Is labour a major determinant of yield gaps in sub-Saharan Africa? A study of cereal-based production systems in Southern Ethiopia

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ABSTRACT

We investigated the role of labour in explaining the yield gap of cereals at both crop and farm levels on smallholder farms in Southern Ethiopia. A household survey containing detailed information of labour use at crop and farm level of ca. 100 farms in a maize-based system around Hawassa and ca. 100 farms in a wheat-based system around Asella was used for this purpose. Stochastic frontier analysis was combined with the principles of production ecology to decompose maize and wheat yield gaps. Actual maize and wheat yields were on average 1.6 and 2.6 t ha\textsuperscript{-1}, respectively, which correspond to 23 and 26% of the water-limited yield (Y\textsubscript{w}) of each crop. For both crops, nearly half of the yield gap was attributed to the technology yield gap, indicating sub-optimal crop management to achieve Y\textsubscript{w} even for the farmers with the highest yields. The efficiency yield gap was ca. 20% of Y\textsubscript{w} for both crops; it was negatively associated with sowing date and with the proportion of women’s labour used for sowing in the case of maize but with the proportion of hired labour used for sowing and weed control in the case of wheat. The resource yield gap was less than 10% of Y\textsubscript{w} for both crops due to small differences in input use between highest- and lowest-yielding farms. The contribution of capital and farm power availability to crop yields, input use and labour use was analysed at the farm level. Labour calendars showed that crops cultivated in Hawassa were complementary, with peak labour occurring at different times of the year. By contrast, crops cultivated in Asella competed strongly for labour during sowing, hand-weeding and harvesting months, resulting in potential trade-offs at farm level. Oxen ownership was associated with capital availability, but not farm power in Hawassa and with both capital availability and farm power in Asella. Farmers with more oxen applied more nitrogen (N) to maize in Hawassa and cultivated more land in Aselia, which is indicative of an intensification pathway in the former and an extensification pathway in the latter. Differences in land/labour ratio and in the types of crops cultivated explained the different strategies used in the two sites. In both sites, although gross margin per unit area increased linearly with increasing crop yield and farm N productivity, gross margin per labour unit increased up to an optimal level of crop yield and farm N productivity after which no further response was observed. This suggests that narrowing the yield gap may not be economically rational in terms of labour productivity. We conclude that labour (and farm power) is not a major determinant of maize yield gaps in Hawassa, but is a major determinant of wheat yield gaps in Asella.

1. Introduction

Despite an abundance of agricultural technologies that can increase crop yields, productivity in sub-Saharan Africa remains well-below what can be potentially achieved with best agronomic practices (van Ittersum et al., 2016). There are large yield gaps for almost all crops in all regions of the continent (Beza et al., 2017; Tittonell and Giller, 2013). The main resources available to smallholders for farming are their land and labour, and their ability to invest in technology depends largely on access to capital. In this context, yield gaps are often a consequence of poor soil fertility and nutrient availability (Vanlauwe et al., 2014; Tittonell and Giller, 2013) and possibly a consequence of trade-offs at farm scale, regarding where and how labour is invested (Kamanga et al., 2014). This is particularly important given the stagnation, or even decline in some regions, of available farm power across the continent (Baudron et al., 2015b).

Current discourses on agricultural development focus on land productivity and seldom consider labour productivity (Woodhouse, 2010). However, it is unclear whether land or labour is the most limiting factor to smallholder production. The land/labour ratio and the seasonality of
labour demand determine whether land or labour is the ‘binding constraint’ (Erenstein, 2006). Farmers are more likely to increase production per unit area through the use of more intensive production practices, i.e. intensification, when the land:labour ratio is low (Jayne et al., 2014) and when there is little temporal overlap between activities. Conversely, increases in production through area expansion while maintaining or reducing input levels per unit area, i.e. extensification, are more likely to occur when the land:labour ratio is high and there is strong competition for labour in specific periods (Leonardo et al., 2015; Baudron et al., 2012).

Most households in rural Ethiopia cultivate less than two ha of land and own cattle (CSA and WB, 2013). Moreover, about 34% of the population lives with less than 1.90 US$ person⁻¹ day⁻¹ (WB, 2017). Despite the yield progress reported for cereals in Ethiopia (Abate et al., 2015; Taffesse et al., 2013), households are often capital constrained and most labour operations are still performed manually or with animal traction (Baudron et al., 2015b). Indeed, a recent analysis for Ethiopia based on the Living Standards Measurement Study (LSMS; Sheahan and Barrett, 2017) indicates that only ca. 30% of the sampled farms used herbicides and there was no record of households owning or renting a tractor. Ploughing one ha of land in the Ethiopian highlands with animal traction takes up to 50 h ‘per pass’ (Aune et al., 2001) and labour is important for operations such as hand-weeding (Amare, 2014; Workayehu and Wortmann, 2011).

The main objective of this study was to understand the role of labour in explaining yield gaps in cereal-based farming systems in Southern Ethiopia. The overarching questions addressed are whether, and to which extent, labour is a limiting factor to crop production across farming systems in sub-Saharan Africa. We hypothesize this is the case in farming systems with relatively narrow growing seasons and dominated by crops with peak demand for labour and draught power overlapping in time. Understanding whether, how and when labour can be a major constraint to smallholder production requires analysis at crop and farm levels. The former is important to capture the contribution of labour use, timing and form to crop production. The latter is needed because of resource constraints, a specificity of smallholder farmers, and because narrowing yield gaps is likely to interfere with other aspects of farm performance (e.g., gross margins and labour productivity). Data from a detailed household survey conducted in 2012 across smallholder maize- and wheat-based farms in Hawassa and Asella, respectively, were analysed for this purpose.

