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Developing country-wide farm typologies: An analysis of Ethiopian smallholders' income and food security

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Abstract
Ethiopia's agricultural sector is highly diverse and subject to change due to different factors such as climate and population growth. Consequently, competition for available land, water, energy, and other inputs increases, posing pressure on the rural population's livelihoods and food security. It is therefore imperative to analyze farmer's production choices under these changing circumstances. The objective of this paper is to develop a methodology to establish country-wide farm typologies allowing for both a spatial and temporal analysis of the evolution of the agricultural sector, and in particular smallholders' food security and income in Ethiopia.
First, household survey data is employed to categorize smallholder farming systems according to their agro-ecological zone, farm size, main activities and degree of intensification. Second, farming systems are extrapolated using a multinomial logit-regression. Resulting combinations of farming-system occurrence and their production activities are harmonized with national statistics and subsequently equipped with the potential to intensify. Compared with other typologies that commonly only focus on the distribution of farming systems, this study fills the typology with data, allowing for the analysis of income and food security over space and time. It is concluded that livestock-oriented systems are less profitable than crop-oriented systems and more prone to food-insecurity. Increased input intensification is one way to reduce pressure on cropland expansion caused by the expected increase in population, but has to go together with other methods to fully alleviate pressure on land and thereby poverty and food insecurity.

1. INTRODUCTION

Ethiopia is one of the fastest growing economies in the world, with an average annual growth in GDP of 10% (Paul et al., 2016). Yet, the largest share of the GDP of the country (46.9%) still comes from agriculture (Diao et al., 2010). 84% of the country's population lives in rural areas, and a rapid increasing population (expected to double by 2050), slow productivity growth and climate-related disasters like droughts increase food insecurity the rural population. Consequently, competition for available land, water, energy, and other inputs increases, posing pressure on the rural population's livelihoods and food security (Bryan et al., 2009; Garnett et al., 2013).
Out of the 112.3 million hectares of land in Ethiopia, 16.4 million hectares is considered to be suitable for arable use and half is currently cultivated with rain-fed crops (Croppenstedt and Demeke, 1997). Livestock keeping is of large importance for both the livelihoods and the national economy of Ethiopia (Leta and Mesele, 2014). Smallholder farmers represent the majority of the rural population in Ethiopia, producing about 90% of the total agricultural output on 95% of the cropped land (Hanjra et al., 2009). However, their productivity is low, partly caused by a lack of access to markets and technology. Large commercial farms focus more on the production of marketable crops. Due to a better access to markets and technology, they are able to produce against less costs, thereby yielding a higher profit.
Different methods have been proposed in the literature to reduce poverty and increase food security among smallholder farming systems. Amongst the potential solutions are better integration to markets and infrastructure networks (Jayne et al., 2003); higher diversification of

production activities (Woldenhanna and Oskam, 2001); adoption of new technologies such as irrigation (Hanjra et al., 2009); establishment of cooperatives (Abebe et al., 2016) and intensification of production (Henderson et al., 2016; Tittonell and Giller, 2013).

The degree of success of these measures depends on the type of smallholder farm. Smallholder farms share some similar characteristics. As suggested by the name, they often have a very limited area of land at their disposal; in Ethiopia on average less than one hectare of land per farm (Dorosh and Rashid, 2013). They are family-operated with no or a very limited amount of hired labor. However, the quality of the biophysical surroundings, the types of crops and livestock produced, the intensity of production and the extent to which production is meant for household consumption or sales to the market highly differs per type of smallholder farm. To analyze the impact of different methods to reduce poverty and increase food security, it is therefore imperative to properly reflect what defines smallholder farmer's production choices, where which types of farming systems are located and what type of investments at which location would have the largest impact.

To analyze the diversity among farming systems, various typologies at different scales have been developed. At the global scale, the most well-known typology are the 72 farming systems of Dixon et al. (2001). Other well-known typologies are the more aggregated typology covering 15 farming systems of Cassman et al. (2005) and the livestock systems of Seré et al. (1995). In Sub-Saharan Africa and Ethiopia in particular, the most common typologies developed are the maps of Jayne et al. (2003) using nationally representative household surveys in Eastern and Southern Africa; Cecchi et al. (2010) using a livelihood analysis to obtain pastoral, agro-pastoral and mixed farming systems; and Otte and Chilonda, (2002), developing a classification of ruminant production systems in sub-Saharan Africa. While these typologies all analyze where and how smallholder systems differentiate, they are not able to quantify systems using production and consumption data in order to analyze changes through space and over time.

The objective of this paper is to develop a methodology to establish country-wide farm typologies allowing for both a spatial and temporal analysis of the evolution of the agricultural sector, and in particular smallholders' food security and income in Ethiopia. This method thereby serves as an excellent way to study ex-ante impact-analysis, linked to for example governmental aims or the millennium development goals. As an example, we evaluate the effect of increased input intensification on future food security of smallholder farmers in Ethiopia.

Compared with other existing typologies this study provides a novel way of developing country-wide spatially explicit farming typologies in three ways: First, it provides a methodology that starts from farm-household data which are extrapolated to cover the whole country and subsequently harmonized with national statistics to match total production at the regional level. Second, it takes the interplay with large farms into account, highlighting the factors that could explain why smallholders continue to produce even if they are not/less competitive compared to larger farms. Third, the resulting typology is filled with data on production and consumption to analyze smallholders' income and food security in a spatially and temporally explicit way.

