Disentangling agronomic and economic yield gaps in Ethiopian wheat based systems for better targeting of development interventions
(Yield Gap Wheat Ethiopia)

Report #3: National yield gap analysis and its components

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1) Background

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 being strictly linked to urbanization and steady economic growth. 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 solely under rainfed conditions and with relatively few inputs such as fertilizers and fungicides. Moreover, operations such as land preparation and sowing are mostly done with animal draught power (cf. Silva et al., under review), which makes row-planting and establishment of the right plant population difficult. Despite the yield progress observed during the past 15 years, with wheat yields doubling to values reaching ca. 2.7 t/ha (FAOSTAT), a large yield gap remains, suggesting there is considerable scope to improve current yields further (www.yieldgap.org). This calls for an in-depth yield gap analysis at national scale so that the main drivers of the yield gaps across different regions can be identified, which helps prioritizing policies and interventions towards wheat self-sufficiency in Ethiopia.

The objective of this report is to disentangle the wheat yield gap in Ethiopia into its constituent parts. For this purpose, we conduct a yield gap analysis at national scale following the framework of van Dijk et al (2017) and using the LSMS-ISA crop cut yield data. The LSMS is The solid line in Figure 1 represents the frontier response function, which corresponds with the maximum yield that can be obtained for a given input level with the best-management practices and technologies used by farmers in a given region. a nationally representative panel dataset and contains information for the Meher seasons (which receives rainfall from June to October) 2011, 2013 and 2015. Despite our earlier concerns of using these data for a yield gap analysis at national level due to data quality problems and sample size (as summarized on our previous report), we think the preliminary results derived from the national analysis of these data (and described in this report) provide interesting insights to build upon more detailed regional analysis using the Wheat Adoption and Impact Surveys of CIMMYT. The results presented here are useful for mapping the current size of the wheat yield gap in different regions of Ethiopia and provide evidence that can be used to determine policies required to narrow the wheat yield gaps in the country.

2) Concepts and definitions

The yield gap (Yg) is defined as the difference between potential (Yp) or water-limited yield (Yw) and actual farmers yield (Ya) under irrigated or rainfed conditions, respectively (Lobell et al. 2009; Ittersum et al. 2013). Yp is the maximum yield that can be achieved under well-defined biophysical conditions, with nutrients and water non-limiting and pests, diseases and weeds effectively controlled. Yw is similar to Yp but considers possible water limitations during the growing season.

Yield gaps can be decomposed into different intermediate yield gaps using a combination of principles of production ecology and methods of frontier analysis (Silva et al., 2017; van Dijk et al., 2017). The approach used to decompose the yield gap is presented in Figure 1. The dashed line in Figure 1 represents a theoretical yield response function to inputs under perfect crop management and up-to-date technologies. These function can be estimated using crop models,

