	72.8	1.06

** DUL = drained upper limit; LL = drained lower limit; SAT = water level at soil saturation; BD = bulk density; CEC = cation exchange capacity; K = potassium; P = phosphors*

Statistical indicators such as root mean square error (RMSE), normalized root mean square error (NRMSE), Willmott's index of agreement (d) were used to evaluate model performance. The indices were calculated from simulated and observed variables using the following formulae:

$$RMSE = \frac{\sum_{i=1}^{n}(\sqrt{(Pi - Oi)^2}}{\text{N}} \quad \text{...} \quad \text{Eq. (1)}$$

Where n is the total number of observations, P_i is the predicted value for the i^{-th} measurement and O_i is the observed value for the i^{-th} measurement.

Where R MSE = root mean square of error and $\overline{O}$ = the mean of observed values

$$d = 1 - \frac{\sum_{j=1}^{n}(Pi-Oi)^2)}{\sum_{j=1}^{n}(|P'i|+|O'i|)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. (2)}$$

where n is the total number of observations, Pi is the predicted value for the i^{-th} measurement, and Oi is the observed value for the i^{-th} measurement, P'i = Pi-Ō and O'I = Oi- Ō.

Sources of yield data for yield gap analysis

Crop models are considered as the most reliable way to estimate Yp and Yw as they account for variation in weather, soil, crop and management and their interactions (van Ittersum et al., 2013). Therefore, the faba bean potential yields (Yp and Yw) at representative sites (Table 1) in the different administrative zones in the major faba bean growing areas were estimated using the calibrated and evaluated CROPGRO-Faba bean model for the period 2000-2009 using crop management data summarized in Table and soil and weather input data mentioned in the sections above.

Table.3. Crop management practices used for simulating faba bean yield at representative sites in major faba bean-growing areas

Factor	Level
Varieties	Gora°, Gebelcho°, Dagem• and Walki
Plant density (plants ha^{-1})	35000
Sowing window	20 June - 30 July
Nitrogen fertilizer rate (kg ha^{-1})	18
Soil type	Nitosol and Vertisol
Nitisol sites	Adadi , Adet, Angacha, Bekoji, Bule, Debre Tabor, Gergera, Holetta ,Hosaena, Kokate ,Kulumsa, Meraro, Nefas Mewcha ,Sekota ,Sinana
Vertisol sites	Agarfa, Ambo, Arsi-Robe , Debark ,Gasera,Ginchi, Kofle ,Kuyu, Sirinka

°Variety released for Nitosols; •variety released for Vertisols

Zonal level Ya data, which was assumed to represent farmer's average yield for the major faba bean growing areas, was obtained from the Central Statistical Agency of Ethiopia for the period 2000-2009 (data available at http://www.csa.gov.et/survey-report/category/26-agricultural-sample-survey).

Yield gap analysis

Yield gaps were estimated as the difference of Yp and Yw with that of Ya as follows:

Yield gaps based on potential yield (Ygp) = Yp – Ya ………… Eq. (3)

Yield gaps based on water limited yield (Ygw) = Yw – Ya ….. Eq. (4)

Since faba bean is solely grown under rainfed conditions in Ethiopia, additional analyses on yield gap were made based on Yw. Accordingly, relative yield (Yra), which shows how the farmers yield are close or far from Yw was calculated as follows:

$$Yra = Ya/Yw \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Eq. (5)}$$

The Yw relative yield in relation to Yp (Yrw) was calculated to estimate the magnitude of water limitation to faba bean production as indicated below

$$Yrw = Yw/Yp \times 100 \qquad \text{Eq. (6)}$$

Moreover, the water limitation index was calculated as follows

$$Yli = ((1-(Yw/Yp)) \times 100 \qquad \text{Eq. (7)}$$

Yield increase if farmers can reach 80% of water-limited potential yield of their locations was also calculated. The limit of 80% is based on Lobell et al. (2009) and van Ittersum et al. (2013) as closing 100% of Ygw is neither possible nor cost-effective because of the fact that perfection of soil and crop management by all farmers is difficult to achieve. Based on this, the yield increase or attainable yield gap (Yga) was calculated as indicated below