The remainder of the paper is organized as follows. In the next section, a framework is established to determine the main indicators necessary to establish a farming-system typology that covers the entire agricultural sector in Ethiopia, taking into account the diversity within smallholder farming systems and their interplay with large-scale commercial farms. Section three lists the data employed. Our analysis takes place on the third administrative level, the so-called woredas. In the results section, impacts on crop and livestock production, poverty and food security status by smallholder farm, production system and woreda are analyzed. The discussion further analyzes the effect of increased intensification on future food security in Ethiopia. Our conclusions ensue.

2. THEORETICAL FRAMEWORK

Agricultural production in Ethiopia is dominated by cultivating food crops and producing traditional livestock. The majority of the crop-dominated farms are mixed, with a few heads of livestock which are mainly used to support crop cultivation (ploughing), for transportation or for sale to cover occasional expenses (Diao et al., 2010). The exact structure of the farms is however diverse, and depends on factors both endogenous and exogenous to the farm. In this section, we provide the main factors that determine agricultural practice in a certain location in Ethiopia and develop a framework that enables the analysis of poverty and food security. The following four factors are selected for this aim: (1) Agro-ecological zone; Ethiopia is characterized by a diverse climate in terms of rainfall and soil fertility, making certain areas more suitable for crop cultivation than other areas. (2) Farm size; smallholder farmers with the primary aim of food self-sufficiency exist next to large commercial farms with the primary aim to sell to the market. (3) Main activity set; based on the preference and ability to grow certain crops and/or to raise livestock. (4) Degree of intensification; the current degree of intensification highlights the ability of the farmer to produce at its full potential and the possibility to enhance productivity given the available area.

2.1 Agro-ecological zone

The agro-ecological zone (AEZ) captures the biophysical and climatic environment on which agriculture is heavily dependent, and thus shapes many of the constraints and opportunities farmers face. The AEZ is based on an existing classification of the Ethiopian Ministry of Agriculture (MoARD). The AEZ classification of MoARD is more commonly referred to as the ‘three Ethiopias’ which are differentiated using altitude and rainfall criteria. The Three Ethiopias are divided into the rainfall-sufficient highland areas (‘moisture-reliable’, dotted area in Figure 5), the drought-prone highland areas (‘drought-prone’, transparent area in Figure 5) and the pastoralist lowlands (‘arid-pastoral’, striped area in Figure 5). The three Ethiopias emphasize the importance of moisture availability for Ethiopia’s rain-fed production systems, since it is often viewed as one of the main constraints for smallholder farmers to move out of poverty (Chamberlin et al., 2006). Moreover, the impact of climate change in Ethiopia has shown to be highly dependent on the agro-ecological zone (Deressa and Hassan, 2009).

2.2 Farm size

Fast rising grain prices, the fear of not being able to feed the population and the rising demand for biofuels have increased the uptake of land by large farms in developing countries (Shete and Rutten, 2015). Large farms compete for productive agricultural land with smallholder farmers. The opinions on whether large-scale farming is beneficial for local farming communities and the country as a whole differ (Von Braun et al., 2009). Especially the interactions between large farms and smallholders and their effects on land ownership, environmental issues, as well as local food security are important to investigate (De Schutter, 2011). In Ethiopia, several studies found that local-level food security can be undermined by the uptake of land from large farms (Shete and Rutten, 2015). In assessing the evolution of smallholder farmer's food security and poverty status, it is therefore essential to take the role of large scale farms and their interactions into account.

The farm size largely determines the outlook of the farm in terms of profit maximization versus self-sufficiency. A smallholder farm can be seen as a farm, producing agricultural outputs, and a household, supplying large part of the labor and capital to the farm. The farm uses non-factor inputs (e.g. pesticides, fertilizers, etc.) and factor inputs (capital, land and labor) to produce outputs. For a family farm in Ethiopia, it is safe to assume that the factor inputs only come from the labor and capital (including land) the household supplies. For a large farm, factor inputs are supplied by external sources (e.g. paid workers). The income from farming is composed of the products that are consumed at the household plus the revenue from selling agricultural outputs. A smallholder farm may also supply factor inputs elsewhere, such as off-farm work. Total income of the smallholder farm therefore stems from the on- and off-farm use of factor inputs. Large farms are generally more specialized and therefore use all their factor inputs on-farm. Smallholder farms have a consumption unit that takes up (part of the) products produced on-farm and spends the revenue from potential off-farm work. This difference between small and large farms is schematically depicted in Figure 1 below. In agricultural household production models, it is often assumed that the farm maximizes profit given a technological and market constraint, whereas the household maximizes utility given a budget constraint. In developing countries, utility is often maximized by reaching food self-sufficiency. Because large farms only have a production unit, profit maximization is key.