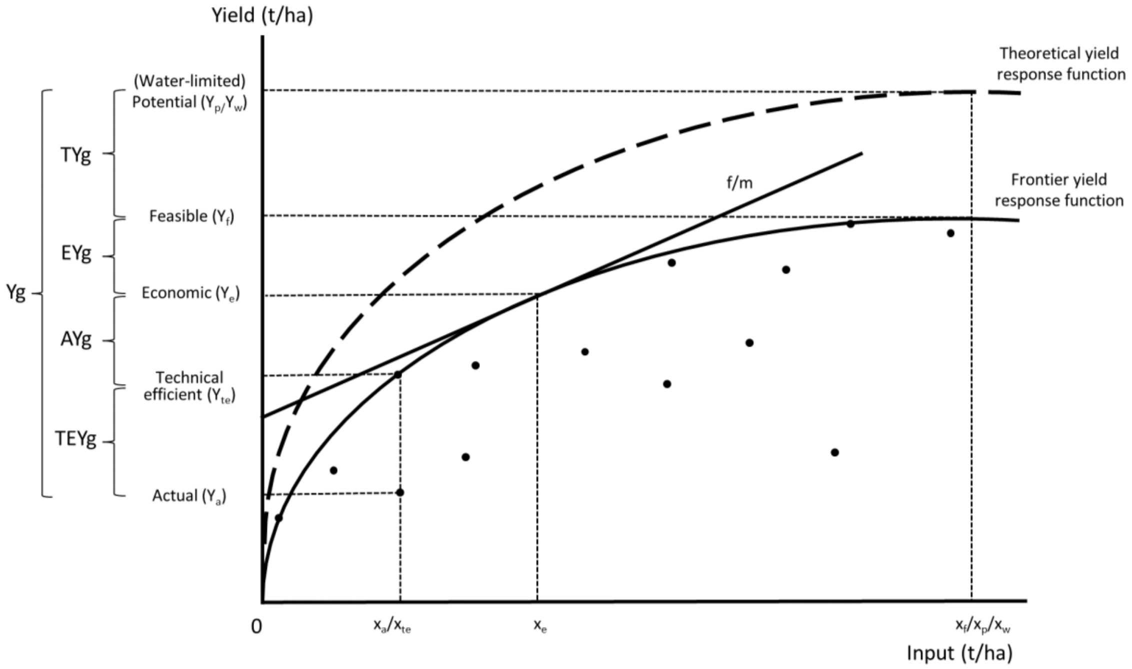

Figure 1: Conceptual framework to decompose yield gaps into efficiency, allocative, economic and technology yield gaps. Source: van Dijk et al. (2017).

highest yields at agricultural research stations and highest yield in farmer contests (Lobell et al. 2009) and its maximum equals Yp, or Yw in case of rainfed crops such as wheat in Ethiopia. The solid line in Figure 1 represents the frontier response function, which corresponds with the maximum yield that can be obtained for a given input level with the best-management practices and technologies used by farmers in a given region.

Five yield levels can be identified in combination with additional information on input (f) and output (m) prices and detailed agronomic information on optimal nitrogen application and seed rate: (1) Ya, (2) technical efficiency yield (Yte), which reflects the best-practice yield for given inputs and agro-ecological conditions, (3) economic yield (Ye), which is the yield level for which the input is profit maximizing; (4) feasible yield (Yf), which measures the best-practice yield if there would be no economic constraints and (5) Yp or Yw, depending on whether conditions are respectively irrigated or rainfed. Combining the different yield levels results in the following four yield gaps that each reflect different causes: (1) the technical efficiency yield gap (TEYg), which measures crop management inefficiencies in production; (2) the allocative yield gap (AYg), which captures the suboptimal allocation of resources; (3) the economic yield gap (EYg), which reflects economic constraints; and (4) the technology yield gap (TYg), which captures lack of access to (advanced) technologies. We refer to Dijk et al. (2017) and Silva et al. (2017) for more information on the conceptual framework.

3) Data used for national yield gap analysis

Data from the Ethiopian Living Standards Measurement Survey - Integrated Surveys in Agriculture (LSMS-ISA) was used for a national yield gap analysis of wheat in Ethiopia. The data was collected in three waves corresponding to 2010-11, 2013-14 and 2015-2016. The objective of the LSMS-ISA is “to improve [the] understanding of the inter-relationship between agriculture and poverty reduction, to improve the capacity of national statistics offices to collect and use this data to inform policy, and to foster innovation in the measurement of agricultural data” (Carletto et al., 2015). The survey began with 4000 households who were tracked and re-interviewed in subsequent waves of the survey. The Ethiopian LSMS-ISA is part of the larger LSMS-ISA program to improve the quality of agricultural data through a collaboration between the World Bank and the national bureau of statistics in the different LSMS-ISA countries.

Two possible measures for farmer wheat yields are recorded in the data. The first is based on farmer recall of crop production and GPS measured area and the second is based on interviewer measured crop cut wheat over a fixed area. We avoid using the farmer recall based measure due to concerns over data quality, particularly referring to field area measurements (cf. Appendix of our previous report). Crop cut data is available for all crops in the dataset (including wheat) and have the additional benefit that the exact date of crop cutting was recorded. As the crop cut was intended to be carried out on or near the date of harvesting, this data can also be used to construct crop harvest calendars (the original dates use the Ethiopian calendar but have been converted into Gregorian calendar to facilitate the construction of crop calendars for use later in this project). The LSMS-ISA dataset also contains many variables on climate and soil characteristics linked through farm or plot GPS locations, which are described at length in the basic information document accompanying the data. There is also a large number of variables recording various crop management operations and farm(er) characteristics.

Table 1. Descriptive statistics of key variables across all waves and regions for crop cut wheat fields. *Source*: LSMS-ISA Ethiopia.

