Wheat yield gaps in the Ethiopian highlands: Magnitude, drivers and policy implications

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Summary

Wheat yields in Ethiopia need to increase considerably to reduce import dependency and keep up with the expected increase in population growth and dietary changes. Despite the yield progress observed in the past, a large yield gap for wheat remains suggesting yield increases in current cultivated land are possible. The objective of this report is to 1) decompose wheat yield gaps in Ethiopia into efficiency, resource and technology yield gaps and 2) embed those yield gaps within broader farm(ing) systems aspects. For this purpose, stochastic frontier analysis was combined with crop growth modelling and applied to a nationally representative panel dataset covering the Meher seasons of 2009/10 and 2013/14. Wheat yields in farmers' fields averaged 1.7 t ha^{-1}, which corresponds to ca. 20% of the water-limited yield potential (Yw). Most of this yield gap was attributed to the technology yield gap (> 50% Yw) but narrowing the efficiency (ca. 8% Yw) and the resource yield gaps (ca. 15% Yw) can double current actual yields. In general, there was little variation in the relative contribution of efficiency, resource and technology yield gaps to the overall yield gap across agro-ecological zones, administrative regions and farming systems. Finally, we note that trade-offs in resource allocation at farm level are likely to occur as wheat is cultivated alongside other crops and that access to draught power and capital do not clearly translate in greater input use for wheat.

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1 Introduction

Ethiopia is the largest wheat producer in sub-Saharan Africa with a record harvest of 4.6 million metric tons registered in 2017 (FAOSTAT). However, during that same year the country imported 1.5 million tons of wheat, corresponding to around US$600 million. Further increases in demand for wheat (and other cereals) are likely to be observed in the future as a result of population growth and dietary changes (van Ittersum *et al.*, 2016). These drivers have put wheat self-sufficiency high on the agenda in the country, with a new initiative of the Ethiopian government stating the country should become wheat self-sufficient in the coming four years.

Increasing wheat yields in Ethiopia, through narrowing yield gaps, is important to reduce the import dependency for this crop in the years ahead. This needs to occur in a smallholder agriculture setting as wheat is cultivated by approximately 4.7 million smallholder farmers on ca. 1.6 million ha. Currently, wheat is produced mostly under rainfed conditions and with relatively few inputs. Despite the yield progress observed during the past 15 years (ca. 63 kg ha^{-1} yr^{-1}), with wheat yields doubling to values reaching ca. 2.7 t/ha (FAOSTAT), current wheat yields reach only ca. 24% of their water-limited potential (www.yieldgap.org). Understanding the drivers behind this large yield gap is thus important to help prioritizing policies and interventions towards wheat self-sufficiency in Ethiopia.

Wheat yield gaps in West Arsi, one of the wheat belts in Ethiopia, were largely attributed to technology yield gaps (Silva *et al.*, 2019). This means that technologies currently used by farmers do not reach agronomic best practices and that considerably more, and better use of, inputs are needed if yield gaps are to be narrowed (Habte *et al.*, 2014; Tanner *et al.*, 1993). Competition for labour during sowing, weeding and harvesting of wheat were also observed in this region as labour peaks for other cereal and legume crops overlap with labour peaks for wheat. This results in potential trade-offs between crops at farm level and calls for a deeper understanding of the farming system aspects in which wheat is currently cultivated.

The objective of this report is two-fold 1) decompose wheat yield gaps in Ethiopia in order to identify relevant management, technological and policy interventions corresponding to efficiency, resource (economic and allocative) and technology yield gaps and 2) embed those yield gaps within broader farm(ing) systems aspects. This was done using a combination of frontier analysis and crop growth modelling applied to a nationally representative panel dataset collected in the Meher seasons of 2009/10 and 2013/14 (Abro *et al.*, 2017; Shiferaw *et al.*, 2014). Such large and spatially explicit dataset was also used for sub-national analyses of wheat yields and yield gaps so that results are made context-specific as much as possible.

2 Materials and methods

2.1 Farm household survey

The Wheat Adoption and Impact Survey (WAIS) was conducted by International Maize and Wheat Improvement Center (CIMMYT) for the purpose of tracking varietal change and assessing the impact of genetic improvement for wheat in Ethiopia. The survey is a panel of households and was conducted in two rounds covering the growing seasons of 2009/10 and 2013/14. As described by Abro *et al.* (2017), the sampling frame comprised the selection of 148 major wheat growing districts of Ethiopia, followed by a random selection of farmers' associations (communities) within these districts and by a random selection of 15 to 18 households within each farmers' association. This resulted in a sample of ca. 2000 representative farmers (Figure 1).

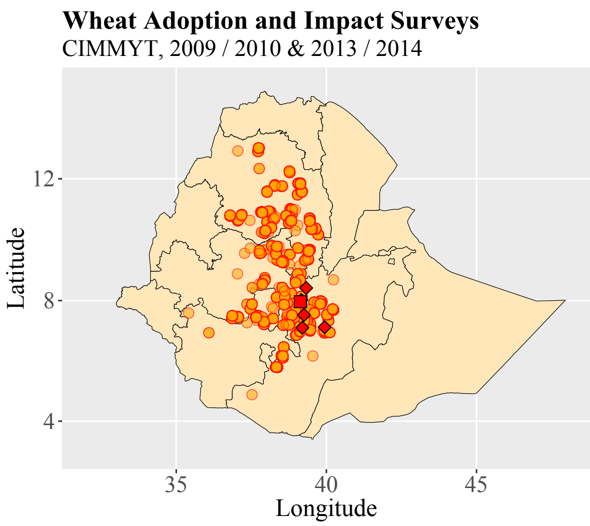

Figure 1. Location of the households (orange circles) interviewed across the Ethiopian highlands during the Meher seasons of 2009 - 2010 and 2013/14. The location of the variety trials (red diamonds) presented by Bezabih *et al.* (2018) and of the case study (red square) documented in Silva *et al.* (2019) are also shown.

The survey includes a wide range of farm and farmer characteristics as well as detailed information on the types and quantities of inputs used and crop yields obtained in all fields of each farm. Descriptive statistics of the data are provided in Table 1 for the administrative zones with more than 100 wheat plots in both survey rounds. The large sample size and national coverage makes this survey suitable for yield gap analysis at national level and to draw comparisons between regions. We focused deeper analyses in West Arsi, North Shoa, East Gojam and South Wollo given their large sample size and homogeneity in terms of agroecological conditions and farming systems (Table 1) but yet different socio-economic conditions (e.g., other crops, land availability).

Table 1. Sample size per administrative region, agro-ecological zone and farming system and mean values of the input-output coefficients for wheat production in the Meher seasons of 2009/10 and 2013/14 across the Ethiopian highlands. Data are presented for regions with more than 100 observations in both survey rounds. Agro-ecological zones were defined as per MoA (1998) and farming systems according to Amede *et al.* (2017). Ya = actual yield, Y_{HF} = highest farmers' yield, Yw = water-limited yield.

	West Arsi	**Arsi**	**North Shoa**	**West Shoa**	**East Shoa**	**Jimma**	**East Gojam**	**North Gonder**	**South Gonder**	**North Wollo**	**South Wollo**	**Hadiya**	**Gurage**	**Other**
Agro-ecology														
Humid highlands (H2)	107	94	0	0	1	85	0	0	0	0	0	0	0	0
Humid sub-afroalpine (H3)	8	61	0	0	0	0	0	0	0	0	0	0	0	0
Sub-humid lowlands (SH1)	0	0	0	0	0	0	0	0	0	0	0	86	0	0
Sub-humid highlands (SH2)	197	0	0	0	82	44	0	0	0	0	0	46	83	49
Moist highlands (M2)	4	120	178	153	0	0	201	73	34	0	102	0	14	171
Moist sub-afroalpine (M3)	0	0	21	0	0	0	14	4	57	0	0	0	0	4
Sub-moist highlands (SM2)	72	3	272	0	108	0	0	0	0	60	375	0	0	0
Sub-moist sub-afroalpine (SM3)	0	0	0	0	0	0	0	0	0	0	83	0	0	0
Other	27	94	0	0	2	0	0	0	0	17	0	0	0	35
Farming system														
Highland mixed	315	367	471	153	103	2	215	77	91	77	560	132	97	259
Highland perennial	20	0	0	0	0	127	0	0	0	0	0	0	0	0
Maize mixed	80	5	0	0	90	0	0	0	0	0	0	0	0	0
Wheat production														
Altitude (x1000 m)	2.37	2.60	2.76	2.63	1.93	2.24	2.53	2.64	2.86	2.90	2.70	2.10	2.20	2.47
Field size (ha)	0.60	0.42	0.35	0.47	0.45	0.30	0.29	0.27	0.24	0.21	0.28	0.39	0.37	0.40
Pairs of oxen (#)	2.41	2.47	1.93	3.67	2.22	1.95	1.58	0.58	0.96	0.79	1.15	1.46	1.79	2.07
Oxen ploughing (days)	14.41	10.54	8.68	10.62	10.65	8.65	9.20	4.83	5.55	4.32	5.43	12.05	10.36	9.76
Seed rate (kg ha^{-1})	207.93	216.08	198.99	155.06	206.95	144.72	187.09	155.42	189.88	171.48	158.73	193.97	163.02	174.97
Nitrogen use (kg N ha^{-1})	23.03	17.91	61.97	46.10	46.19	24.82	56.37	26.42	23.20	30.30	42.43	62.19	42.14	39.50
Phosphorus use (kg P ha^{-1})	18.24	16.50	20.53	14.85	19.80	10.34	18.51	5.38	10.72	6.64	13.17	32.83	17.79	16.74
Herbicide use (L ha^{-1})	0.84	0.77	2.53	0.81	0.46	0.77	0.16	0.02	0.35	0.76	0.01	1.01	0.95	1.11
Hand-weeding (persday ha^{-1})	11.65	12.75	33.15	18.64	17.13	22.65	32.01	46.95	65.86	63.99	58.91	9.90	13.96	14.94
Labour use (persday ha^{-1})	41.44	49.43	82.29	59.20	57.88	77.08	80.43	82.82	102.48	101.04	94.85	59.38	54.68	59.30
Ya (t DM ha^{-1})	2.22	2.23	1.72	1.54	1.82	1.38	1.76	1.16	1.48	1.46	1.20	1.99	1.74	1.40
Y_{HF} (t DM ha^{-1})	4.58	4.37	3.82	3.97	3.73	3.70	3.47	2.78	3.23	3.07	3.21	4.24	3.05	3.54
Yw (t DM ha^{-1})	10.10	10.20	9.79	9.49	8.56	9.44	8.99	9.30	8.66	9.26	9.50	9.02	10.21	9.70

2.2 Yield gap analysis at field level

2.2.1 Concepts and definitions

The yield gap analyses conducted in this paper build upon the frameworks of Silva *et al.* (2017) and van Dijk *et al.* (2017). These frameworks make use of four yield levels to decompose the yield gap between the potential (irrigated conditions) or water-limited yields (rainfed conditions) and the actual yield, as depicted in Figure A1.