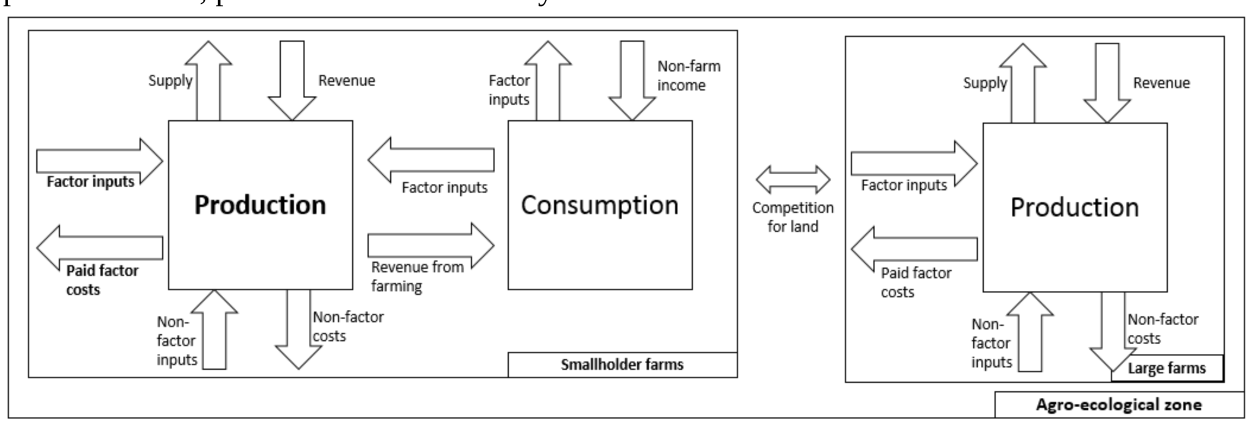

Figure 1: Main factors that determine the agricultural sector in Ethiopia

2.3 Activity set

Because large farms mostly focus on profit maximization, they often specialize in a very limited number of products. Smallholder farmers often have a crop portfolio in combination with raising a limited number of livestock. The set of crop and livestock activities reflects the farmers' preferences to grow certain crops and/or raise livestock, given the agro-ecological and economic context. These preferences in activities are usually grounded in local/family history, influenced by the AEZ and the advantage of using knowledge accumulated through experience. The first important differentiation in grouping the farm-activity set is between those farmers who do not have any cropland and thereby only focus on keeping livestock (**Livestock-keepers**) and those who do have land and focus on a mix of crop and livestock activities. Mixed crop-livestock systems are further disaggregated into four groups depending on the main crops they cultivate:

- **Millet-Sorghum:** where the cultivation of millet or sorghum is dominant;
- **Maize**: where the cultivation of maize is dominant;
- **Wheat-barley-teff**: where wheat, barley or teff are the dominant crops;
- **Perennials:** where the main crops are perennials (e.g. coffee or enset).

The combination of mixed crop-livestock systems is selected to cover the most important staple crops in Ethiopia and the combinations in which they most often occur. It is further complemented by perennial crops to account for the area suitable for coffee cultivation.

2.4 Degree of intensification

Sub-Saharan Africa, and especially smallholder farming systems, are characterized by a low productivity and therefore large yield gaps (Henderson et al., 2016; Tittonell and Giller, 2013). The yield gap is defined as the difference between the actual and the optimal yield that can be achieved on farm, and is therefore a major factor to determine the potential for increasing food production. The size and potential to close the yield gap depend on the farm activities and the agro-ecological context of the farm. For instance, it may not be possible to resolve for a loss in yield caused by adverse weather effects, because this falls outside the reach of farmers. However, it may be possible to close the part of the yield gap caused by the inadequate application of inputs (Henderson et al., 2016; Tittonell et al., 2005).

Together, these four factors define the agricultural sector in Ethiopia, as depicted in Figure 1. In a given agro-ecological zone, both large commercial and smallholder farms may exist. Where the large farm only focuses on a very limited number of production activities, the smallholder farm focuses on both production and consumption using a portfolio of crop and livestock activities. For both the smallholder and the large farm, factor inputs (land, labor, capital) and non-factor inputs (fertilizers, pesticides) lead to the supply of products. The degree to which these inputs are used determines the degree of intensification and helps to explain the potential yield gap.

3. DATA

To establish a representative typology of Ethiopia's agricultural sector that covers the whole country, a combination of household survey and agricultural census data is used. For each factor, one or more datasets are used. The AEZ is based on an existing classification of the Ethiopian Ministry of Agriculture (MoARD). The farm size is split up into smallholder and large scale farms. For smallholder farms, the Ethiopian Rural Socioeconomic Survey (ERSS) and the Ethiopian Agricultural Sample Enumeration (EASE) are used. To account for large farms, the World Bank report on large and medium scale commercial farms is used. The activity set and degree of intensification is also based on data from the ERSS. To extrapolate the distribution of farming systems across the country, data from the rural atlas of Ethiopia is used (CSA, 2006). This section lists the different datasets and describes their main elements used.

3.1 The Ethiopia Rural Socioeconomic Survey (ERSS)

The ERSS dataset covers smallholder farms. It results from the LSMS-ISA project led by the World Bank and funded by the Bill and Melinda Gates Foundation. The survey consists of three rounds of questionnaires which were administered between September 2011 and March 2012. The ERSS dataset covers information regarding crop- and livestock technology (variable and fixed inputs used, yields obtained) and market access (degree inputs bought and outputs sold to the market and the costs to get to the market) as well as socio-economic household information (e.g. farm-size and whether the farm experienced a food shortage). Of specific importance for this study are the post planting questionnaire (Sept-Oct 2011), the livestock questionnaire (Nov-Dec 2011) and the post-harvest questionnaire (Jan-March 2012).

The ERSS data is representative at the first administrative region (Figure 2 left), composed of the regions of Tigray, Afar, Amhara, Oromiya, Somali, Benishangul Gumuz, SNNP, Gambella, Harari, and Dire Dawa. All regions of Ethiopia are surveyed except Addis Ababa, three zones in the Afar region and six zones in the Somali region. However, many woredas (3rd administrative level) have not been surveyed and in most of the surveyed woredas, between 6 and 14 farms are found to have reliable information (Figure 2, right). In total, 3969 households are included in the ERSS data, after cleaning 3408 farm households are left, of which 2384 households can be linked to a woreda.