Variables	**Region**	**Wave 1 (Meher 2011)**	**Wave 2 (Meher 2013)**	**Wave 3 (Meher 2015)**
Number of fields (*n*)	Amhara	45	81	171
	Oromia	60	89	148
	SNNP	59	87	90
	Tigray	28	34	54
Crop cut wheat yield (kg FM/ha)	Amhara	1712	1287	1274
	Oromia	1912	1279	2128
	SNNP	1883	1304	1170
	Tigray	1748	1296	1485
Fields with Irrigation (proportion)	Amhara	0.09	0	0.01
	Oromia	0	0	0
	SNNP	0	0	0
	Tigray	0.07	0.06	0.04
Fields with damage (proportion)	Amhara	0.40	0.36	0.44
	Oromia	0.37	0.25	0.44
	SNNP	0.47	0.28	0.69
	Tigray	0.14	0.50	0.89
Fields with fallow (proportion)	Amhara	0.67	0.14	0.10
	Oromia	0.98	0.10	0.16
	SNNP	0.78	0.15	0.08
	Tigray	0.82	0	0.02
Seed type (improved vs. traditional) (proportion)	Amhara	0	0.11	0.05
	Oromia	0.10	0.06	0.03
	SNNP	0.14	0.09	0.17
	Tigray	0.18	0.21	0.11
Fields with mineral fertilisers (proportion)	Amhara	0.42	0.53	0.63
	Oromia	0.48	0.69	0.67
	SNNP	0.76	0.63	0.82
	Tigray	0.75	0.85	0.76
Fields with organic fertilisers (proportion)	Amhara	0.02	0	0.02
	Oromia	0.05	0	0
	SNNP	0	0	0.01
	Tigray	0	0	0
Fields with Manures (proportion)	Amhara	0.24	0.28	0.15
	Oromia	0.13	0.09	0.1
	SNNP	0.12	0.14	0.08
	Tigray	0.32	0.41	0.52
Fields with Herbicides (proportion)	Amhara	0.13	0.11	0.22
	Oromia	0.57	0.64	0.68
	SNNP	0.46	0.39	0.60
	Tigray	0.11	0.03	0.07
Fields with Fungicides (proportion)	Amhara	0.02	0	0.01
	Oromia	0	0.01	0.17
	SNNP	0.10	0.02	0.01
	Tigray	0	0.03	0

We restrict our attention to the four largest regions in Ethiopia: Amhara, Oromiya, Southern Nations, Nationalities, and Peoples' (SNNP) Region and Tigray. Virtually all the crop cut wheat fields fell into these four regions (98.7%). We also restrict our attention to fields on which only wheat was grown. The reason for this restriction is that several questions about chemical use were asked at the field, as opposed, to crop level. If wheat is grown side by side with another crop, it is not possible to distinguish whether fertilizer, for example, was applied to wheat or to the other crop. There is also no way to distinguish between fields in which wheat was inter-cropped with another crop or grown alongside the other crop. As 97.4% of crop cut wheat fields contained only wheat we decided to focus only on these fields. Table 1 contains descriptive statistics of the crop cut yield data and crop management variables used in this study (n = 902 wheat fields split across three survey waves, Meher seasons 2011, 2013 and 2015).

4) Methodology

We follow the framework of van Dijk et al (2017) to disentangle the yield gap into its constituent parts (Figure 1). For a full description of the methodology, and related terms, the reader is referred to that manuscript. In the framework, observed yields are compared to a biophysical maximum yield derived from crop simulation models. By estimating a stochastic frontier (SF) model for the frontier yield production function a comparison can be drawn between the observed field level yields and the predicted yields that would be observed if all farmers operated on the technical efficiency frontier. In this report, we relate crop cut wheat yields to a set of biophysical factors and binary crop management variables to define the technical efficiency frontier. The procedure for collecting crop cut production relies on using a random number table to mark out a random sub plot of each field on which the crop is sampled to determine the yield. By doing so, border and edge effects should not cause measurement error in expectation (a step by step guide to this random process can be found in the crop cutting manual available in http://microdata.worldbank.org/index.php/catalog/2247).

The statistical model for stochastic frontier estimation is given by Equations 1, 2, 3 and 4 and is estimated using maximum likelihood (see Aigner et al., 1977, for details). The composite error term $\mathcal{E}_{ijk}$ is composed of a symmetric stochastic error v_{ijk} and a truncated random normal term u_{ijk}. For the purposes of this report we can again think of v_{ijk} itself as being composed of a stochastic error term and an error term due to the crop cutting procedure.

$$y_{ijk} = f(x_{ijk}, \Theta) + \mathcal{E}_{ijk} \qquad (1)$$

$$\mathcal{E}_{ijk} = v_{ijk} - u_{ijk} \qquad (2)$$

$$v_{ijk} \sim N(0, \sigma_v^2) \qquad (3)$$

$$u_{ijk} \sim N^{+}(0, \sigma_u^2) \qquad (4)$$

The frontier yield curve and the actual observed yields are used to establish the Technical Efficiency Yield gap (TEYg). We also estimate the feasible yield, which is achieved when inputs are used by all farmers and on all fields (this is the case in this analysis because inputs are defined as categorical not continuous variables), and the related 'Allocative + Economic'

Yield gap (EYg). In practice this means using the estimated frontier parameters to predict the frontier yield that would be achieved per field were all farmers to use inputs including fertilizer, biocides and manure. Unlike van Dijk et al. (2017), we do not estimate the economic yield, and could thus not separate the allocative and economic yield gap because, due to data quality issues, data on wheat and input prices was not forthcoming from the dataset. Finally, because many farmers report damage due to weather, insects or other sources, we used a binary variable damage (1/0) to split our sample into those wheat fields on which damage was reported and those where it was not. Damage is not always under the control of the farmer. However, damage due to insects or other pests may be prevented by using biocides so we also define a Feasible Yield (no damage), which is the yield achieved at the frontier when all farmers use inputs and there is no damage.