The water-limited yield (Yw) refers to the maximum yield that can be obtained under rainfed conditions in a well-defined biophysical environment (van Ittersum *et al.*, 2013). Yw can be simulated using crop growth models or derived from field trials with high levels of nutrients applied and pests, diseases and weeds fully controlled. The highest farmers yields (Y_{HF}) refer to the maximum yields (e.g., average above the 90^{th} percentile of actual farmers' yields) observed in a sample of farmers sharing similar biophysical conditions (weather and soils) and technologies adopted (e.g., varieties). Differently from Y_{HF}, van Dijk *et al.* (2017) considers economic yields (Ye) and feasible yields (Yf): the former refers to yield level in which marginal costs are equal to marginal revenue and the latter refers to the maximum yield that can be reached with available technology and best-practice management but without economic constraints. The technically efficient yields (Y_{TEx}) comprise the maximum yield that can be achieved for a given input level and they can be computed using methods of frontier analysis in combination with concepts of production ecology. Finally, the actual yield (Ya) refers to the yield observed in farmers' fields as often recorded in farm surveys.

Three intermediate yield gaps can be distinguished based on these yield levels. The efficiency yield gap is defined as the difference between Y_{TEx} and Ya and it is explained by crop management imperfections related to time, form and/or space of the inputs applied. The resource yield gap is defined as the difference between Y_{HF} and Y_{TEx} and captures the yield penalty due to a sub-optimal amount of inputs applied. According to van Dijk *et al.* (2017), the resource yield gap can be decomposed into an allocative yield gap ($Ye - Y_{TEx}$) and into an economic yield gap ($Yf - Ye$). The technology yield gap is defined as the difference between Yw and Y_{HF} (Silva *et al.*, 2017) or between Yw and Yf (van Dijk *et al.*, 2017), which can be caused by resource yield gaps of specific inputs and/or the use of technologies in farmers' fields where Yw is not achieved.

2.2.2 Stochastic frontier analysis (Y_{TEx})

Stochastic frontier analysis (SFA) was used to estimate the production frontier and the efficiency yield gap for wheat production in Ethiopia. The estimated models assumed a Cobb-Douglas functional form (i.e., second-order terms not included) to describe the relationship between wheat yield and vector of agronomic relevant inputs. Models with a translog functional form were also fitted but are not presented because the results were consistent across specifications and the Cobb-Douglas model is of easier interpretation. The formulation of the stochastic frontier model and the calculation of the technical-efficient yields (Y_{TEx}) and efficiency yield gaps (EffYg) were as follows (Silva *et al.*, 2017; Battese & Coelli, 1995):

$$ln\, y_{it} = \alpha_0 + \sum_{k}^{K} \beta_k \, ln\, x_{kit} + v_{it} - u_{it} \tag{1}$$

$$v_{it} \sim N(0, \sigma_v^2) \tag{2}$$

$$u_{it} \sim N^+(0, \sigma_u^2) \tag{3}$$

$$\text{EffYg}_{it} = 1 - exp(-u_{it}) \tag{4}$$

$$\text{Y}_{\text{TEx}_{it}} = y_{it} \times exp(-u_{it})^{-1} \tag{5}$$

where y_{it} represents the wheat dry-matter (DM) yield reported in farm i and in year t, x_{kit} is a vector of agronomic inputs k and, α_0 and β_k are parameters to be estimated. The stochastic frontier accounts for two random errors, v_{it} (random noise) and u_{it} (technical inefficiency), which are assumed to be independently distributed from each other and to follow a normal (Equation 2) and half-normal distribution truncated at 0 (Equation 3), respectively - for further details see Battese & Coelli (1995).

The vector of inputs x_{kit} was defined according to principles of production ecology (van Ittersum & Rabbinge, 1997). The growth-defining factors included in the analysis were the growing degrees day and temperature seasonality (both obtained from the climate zonation of van Wart *et al.*, 2013), the year of the survey (2009/10 / 2013/14) and the seed rate and type of variety (improved, landrace, unknown) reported by the farmer during the survey. The growth-limiting factors related to water considered were the aridity index (also from van Wart *et al.*, 2013), soil available water (obtained from the Africa Soil Information Service, AfSIS) and the farmer reported soil depth (deep, medium, shallow), occurrence of water logging (yes / no), occurrence of drought (yes / no), use of water conservation techniques (yes / no) and ploughing frequency (less than three times, three times, four times, more than five times). The growth-limiting factors related to nutrients comprised the farmer reported soil fertility (rich, medium, poor), manure use (yes / no), incorporation of crop residues (yes / no), previous crop type (cereal, legume, other) and N applied (kg N ha^{-1}). A categorical variable was included to differentiate fields with zero N applied from fields with N applied. P applied was not included due to collinearity between this variable and N applied. Finally, the growth-reducing factors included were the farmer reported herbicide use (L ha^{-1}), hand-weeding (person-day ha^{-1}), a categorical variable to distinguished weeded from non-weeded fields, pesticide use (yes / no) and occurrence of pests or diseases (yes / no). Missing data on seed rate were filled with the mean value of the pooled sample. All continuous input-output variables were mean-scaled and ln-transformed prior to the analysis, so that coefficients report elasticities at the mean of the data.

The stochastic frontier model (Equations 1 - 3) was fitted to the pooled sample (national analysis) and to subsets of the data for selected regions (regional analysis for West Arsi, North Shoa, East Gojam and South Wollo) using maximum likelihood, as implemented in the *sfa()* function of the R package *frontier* (Coelli & Henningsen, 2013). Efficiency yield gaps (Equation 4) and technical efficient yields (Equation 5) were derived from the stochastic frontier model fitted to the pooled sample. The same model was also fitted to the pooled sample with ordinary least squares (OLS) with the *lm()* function in R for comparative purposes. For these analyses, the data was used as a cross-section rather than as a panel of households meaning that technological change and time-(in)variant technical inefficiencies were not tested.

2.2.3 Input use across yield percentiles (Y_{HF})

Farmers' fields within a well-defined biophysical environment were categorized into highest-, average- and lowest-yielding based on their actual yields (Silva *et al.*, 2019). Highest-yielding fields were identified as the observations above the 90th percentile of Ya and the highest-farmers' yields (Y_{HF}) were computed as the mean Ya for these fields. Similarly, the lowest-yielding fields were identified as the observations below the 10th percentile of Ya and the average-yielding fields as the observations between the 10th and the 90th percentile of Ya. Average-farmers yields (Y_{AF}) and lowest-farmers yields (Y_{LF}) were estimated as the average Ya for the respective group. The estimation of Y_{HF}, Y_{AF} and Y_{LF} was done for an unique combination of year $\times$ climate zone $\times$ soil fertility. Year refers to the 2009/10 or the 2013/14 survey rounds, the climate zones were obtained from the Global Yield Gap Atlas (van Wart *et al.*, 2013) and the soil fertility was based on farmer judgement.

The comparison of input use across the highest-, average- and lowest-yielding fields provides insights into the resource yield gap. Significant differences across the different field categories were tested with analysis of variance (ANOVA) followed by a Tukey HSD post-hoc test (considering a 5% significance level) for the following variables: wheat yield, seed rate, N applied, total labour use (for land preparation, sowing, hand-weeding and harvesting), labour use for hand-weeding and herbicide use. The analysis were conducted for selected administrative regions in the Ethiopian highlands with the *scipy* and *statsmodels* libraries in python.

2.2.4 Crop modelling and variety trials (Yw)

Water-limited yields of wheat across Ethiopia were simulated with the crop model WOFOST (Boogaard *et al.*, 2014) for the period 2012 - 2017 following the protocols of the Global Yield Gap Atlas (GYGA; Grassini *et al.*, 2015; van Bussel *et al.*, 2015). These are based on a bottom-up approach, in which Yw is estimated within a spatial framework based on local weather, soil and agronomic data.

Daily weather data for 12 weather stations across the country were acquired from the National Meteorology Agency of Ethiopia. All these weather stations had missing data and we were able to use the observed weather data for 8 weather stations only. For the other 4 weather stations gridded weather data was used instead given the large amount of missing data. Missing temperature records were generated using the relation between NASA-POWER and observed data (as described in van Wart *et al.*, 2015), while missing rainfall data were filled based on data from the Tropical Rainfall Measuring Mission (TRMM) of NASA. Gridded soil data on rootable depth and soil water availability were obtained from AfSIS and crop management information were obtained through expert knowledge and literature review (as per www.yieldgap.org/Ethiopia).

The technology yield gap was calculated as the difference between Yw and Y_{HF} for an unique combination of year $\times$ climate zone $\times$ soil fertility class (Section 2.2.3.). The simulated Yw was further compared with wheat yields observed in variety trials conducted in 2016 and 2017 in Debre Zeit, Kulumsa, Bekoji and Dawa Busa (Bezabih *et al.*, 2018). This comparison was done for West Arsi region only to cross-validate the simulated Yw and assess the contribution of possible differences in yield potential of different varieties to the technology yield gap. The contribution of sub-optimal amounts of inputs to the technology yield gap was not assessed in this report but can be done in the future following the methodology of van Dijk *et al.* (2017).