3.2 The Ethiopian Agricultural Sample Enumeration (EASE)

The EASE census data from 2001/2002 comprises data in six domains: land use, area and production, livestock, farm practice, implements, and socio-economic situation. For each, disaggregated results at woreda level are available. Like ERSS, the EASE does not cover three zones in the Afar region and six zones in the Somali region on a woreda level. The EASE dataset is used to harmonize data on cropped area, animal numbers and production by agro-ecological zone and activity-set obtained from the ERSS.

Figure 2: Map of the first administrative level of Ethiopia on the left (Ethiovisit, 2015) and the number of farms by woreda (third administrative level) which are included in the ERSS survey on the right

3.3 Large and medium scale commercial farms

To depict large farms, we use the report from the large and medium scale commercial farms sample survey 2014/2015 giving crop areas, production and yields in large farms by region as well as a World Bank working paper with information on 2002 areas and maps of large farms in 1990, 1995, 2006 and 2014 (Ali et al., 2015). To estimate and locate crop areas of large farms in the same year as the EASE, we start from the 2014 crop areas by region that we scale down homogeneously in order to match the 2002 total large farm area (446,376 ha, (Ali et al., 2015)). Sesame is the most cultivated crop by large farms, representing 30% of their total cultivated area, followed by coffee (11%) and sorghum (10%). Large farms are not further decomposed by activity set and input intensity. We identify on the 1995 map woredas that have large farms and assume they remain the same in 2000. Last, we allocate the 2002 regional crop areas to the corresponding woredas proportionally to cropland by woreda. Figure 3 shows the share of large farms in terms of total cropland area by woreda.

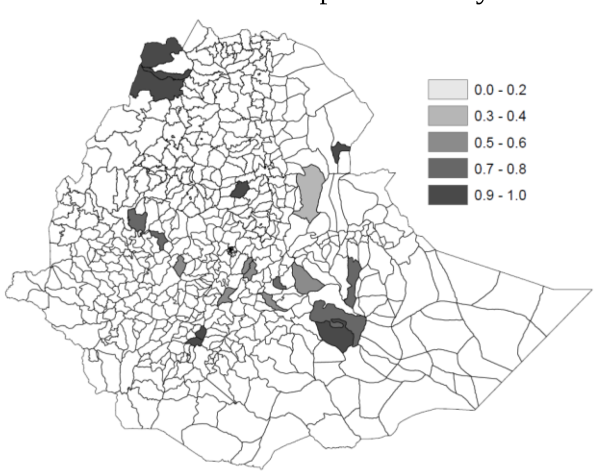

Figure 3: Share of large farms in terms of total cropland by woreda (Ali et al., 2015).

3.4 Population data

In order to analyze the evolution of smallholder farmer's poverty and food security status over time, we make use of different local sources to calculate total and rural population numbers and population growth over the 2000-2030 period at *woreda* level (Adugna, 2015: 5; CSA, 2006: 38; CSA, 2013).

4. METHODOLOGY

The total amount of cropland and livestock used for agricultural purposes is allocated amongst the farming systems using various statistical methods. After we have deducted the area of cropland for large farms from the total cropland by woreda in Ethiopia, we allocate the remaining cropland and livestock to smallholder farmers of different types. To assign the cropland and livestock to smallholder farmers with different activity sets, the share of each farm activity-set for smallholder farmers by woreda is estimated and their associated inputs and outputs are calculated. Second, the data with respect to cropland, yields and livestock numbers is harmonized. Third, for each crop and woreda the degree of intensification is estimated. Together with the already existing data on agro-ecological zone, this forms a country-wide spatial typology of the Ethiopian agricultural sector.

4.1 Smallholder farmers

We start by allocating farmers to a certain activity set based on the most important crop cultivated in terms of land area. The most important crop can be either one of the staples wheat, barley, teff, millet, sorghum, or maize or a perennial. Upon their occurrence as the dominant crop, the farm is allocated to the corresponding farming system as defined in section 2.3. If the most important crop in terms of land area was different from the above mentioned crops, we would look at the second and third most important crops in terms of area. The remaining farms that could not be classified (107/3408) were dropped from the analysis.

The resulting micro-level data provides us with an account of all the activities that an individual farmer undertakes. For each activity, data with regard to the factor and non-factor inputs and costs, supply, revenue and use of the resulting product are obtained. However, the data does not encompass the whole country (see Figure 2, right), nor is it representative at the woreda level. Aggregating the household-level data may therefore result in inconsistencies between the aggregated and actual amount of e.g. cropland per crop. The combination of smallholder farm-sized data and their activity-set therefore needs to be extrapolated in order to cover the whole country, as well as harmonized with national data in order to make it representative at the woreda level.

4.1.1 Spatial extrapolation

To extrapolate the smallholder farm data by activity set, available statistical data at the woreda level is used to estimate the relationship between the activity set and information about the geographical, as well as infrastructural characteristics of the woreda. More formally, given J non-intersecting choice combinations of activity sets, we observe a multinomial sample $y_i =$

$\{y_{ij}\}_{j=1}^{J}$ that records the number of farmers choosing a certain combination of farm-activity set j = 1, …, J and the total number of responses n_i in woreda i. According to the logistic link the probability of randomly drawing a single response from the jth category in woreda i is given as:

$$p_{ij} = \frac{\exp \mu_{ij}}{\sum_{i=1}^{J} \exp \mu_{ik}}, \qquad (1)$$

where the log odds μ_{ij} is modeled in terms of $x_i\beta_j$. x_i are p woreda specific explanatory variables and β_j are the corresponding coefficients for the jth category, with β_J set to be zero for purposes of identification (see e.g. Holmes and Held, 2006). The woreda-specific explanatory variables are reported in Table 1.