Water-limited yields were simulated for the survey years with WOFOST using the protocols of the Global Yield Gap Atlas and recent weather data (Grassini et al., 2015 and van Bussel et al., 2015). These water-limited yields were linked to the field level data based on the GPS coordinates of the crop cut field and on the GPS coordinates of the nearest weather station to each field. The results of these simulations are freely available for download at http://www.yieldgap.org/ethiopia.

5) Main results of the national yield gap analysis

To begin, we fit a series of ordinary least squares (OLS) models to the sample of crop cut wheat fields. This process aids the selection of a suitable model and establishes whether the OLS residuals are. The results of fitting OLS models to the sample of crop cut wheat fields are shown in Table 2. Our strategy for fitting the model is simple. We sequentially add climate, field characteristics and soil characteristics, followed by crop management variables. Each model also includes damage, wave and region dummies to account for season and region fixed effects, and to differentiate between fields on which damage was reported and fields where it was not. The improvement in model fit is judged by the adjusted R-squared of each model.

In Model 1 we account for annual rainfall, the start of the wettest quarter of the year and the average rainfall in the wettest quarter of the year. In Model 2 we add the plot elevation and the square root of the slope of the plot. The square root of plot slope is taken to induce normality and improve model fit. In Model 3 we add several soil controls derived from the Global Yield Gap Atlas (GYGA) and the African Soil Information Service (AFSIS). Specifically we control for available water capacity of fine earth aggregated over the effective root zone depth (cm3/cm3), effective root zone depth (cm) and soil moisture content at wilting point (cm3/cm3). These variables relate to soil available water for crop growth and, despite some overlap between them, provide different information about soil water properties. Finally, in Model 4 we add variables for mineral and organic fertilizer, as well as biocides, manure, irrigation, seed type and whether the field was left fallow in the previous season.

Controlling for climatic, geographical and soil characteristics leads to a better OLS fit for the model (Table 2). We find that the significance of the total amount of rainfall and the start of the wettest quarter is inconsistent across all models and no, or marginally, significant in Model 4. The average wettest quarter rainfall, on the other hand, is significant and negative in all four models. The soil variables included were mostly non-significant in Models 1 – 4. Plot elevation

Table 2. OLS results from four models. Note: *, **, * and . indicate that the corresponding regression coefficients are statistically significant at the 0.1% and 1%, 5% and 10%, respectively.**

	Model 1	Model 2	Model 3	Model 4
Intercept	8.117***	7.350***	6.787***	6.711***
Irrigation_Yes				-0.012
Seed type_Improved				-0.029
Mineral fertiliser_Yes				0.157***
Organic fertiliser_Yes				0.232
Manure_Yes				0.058
Herbicide_Yes				0.125*
Pesticide_Yes				0.181
Fungicide_Yes				0.225.
Fallow_Yes				-0.025
Damage_Yes	-0.501***	-0.453***	-0.443***	-0.419***
Total rainfall (mm/year)	0.000.	0.000*	0.000*	0.000.
Start of wettest quarter (dekad)	-0.006	-0.008.	-0.010*	-0.006
Rainfall wettest quarter (mm)	-0.002***	-0.001***	-0.002***	-0.001***
Elevation (m)		0.000***	0.000***	0.000***
sqrt(Slope) (%)		-0.042**	-0.030.	-0.006
Water holding capacity (cm^3/cm^3)			-0.025	-0.032
Rootable soil depth (cm)			0.001	0.001
Soil moisture wilting point (cm^3/cm^3)			0.027*	0.021.
Wave_2	-0.480***	-0.444***	-0.463***	-0.474***
Wave_3	-0.148**	-0.157**	-0.172**	-0.226**
Region_Oromyia	0.188***	0.217***	0.275***	0.204***
Region_SNNP	-0.027	0.027	0.079	0.030
Region_TIGRAY	0.142*	0.212**	0.319***	0.267**
Number of fields (*n*)	946	902	902	902
R^2	0.19	0.213	0.229	0.26
Adj.-R^2	0.182	0.204	0.216	0.241