2.2.5 Upscaling yield gaps to higher levels

Wheat yields and yield gaps were averaged across administrative zones, agro-ecologies or farming systems (as per Table 1). The administrative zones were retrieved from the household survey while the other classifications were obtained from secondary sources based on the GPS coordinates of the individual households. The agro-ecological classification used combines temperature, elevation and the length of the growing season for the main crops and was retrieved from the Ministry of Agriculture of Ethiopia (MoA, 1998). The farming system classification combines agro-ecological information with expert knowledge of the main farming systems in Ethiopia as documented by Amede *et al.* (2017).

2.3 Allocation of resources at farm level

2.3.1 Interactions between crops

Wheat cultivation by smallholders in the Ethiopian highlands occurs alongside the cultivation of other crops. This has important implications for the allocation of resources at the farm level and may lead to trade-offs depending on the level of resource constraints faced by individual households. Crop area shares of wheat, other cereals (e.g., barley and tef), pulses (e.g., faba bean, field peas and chickpeas), oilcrops and vegetables were computed to assess the level of specialization in wheat production of each individual household. Resource allocation at farm level was further studied by comparing the number of ploughing days, labour use for weeding and total labour use (incl. land preparation, sowing, hand-weeding and harvesting) for wheat and for other crops within each household. It was not possible to relate the amount of labour used with the time of the different management operations as the dataset lacked information on the latter.

2.3.2 Oxen ownership

The pairs of oxen owned by each household were used to investigate whether wheat production is associated with intensification or extensification pathways (Silva *et al.*, 2019). Four different groups were identified based on this information namely households with no oxen, households with one pair of oxen, households with two pairs of oxen and households with three or more pairs of oxen. Significant differences in wheat yield, resource availability and input use between households owning different pairs of oxen were tested with ANOVA followed by a Tukey HSD post-hoc test, as explained in Section 2.2.3. The variables considered were cultivated wheat area, total labour use for wheat (land preparation, sowing, hand-weeding and harvesting), farm assets as reported by each household (excluding livestock), seed rates, N fertiliser rates, herbicide use and labour use for hand-weeding (all used specifically for wheat production). Group comparisons were conducted for selected administrative regions in the Ethiopian highlands with the *scipy* and *statsmodels* libraries in python.

2.4 Stakeholder workshop in Addis Ababa

Project and stakeholder workshops were organized in ILRI campus between 14^{th} and 18^{th} June 2019. The stakeholder workshop was hosted by a CCAFS funded project on 'Crop Nutrient Gaps'. The aims of the workshop were to present and discuss the size of the sustainable intensification challenge in sub-Saharan Africa and Ethiopia in relation to site-specific nutrient management. Policy makers, private sector and researchers were invited to the workshop where the results described in this report were presented.

3 Results

3.1 Wheat yields and yield gaps in the Ethiopian highlands

3.1.1 Magnitude and spatial variability

Actual farmers' yields of wheat were on average 1.7 t ha^{-1} for the pooled sample, which corresponds to a yield gap closure of 18% Yw, but there were differences across agro-ecologies, administrative zones and farming systems (Figure 2). Yw varied between 8.5 - 9.0 t ha^{-1} in the moist sub-afroalpine areas (M3) of South Gonder and the sub-humid lowlands (SH1) of Hadiya, and ca. 10.0 t ha^{-1} in the humid highlands (H2) and humid sub-afroalpine areas (H3) of West Arsi and Arsi (Figures 2A and 2B). The lowest Ya (less than 1.6 t ha^{-1}) was recorded in the moist and sub-moist agro-ecologies (M2, M3, SM2 and SM3) while the highest Ya (1.8 - 2.2 t ha^{-1}) was recorded in the humid (H2 and H3) and sub-humid agro-ecologies (SH1 and SH2). No major differences in Yw and Ya were observed across farming systems (Figure 2C).

Wheat yield gaps were mostly attributed to the technology yield gap (> 50% Yw) but narrowing efficiency and resource yield gaps can double Ya (Figure 2). This is true for different agro-ecologies, administrative regions or farming systems. The efficiency yield gap was on average 8% Yw and did not differ much between agro-ecologies, administrative regions or farming systems (Figures 2D, 2E and 2F). The resource yield gap was on average 16% Yw and was smallest in the sub-humid and humid highlands (SH2 and H2) and greatest in the sub-humid lowlands and sub-moist agro-ecologies (SH1, SM2 and SM3; Figure 2D). In terms of administrative regions, the resource yield gap was as low as 10% Yw in West Arsi, East Gojam and South Gonder and as large as 20% Yw in N Shoa, W Shoa, Jimma and South Wollo (Figure 2E). A larger resource yield gap (ca. 20 % Yw) was also observed for highland perennial farming systems than for highland or maize mixed farming systems (ca. 15% Yw, Figure 2F). In summary, fine-tuning crop management practices with current farmers' technologies can contribute to considerable increases in Ya but narrowing yield gaps towards Yw requires greater amounts, and more efficient use, of inputs than currently observed in the Ethiopian highlands.

3.1.2 Production frontier and yield variability

The magnitude, sign and significance of the effects of growth-defining, -limiting and -reducing factors on wheat yields were consistent between the OLS and SFA models fitted to the pooled sample (Table 2). Wheat yields decreased with increased growing degrees days, temperature seasonality and aridity index, and there were no significant differences across years. There was a positive significant effect of seed rate on wheat

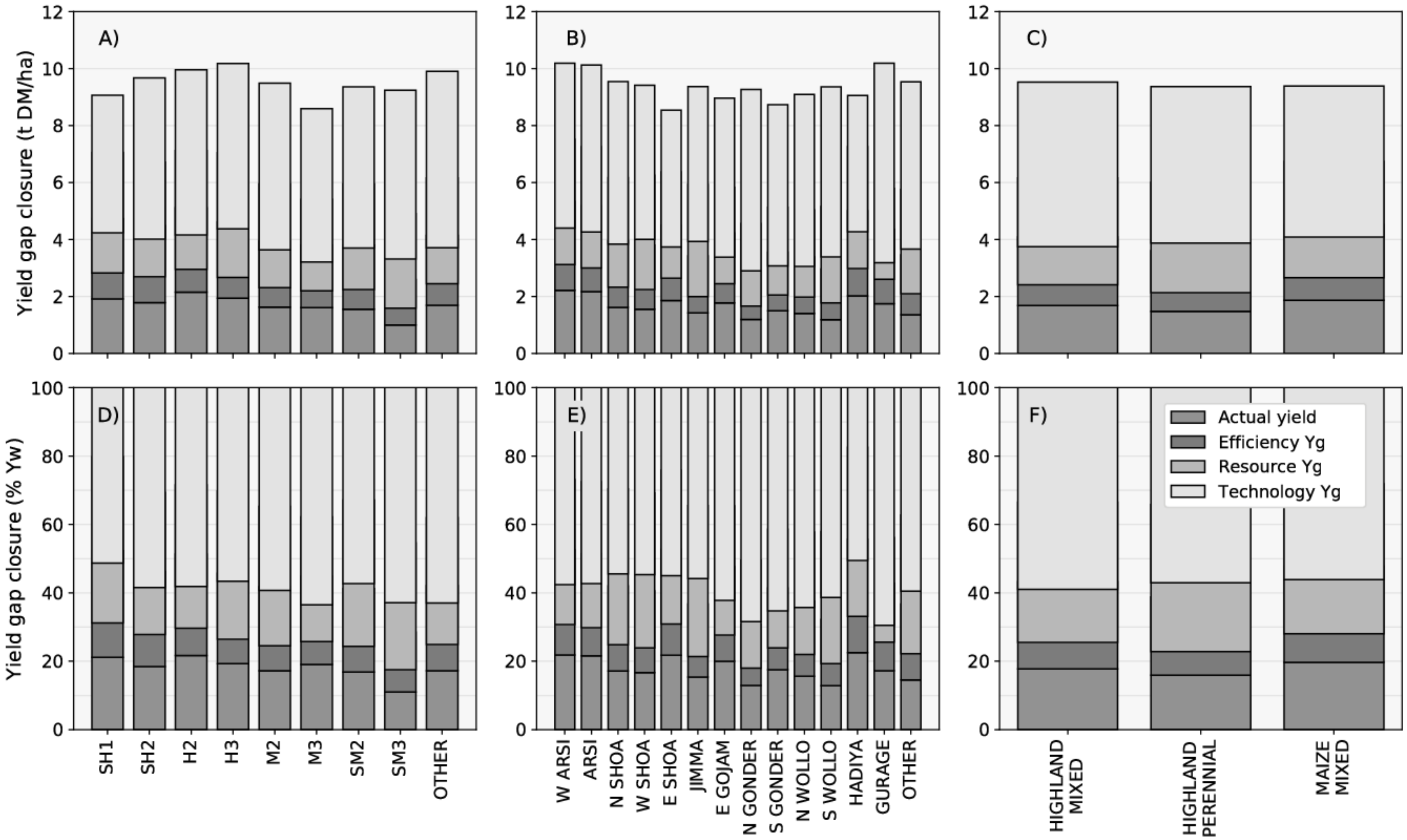

Figure 2. Magnitude and variability of wheat yields and yield gaps in the Ethiopian highlands disaggregated by A, D) agro-ecological zone, B, E) administrative region and C, F) farming system. Panels in the top row show data in absolute terms (t DM ha^{-1}) and panels in the bottom row show data in relative terms (% Yw). Codes: SH1 = 'sub-humid lowlands', SH2 = 'sub-humid highlands', H2 = 'humid highlands', H3 = 'humid sub-afroalpine', M2 = 'moist highlands', M3 = 'moist sub-afroalpine', SM2 = 'sub-moist highlands', SM3 = 'sub-moist sub-afroalpine'.