We estimate the model in Eq. (1), in a Bayesian fashion, in the spirit of (Polson et al., 2013). The main difference to their approach is that due to the limited sample size, the potentially large number of explanatory variables, and the lack of theoretical evidence we want to remain as agnostic as possible regarding the choice of explanatory variables. A natural way of letting the available data dictate the choice of variables is to employ Bayesian model averaging, as pioneered by George and McCulloch (1993) and Kuo and Mallick (1998). This form of adaptive model averaging involves imposing a mixture normal prior on each β_{kj}:

$$p(\beta_{kj}|\delta_{kj}) = \delta_{kj}N(0,\tau_0^2) + (1-\delta_{kj})N(0,\tau_0^2) \quad , \qquad (2)$$

where δ_{kj} is a binary random variable and the prior variances are chosen so that $\boldsymbol{\tau_0^2} \gg \boldsymbol{\tau_1^2}$.

Table 1: Variables used for extrapolation

variable	description	Source
Population density	Population density in persons per km2	CSA (2006)
Average elevation	Average woreda elevation in meters above mean sea level	CSA (2006)
Average slope	Mean slope in percentage	
Average rain	Mean monthly rainfall in mm	CSA (2006)
Road density	All weather road density (m/sq.km.)	CSA (2006)
cooperative and type in the woreda	Split into coffee marketing, multipurpose, no cooperative, saving & credit and vegetable marketing	CSA (2006)
Number of cooperatives	Number of cooperatives in woreda	CSA (2006)
Total members involved	Total members active in a cooperative in a woreda	CSA (2006)
Dominant crop	Dominant crop in the woreda; dummy for barley, maize, millet, pastoral, sorghum, teff or wheat	CSA (2006)
Secondary crop	Secondary crop in the woreda; dummy for barley, maize, millet, pastoral, sorghum, teff or wheat	CSA (2006)
area	Size of the woreda in km^2	Shapefile of Ethiopia

aez	Dummy for drought prone area and arid pastoral area (moisture reliable treated as base category)	Shapefile of Ethiopia
Spatial weights	For population, elevation, slope, rainfall, road density and area	

4.1.2 Spatial Harmonization

The spatially extrapolated ERSS data of individual farm households is then harmonized with the data from the agricultural census (EASE). This should result in data by activity-set and by woreda that, when aggregated over the activity sets, is fully consistent with national statistics at woreda level for the base year. The following model minimizes the variation between the extrapolated average area by crop and animal numbers by type for each activity set and woreda with the woreda's total area by crop and animal numbers by type from the EASE:

$$\operatorname{Min} D = \sum_{w,f,c,u,l} \left(\sqrt{x^*_{w,f,c,u} - x_{f,c,u}} + \sqrt{n^*_{w,f,l} - n_{f,l}} \right) \tag{3}$$

$$\overline{N}_{w,l} = \sum_f \left(n^*_{w,f,l} \cdot S_{w,f} \right) H_w \tag{4}$$

$$\overline{X}_{w,c,u} = \sum_f \left(x^*_{w,f,c,u} \cdot S_{w,f,c} \right) H_{w,c} \tag{5}$$

$$U^c_{w,f} = \sum_c \sum_u x^*_{w,f,c,u} > 0 \tag{6}$$

$$U^l_{w,f} = \sum_l n^*_{w,f,l} > 0 \tag{7}$$

$$M_{w,c} = \sum_u \left(\sum_f \left(x^*_{w,f,c,u} \cdot S_{w,f,c} \right) H_{w,c} - \overline{X}_{w,c,u} \right) < 0.1 \tag{8}$$

where D represents the objective function which minimizes the difference between ha land by crop and animals by type from the survey data and the national statistics. The subscripts w, f and c, u and l denote the woreda, activity-set, crop, crop use and animal type respectively. $x^*_{w,f,c,u}$ denotes the number of hectares allocated to each crop for each use by activity-set within each woreda after adjustment with the national statistics. $n^*_{w,f,l}$ denotes the number of animals by activity-set within each woreda after adjustment with the national statistics. $x_{f,c,u}$ is the number of hectares allocated to each crop by activity-set from the survey data. $n_{f,l}$ is the number of animals allocated to each type by activity-set from the survey data. $\overline{N}_{w,l}$ is the total number of animals by type by woreda from the national statistics. $\overline{X}_{w,c,u}$ is the total area (ha) by crop by woreda from the national statistics. $S_{w,f}$ represents the share allocated to each activity set within each woreda. H_w depicts the total number of farm holders in each woreda. $U^c_{w,f}$ and $U^l_{w,f}$ represent the area (ha) by farm in the woreda, $M_{w,c}$ represents the area (ha) for specific crops in the woreda.

Equations 4 through 8 are accounting identities. Equation (4) ensures that the total number of animals per type per woreda is equal to the total number of animals available from the national statistics. Equation (5) ensures that the total computed land area per crop by use by woreda is equal to the total area available by crop from the national statistics. Equations (6) and (7) state that each activity-set with respectively cropland or livestock that occurs in a woreda according to the spatial extrapolation must also occur in the harmonized statistics. Equation (8) states that the difference between cropland by crop from the national statistics and harmonized cropland by crop must be less than 100 hectares.