2. Framework of analysis

The main concepts for explaining yield gaps at crop level have been documented elsewhere (Silva et al., 2017a, 2017b). The yield gap is defined as the difference between the climatic potential yield (YP) or the water-limited yield (YW) and the actual farmers yield (Ya) under irrigated or rainfed conditions, respectively (van Ittersum and Rabbinge, 1997). Yield gaps can be decomposed into efficiency, resource and technology yield gaps if methods of frontier analysis are combined with concepts of production ecology and applied to individual farm level data (Fig. 1A). The efficiency yield gap is defined as the difference between technical efficient yields (YTEx) and Ya, and indicates by how much output can be increased for a given input level and can be explained by differences in timing, frequency, space and form of inputs applied, which in turn are affected by prioritization of crop management, availability of farm power and/or labour quality. The resource yield gap is defined as the difference between highest farmers’ yields (YHF) and YTEx, and captures the contribution of sub-optimal input quantities required to achieve YHF. Finally, the technology yield gap captures the difference between YW and YHF, which can be attributed to resource yield gaps of specific inputs and/or differences in resource use efficiency between technologies used by
In this paper, we apply these concepts to a production system in which resource availability and allocation may lead to trade-offs at farm level when closing the yield gap of multiple crops. A first step of analysis is to understand whether the availability of animal traction limits the area cultivated (Fig. 1B), which is still the case in many African smallholder farming systems (Ollenburger et al., 2016; Leonardo et al., 2015; Baudron, 2011). Second, the impact of alternative resource allocation strategies used by farmers to crop yield gaps is explored at farm level (Fig. 1C). These may differ for different crops both in the quantity of input used (Tittonell et al., 2007) and in timing of the operations performed (Kamanga et al., 2014). Limited availability of labour, capital and land, and their prioritization to different activities, induces trade-offs at farm level (Fig. 1D). Capital constraints may result in production trade-offs when land:labour ratios are low while labour may limit crop production when the land:labour ratio is high and when there is a lack of capital to adopt labour-saving technologies.

3. Material and methods

3.1. Household survey

Individual farm data was collected in 2012 within the project ‘Farm Mechanisation and Conservation Agriculture for Sustainable Intensification’ (FACASI, www.facasi.act-africa.org). The purpose of the farm survey was to map the potential demand for mechanisation in Eastern and Southern Africa. A total of 200 farmers were interviewed in Southern Ethiopia (100 interviews per site: Hawassa and Asella) using a semi-structured questionnaire requesting detailed information on labour use at crop and farm level. Households were selected using a systematic sampling procedure in each village based on transect routes across the village in which every fourth household, on alternate sides of the track, was sampled. In case one of the selected households was not available, the next one was selected.

Hawassa is located in the Rift Valley at a mean elevation of 1708 m above sea level, while Asella is located in the Southern highlands at a mean elevation of 2430 m above sea level. This difference in elevation affects climatic conditions (Fig. A1, Supplementary Material) and the type of crops cultivated in each site. Minimum and maximum temperatures are higher throughout the year in Hawassa compared to Asella as these were the main crops in each site (Table 1). We assumed the relationship between crop yield and a vector of inputs defined according to the principles of production ecology to be approximated by a translog functional form and regressed the efficiency yield gap on a set of explanatory variables. The inefficiency effects stochastic frontier model used builds upon Battese and Coelli (1995) and its formulation is summarized as follows:

\[ \text{Labour use}_{it} = \sum_{j} [ \text{Family labour}_{ij} \text{(person\-day)} + \text{Hired labour}_{ij} \text{(person\-day)} ] = \sum_{i} \text{Area}_{it} \text{(ha)} \]

where ‘Family labour’ and ‘Hired labour’ refer to the person-days (standardized to an 8 h working day) used for management operation in month \( t \) by household \( i \) and ‘Area’ to the area cultivated with management operation \( o \) by household \( i \). The management operations considered were land preparation, crop establishment (i.e., sowing), fertiliser application (both mineral and organic), hand-weeding and harvesting. Post-harvest operations such as threshing, winnowing and marketing of the crops were not considered. The same approach was used to analyse the seasonal demand for animal power.

3.2. Estimating and explaining yield gaps

3.2.1. Stochastic frontier analysis

The yield gap analysis focused on maize in Hawassa and wheat in Asella as these were the main crops in each site (Table 1). We assumed the relationship between crop yield and a vector of inputs defined according to the principles of production ecology to be approximated by a translog functional form and regressed the efficiency yield gap on a set of explanatory variables. The inefficiency effects stochastic frontier model used builds upon Battese and Coelli (1995) and its formulation is summarized as follows:

Table 1

<table>
<thead>
<tr>
<th>Farm</th>
<th>Crop yield (t ha(^{-1}))</th>
<th>N applied (kg N ha(^{-1}))</th>
<th>P applied (kg P ha(^{-1}))</th>
<th>Crop area (ha)</th>
<th>Total labour (person-days ha(^{-1}))</th>
</tr>
</thead>
</table>
| Hawassa
| Maize | 93 | 1.6 | (1.1) | 65.5 | (76.3) | 26.6 | (67.3) | 0.5 | (0.4) | 92.8 | (73.1) |
| Bean | 34 | 1.0 | (0.8) | 25.5 | (40.5) | 12.3 | (15.5) | 0.2 | (0.2) | 100.1 | (78.0) |
| Enset | 51 | 0.6 | (0.8) | 0.0 | -- | 0.0 | -- | 0.3 | (0.3) | 92.2 | (81.0) |
| Asella
| Wheat | 100 | 2.6 | (1.7) | 46.2 | (24.5) | 32.4 | (15.5) | 1.1 | (1.6) | 72.5 | (38.0) |
| Barley | 60 | 2.1 | (0.9) | 30.9 | (20.3) | 27.6 | (12.9) | 0.7 | (0.6) | 74.5 | (46.2) |
| Tef | 28 | 1.2 | (0.4) | 23.8 | (13.3) | 20.4 | (8.8) | 0.5 | (0.2) | 91.1 | (52.6) |
| Sorghum | 16 | 2.1 | (0.8) | 6.1 | (10.8) | 6.1 | (11.9) | 0.4 | (0.2) | 66.6 | (37.8) |
| Pea | 36 | 1.5 | (0.7) | 18.3 | (11.1) | 18.4 | (11.4) | 0.5 | (0.3) | 52.5 | (22.1) |
| Faba bean | 26 | 1.8 | (0.8) | 23.9 | (27.9) | 22.4 | (26.2) | 0.3 | (0.1) | 82.4 | (40.6) |
where \( y_i \) denotes the yield of maize or wheat reported in farm \( i \), \( x_i \) a vector of agronomic inputs \( k \) and \( j \) (both first- and second-order terms) assumed to explain variability in crop yields and \( z_i \), a vector of management and labour quality variables, \( l \) assumed to explain the efficiency yield gap. Two independently distributed random errors were included in Eq. (2) to capture random noise, \( v_i \) and technical inefficiency, \( u_i \) (see Battese and Coelli, 1995, for details on distributional assumptions and model estimation). The parameters \( \alpha_0, \beta_k, \eta_j, \delta_l, \delta_h, v_i \) and \( u_i \) were estimated in a single-step procedure using maximum likelihood (R package frontier; Coelli and Henningsen, 2013). The efficiency yield gap, and \( Y_{TESS} \) were estimated as follows:

\[
\text{EffYg}_i = 1 - \exp(-u_i)
\]

(4)

\[
Y_{TESS} = Y_{AF} \times \exp(-u_i)^{-1}
\]

(5)

Four different stochastic frontier models (Eqs. (2) and (3)) were estimated for maize and wheat. Model I was estimated without inefficiency effects and it was used to assess the sign of the parameter estimates and to quantify the efficiency yield gap (cf. Fig. 4). Models II and III included inefficiency effects related to the frequency and timing of management operations, respectively, and model IV included inefficiency effects related to the quality of labour used (source and gender).

The stochastic frontier models were estimated using farmer reported data on crop yields \((y_i)\) and on growth-defining, -limiting and -reducing factors \((z_i)\) for unique farm \( \times \) crop combinations. Dry matter yields of maize and wheat (kg DM ha\(^{-1}\)) were used as dependent variables. These were calculated by assuming a standard moisture content of 15.5 and 13.5% for respectively maize and wheat (www.yieldgap.org). Differences in growth-defining factors were accounted for by using categorical variables for different communities (maize: Wondo Genet vs. Hawassa Zuria; wheat: Haro Bilalo vs. Gara Silingo). The only growth-limiting factor considered for both crops was the rate of N applied (kg N ha\(^{-1}\)). We were not able to account for the effects of P applied due to collinearity between this variable and N applied (as the main fertiliser used in Ethiopia is diammonium phosphate, DAP), and of organic amendments due to the low number of observations. Growth-reducing factors considered for maize were labour used for the first hand-weeping (person-days ha\(^{-1}\)), labour used for the second hand-weeping (person-days ha\(^{-1}\)) and intercropping with bean (yes or no) while for wheat these included labour used for the first hand-weeping (person-days ha\(^{-1}\)) and labour used for herbicide application (person-days ha\(^{-1}\)). The latter is assumed to be a proxy for the actual amount herbicide applied. Our analysis over-estimates the efficiency yield gap because we were not able to control for differences in crop varieties, sowing densities and soil conditions. Input-output variables were mean-scaled and ln-transformed prior to the analysis.

The determinants of the efficiency yield gap \( (v_i) \) related to the frequency of management operations were the number \( (#) \) of ploughing, sowing, fertiliser and weed-control operations. The determinants related to the timing of management operations were sowing date (month), date of first fertiliser application (month after sowing) and date of first weed control (month after sowing). The number of sowing operations and sowing date was only considered for maize due to collinearity effects between these variables, similar to the date of first fertiliser application and first weed control for wheat. The sowing window for wheat in Asella is narrow and most farmers perform a basal fertiliser application at sowing and a first weeding up to two weeks after sowing. Finally, the determinants related to labour quality were the proportion of hired labour used for land preparation (%), the input of animal power used for land preparation (animal-days ha\(^{-1}\)) and the proportion of hired labour (%), female labour (%) and child labour (%) used for sowing and for weed control. No data transformations were applied to the \( z_i \) variables.

3.2.2. Yield distribution and response to inputs

The resource yield gap due to N, P and labour was studied by comparing yields and input use among farmers with the highest, average and lowest yields. Farmers with highest yields were identified as the observations above the 90th percentile of Ya and the highest farmers’ yield \((Y_{HP})\) was calculated as the mean Ya for these observations. A similar approach was used to identify farmers with smallest yields \((Y_{LF}, \text{mean Ya for observations below the 10th percentile of Ya})\) and average farmers’ yields \((Y_{AF}, \text{mean Ya for observations between 10th and 90th percentile of Ya})\). Significant differences in crop yields, input use and labour use between \(Y_{HP}, Y_{AF} \) and \(Y_{LF}\) were tested using analysis of variance (ANOVA) followed by a Tukey HSD post-hoc test (p-value \( \leq 0.05; \text{agricol} \text{ar} \text{e} \text{r} \text{ p} \text{a} \text{c} \text{k} \text{e} \text{ } x \text{t} \text{e} \text{m} \text{a} \text{t} \text{i} \text{t} \text{i} \text{o} \text{n} \)) (package rsm; de Mendiburu, 2015). Observations with organic fertiliser were not considered to avoid confounding.