Table 2. Parameter estimates of the multiple regression (OLS) and stochastic frontier (SFA) models estimated for wheat-based production systems in the Ethiopian highlands (Meher seasons of 2009/10 and 2013/14). The same model was fitted to the pooled sample (Ethiopia) and to selected regions (West Arsi, North Shoa, East Gojam and South Wollo). Significance is indicated by the codes: '***' 0.1% '**' 1% '*' 5% '#' 10%. n.a. = not applicable.

	OLS ETHIOPIA	SFA ETHIOPIA	SFA W ARSI	SFA N SHOA	SFA E GOJAM	SFA S WOLLO
Intercept	0.015	0.488 ***	0.160	-0.058	0.897 **	2.761 ***
2013_Meher	-0.016	-0.032	-0.210 ***	0.132 #	-0.089	0.030
Defining factors						
Growing degrees day	-0.899 ***	-0.892 ***	-0.186	-0.085	-2.487 **	-1.624 **
Temperature seasonality	-0.425 ***	-0.412 ***	-0.562 #	0.504 #	0.466	1.566 ***
Seed rate (kg/ha)	0.147 ***	0.125 ***	-0.027	0.376 ***	0.188 ***	0.268 ***
Variety_Landrace	-0.030	-0.029	-0.054	0.009	0.054	-0.016
Variety_Unknown	0.060	0.069 #	-0.146	-0.303 #	-0.068	0.145
Limiting factors [water]						
Aridity index	-0.517 ***	-0.516 ***	0.062	-0.651	-1.140 #	-0.404
Soil available water	0.010	0.015	0.009	0.248	0.505	0.461 *
Soil depth_Medium	-0.100 ***	-0.102 ***	-0.124 *	-0.080	-0.060	-0.143 **
Soil depth_Shallow	-0.111 ***	-0.107 ***	-0.220 **	-0.051	0.041	-0.133 *
Water logging_Yes	-0.389 ***	-0.365 ***	-0.184	-0.513 ***	0.043	-0.223 ***
Drought_Yes	-0.439 ***	-0.429 ***	-0.622 ***	-0.752 **	-0.458 ***	-0.266 **
Water conservation_Yes	0.025	0.037	0.111 #	0.056	0.051	0.023
Plough frequency_Three	-0.061	-0.076	0.323 #	-0.141	0.079	-0.207 **
Plough frequency_Four	0.020	0.005	0.238	-0.130	0.154	-0.115
Plough frequency_>Five	0.102 *	0.091 #	0.257	-0.133	0.218	0.096
Limiting factors [nutrients]						
Soil fertility_Medium	-0.055 **	-0.063 ***	-0.029	-0.031	-0.215 ***	-0.070
Soil fertility_Poor	-0.165 ***	-0.168 ***	-0.219 *	-0.047	-0.343 ***	-0.140 *
N applied_No	2.988 ***	3.001 ***	3.233 ***	4.886 ***	2.828 ***	2.932 ***
N applied (kg N/ha)	0.247 ***	0.247 ***	0.282 ***	0.390 ***	0.226 ***	0.244 ***
Manure use_Yes	0.074 **	0.074 **	-0.102 #	0.184 **	0.050	0.080
Crop residues_Yes	0.025	0.021	-0.056	0.059	0.092	-0.174 *
Previous crop_Legume	-0.013	-0.004	-0.144 *	0.071	0.127	0.012
Previous crop_Other	0.122 ***	0.124 ***	0.084	0.083	0.048	0.108
Reducing factors						
Herbicide use (L/ha)	0.014 ***	0.014 ***	-0.005	-0.011	0.008	0.025
Hand-weeding (person-day/ha)	-0.002	-0.002	-0.008 *	-0.005	0.003	0.183 ***
Weeding_Yes	-0.029	-0.019	0.373 *	0.028	-0.433 *	-2.410 ***
Pesticide use_Yes	0.102 #	0.092 #	0.191 *	-0.248	0.023	n.a.
Disease occurence_Yes	-0.337 ***	-0.314 ***	-0.429 ***	-0.371 ***	-0.398 ***	-0.352 ***
Pest occurrence_Yes	-0.143 *	-0.134 #	-0.084	0.263	0.121	-0.400 *
Model evaluation						
$\sigma^2 = \sigma_v^2 + \sigma_u^2$	n.a.	0.553 ***	0.455 ***	0.559 ***	0.268 ***	0.505 ***
$\gamma = \sigma_u^2 / \sigma^2$	n.a.	0.645 ***	0.847 ***	0.627 ***	0.694 ***	0.714 ***

yield and increasing the former by 1% resulted in a 0.13% increase of the latter. Plots where water logging or drought were observed by the farmer yielded ca. 40% less than plots where these were not observed, and plots with deeper soils yielded ca. 10% more than plots with medium or shallow soil depths. Frequent ploughing (more than five times) increased wheat yield significantly compared to less than two, three or four ploughings. Wheat yields were greater in plots where no N was applied compared to plots where N was applied, and there was a clear yield response to N: wheat yield increased by ca. 0.25% with an 1% increase in N applied. A small (ca. 7%) positive effect of manure use on wheat yield was also observed and fertile plots yielded ca. 6% and 17% more than medium and poor fertile plots, respectively. Finally, herbicide use was positively associated with wheat yields (elasticity ca. 0.01%) and plots where pests or diseases were reported exhibited significantly lower yields (15 - 30%) than plots where these were not reported.

The same stochastic frontier model was fitted to a subset of the data for the regions West Arsi, North Shoa, East Gojam and South Wollo (Table 2). The results obtained for individual regions were consistent with the results of the national analysis reported above. This was particularly true for the effects of seed rate (only non-significant in West Arsi), N application rate (strongly positive in all regions), occurrence of drought (strongly negative in all regions) and occurrence of diseases (strongly negative in all regions). The most notorious difference between both national and regional analyses was that the significance of biophysical variables (e.g., growing degrees day, temperature seasonality and aridity index) observed in the former tend to disappear in the latter.

3.2 Determinants of wheat yield gaps at field level

3.2.1 Efficiency yield gap: Time, space and type of inputs used

Although the efficiency yield gap explained less than 10% of the overall yield gap (Figure 2), it is worth noting that for some low-yielding fields improving the time, space and form of the inputs used can contribute per se to nearly doubling the current yields (Figure A3 - Supplementary Material). Previous research showed that the proportion of hired labour for sowing and weeding was positively associated with the efficiency yield gap of wheat in Asella, West Arsi (Silva *et al.*, 2019). As a next step, we suggest to investigate the contribution of field area, seed source, labour quality and plot distance from the homestead to the efficiency yield gap as these are the main proxies for time, space and form of inputs used available in the dataset.

3.2.2 Resource yield gap: Yield response to inputs

Y_{HF} were ca. 4 t ha^{-1} in West Arsi and North Shoa and around 3 t ha^{-1} in East Gojam and South Wollo (Figure 3A and Table 1). Y_{AF} and Y_{LF} were greatest in West Arsi (2.1 and 0.8 t ha^{-1}), intermediate in East Gojam (1.6 and 0.6 t ha^{-1}) and North Shoa (1.4 and 0.4 t ha^{-1}) and smallest in South Wollo (1.2 and 0.4 t ha^{-1}). The drivers of the resource yield gap are partly summarized in Table 2, for variables like seed and N rates, and further insights into these are provided in Figure 3 (as described below).

Y_{HF} were associated with significantly greater seed and N application rates compared to Y_{AF} and/or Y_{LF} across all four regions (Figures 3B and 3C). Seed rates in highest-yielding fields were ca. 250 kg ha^{-1} in North Shoa, East Gojam and South Wollo, which was significantly more than the average 175 kg ha^{-1} used in average- and lowest yielding fields. The variation in seed rates between field classes was smaller in West Arsi compared to other regions: ca. 216 and 186 kg ha^{-1} in highest- and lowest-yielding fields, respectively. N application rates in highest-yielding fields were ca. 80 kg N ha^{-1} in North Shoa, East Gojam and South Wollo. This was significantly greater than the ca. 60 kg N ha^{-1} used in average-yielding fields in North Shoa and East Gojam, the ca. 40 kg N ha^{-1} used in South Wollo and the ca. 32 kg N ha^{-1} observed across the lowest-yielding fields in either of the three regions. *N application rates for all field classes were smallest in West Arsi as there was no data regarding the amount of urea used by farmers in this region.* Despite this problem, the amount of N applied with diammonium phosphate (DAP) differed significantly between Y_{HF} (32 kg N ha^{-1}), Y_{AF} (21 kg N ha^{-1}) and Y_{LF} (17 kg N ha^{-1}).

Labour use for land preparation, sowing, hand-weeding and harvesting was significantly greater for Y_{HF} than for Y_{AF} and Y_{LF} in all regions except West Arsi (Figures 3D and 3E) and there were no clear differences in herbicide use across groups and regions (Figure 3F). As an example, highest-yielding fields were associated with a total labour use of ca. 140, 120 and 90 person-day ha^{-1} in South Wollo, North Shoa and East Gojam, respectively, while labour use ranged between 60 - 80 person-day ha^{-1} in the lowest-yielding fields of these regions. Considerably more labour was used in North Shoa, East Gojam and South Wollo than in West Arsi and there was an inverse relationship between labour use for hand-weeding and herbicide use (Figures 3E and 3F). This is best seen in West Arsi, where herbicide use was highest (ca. 0.8 L ha^{-1}) and labour for hand-weeding lowest (ca. 12 person-day ha^{-1}).