4.2 Degree of intensification

We consider three different input intensity levels: low, medium and high input intensity. The focus is on intensification achieved through the application of nitrogen and phosphorus, where the agro-ecological zone already capture part of the biophysical conditions. The literature distinguishes various ways to measure the potential yield that can be obtained by using the optimal amount of fertilizers. When the focus is on estimating multiple-outputs together, the SFA frontier can be used to estimate the maximum level of production (Henderson et al., 2016). When the focus is on single-outputs, response functions are often used. Commonly used crop response functions that estimate the relationship between inputs and yields are polynomial specifications (Frankle, 1976) (specifically the quadratic (Croppenstedt and Demeke, 1997; Finger and Hediger, 2009; Frankle, 1976) and square root function (Finger and Hediger, 2009; Llewelyn and Featherstone, 1997), the von Liebig function (Finger and Hediger, 2009; Frankle, 1976; Llewelyn and Featherstone, 1997) and the Mitscherlich-Baule function (Frankle, 1976; Harmsen, 2000; Llewelyn and Featherstone, 1997; van der Velde et al., 2014). Especially the Mitscherlich-Baule is suitable because of its attractive properties of continuous marginal productivities and a growth plateau. However, this functional form requires information on the levels of N and P in the soil before additional nutrients are added. Since this information is not available in this study, we estimated the square root functional form. Because we estimate the effect of both nitrogen and phosphorus on yield, the quadratic function takes the following form:

$$Y = \alpha_0 + \alpha_1 N + \alpha_2 P + \alpha_3 N^2 + \alpha_4 P^2 \quad (9)$$

Where α_0 is the intercept; i.e. the yield that would be achieved if no inputs were added; α_1 is the coefficient belonging to the quantity of nitrogen N, α_2 is the coefficient belonging to the quantity of phosphorus P, and α_3 and α_4 are the coefficients belonging to the squared terms of nitrogen and phosphorus.

The ERSS dataset is used to obtain the relationship between respectively N and P and the level of yield for smallholder farmers in Ethiopia. DAP is converted into N and P based on the assumption that the average bag of UREA contains 46% of Nitrogen and the average bag of DAP contains 18% nitrogen and 46% of phosphorus pentoxide (P2O5), meaning 20% P. So, a 50 kg bag of DAP contains 9 kg N and 23 kg P2O5 (=10 kg P).

The regression results lead to concave curves for all crops, with an optimum that is slowly decreasing (see