$$Y_{inc} = [(0.8*Yw)/Ya) - 1]*100 \qquad \text{Eq. (8)}$$

Results and Discussion

Model calibration and evaluation

The cultivar coefficients estimated through the calibration process for four faba bean variety studied are presented in Table 4. The genetic coefficients were sensitive enough to capture the differences among varieties. The cultivars specifically differ in the period between plant emergence and flower appearance (R1). The statistical indices used to measure model performance during calibration for days to flowering, days to maturity and grain yield show a good agreement between the measured and simulated values (Fig. 2a). The performance of the calibrated model was also evaluated against the independent data set of experiments carried out in 2015 crop season. The Model evaluation indicated a good agreement between measured and simulated days to flowering (RMSE = 4 days; d = 0.92), maturity (RMSE = 7 days; d =0.93), and grain yield (RMSE=0.6 t ha^{-1}; d = 0.8), (Fig. 2b). The simulated yield varied from 2.1 to 4.4 t/ha, whereas the observed yield varied from 2.2 to 4.1 t/ha. The performance of the CROPGRO–faba bean legume model in the current study is similar to the one reported for CROPGR- chickpea and CROPGRO-dry bean in Ethiopia (Tesfaye and Walker, 2006) indicating the ability of the model in simulating the phenology and yield of legume crops in Ethiopia.

Table 4. Cultivar coefficients of the four faba bean cultivars

Trait	Abbreviation	Unit	Cultivar			
			Gora	Gebelcho	Dagem	Walki
Critical short day length below which reproductive development progresses with no day length effect	CSDL	h	24	24	24	24
Slope of the relative response of development to photoperiod with time (positive for short day plants)	PPSEN	h	-0.31	-0.31	-0.31	-0.31
Development parameters						
Time between plant emergence and flower appearance (R1)	EM-FL	PT	18.5	19.5	21.5	24.5
Time between first flower and first pod (R3)	FL-SH	PT	10.9	11.5	11.5	11.5
Time between first flower and first seed (R5)	FL-SD	PT	21	22	21	23
Time between first seed (R5) and physiological maturity (R7)	SD-PM	PT	34.5	35.5	43	38.5
Time between first flower (R1) and end of leaf expansion	FL-LF	PT	46	48	46.5	47
Growth parameters						
Maximum leaf photosynthesis rate at 30 8C, 350 vpm CO_2, and high light	LFMAX	mg CO_2/m^2s^{-1})	0.65	0.7	0.6	0.55
Specific leaf area of cultivar under standard growth conditions	SLAVR	Cm^2/g	280	285	285	335
Maximum size of full leaf	SIZLF	Cm^2	135	135	115	135
Maximum fraction of daily growth that is partitioned to seed shell	XFRT	-	0.6	0.6	0.6	0.6
Maximum weight per seed	WTPSD	g	0.70	0.8	0.4	0.7
Seed filling duration for pod cohort at standard growth conditions	SFDUR	PT	21.0	20.5	22.5	20.8
Average seed per pod under standard growing conditions	SDPDV	seeds/pod	2.5	2.6	2	2.6
Time required for cultivar to reach final pod load under optimal conditions	PODUR	PT	20	20	22	20
Maximum shelling percentage [seed 100%/ (seed/pod)] at maturity (THRESH) (%)	THRSH	Threshing (%)	70	75	65	75.3
Fraction protein in seeds	SDPRO	g(protein)/g (seed)	0.315	0.315	0.315	0.315
Fraction oil in seeds	SDLIP	g(oil)/g(seed)	0.02	0.02	0.02	0.02