3.2.3 Technology yield gap and agronomic best practices

Most fields in West Arsi had a Yw benchmark between 9 and 10 t ha^{-1} in 2009 and between 10 and 11 t ha^{-1} in 2013, which was considerably greater than the values observed for Y_{HF} during the same years (Figures 4A and 4B). Slightly lower Yw values were

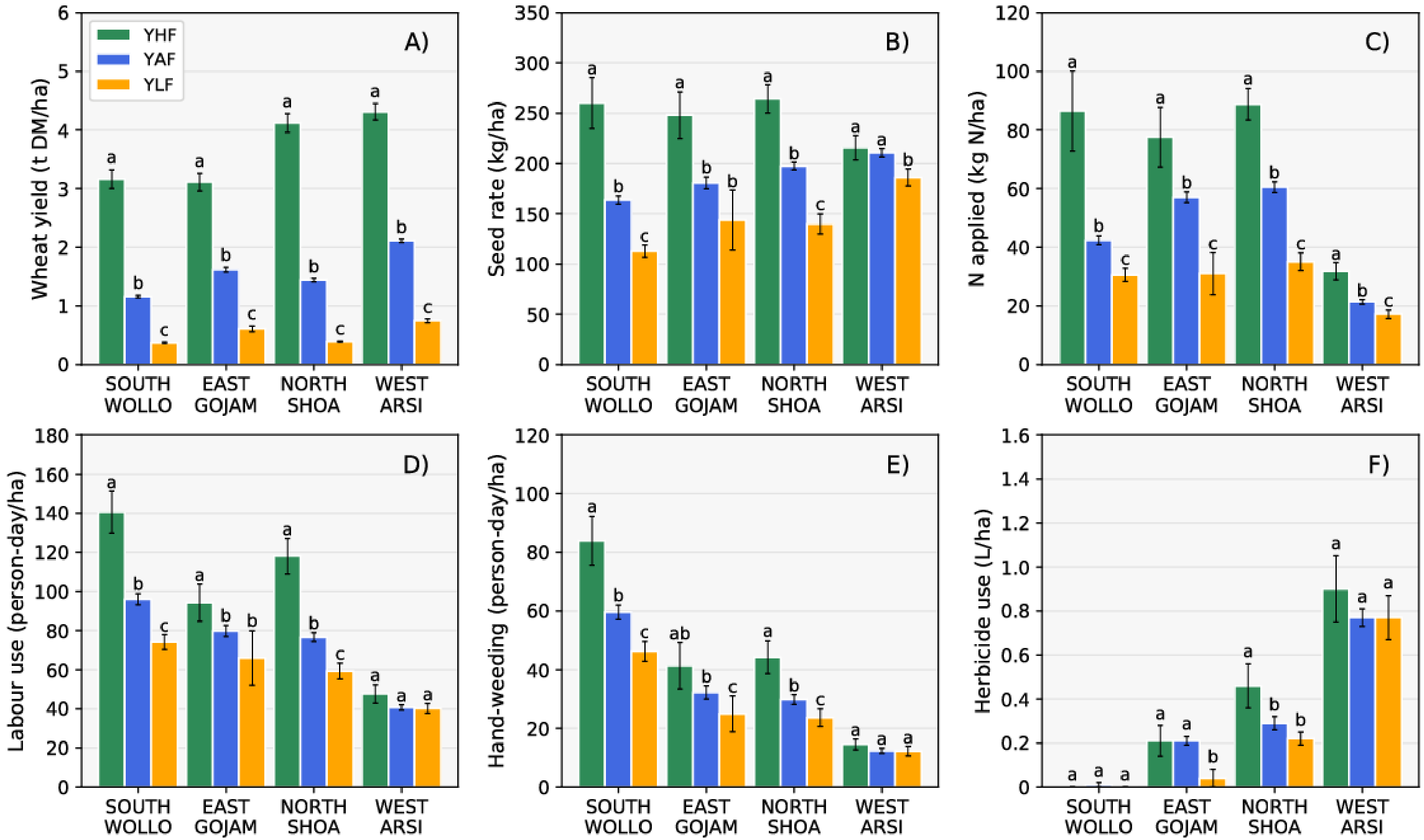

Figure 3. Wheat yield and input use across highest- (Y_{HF}), average- (Y_{AF}) and lowest-yielding fields (Y_{LF}) in selected regions of the Ethiopian highlands. Bars show the average value across the Meher seasons of 2009/10 and 2013/14. Error bars show the standard error of the mean and different letters show differences between groups in each region at 5% significant level.

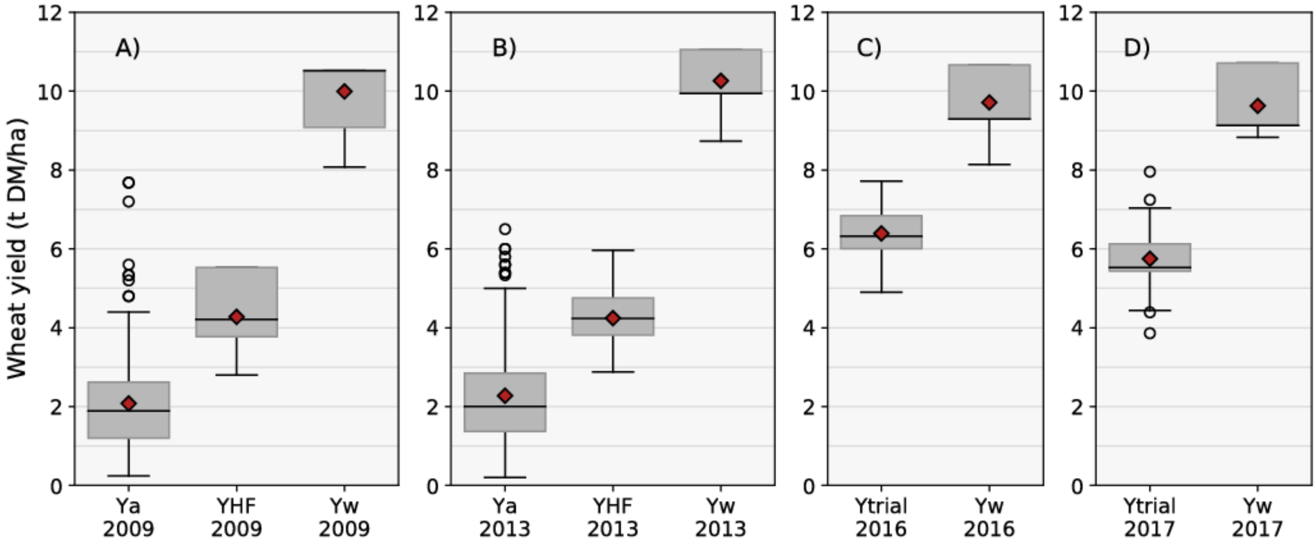

Figure 4. Magnitude and variation of wheat yields in West Arsi region as per A-B) the farm survey, Ya and Y_{HF}, and C-D) the variety trials conducted in Kulumsa and described in Bezabih *et al.* (2018), Ytrial. Simulated year-specific Yw are shown to assess differences in biophysical conditions (i.e., solar radiation, temperature and rainfall) between the different years.

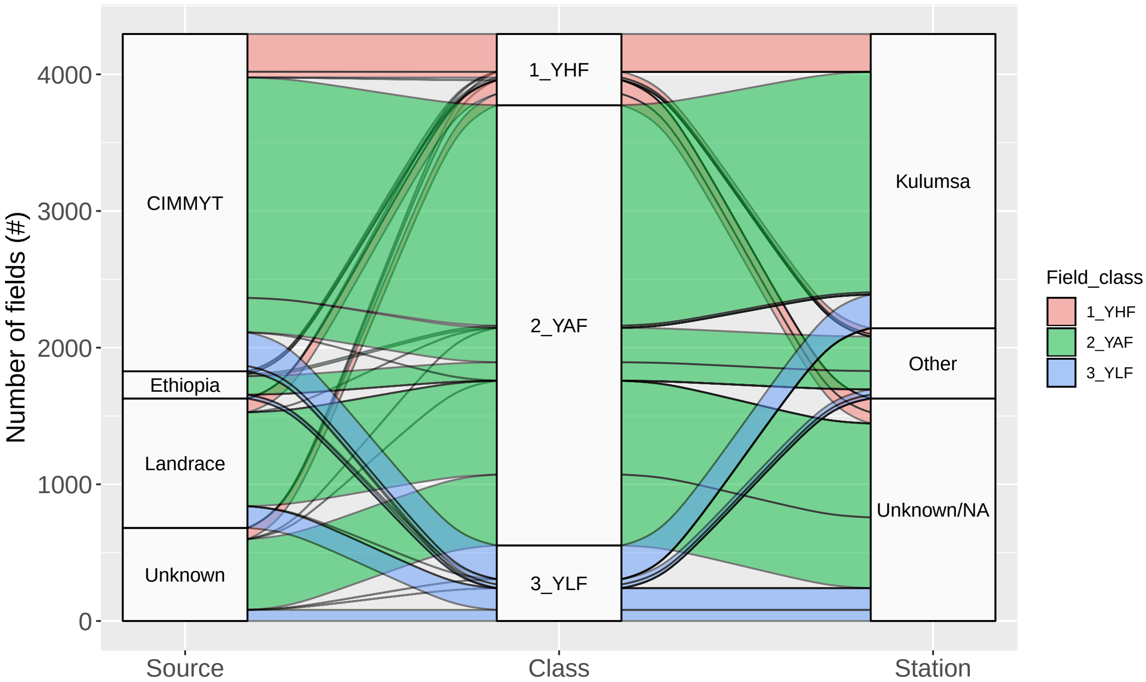

Figure 5. Source of the bread wheat varieties found across farmers' fields in the Ethiopian highlands. Data refers to the 2009/10 and 2013/14 Meher seasons. Codes: YHF = highest-yielding fields, YAF = average-yielding fields, YLF = lowest-yielding fields.

observed in 2016 and 2017, when the variety trials described by Bezabih *et al.* (2018) were conducted in Kulumsa, West Arsi. The yields observed in these trials ranged between 4.5 and 8.9 t ha^{-1} in 2016 and between 3.9 and 8.0 $^{-1}$ in 2017 (Figures 4C and 4D). Despite differences in varieties used in the highest-yielding fields and the variety trials (data not shown), most of the former were improved varieties bred in Kulumsa with parental material from CIMMYT (Figure 5). This means that varieties used by farmers can reach yields up to ca. 80% Yw on-station and are unlikely to explain the technology yield gap.