The univariate relationships between crop yield and input and labour use was further studied using boundary line analysis (Shatar and McBratney, 2004; Webb, 1972). For this purpose, the independent variables were sorted in ascending order and the following model (cf. Fermont et al., 2009) was fitted to the observations with largest yield per unit input (boundary points; Schnug et al., 1996):

\[
y_{\text{boundary}} = \frac{y_{\text{max}}}{1 + (K \times \exp(-R \times x))}
\]

(6)

where \( y_{\text{max}} \) is the \( Y_{ISP} \) estimated for each crop, \( x \) is the independent variable, \( K \) and \( R \) are constants to be estimated using nonlinear least squares (nlx function in R; R Core Team, 2013). Two observations with maize yields greater than 8t ha\(^{-1}\), one observation with more than 600 kg N ha\(^{-1}\) applied for maize and another one with ca. 200 kg N ha\(^{-1}\) applied for wheat were excluded from the analysis. Results for maize and wheat are presented in Fig. 5 and results for other crops are presented in Supplementary Material (Figs. A7 and A8).

3.2.3. Simulated Yw and Yp

Yw was used as the biophysical benchmark for Ya, and to quantify the technology yield gap, because farmers in both sites operate under rainfed conditions. Estimates of Yp were used as well to report the yield penalty associated with sub-optimal water supply (Yp - Yw). The source of Yp and Yw used in this study was the Global Yield Gap Atlas (GYGA, 2016) and information was only available for maize and wheat. Simulations for maize in Hawassa were conducted with the Hybrid-Maize model (Yang et al., 2004) for the years 1999-2012 using weather data for Arse-Negele and considering silt loam, clay loam and sandy loam soil types. Simulations for wheat in Assela were performed with the WOFOST model (Boogaard et al., 2013) for the years 1998–2011 using the weather data for Kulumsa and considering silt loam, clay loam and sandy loam soil types. Both models were parametrized based on expert knowledge from local agronomists and evaluated against published experimental data for each crop (www.yieldgap.org/ethiopia).

3.3. Embedding yield gaps within farm dynamics

Further insights into the drivers of yield gaps and their crop level determinants were obtained by conducting different analyses at farm level. These captured the contribution of resource availability to management practices explaining the yield gap as well as the relationship between crop yield and farm performance indicators. Resource allocation at farm level was also studied to assess whether there is competition, substitution or complementary use of land and labour between different crops (Fig. 1D). Results are presented as Supplementary Material (Figs. A9 and A10).
3.3.1. Resource availability at farm level

Farms were classified according to the number of pairs of oxen owned. These resulted in three different groups in Hawassa (none, one pair and two pairs or more) and only two groups in Asella (one pair and two or more pairs). This classification was done to test whether oxen ownership relates to labour, land and capital availability, and to analyse its relationship with input use and crop yield. Significant differences between groups of farms with different oxen ownership were tested for farm assets (index), farm size, maize and wheat yields, and input and labour use for maize and wheat using ANOVA and the Tukey HSD post-hoc test, as specified above. An index estimating the value of farm assets was developed based on the number of productive assets (e.g., ploughs, hoes and water pumps but not the number of livestock) possessed by each household and their relative economic value (ILRI, 2011; BMGF, 2010). Cultivated area refers to the total area (in ha) cultivated by each household, input use includes N application rates to maize and wheat, and labour use includes animal power used for ploughing and sowing and manual labour used for the 1st weeding also for maize and wheat.

3.3.2. Yield gaps and farm performance

Farm performance was evaluated based on food production (using N productivity as an indicator), economic viability (gross margin) and returns to labour. The contribution of livestock production to these indicators was not assessed, which means that our calculations may be slightly under-estimated.

N productivity at farm level is a metric that includes the productivity of all crops cultivated within the farm, as opposed to yield which is a crop-specific metric, and was calculated (in kg N ha⁻¹, Silva et al., 2017a) as follows:

\[ N_{\text{productivity}} = \frac{\text{Total N output}}{\text{Total land area}} \]

Fig. 2. Labour calendar (person-days/ha) for crop-specific management operations across smallholder farms in Hawassa and Asella, Southern Ethiopia. The main crops in Hawassa are A) maize, C) bean and E) enset, and in Asella B) wheat, D) other cereals such as barley, tef and sorghum and F) pulses such as pea and faba bean. Peak periods of labour demand for the different crops are highlighted in grey.
where 'Yield' and 'Area' refer to the dry matter yield and area, respectively, of crop \( j \) in farm \( i \) as reported in the household survey. N concentration in harvested products ('N content' on a dry matter basis) was taken from Mellisse et al. (2017): 1.13% for maize, 0.75% for kocho (enset), 3.78% for bean and faba bean, 1.25% for barley, and 1.76% for tef. The N contents of wheat (2.15%), sorghum (2.10%) and pea (4.15%) were taken from Nijhof (1987).

Gross margin (ETB ha\(^{-1}\)) was estimated as the difference between revenues on the one hand and fertiliser and labour costs per unit area on the other hand. Returns to labour (RTL, ETB person\(-\)day\(^{-1}\)) were calculated as gross margin per unit labour used. The calculation of gross margin considered the costs of fertilisers and non-family labour paid in-cash or in-kind to perform particular tasks (referred to as hired labour below). The calculation of these indicators was done as follows:

\[
\text{N productivity}_{ij} = \frac{\sum_{j} \text{Yield}_{ij} \times \text{N content}_{ij} \times \text{Area}_{ij}}{\sum_{j} \text{Area}_{ij}}
\]

\[
\text{Revenue}_{ij} = \sum_{j} \text{Yield}_{ij} \times \text{Price}_{ij}
\]