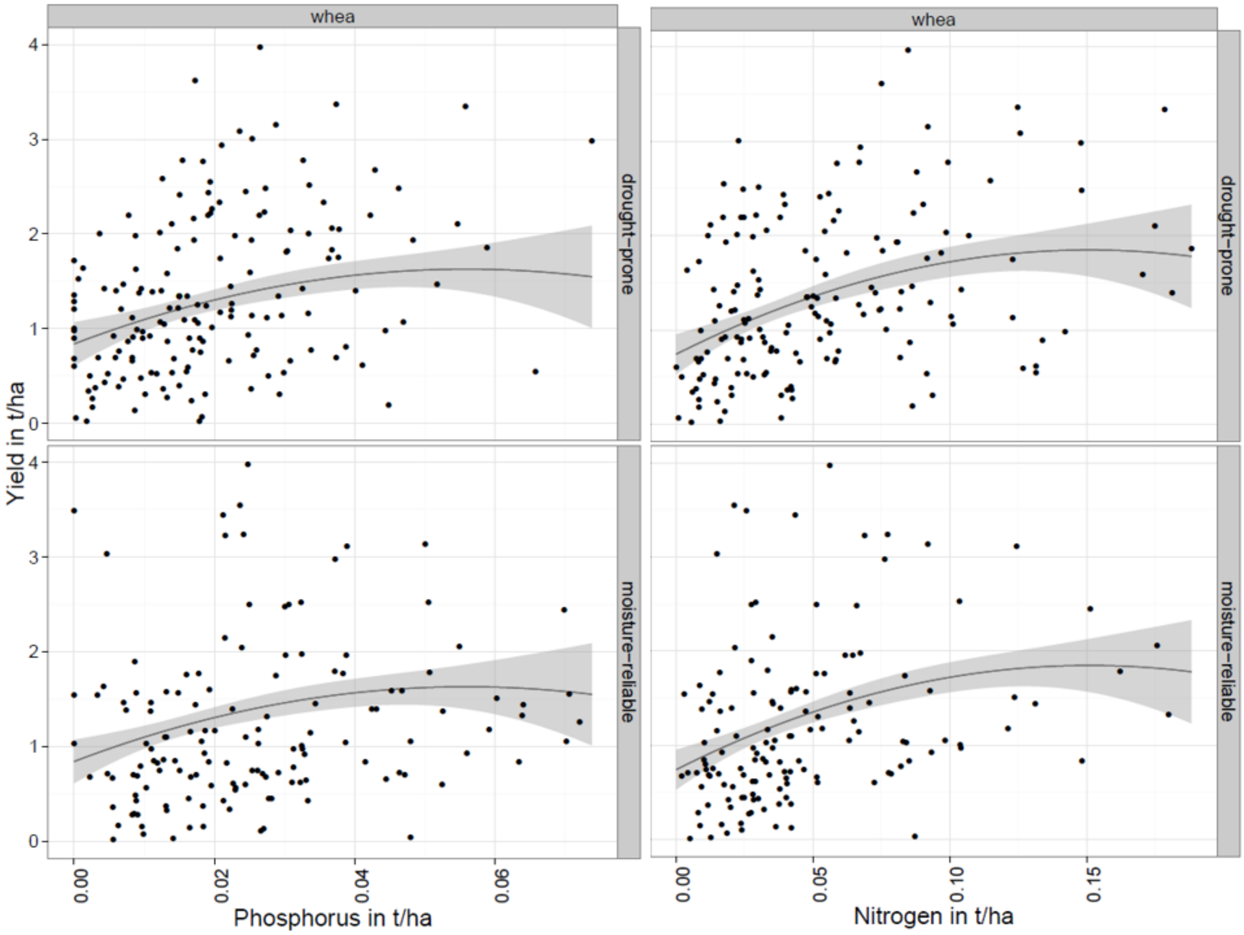

Figure 4 for an example for wheat). Taking the first-order derivative with respect to the amount of N and P and subsequently inserting these values into equation (9) leads to the optimal input-yield combinations by crop and AEZ. We distinguish three levels in the degree of intensification: the base level, in which is the harmonized yield by woreda and farm-activity set, high inputs, which is the optimal input-yield combination and medium inputs, which is 50% of the optimal N and P use, and the yield related to these inputs.

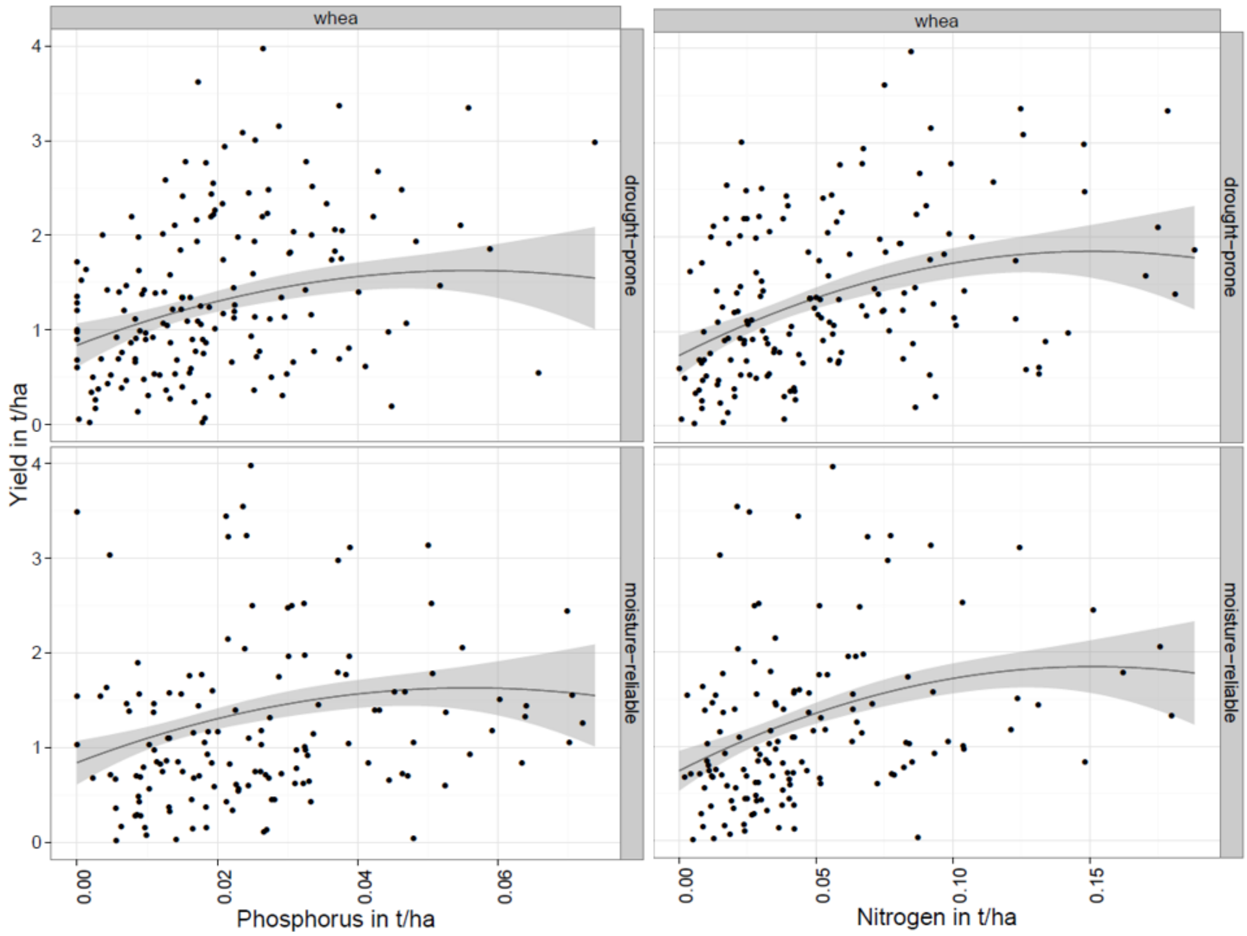

Figure 4: Relationship between nitrogen and yield (left) and phosphorus and yield (right) for wheat for the moisture reliable zone (1), drought-prone zone (2) and total respectively.