The low amount of fertilisers used in highest-yielding fields (Figure 3C) is the most likely driver of the technology yield gap of wheat across the Ethiopian highlands. This is reflected in the difference between the feasible yield (Yf) and Y_{HF}, following the methodology of van Dijk *et al.* (2017), which was not quantified in the current analysis. For the sake of example, assuming a N content in the grain of 2% and a recovery fraction of 0.5 kg N uptake kg^{-1} N applied, water-limited wheat yields of 10 t DM ha^{-1} would require 200 kg N uptake ha^{-1} and 400 kg N applied ha^{-1}. This is more than four times the N application rates observed in highest-yielding fields (Figure 3C). Other factors explaining this yield gap may include poor crop establishment and poor weed control, which currently rely heavily on draught power and manual labour, and poor pest and disease control (as partly shown in Table 2). It is also important to consider that row planting improves radiation interception under high seed rates (high plant populations) as compared to the current farmer practice of broadcasting.

3.3 Farming systems and intensification pathways

3.3.1 Crop diversity at farm level

The total cultivated land area was on average 2 ha in West Arsi and North Shoa and 1.5 and 1.4 ha in East Gojam and South Wollo, respectively (Figure 6). This land was allocated differently to different crops in different regions. The share of wheat to the total cultivated land was greatest in South Wollo and West Arsi, on average ca. 45%, and smallest in North Shoa and East Gojam, on average 35 and 25% respectively. This means that wheat is a major crop in West Arsi and South Wollo but more of a secondary crop in North Shoa and East Gojam. In West Arsi, households allocated 46% and 7% of the cultivated land to other cereals (mostly barley) and to legumes (mostly faba bean), respectively (Figure 6A). In North Shoa, the share of other cereals (mostly barley and red tef) and legumes (mostly faba bean) to the total cultivated land was around 30% each (Figure 6B). In East Gojam, around 60% of the cultivated land was allocated to other cereals (mostly red and white tef) and only ca. 10% was cultivated with legumes (Figure 6C). In South Wollo, both other cereals and legumes were cultivated on ca. 25%

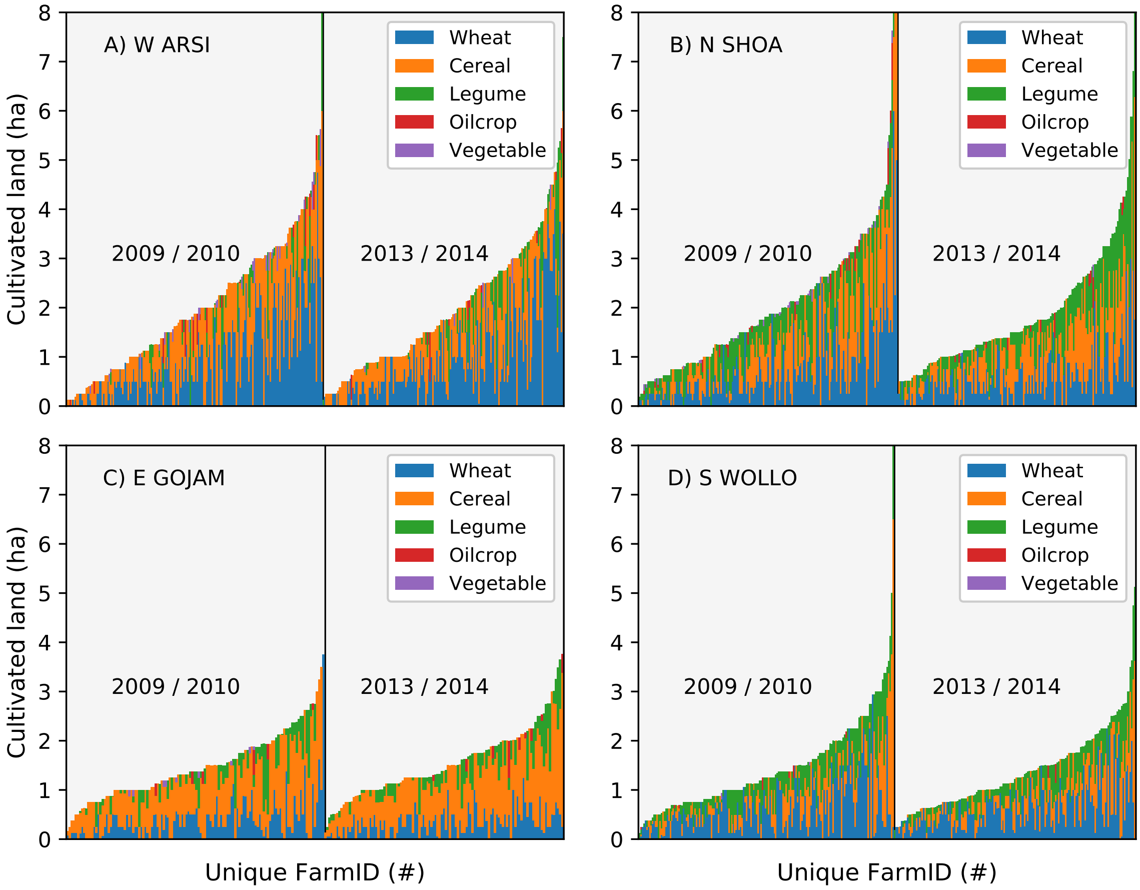

Figure 6. Cultivated land per household during the 2009/10 and 2013 -2014 Meher seasons in selected regions of the Ethiopian highlands: A) West Arsi, B) North Shoa, C) East Gojam and D) South Wollo. Different colors depict different types of crops.

of the total cultivated land (Figure 6D). The crop yield and number of fields of the main crops cultivated in each region are provided in Figure A2.

The relationship between the land and labour allocated to wheat and other crops by individual households yielded unclear results (Figure A4). Further research is thus needed to investigate these aspects more closely, preferably for subsets of the data with more homogeneous land-labour ratios and oxen ownership.

3.3.2 Availability of land, labour and capital

Oxen ownership was associated with slightly greater yields in West Arsi, North Shoa and East Gojam but not in South Wollo (Figure 7A). In addition, households with greater number of oxen pairs tended to cultivate greater wheat areas than households with less oxen pairs (Figure 7B). This was particularly true in West Arsi and North Shoa, where land is more 'abundant' (Figures 6A and 6B), and not as much in East Gojam and South

Wollo, where land is constrained (Figures 6C and 6D). No significant differences in total labour use for wheat were observed for different levels of oxen ownership in either region (Figure 7C), hence oxen ownership did not translate in labour savings per unit land. Finally, the economic value of farm assets increased on average with increasing oxen ownership, which was particularly clear in West Arsi and North Shoa (Figure 7D). In summary, oxen ownership was a proxy for the availability of both draught power and capital availability and was associated with greater larger wheat area and yield, particularly in the regions with largest amount of cultivated land per household (i.e., West Arsi and North Shoa).

No major significant differences in input use for wheat were observed across different levels of oxen ownership in either region (Figure A5). This was true for seed rates, N application rates, herbicide use and labour use for hand-weeding. These results suggest that access to draught power, and capital, do not always translate into intensification of wheat production through yield gap closure but rather into increases in wheat production through expansion of cultivated land.

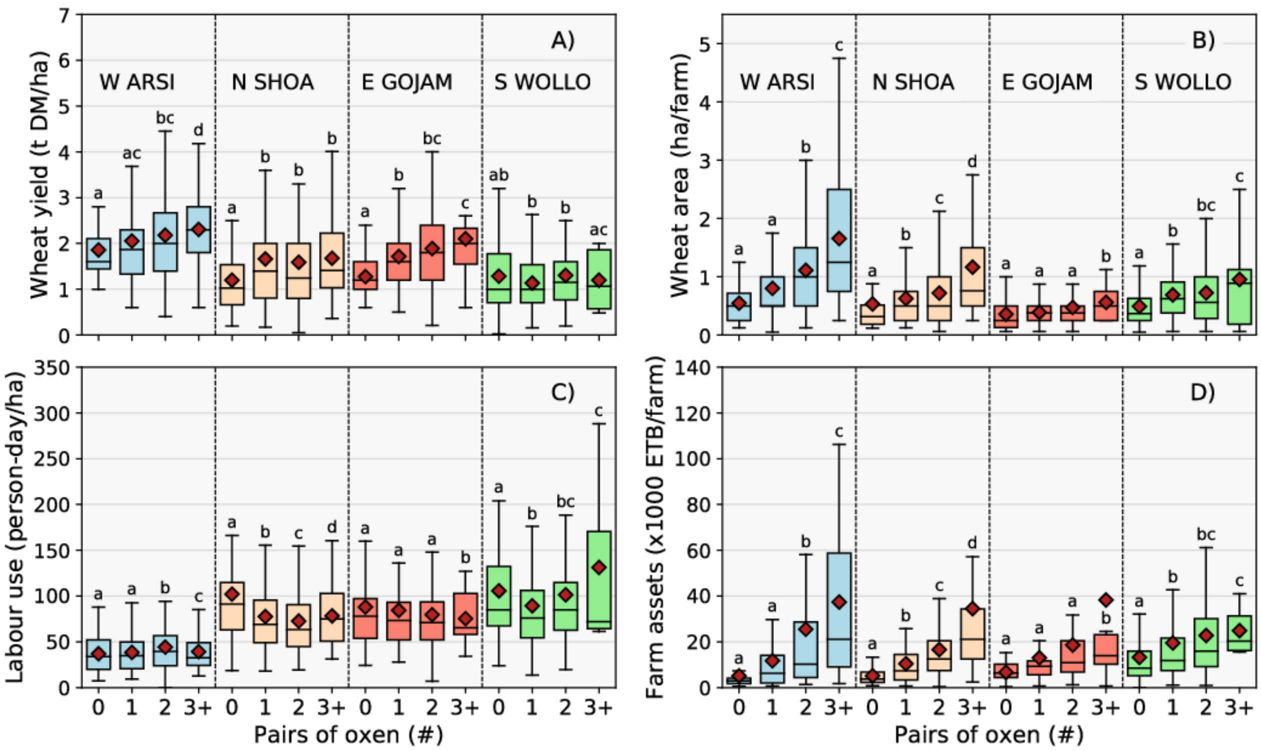

Figure 7. Relationship between number of pairs of oxen owned by households and A) wheat yields, B) wheat cultivated area, C) labour use for land preparation, sowing, hand-weeding and harvesting of wheat and D) farm assets owned by households for selected regions in the Ethiopian highlands (West Arsi, North Shoa, East Gojam and South Wollo). For each region, lower-case letters depict significant differences between groups at 5% significance level.