PT= Photo thermal days

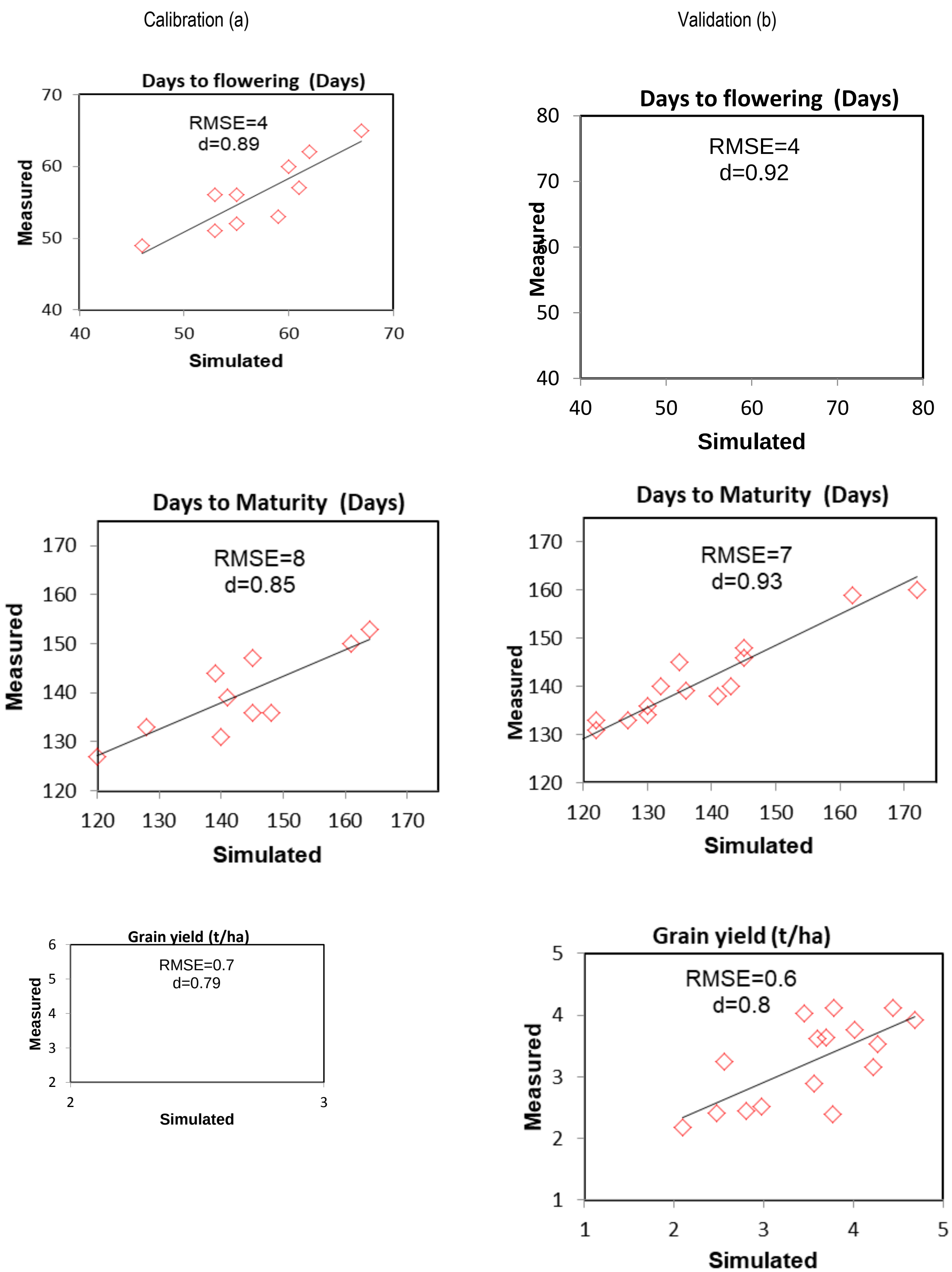

Figure 2. Relationship between measured and simulated number of days to flowering, days to physiological maturity and grain yield (t/ha) during the calibration phase (a) and validation phase (b) RMSE= root means square error, d= index of agreement

Actual, potential and water limited potential yields

The actual faba bean yield (Ya) was generally very low in the major growing zones of Ethiopia (Table 5). The zonal level actual yield ranged from 0.8 t ha^{-1} in Wolayta zone to 1.5 t ha^{-1} in Arsi zone with an average yield of 1.2 t ha^{-1} across zones (Table 5). Annual Ya variability was very high (>20%) in Wolayta, Gedio, West Shewa, Kembata Tembaro, Hadiya, and North Gondar zones while it was relatively low (< 20%) in Bale, Arsi, North Wollo, South Gondar, Southwest Showa, West Arsi and Waghimra zones (Table 5). There was a high (21%) spatial variability of Ya across the major faba bean growing zones.