\[
\text{Total Cost}_{ij} = \sum_{j} \text{Fertiliser used}_{ij} \times \text{Fertiliser price} + \sum_{j} \text{Labour hired}_{ij} \times \text{Wage}
\]
Gr. Marg.\textsubscript{i} = Revenue\textsubscript{i} (ETB ha\textsuperscript{-1}) − Total Cost\textsubscript{i} (ETB ha\textsuperscript{-1}) \hspace{1cm} (10)

\[ RTL\textsubscript{i} = \sum_{j} \frac{\text{Gr. Marg.}\textsubscript{i}}{\text{Labour used}\textsubscript{i} (\text{person−day ha}\textsuperscript{-1})} \hspace{1cm} (11) \]

where \( j \) denotes a specific crop and \( i \) a specific farm. The underlying crop data used to calculate gross margin and returns to labour were: 'Yield' which refers to farmer self-reported yield corrected to dry matter content, 'Fertiliser used' which refers to the amount of urea or DAP applied, 'Labour hired' from land preparation to harvesting and 'Labour used' which is the total amount of family and hired labour used between land preparation and harvesting. Input-output prices were obtained from key informants in each site and included the market price of harvested crop product ('Price'), the unit price of urea and DAP ('Fertiliser price') and the unit price paid for hiring labour for different operations ('Labour wage'). Farm revenue assumes all crop production is sold, and thus corresponds to the 'best-case scenario' in terms of economic performance. The total cost of production is slightly underestimated due to lack of data on the amount of seed and herbicide used. Family labour costs were not considered in the calculations.

The relationship between the aforementioned indicators, and between those and crop yield, was studied to identify trade-offs or synergies between closing the yield gap and optimising different indicators, respectively. These were studied using quantile regressions (quantreg R package; Koenker, 2016) fitted to the top 90th percentile of the data, i.e., the observations with largest gross margin or returns to labour per unit farm N productivity or crop yield.

### 4. Results

#### 4.1. Labour calendars for crop production

The seasonality of labour used for crop production differed strongly between the two sites (Figs. 2 and 3). In short, the three main crops cultivated in Hawassa showed a complementary use of labour throughout the year while the crops cultivated in Asella competed strongly for labour at the time of sowing, hand-weeding or harvesting. This was true for both labour and animal draught power, which was more important in Asella than in Hawassa (Fig. 3). Further details on labour dynamics in terms of timing (Fig. A4), amount (Fig. A5) and quality (Table A1) for management operations are provided in the Supplementary Material.

The complementary use of labour observed in Hawassa can be explained by the type of crops cultivated in this site (Fig. 2A, C and E). Land preparation for maize cultivation is performed, both manually and with animal traction, between January and April, depending on rainfall and pest abundance. Most farmers apply basal mineral fertiliser, and some apply fertiliser as a top dressing up to two months after sowing. Animal traction is often used up to one month after sowing to break surface crusts between rows of maize and control weeds, a ridging practice locally known as shilshalo (Fig. 3A), and two hand-weedicings are common between May and June. The maize growing season ends in October–November. Labour requirements for maize are minimum between July and September, when labour is used to grow a bean crop, often intercropped with maize (land preparation and sowing in July, hand-weeding in August and harvesting slightly before the maize crop.
4.2. Yield gaps and yield variability

4.2.1. Efficiency yield gap

In Hawassa, there was a positive linear and quadratic effect of N application on maize yields and yield response to N increased with increasing input of labour for the second hand-weeding (Model I without inefficiency effects; Table 2). In addition, labour used for the first hand-weeding had a positive effect on maize yields and maize yield response to labour used for the first hand-weeding increased with increasing input of labour used for the second hand-weeding, when the number of management operations was included as inefficiency effects (Model II). The effects of N application on maize yields were ‘diluted’ when the timing of management operations was included as an inefficiency effect (Model III) and sowing at later months resulted in significantly wider efficiency yield gaps. Finally, there was a significant effect of N (positive) and N × labour used for the first hand-weeding (negative) on maize yields when the effects of labour quality on the efficiency yield gap were considered (Model IV). In that model, a greater proportion of women’s labour used for sowing was associated with significantly wider efficiency yield gaps. Across all models, significantly smaller maize yields were reported for Wondo Genet than for Hawassa Zuria, but in Model IV the difference was only significant at 10% significance level.

The variables that best explained the production frontier and efficiency yield gaps for wheat in Asella (Table 2) were considerably different from maize in Hawassa. In Asella, there was a statistically significant positive (linear) effect of herbicide use on wheat yields, which was consistent across all models. Moreover, significantly positive (linear and quadratic) effects of labour used for the first hand-weeding on wheat yields were observed in all but Model IV. Significant effects of N application on wheat yields (quadratic) were only observed when variables of labour quality were included as inefficiency effects (Model IV). The proportion of hired labour used for ploughing (at 10% significance level only), sowing and weed control were positively associated with the efficiency yield gap, which indicate that wheat yield gaps in Asella are closely linked to labour quality for some management operations.

Based on Model I, the efficiency yield gap was on average 1.6 and 1.7 t ha⁻¹ (or 49% and 38% of Yₜₓₑₓ) for maize and wheat (Fig. 4A and B), respectively. The variability of Yₜₓₑₓ was large for maize in Hawassa (standard deviation ca. 1.5 t ha⁻¹) and for many farms the efficiency yield gap was well above 50% of Yₜₓₑₓ, especially at low Ya levels. Conversely, the variability of Ya and Yₜₓₑₓ of wheat in Asella was smaller compared to maize in Hawassa, and only few farms exhibited efficiency yield gaps greater than 50% of Yₜₓₑₓ.