is positively and significantly associated with wheat yields. This reflects the fact that wheat grows better at higher altitudes. The (square root) of the plot slope is negatively and significantly associated with wheat yields but the significance disappears once we control for soil and field management variables. The effects of fertilizer and herbicide use are positive and significant in Model 4. As we move across Models 1 to 4 we see an increase in the adjusted R-squared indicating that inclusion of each group of variables improves the model fit slightly. As a final step we remove any variable for which the standard error of the estimated coefficient was more than twice the estimate. This heuristic is useful for obtaining a more parsimonious model (Battese et al., 1996). It may seem strange to remove variables like irrigation or seed type from the model. However, from Table 1 we see that only a small proportion of fields actually employ any form of irrigation or use improved wheat seeds. The results of this procedure are shown in the first model of Table 3. The skewness of the residuals of the OLS model is -0.446 warranting the use of a stochastic frontier model. The second column of Table 3 shows the results of fitting the same model using SF instead of OLS to estimate the parameters of Equation 1. As expected, the intercept is larger for the SF model compared to the OLS model. The other coefficients are fairly similar between the two models.

Table 3. OLS and SF results for chosen model. Note: *, **, * and . indicate that the corresponding regression coefficients are statistically significant at the 0.1% and 1%, 5% and 10% levels, respectively. Stochastic frontiers analysis carried out using the R package "frontier".**

	OLS model	SF model
Intercept	6.696***	7.596***
Mineral fertiliser_Yes	0.159***	0.147***
Manure_Yes	0.067	0.084.
Herbicide_Yes	0.128**	0.121**
Pesticide_Yes	0.176	0.181
Fungicide_Yes	0.222.	0.204.
Damage_Yes	-0.420***	-0.344***
Total rainfall (mm/year)	0.000.	0.000**
Start of wettest quarter (dekad)	-0.006	-0.005
Rainfall wettest quarter (mm)	-0.001***	-0.002***
Elevation (m)	0.000***	0.000***
Water holding capacity (cm^3/cm^3)	-0.033.	-0.033.
Rootable soil depth (cm)	0.001	0.001
Soil moisture wilting point (cm^3/cm^3)	0.022*	0.015
Wave_2	-0.462***	-0.557***
Wave_3	-0.208***	-0.225***
Region_Oromyia	0.206***	0.199***
Region_SNNP	0.025	-0.041
Region_Tigray	0.257**	0.153.
Number of fields (*n*)	902	902
R^2	0.259	
Adj.-R^2	0.244	
sigmaSq		0.675***
gamma		0.801***

Table 4 presents the yield levels that can be calculated from the available data and models in our framework. The first column of Table 4 shows the average actual yield levels averaged across all waves of the data, which range between ca. 1300 and 1800 kg/ha. The second column of Table 4 shows the technical efficiency yield, the yield that would be achieved if all farmers were operating at the frontier yield production function, which ranges between ca. 2000 and 2700 kg/ha. The feasible yield represents the yield level achieved when operating on the frontier function and applying fertilizer, biocides and manure together. This is calculated by predicting the frontier function (Equation 1) using the parameters from Table 3 column 2 and setting the binary inputs for fertilizer, biocide and manure use to one, which results in yields ranging between 3500 and 4500 kg/ha. The feasible yield without damage represents the feasible yield when no damage due to weather, insects or other factors occurs and it ranges between ca. 4000 and 5100 kg/ha. This is calculated in an analogous manner to the feasible yield but now the dummy variable for damage is also set to zero for all fields. Finally, the water limited potential yield (Yw) derived from GYGA crop simulation models provides a biophysical ceiling or maximum wheat yield level. This benchmark is above 8000 kg/ha for Amhara and SNNP, ca. 7600 kg/ha for Oromyia and 5500 kg/ha for Tigray.

Table 4. Average wheat yields (kg/ha) across different regions in Ethiopia.

Region	Actual yield (t/ha)	Technical efficient yield (t/ha)	Feasible yield with damage (t/ha)	Feasible yield without damage (t/ha)	Water-limited yield (t/ha)
Amhara	1.34	2.06	3.78	4.30	8.20
Oromyia	1.81	2.77	4.57	5.13	7.63
SNNP	1.29	1.99	3.46	4.05	8.27
Tigray	1.46	2.37	4.17	5.07	5.46

The yield gaps which correspond to the yield levels of Table 4 are presented in Table 5 in absolute and relative terms and summarized in Figure 1. With the exception of Tigray, the technology yield gap is the largest (>40% of Yw) gap across all regions. The combined allocative and economic yield gap is around twice the size of the technical efficiency yield gap and between 20 and 45% of Yw. Based on these results, closing the technical efficiency yield gap could lead to wheat yields between 2000 and 3000 kg/ha in most regions of Ethiopia. In addition, improving access to key inputs like fertilizer and biocides could lead to yield levels as high as 3000 - 4000 kg/ha.