The average potential yield (Yp) varied from 4.0 t ha^{-1} in North Gonder to 4.7 t ha^{-1} in Southwest Shewa and West Gojam zones with an average of 4.4 t ha^{-1} across zones (Table 5). As expected, there was small spatial (4%) and temporal variability (<6%) of Yp in the major faba bean growing areas of Ethiopia indicating the similarity of defining factors (climatic conditions) across the faba bean growing areas in the country.

The water limited yield potential ranged from 2 .6 t ha^{-1} in Waghimra zone to 4 .6 t ha^{-1} in West Showa zone with an average value of 3.9 t ha^{-1} across zones (Table 3). The temporal Yw variability was in the range of 3 - 22% with the highest variability in Waghmira zone followed by Southwest Showa (Table 5). Most zones have Yw of above 4 t ha^{-1} except North and South Gondar, Southwest Shewa and Waghimra.

Table 5. Mean absolute potential, water limited and actual yields (t ha^{-1}) of faba bean with SD and CV in major growing zones in Ethiopia

Zone	Potential yield (Yp)			Water-limited yield (Yw)			Actual yield (Ya)		
	Mean	SD	CV (%)	Yw	SD	CV (%)	Mean	SD	CV (%)
Arsi	4.5	0.16	4	4.0	0.34	9	1.5	0.26	18
Bale	4.2	0.13	3	4.2	0.12	3	1.3	0.19	14
Gedio	4.4	0.15	3	4.3	0.13	3	1.1	0.30	28
Hadiya	4.5	0.25	5	4.4	0.22	5	1.3	0.28	21
K. Tembaro	4.5	0.27	6	4.4	0.23	5	1.1	0.26	24
N. Gondar	4.0	0.15	4	3.8	0.11	3	1.1	0.22	21
N. Wollo	4.3	0.21	5	4.1	0.19	5	1.2	0.16	13
S. Gondar	4.3	0.15	4	3.0	0.42	14	1.1	0.21	19
SW. Shewa	4.6	0.24	5	3.3	0.68	20	1.3	0.24	18
W. Gojam	4.6	0.22	5	4.2	0.15	4	1.1	0.22	20
Waghimra	4.5	0.23	5	2.6	0.55	22	1.4	0.27	19
W. Arsi	4.5	0.18	4	4.2	0.30	7	1.2	0.21	17
W. Shewa	4.7	0.19	4	4.6	0.17	4	1.5	0.38	26
Wolaita	4.4	0.25	6	4.3	0.24	6	0.8	0.29	36
Average	**4.4**		**4**	**3.9**		**8**	**1.2**		**21**

Calculated relative yields indicated that Yw comprised more than 90% of the Yp for most sites except South Gondar, Southwest Shewa, and Waghmira (Table 6). This is also supported by the calculated water-limitation index whereby Waghimra, South Gondar, and Southwest Shewa had higher (28 - 44%) water limitation index. A higher index indicates a higher risk of water limitation (Salto, et al., 2017). On the other hand, Bale.

Gedio, Hadiya, Kembata Tembaro, North Gondar, North Wollo, West Shewa and Wolita zones had lower (<5%) water limitation index while West Gojam and West Arsi had intermediate level of the index (Table 6).

The average water limitation index across locations is 11% indicating that water is not a major limitation for faba bean productivity in most growing areas. This is because faba bean is grown during the main season and it is mostly planted after full onset of the rains (e.g., Degago, 2000) so that the crop did not experience extended dry spells after establishment (Fig. 1).

Table 6. Relative yields, water limitation index and yield increase required to achieve 80% of the water-limited yield of faba bean in major growing zones in Ethiopia

Zone	Yw/Yp (%)	Ya/Yw (%)	Water limitation index	Yield increase with 80% water-limited yield gap closure (%)
Arsi	89	37	11	117
Bale	98	31	2	156
Gedio	98	26	2	213
Hadiya	96	31	4	161
Kembata Tembaro	97	25	3	221
N. Gondar	96	28	4	187
N. Wollo	97	30	3	169
S. Gondar	70	37	30	118
SW. Shewa	72	39	28	103
W. Gojam	92	26	8	208
Waghimra	56	56	44	44
W. Arsi	93	29	7	177
W. Shewa	99	33	1	145
Wolaita	98	19	2	327
Average	89	32	11	168

Potential and water-limited yield gaps

The results indicate that farmers are currently getting less than 40% of the water limited yield potential of faba bean except in Waghimra. The actual yields are between 30-39% of the water limited yields in many of the zones studied (Aris, Bale, Hadiya, North Wello, South Gondar, Southwest Shewa, Waghimra and West Showa) while it ranged between 19-29% in some of the zones (Gedio, Kembata Tembaro, North Gondar, West Gojam, West Arsi and Wolita) (Table 5).