4.2.2. Resource yield gap

The magnitude of Yₚₓₑₓ, Yₐₓ and Yₖₓ for maize in Hawassa were 4.0, 1.6 and 0.2 t ha⁻¹, respectively (Figs. 5A - 5D). Yₚₓₑₓ were obtained with significantly more mineral N applied (111 kg N ha⁻¹), compared to Y₆ₐ (59 kg N ha⁻¹) and Yₜₖ (41 kg N ha⁻¹), and there was no significant difference in mineral N applied between these last two groups (Fig. 5A). These results confirm the statistically significant positive effect of N applied on the production frontier for maize (Table 2). Similar results were observed for mineral P applied (Fig. 5B). No significant difference between Yₚₓₑₓ, Y₆ₐ and Yₕₓ was observed regarding animal draught power used for ploughing and sowing (Fig. 5C) and regarding the labour used for the first hand-weeding (Fig. 5D and Table 2).

For wheat in Asella, Yₚₓₑₓ, Y₆ₐ and Yₕₓ were 4.9, 2.6 and 1.1 t ha⁻¹, respectively (Figs. 5E - 5H). In contrast with maize in Hawassa, there were no significant differences in mineral N applied to wheat between Yₚₓₑₓ (57 kg N ha⁻¹), Y₆ₐ (43 kg N ha⁻¹) and Yₕₓ (36 kg N ha⁻¹; Fig. 5E). This is confirmed by the lack of significant effects of N applied in the production frontier of wheat (Table 2). Highest farmers’ yields were attained with 42 kg P ha⁻¹ (Fig. 5F), which is significantly more than the P application rates used by the average (30 kg P ha⁻¹) and the...
lowest yielding farmers (28 kg P ha\(^{-1}\)). Highest farmers’ yields were also associated with more animal power and labour use (Fig. 5G and H).

4.2.3. Technology yield gap

The largest share of maize and wheat yield gaps was attributed to the technology yield gap. For maize this was 3.2\(\text{t ha}^{-1}\), or 45% of \(Y_w\) (Figs. 5A - 5D), and for wheat 5.2 \(\text{t ha}^{-1}\), which corresponds to 52% of \(Y_w\) (Figs. 5E - 5H). The simulated \(Y_w\) for maize was on average 7.0 \(\text{t ha}^{-1}\) but was highly variable (standard deviation of ±3.7 \(\text{t ha}^{-1}\)), which indicates high rainfall variability between years. For wheat, the simulated \(Y_w\) was 10 \(\text{t ha}^{-1}\) and its inter-annual variability was low (standard deviation of ±1.2 \(\text{t ha}^{-1}\)), suggesting a more uniform inter-annual rainfall distribution. A large difference between \(Y_p\) and \(Y_w\) was observed for maize (3.5 \(\text{t ha}^{-1}\)) but not for wheat (0.9 \(\text{t ha}^{-1}\), data not shown). These results indicate that maize-based farming systems in Hawassa are more affected by water limitations and by climatic risk (due to erratic distribution and amount of rainfall) than wheat-based farming systems in Asella.

4.3. Farm power and capital availability

In Hawassa, oxen ownership was associated with capital availability, but not with farm power, as farms with more pairs of oxen had significantly more assets (and/or assets of greater value) than farms with less pairs of oxen (Fig. 6A). However, there was no difference in the cultivated area between the different groups (Fig. 6B). Conversely, oxen ownership in Asella was associated with both capital availability and farm power as farms with more pairs of oxen were found to have significantly more, and/or more valuable, assets (Fig. 6C), and significantly larger cultivated area than farms with fewer oxen (Fig. 6D).

Oxen ownership in Hawassa was positively associated with greater maize yields and \(N\) application rates for maize, but not with more animal power used for ploughing and sowing or more labour used for hand-weeding. Farms owning two or more pairs of oxen produced ca. 3.2 \(\text{t maize ha}^{-1}\), which is significantly greater than the 2.7 and 1.7 \(\text{t ha}^{-1}\) produced by respectively farms with one pair of oxen or no oxen (Fig. 6E). \(N\) application rates were nearly double in farms with two or more pairs of oxen compared with farms with no oxen (120 vs. 53 kg N ha\(^{-1}\); Fig. 6F). No significant difference was observed in animal power used for ploughing and sowing (2–12 animal-days ha\(^{-1}\); Fig. 6I) or total labour used for the first hand-weeding (5–15 person-days ha\(^{-1}\); Fig. 6J) between groups differing in oxen ownership.

Increased oxen ownership and availability of animal traction in Asella resulted in more cultivated area, but not higher wheat yields. This is demonstrated by the significant differences in cultivated area between groups with one pair or two or more pairs of oxen (Fig. 6D) and by the lack of significant differences in wheat yields between the two groups: 2.9 vs. 3.5 \(\text{t ha}^{-1}\) for farms owning respectively one or two or more pairs of oxen (Fig. 6G). Similarly, no significant difference in \(N\) applied to wheat was observed between the two groups (ca. 50 kg N ha\(^{-1}\), Fig. 6H). An increase in oxen ownership did not translate into a reduction of animal power used per unit area for ploughing and sowing (Fig. 6K), while farms with two or more pairs of oxen tended to use slightly less labour for the first hand-weeding (Fig. 6L) and slightly more labour for herbicide application than farms with one pair of oxen (data not shown), but the differences were not significant.

4.4. Crop and farm performance indicators

Farm \(N\) productivity in Hawassa was ca. 15 kg N ha\(^{-1}\) on average, which is much less than the average of 41 kg N ha\(^{-1}\) observed in Asella (Fig. 7). This indicator was positively associated with gross margin per ha at farm level in both sites (Fig. 7A). The average gross margin observed in Hawassa was ca. 4 kETB ha\(^{-1}\) and ca. 16 kETB ha\(^{-1}\) in Asella where farmers grow crops of higher value such as pulses, tef, wheat and barley. A quadratic relationship was observed between farm \(N\) productivity and returns to labour in both sites meaning that returns to labour increase up to 37.6 and 61.5 kETB ha\(^{-1}\) in Hawassa and Asella, respectively, after which returns to labour decline as \(N\) productivity increases (Fig. 7B). Returns to labour were ca. 103 ETB person-day\(^{-1}\) in
Hawassa and ca. 324 ETB person-day$^{-1}$ in Asella, which again points to better economic farm performance in Asella than in Hawassa.