Table 5. Wheat yield gaps in absolute and relative terms across different regions in Ethiopia.

Region	Efficiency Yg (Yte – Ya)	Allocative + Economic Yg (Yf – Yte)	Allocative + Economic Yg (no damage)	Technology Yg (Yw – Yf)	Total Yg (Yw – Ya)
			Absolute yield gaps in t/ha		
Amhara	0.72	1.72	0.52	3.91	6.87
Oromyia	0.96	1.80	0.57	2.50	5.82
SNNP	0.70	1.47	0.59	4.22	6.98
Tigray	0.90	1.81	0.90	0.39	4.00
			Relative yield gaps as % Yw		
Amhara	10.5	25.0	7.6	56.9	100.0
Oromyia	16.4	31.0	9.7	42.9	100.0
SNNP	10.0	21.0	8.5	60.4	100.0
Tigray	22.5	45.2	22.5	9.8	100.0

The large technology yield gap, and small technical efficiency yield gap, suggest that narrowing wheat yield gaps in Ethiopia is best achieved through major transformative changes in current farming systems rather than with fine-tuning of current. The former may encompass changes in crop establishment method, from current broadcasting to row-planting, and mechanization of land preparation and crop establishment operations, while the latter mostly relates to improved time, form and space of inputs applied. Further research will focus on establishing the actual contribution of these factors to the different yield gaps in different regions with a more detailed analysis of farm data at regional level.

6) Summary of national level analysis

In this report we consider the wheat yield and wheat yield gap in Ethiopia using three waves of crop cut data from the LSMS-ISA survey. Our results indicate the size of the overall yield gap and the size of its constituent parts. We find evidence of a large technology yield gap in most regions of Ethiopia. But, there is also substantial room to close the yield gap with policies that target the technical efficiency yield gap and the economic yield gap. The results of our estima-