The low actual yields lead to high level of potential and water limited yield gaps across zones (Fig. 3). The potential yield gap ranged between 2.9 t ha^{-1} in North Gondar to 3.6 t ha^{-1} in Wolyita. On the other hand, the water limited yield gap ranged between 1.1 t ha^{-1} in Waghimra to 3.5 t ha^{-}1 in Wolayita (Figure 3).

In some of the faba bean growing zones (Gedio, Kembata Tembaro, West Gojam, West Shewa and Wolayta) the water limited yield gap was very high (> 3 t ha^{-1}) while it was intermediate (1.9 – 2.9 t ha^{-1}) in a few zones (Bale, North, Gonar, North Wollo, South

Gondar and Southwest Shewa). Wide yield gaps suggest that there is a large scope of improving crop yields under rainfed conditions (Lobell et al. 2009; van Ittersum et al. 2013). Waghimra, which had the highest water limitation index (Table 6), had the lowest water limited yield gap (Fig. 3). These results, in general, indicate that in most of the faba bean growing zones water limitation is not a major contributor for the observed huge yield gaps. Therefore, the major faba bean production problems are related to disease and poor agronomic practices (Agegnehu and Yirga, 2009; Agegnehu et al., 2006; Getnet and Yehizbalem, A. 2017), and timely availability of information and inputs (Anderson, et al., 2016). The problem of water limitation, however, is very clear in some the zones such as Waghimra.

The analysis on the increases required to achieve the attainable yield of faba bean showed a yield increase range of 44% in Waghimra to 327% in Wolayita with an average of 168% across zones (Table 6). In most of the zones, the increase required to achieve the attainable yield is in the range of 100-200% indicating a real scope for increasing faba bean yield in the county through identification of major yield limiting factors and designing appropriate interventions. Like the problem in many other crops in Ethiopia (e.g., Schneider and Anderson, 2010), the major constraints for high faba bean productivity include lack of improved high yielding and disease resistant varieties, weeds and abiotic constraints related to poor soil fertility and soil degradation and limited extension services on improved crop management practices of faba bean.

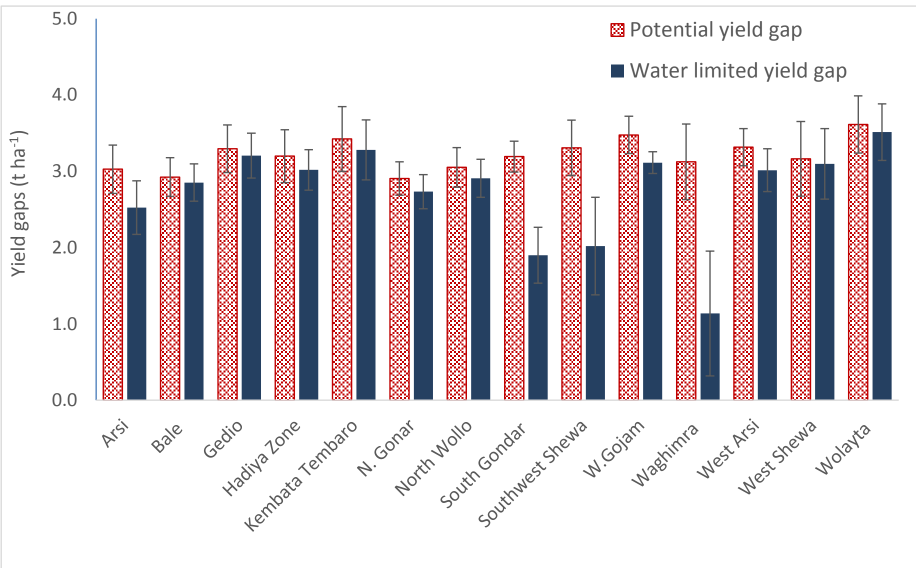

Figure 3. Mean potential and water limited yield gaps of faba bean in major growing zones of Ethiopia. Vertical lines on bars represent standard deviations.