3.4 Feedback from stakeholders

The stakeholder workshop was attended by colleagues from the Ministry of Agriculture of Ethiopia, the Ethiopian Institute for Agricultural Research (EIAR), the fertiliser industry and other organizations (e.g., AGRA). The framework used for analysis and results were well-received and there were questions as to which extent climate information services (seasonal and short-term forecasting) could be used to help reducing efficiency and resource yield gaps. Also, there was a general agreement that few farmers in the highlands are achieving wheat yields as high as 8 t ha^{-1} and that low use of inputs is a major determinant of wheat yield gaps in the country.

4 Conclusion and next steps

Wheat yields in farmers' fields across the Ethiopian highlands were well below the water-limited yield potential, the benchmark for what can be achieved with best agronomic practices under rainfed conditions. Yield gap closure was on average only ca. 20% of the water-limited yield, with some regions showing even lower levels. Most of the yield gap was attributed to the technology yield gap, meaning that the amount of inputs used in highest-yielding fields was not high enough to reach the water-limited yield and that lack of technologies as to crop establishment and pest, disease and weed control remain. Despite their small share in explaining the wheat yield gap, narrowing the efficiency and resource yield gaps can nearly double actual yields and contribute to realise the yield progress needed to achieve wheat self-sufficiency in Ethiopia in the future (van Ittersum *et al.*, 2016). However, achieving this requires increases in input use to the levels used in highest-yielding fields and fine-tuning current crop management practices in relation to the time, space and form of the inputs used. These results are in line with the ones obtained from the Living Standards Measurement Study (LSMS) as summarized by (Morley *et al.*, 2019).

Wheat is cultivated in the Ethiopian highlands alongside other cereal and legume crops. In terms of crop area share, it is a major crop in regions like West Arsi and South Wollo and a more secondary crop in regions like North Shoa and East Gojam. This is likely to induce trade-offs in resource allocation at the farm level, especially because smallholder farmers tend to face resource constraints and the different crops compete for labour in key periods of the growing season (Silva *et al.*, 2019). Adding to this, households with more access to draught power and capital are not investing more in inputs per unit land of wheat but rather cultivating more land with wheat. This is particularly true in regions where the total cultivated land per household is greatest, such as West Arsi and North Shoa, and leaves the resource yield gap unexplained from a farm(ing) systems perspective.

Further research should focus on identifying the determinants of the efficiency yield gap and on disentangling the technology yield gap through the estimation of the feasible yield assuming no economic constraints, as explained in this report. If possible, these should be combined with agronomy trials that can help understanding wheat performance under high-yielding conditions. Finally, it is also important to understand whether or not narrowing yield gaps towards (80%) Yw is desirable from an economic and/or labour productivity perspective under prevailing conditions.

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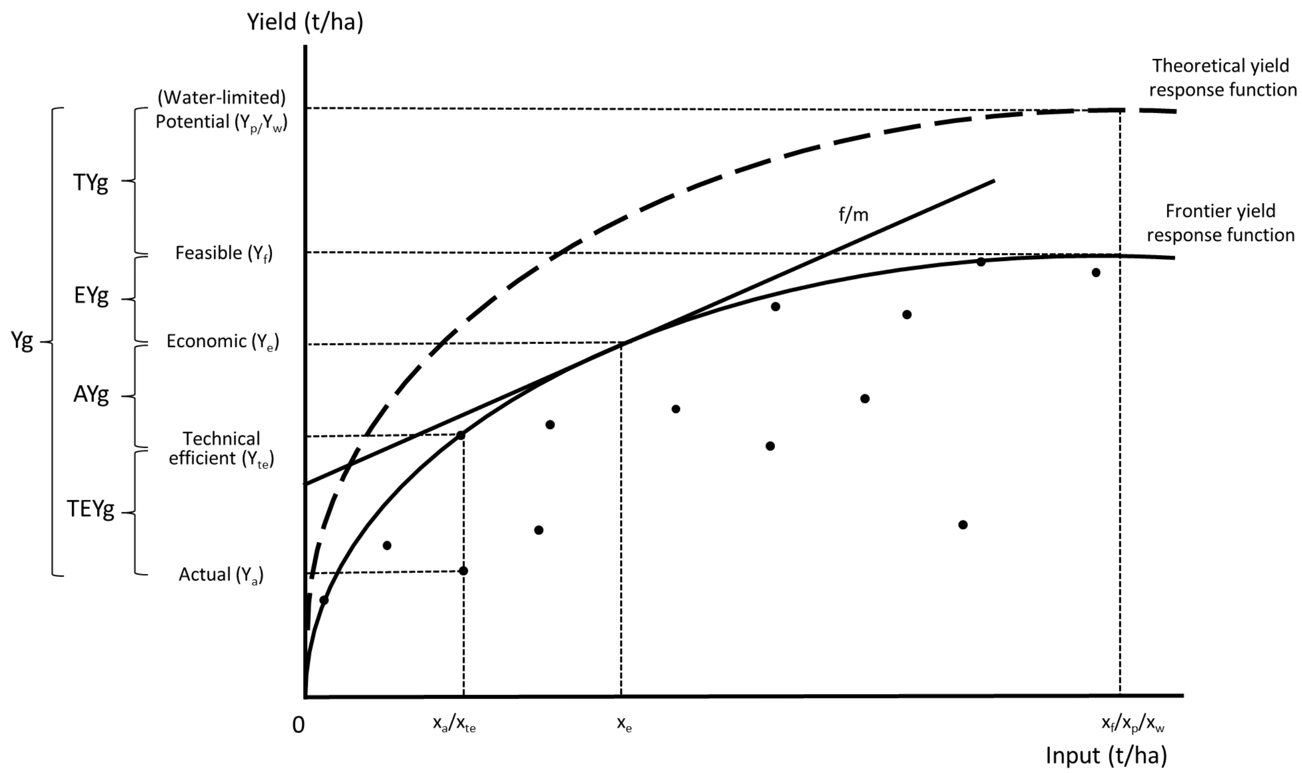

Figure A1. Conceptual framework to decompose yield gaps into efficiency, resource (allocative and economic) and technology yield gaps. Source: van Dijk *et al.* (2017).

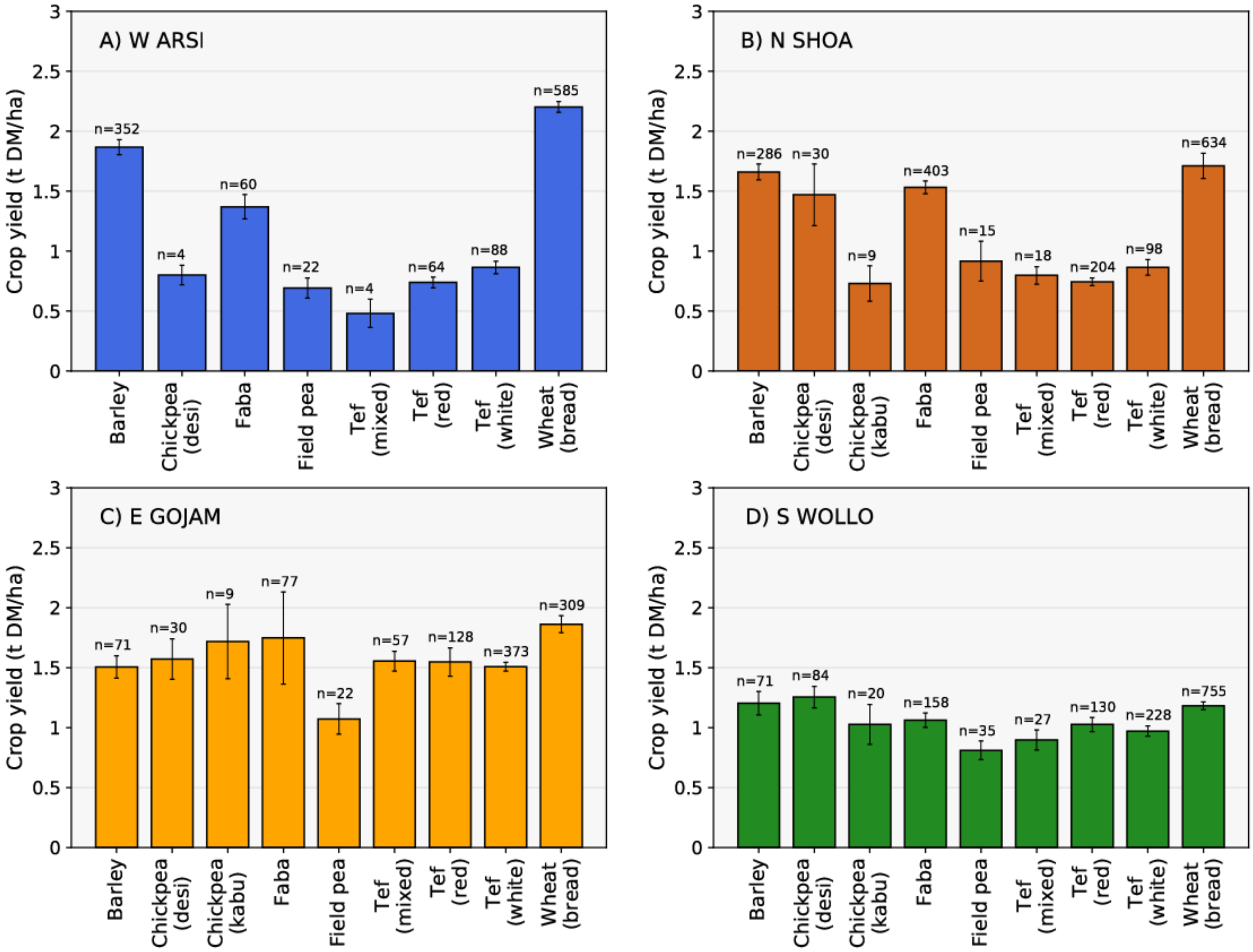

Figure A2. Descriptive statistics of crop yields for selected regions in the Ethiopian highlands: A) West Arsi, B) North Shoa, C) East Gojam and D) South Wollo. Data refers to the 2009 - 2010 and 2013 - 2014 Meher growing seasons. Error bars show the standard error of the mean and sample sizes per crop per region are shown on top of each bar.