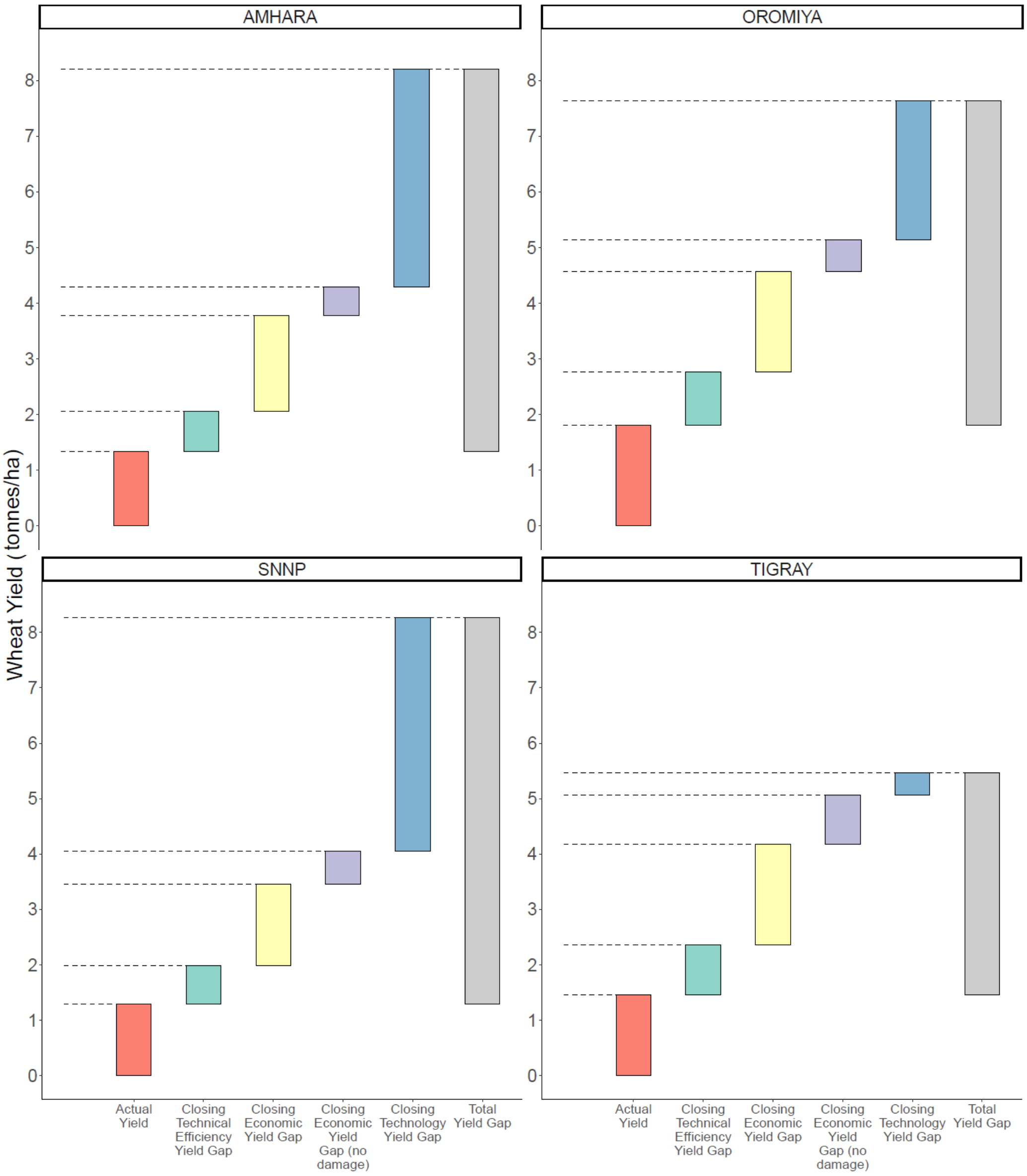

Figure 2. Wheat yield and yield gaps across different regions in Ethiopia in the regional level analysis. 'Economic Yield Gap' in this figure refers to the 'Allocative + Economic Yield Gap' defined in the main text.

tions indicate that mineral fertilizer and herbicide play important roles as inputs that can increase wheat yields in Ethiopia. Future work may consider focused studies in wheat growing areas of Ethiopia where these technologies are more widely used.

This report has limitations. We have restricted our attention to variables that are available in all three years and are not subject to the systematic errors that were uncovered as part of this project. For example, it would be natural to include the fertilizer, seed and labour rates applied per wheat field as regressors in our model. However, the low quality of several key quantities (not least GPS area measurements) makes this impossible. We should expect a degree of residual confounding due to omission of these key variables. We have not accounted for farmer heterogeneity in our estimations. Incorporating farmer heterogeneity or accounting for endogeneity is a suitable next step but will be difficult to achieve in a stochastic frontier framework as methods for dealing with these statistical problems are not widely understood or implemented in available software.

7) Update on regional level analysis and next steps

The national analysis presented in this report provides a first step towards mapping the magnitude, and associated causes, of wheat yield gaps in Ethiopia. However, it still lacks details on important agronomic variables explaining wheat yields and yield gaps and on a broader range of factors at farming systems level. These aspects will be considered in a more focused regional level analysis of wheat yield gaps in Ethiopia using the Wheat Adoption and Impact Surveys (WAIS).

The WAIS were analyzed further, particularly in relation to the location, i.e., latitude, longitude and elevation, of the individual households surveyed (Figure 3) and to the simulated water-limited yields (Figure 4). As shown in Figure 3A, the dataset covers different administrative regions in Ethiopia where wheat production is important such as Arsi, Gojam, Shoa and Wollo. Wheat production takes place mostly in the highlands, with most fields being located at an elevation greater than 2250 m and smaller than 3000 m above sea level (a.s.l., Figure 3B). The variation in elevations is particularly evident in Arsi and Shoa, where wheat is also cultivated at lower altitude (1500 – 2250 m a.s.l.). No clear relationships were observed between wheat yields and latitude or longitude (data not shown). As for elevation, only in Arsi there was a statistically significant quadratic effect of elevation on wheat yields with the maximum yields being observed at ca. 2500 m a.s.l. (Figure 3C).