Gross margin per ha at crop level increased linearly with maize and wheat yields (Fig. 7C) indicating little trade-off between closing the yield gap and maximising the gross margin within the yield ranges reported. The difference in gross margin observed between crops reflected again the greater profitability of wheat in Asella as compared to maize in Hawassa. Similarly to the farm level analysis, there was a quadratic relationship between crop yield and returns to labour at crop level (Fig. 7D) with optimal returns to labour observed at 3.9 t maize ha$^{-1}$ in Hawassa and 4.0 t wheat per ha$^{-1}$ in Asella. These yields are comparable to the $Y_{HF}$ observed for maize in Hawassa but less than $Y_{HF}$ observed for wheat in Asella (cf. Fig. 5).

5. Discussion

5.1. Scope for intensification in Southern Ethiopia

The yield gap was on average 5.4 t ha$^{-1}$ (or 77% of $Y_w$) for maize in Hawassa and 7.4 t ha$^{-1}$ (or 74% of $Y_w$) for wheat in Asella. These confirm large yield gaps for these crops in Ethiopia reported earlier (Hoffmann et al., 2017; van Ittersum et al., 2016). For maize, the efficiency yield gap was 23% of $Y_w$, the resource yield gap was 9% of $Y_w$ and the technology yield gap was 45% of $Y_w$. For wheat, the efficiency and resource yield gaps were respectively 17 and 5% of $Y_w$ and the technology yield gap was ca. 52% of $Y_w$. Smaller efficiency yield gaps for maize in Hawassa were associated with early sowing and, to a less extent, a smaller proportion of women’s labour involved in sowing (probably confounded with resource constraints), while for wheat in Asella the efficiency yield gap increased in tandem as the amount of hired labour used for sowing and weeding increased (Table 2). It is well known that sowing and weeding are labour intensive and tedious operations, and their impact on wheat yield in Ethiopia has been well documented (Nyssen et al., 2011; Taa et al., 2004; Tanner et al., 1993). The small resource yield gap can be attributed to the small variation in input use between the farms studied, particularly for N and P applied (Fig. 5). The technology yield gap was nearly double the size of the efficiency yield gap for both crops which suggests that major transformative changes in farming are required to raise yields as opposed to ‘tweaks’ in the system such as conservation agriculture, timely weeding or better fertiliser placement.

The large technology yield gaps observed for maize and wheat in Southern Ethiopia (Fig. 5) can be explained by resource yield gaps of specific inputs and by a lack of adoption of precision agriculture technologies to reach $Y_w$. For maize, resource yield gaps due to N are key as the N application rates required to reach $Y_w$ are much greater than the maximum rates observed in farmers’ fields (Fig. 5A). The N application rates observed in Hawassa were positively associated with oxen ownership (Fig. 6E), a proxy for capital (Fig. 6A), which points to the prevalence of capital constraints in this site. In addition, the sowing window is considerably longer in farmers’ fields (Fig. 2A) than assumed in the crop model simulations of $Y_w$ and farmers use broadcasting rather than localized fertiliser placement methods (Sime and Aune, 2014). For wheat, the most striking differences between $Y_{HF}$ and $Y_w$ relate to the crop establishment method (broadcasting seed in farmers’ fields vs. row planting in the simulations; Alemu et al., 2014), and the low N application rates compared to what is required to achieve $Y_w$ (on-farm trials in the region use up to 180 kg N ha$^{-1}$; Habte et al., 2014). Other factors may relate to sub-optimal sowing densities, possible limitations of other nutrients and lack of biocides to control pests and diseases (used by less than 10% of the farmers surveyed). Further research is required to clarify the actual contribution of these factors to the technology yield gap.
5.2. Implications for agricultural development in sub-Saharan Africa

Boosting the inputs of farm power seem to be necessary and desirable in farming systems with relatively narrow growing seasons and competition for labour among different crops, as is the case of Asella, but less of a priority in farming systems with the characteristics observed in Hawassa (Figs. 2 and 3). Hawassa is dominated by 'maize mixed farming systems' (Dixon et al., 2001) and characterized by an 'unimodal wet season' (Herrmann and Mohr, 2011; Fig. A1A - Supplementary Material). This type of farming system covers ca. 10% of the land area and ca. 15% of the agricultural population of sub-Saharan Africa, being spread mostly across Eastern Africa (Dixon et al., 2001), a region largely dominated by unimodal wet season rainfall regimes (Herrmann and Mohr, 2011) with relatively long growing seasons. Conversely, 'highland temperate farming systems' are dominant across the Ethiopian highlands, where Asella is located, covering ca. 2% of the land area and ca. 7% of the agricultural population in the continent (Dixon et al., 2001). The dual wet season (unimodal - unimodal) rainfall regime characterizing this farming system (Fig. A1C - Supplementary Material), allows for a single growing season with a relatively narrow sowing window (Figs. 2 and 3). This leads to labour competition among the different crops throughout the growing season in this farming system, as reported in our study for the first time.