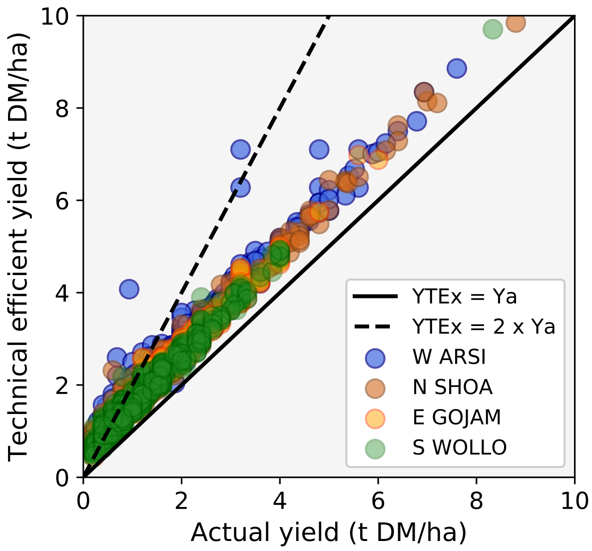

Figure A3. Actual (Ya) and technical efficient (Y_{TEx}) wheat yields for selected regions in the Ethiopian highlands during the 2009 - 2010 and 2013 - 2014 Meher growing seasons. The solid line shows no efficiency yield gap and the dashed line shows an efficiency yield gap equal to 50% Y_{TEx}.

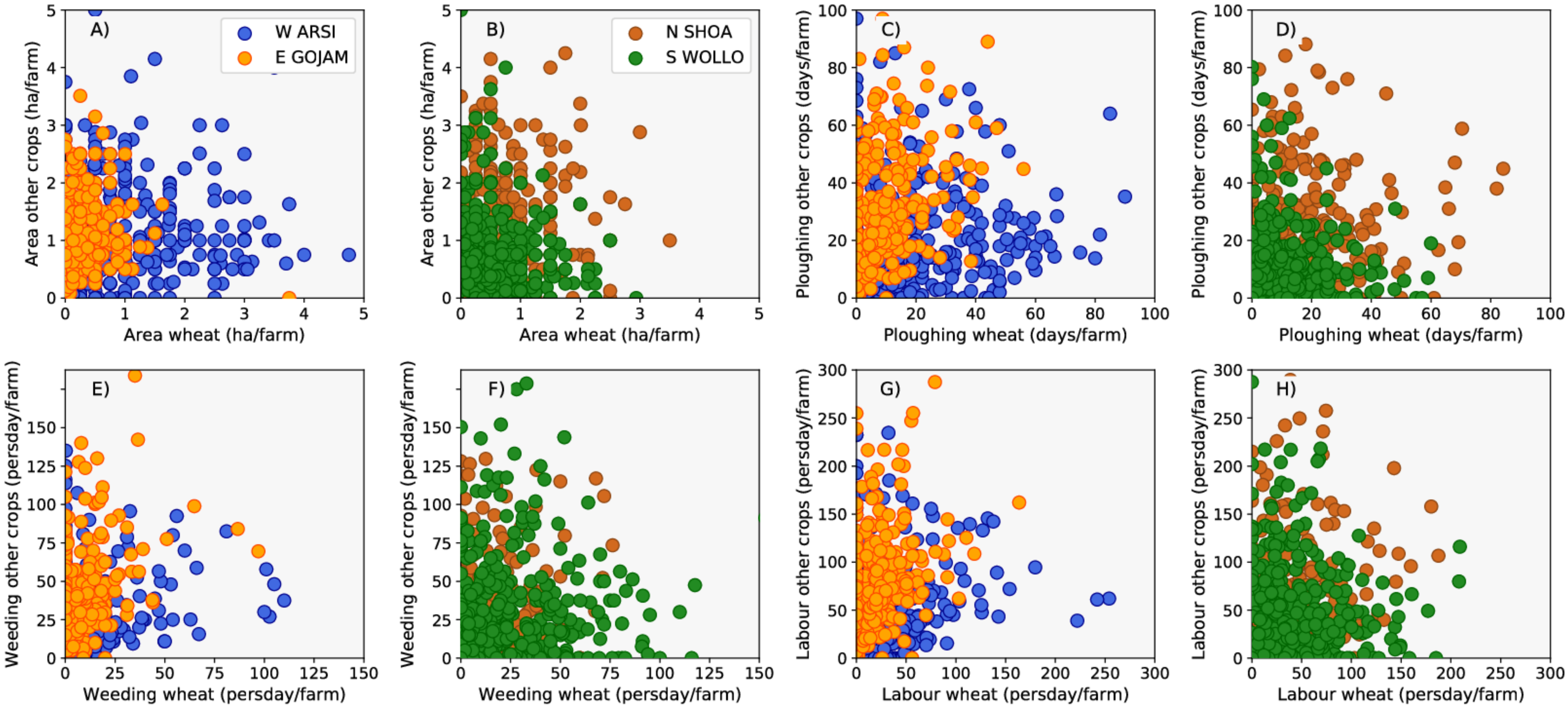

Figure A4. Land and labour allocation for wheat and other crops in selected regions of the Ethiopian highlands (West Arsi, North Shoa, East Gojam and South Wollo). Each observations depict an individual household in the 2009 - 2010 or 2013 - 2014 Meher growing seasons.

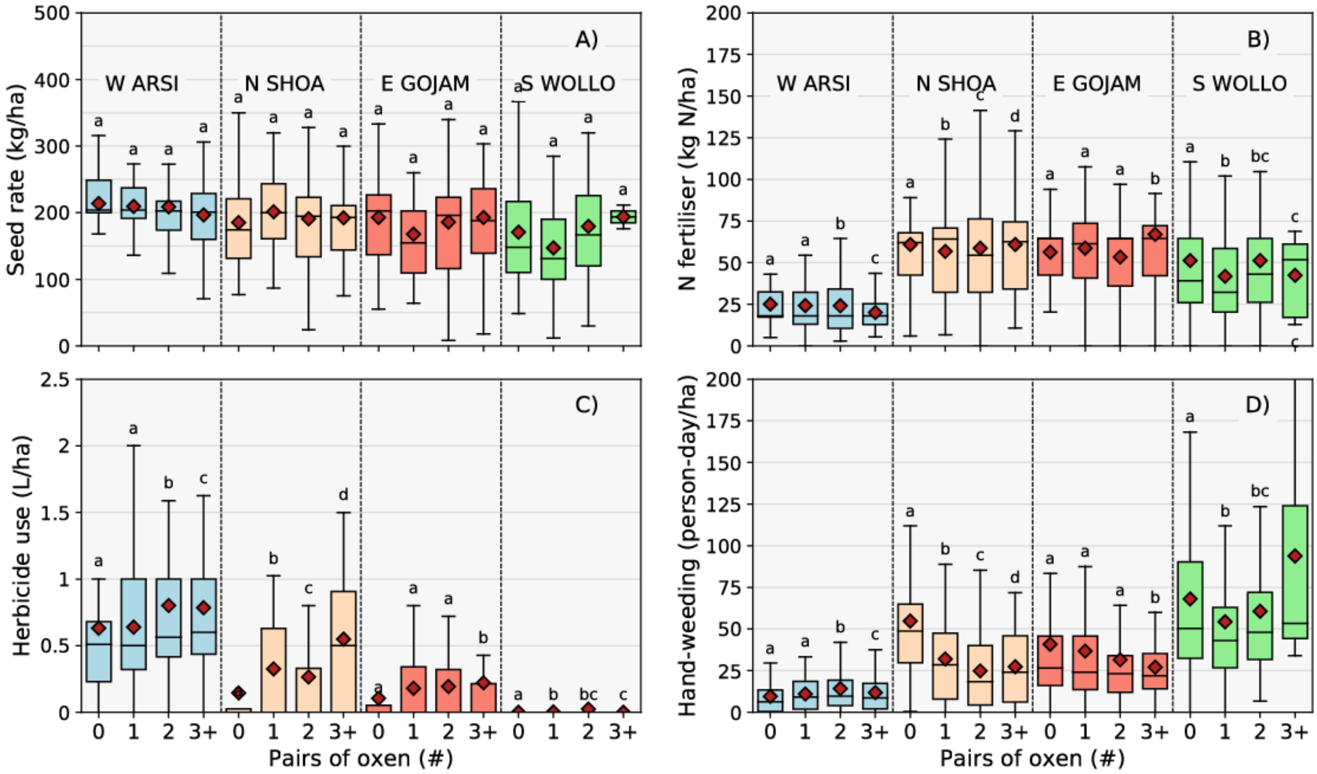

Figure A5. Relationship between number of pairs of oxen owned by households and A) seed rates, B) N fertiliser use, C) herbicide use and D) labour use for hand-weeding for selected regions in the Ethiopian highlands (West Arsi, North Shoa, East Gojam and South Wollo). For each region, lower-case letters depict significant differences between groups at 5% significance level.