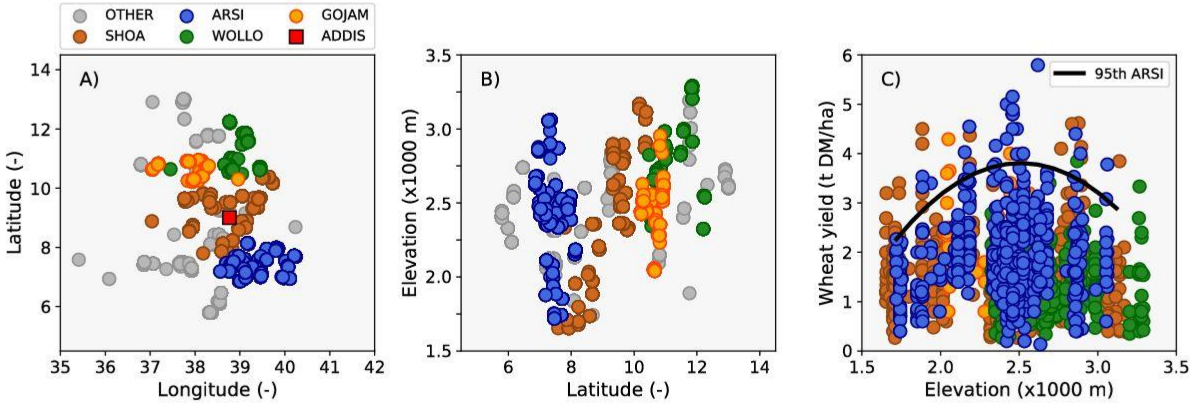

Figure 3. Location of the households included in the Wheat Adoption and Impact Survey (2011 ad 2013): A) latitude and longitude of the individual households, B) latitude and elevation of the individual households, C) relationship between elevation and wheat yield. Wheat yields presented in C) refer to the average wheat yield per household across fields and years and the solid line shows a quantile regression (95th percentile) between elevation and wheat yields in Arsi only.

The WAIS dataset was combined with the simulated water-limited yield per climate zone and wheat yield gaps were estimated for individual households in different administrative regions in Ethiopia (Figure 4). Actual wheat yields in farmers' fields were between 0 – 8 t/ha, while water-limited yields ranged between 6.5 – 10.5 t/ha (Figure 4A). This indicates the existence of a large yield gap for wheat in Ethiopia, which is independent of the elevation (Figure 4B) or administrative region (Figure 4C). On average, the yield gap closure is ca. 20% of the water-limited yields which is in line with the findings of Silva et al. (under review).

The next steps of the regional analysis will include the estimation of stochastic frontier models, and decomposition of wheat yield gaps into its intermediate yield gaps, following the framework presented in this report. For this purpose, it is important to define first a suitable unit of analysis from a biophysical and/or ‘farming systems’ perspective. The unit of analysis can be defined based on three different secondary data sources, namely 1) the administrative regions presented in Figure 4C, 2) the farming systems classification of Tilahun et al. (2011) or 3) the agroecological zones for wheat in Ethiopia (MoA, 1998). Options 2 and 3 will be explored in the weeks ahead, as recommended by dr Kindie Tesfaye and dr Frédéric Baudron.

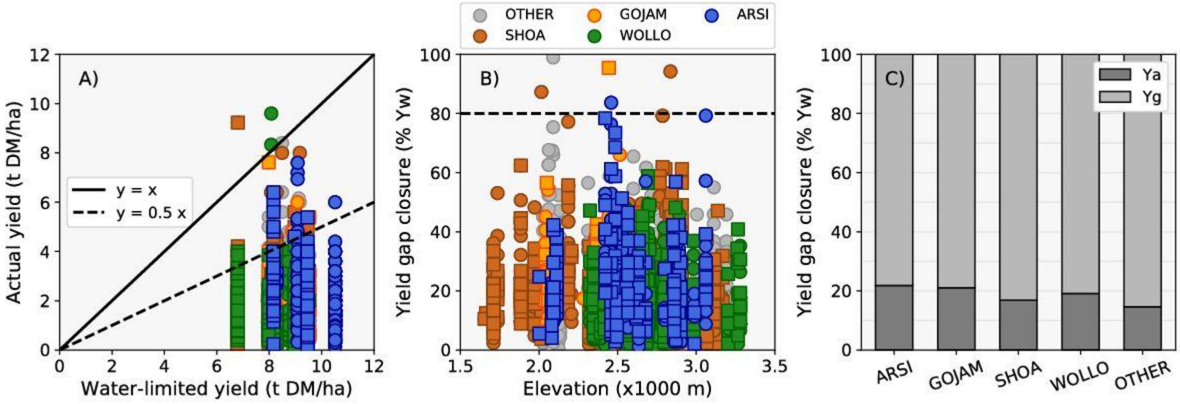

Figure 4. Magnitude and variability of wheat yield gaps in the Ethiopian highlands: A) actual yields and water-limited yields, B) yield gap closure in relation to elevation for individual households, C) average actual yield and yield gap for different regions.

Finally, the yield gap analysis will be linked to a policy analysis in order to assess the feasibility, and prioritize, interventions that can contribute to narrowing yield gaps. The relative contribution of the efficiency, resource and technology yield gaps are per se indicative of whether fine-tuning of current practices or major transformative changes in current farming systems are needed if yield gaps are to be narrowed. In addition, we will focus on the effects of improved wheat varieties and interactions between N and herbicide use / hand-weeding by considering these effects in the estimation of the stochastic frontier models. If time and data allows, we propose to 1) assess implications of the crop establishment method for actual yields and labour use efficiency as we expect this to be an important determinant of the technology yield gap and 2) explore the economic incentives for closing the wheat yield gap under current input/output prices.

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