Oxen ownership was associated with farm power and/or capital availability (Baudron et al., 2015b; Aune et al., 2001) and there were clear differences between the two sites regarding this metric (Fig. 6). In Hawassa, more oxen was associated with crop intensification, i.e., increase in yield with no impact on cultivated area (Fig. 6B and F). Conversely, in Asella, more oxen resulted in extensification of crop production, i.e., larger cultivated area but no impact on yield (Fig. 6D and G) rather than higher labour use efficiency (i.e., a decrease in the number of days worked per unit area, Fig. 6K and L). This contrast between the two sites may well be explained by differences in land:-labour ratio; population density in Hawassa is more than 600 persons km$^{-2}$ while in Asella it is ca. 200 persons km$^{-2}$ (based on the 2007 census). A tendency towards extensification has been observed in other farming systems across sub-Saharan Africa as well, but only when land is abundant (Ollenburger et al., 2016; Leonardo et al., 2015; Baudron et al., 2012).

These pathways have important implications for agricultural development and for the interventions required to close yield gaps. Capital and land, not labour, constraints predominate in Hawassa (Fig. 6A), where gross margin per ha at crop and farm level are also small compared to the national poverty line (Fig. 7A and C). Lack of capital and small farm sizes most likely drove many farmers to replace staple crops (i.e., maize and beans) by high value crops, such as khat and coffee in this site (Mellisse et al., 2017). This strategy is often observed in farming systems dominated by small farms (van Vliet et al., 2015; Hazell et al., 2010). Conversely, labour constraints may still be problematic for some farms in Asella (Fig. 2), particularly during the months of ploughing and sowing, hand-weeding and harvesting wheat (Fig. A9, Supplementary Material). Despite the linear increase of gross margin per unit area with increasing wheat yield and farm N productivity, the gross margin per labour unit did not increase any further after an optimal level of crop yield and farm N productivity (Fig. 7B and D). This points to the importance of increasing labour productivity and questions the desirability of narrowing yield gaps beyond $Y_{HF}$ in these farming systems with current technologies.

5.3. Opportunities for labour-saving technologies

Labour-saving technologies can reduce the number of management operations (e.g., conservation agriculture; Nyssen et al., 2011) or the actual amount of labour required per management operation (e.g.,
mechanisation and herbicides). These can contribute to increase labour use efficiency (Fig. 5) by increasing crop yield through improved timeliness and precision (e.g., sowing depth and row planting), and/or reducing labour demand for critical management operations. For example, the ‘bed-and-furrow’ system proposed by Nysseń et al. (2011) would be a suitable option to decrease labour demand for land preparation and sowing in Asella (Fig. A9D, Supplementary Material). Herbicides are already widely used for wheat in this site (Fig. 5H), and reduce the labour requirements for hand-weeding to less than 10 person-days ha⁻¹ (Fig. 2B). Two-wheel tractors may be an option for smallholder farms in Asella, and similar areas in the Ethiopian highlands, to ensure labour is less limiting at sowing and to reduce dependency on draught animals for land preparation. Draught animals are currently used for less than six months a year (Fig. 3) while they require a large daily intake of crop residues and fodder (Baudron et al., 2015b). Decreasing the stock of animals would have a number of advantages at systems level as it would free crop residues to be used as soil amendments (Baudron et al., 2014) and reduce the grazing pressure on, already degraded, communal lands (Baudron et al., 2015a). However, this is unlikely to be a popular strategy among farmers due to the cultural and financial importance of livestock.

The stagnation or even decline of farm power observed across different regions in SSA has re-opened the debate on mechanisation of smallholder agriculture in Africa (Baudron et al., 2015b). Indeed, ‘suitable, reliable and affordable mechanisation’ is recognized as a key strategy to accelerate agricultural growth in Africa (Malabo Declaration of the African Union). Our analysis offers evidence that labour is a major limiting factor in some smallholder farming systems, and points to a strong demand for mechanisation in these systems, contrary to what is often stated (Diao et al., 2016). This may be further exacerbated in the future by out-migration from rural to urban areas, particularly in Southern Ethiopia (Bezu and Holden, 2014), and the preference of household members for more regular sources of income (Frelat et al., 2016; Haggblade et al., 2007). Moreover, herding and household chores - such as water and fuelwood collection - also require a substantial amount of labour (Fig. A12; Supplementary Material), which further constrain the labour available for agricultural production. Reducing labour drudgery at farm level is especially important for men who are in charge of most crop management activities in our study sites (van Eerdedwijk and Danielsen, 2015; Fig. A6; Supplementary Material).

6. Conclusions

We investigated whether labour is a major determinant of yield gaps in two contrasting cereal-based farming systems in Southern Ethiopia. Indeed, this was the case in farming systems where peak demand for management of different crops occurs in the same period (highland temperate mixed farming systems in Asella) but not in farming systems with complementary crop calendars (mixed maize farming systems in Hawassa). Moreover, oxen ownership was associated with intensification of maize production in Hawassa and extensification of wheat production in Asella as farms with more oxen used higher rates of mineral N fertiliser in Hawassa and cultivated more land in Asella, while no difference in labour use efficiency between farms differing in oxen ownership was observed in either site. However, the central role of oxen as a source of traction in Asella may become problematic in the future, given the seasonality observed in the use of animal draught power and the large amounts of biomass needed to maintain the animals throughout the year. Replacing animal draught power by mechanisation (e.g., two-wheel tractors) would thus free crop residues and communal grazing areas in addition to spare time for household members to engage in more rewarding off-farm activities.

Yield gaps were large in both farming systems: 77% of Yw for maize in Hawassa and 74% of Yw for wheat in Asella. For both crops, this yield gap was largely attributed to the technology yield gap (45 and 52% of Yw for maize and wheat, respectively). This indicates that transformative changes, rather than fine-tuning current practices, are needed to narrow yield gaps in the farming systems studied. Mechanisation is an example of the transformative changes needed if yield gaps are to be narrowed across the Ethiopian highlands as it improves the timeliness and precision of land preparation and crop establishment. In turn, these allow for more efficient fertiliser application and weed control later in the season. Our results also show that narrowing yield gaps may not be economically rational given the current prices that farmers receive for their produce.

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Appendix A. Supplementary data

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References