Besides the average yields presented above, water limited yield potential and yield gap using specific varieties is presented in Table 7. Two of the four varieties studied (Gebelcho and Gora) had similar average water limited yield potential (> 4 t ha^{-1}) while

Degem and Walki had a water-limited yield potential of less than 4 t ha^{-1}. Temporal and spatial water limited yield potential variabilities were high for variety Walki but were low for variety Dagem. Average water limited yield gasp were 3 t ha^{-1} for Gora and Walki, 2.7 t ha^{-1} for Gebelcho and 2.2 t ha^{-1} for Degem. The results indicate that the level of yield gaps could vary depending on the type of variety used in the estimation of water limited yield potentials. The variation in water limited yield, which also affects the yield gap may also be affected by the soil type are cultivated on as it influences the amount of water made available for the plant from each rainfall event.

Table 7. Water limited potential yield and water-limited yield gap (t ha^{-1}) and coefficient of variation, CV (%) of four varieties of faba bean in the major growing zones in Ethiopia

Zone	Gora			Gebelcho			Dagem			Walki		
	Mean	CV	Ywg	Mean	CV	Ywg	Mean	CV	Ywg	Mean	CV	Ywg
Arsi	4.2	10	2.8	4.0	6.4	2.5	3.5	5	2.0	4.3	11	2.8
Bale	4.6	3	3.3	4.0	2.8	2.7	3.4	2	2.1	4.6	4	3.3
Gedio	5.0	2	3.9	4.0	3.7	2.9	3.5	3	2.4	4.7	4	3.6
Hadiya	4.8	6	3.5	4.2	4.5	2.9	3.6	5	2.3	4.8	7	3.4
K. Tembaro	4.9	5	3.8	4.1	5.8	3.1	3.6	4	2.5	4.8	7	3.8
N. Gonar	4.0	3	2.9	3.8	3.3	2.7	3.3	3	2.2	4.2	4	3.1
N. Wollo	4.6	5	3.4	4.0	4.4	2.7	3.4	4	2.2	4.6	6	3.3
S. Gondar	2.8	15	1.7	3.0	13.0	1.9	2.8	11	1. 7	2.6	19	1.5
SW. Shewa	3.4	22	2.1	3.5	16.3	2.2	3.2	13	1.8	3.3	26	2.0
W. Gojam	2.5	23	1.4	2.8	18.1	1.7	2.6	16	1.5	2.4	27	1.3
Waghimra	4.4	10	3.0	4.3	4.7	2.9	3.7	3	2.3	4.6	10	3.2
W. Arsi	4.5	4	3.3	4.1	3.4	2.9	3.6	3	2.4	4.5	4	3.3
W. Shewa	4.9	4	3.4	4.4	4.1	2.9	3.8	4	2.3	5.3	5	3.8
Wolayta	5.0	5	4.2	4.1	5.9	3.2	3.5	5	2.7	4.7	7	3.9
Average	**4.3**	**8**	**3.0**	**3.9**	**7**	**2.7**	**3.4**	**6**	**2.2**	**4.2**	**10**	**3.0**

Thus, in the major rainfed faba bean producing zones in the three regions there is a sufficient gap that could be closed by improved management practices in future.

Conclusion

Both potential and water limited yield potentials and respective yield gaps were very high across the major faba bean growing zones in Ethiopia. Farmers are currently getting less than 40% of the water limited yield penitential of faba bean in all major growing areas of Ethiopia. The size of the faba bean water limited yield gap varied across the zones under study although it is clear that zones in higher rainfall areas constitute the highest yield gap indicating scope for increasing yield on these zones through improved agronomic and crop protection interventions. In zones like Waghimra, water is a major limiting factor and yield-increasing interventions need to focus on water harvesting, choice of appropriate planting date and introducing drought tolerant varieties. The level of yield gaps could vary depending on the type of crop varieties used in the estimation of potential yields. The results of this study indicated the possibility of increasing faba bean yield by 100 - 300% to achieve 80% of the water-limited yield potential.

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