5. RESULTS

In this section we discuss the distribution of smallholder farm systems, impacts on crop and livestock production, poverty and food security status by smallholder farm, production system and woreda.

5.1 Farm systems in Ethiopia

The spatial extrapolation of farm-activity sets across woredas results in woreda-unique combinations of agro-ecological zone and farm-activity set for smallholder farms in Ethiopia. Farmer's production activities are strongly dependent on the bio-physical conditions in which they operate as reflected by the occurrence of farm-activity sets in agro-ecological zones. The farm-activity sets wheat-barley-teff and perennials are limited to the moisture reliable and drought-prone zone, the other farm-activity sets occur in all agro-ecological zones.

There can be several activity-sets in a woreda but for simplification, Figure 5 shows the dominant combination of activity-set and AEZ by woreda (right). The livestock-keeping and millet-sorghum activity sets dominate in almost all the arid AEZ along the border with Somalia, which are less suited for crop production. The millet-sorghum activity-set is also widely spread in the half-North of Ethiopia. The area allocated to maize spreads out over the whole of Ethiopia, but is dominant in the half-South of the country and especially in the South-West. The dominant crops in millet-sorghum as well as maize may be produced both for human consumption as well as for feed-inputs. This may explain their occurrence in all zones. The perennial activity-set is only dominant in few woredas in the SNNP and Oromiya region. Finally, the wheat-barley teff activity-set is dominant in the highlands, cutting through the middle of Ethiopia from North to South.

The resulting selection of farming systems can be related to the existing literature on farming systems in Sub-Saharan Africa (Dixon et al., 2001; Otte and Chilonda, 2002). The map on the left in Figure 5 shows the Dixon's farming systems (Dixon et al., 2001). There is generally a quite good agreement between the typologies. The area dominated by livestock-keepers in our typology fits quite well the pastoral and arid-pastoral systems in Figure 5. If we also include the millet-sorghum mixed system, the area is broader in our analysis. It then also encompasses the arid-pastoral millet-sorghum and cereal-root crop mixed system of Dixon et al. in the North-East of the country. However, the area in the Mid-East is mostly indicated as pastoral by Dixon et al. while the dominant system we find is millet-sorghum.

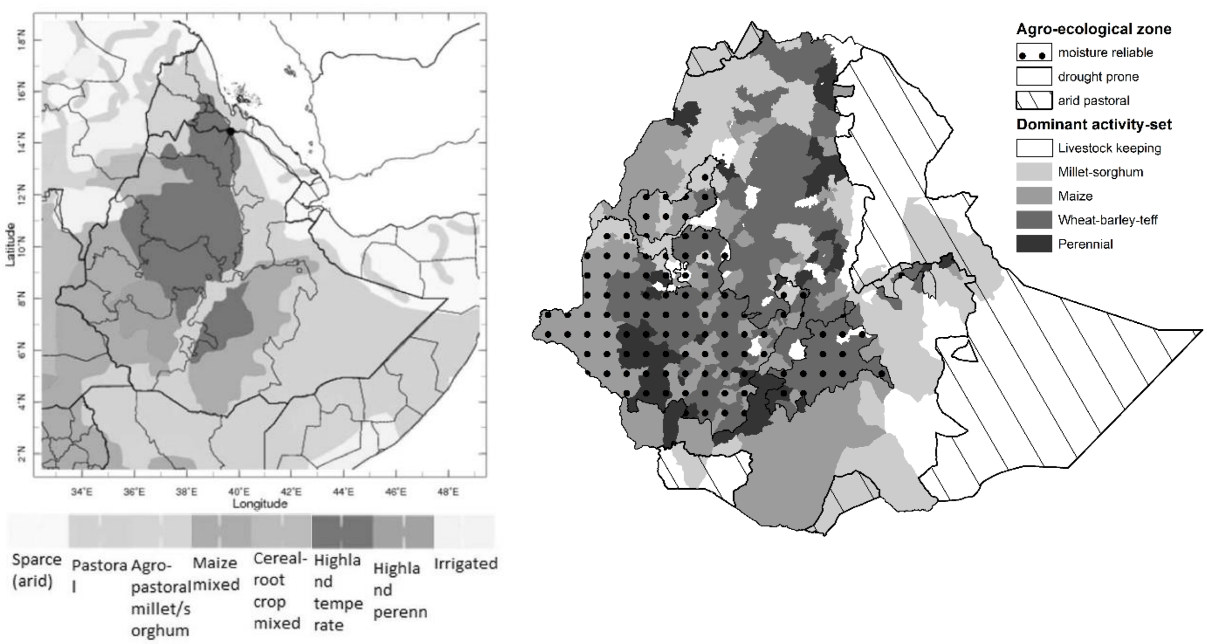

Figure 5: Dominant farm-activity set by woreda according to extrapolated data (left) versus Dixon's farming systems (right)

5.1.1 Harmonized area and livestock numbers

The harmonization process results in some deviations in cropland by crop and livestock by animal per farm-activity set and agro-ecological zone before and after harmonization.

Figure 6 below shows the comparison of land allocation by crop by farm-activity set and agro-ecological zone between before (left) and after (right) harmonization. The crops that are used in the harmonization process are all important staple crops (teff, wheat, barley, maize, sorghum, millet, rice, potatoes, sweet potatoes), the most important pulses (beans, chickpeas), some oilseeds (sesame, groundnuts, rapeseed, sunflower, soybeans). For reasons of representation, only the crops used to define the activity-set and their aggregates are depicted in Figure 6. Crop-portfolio and farm-size largely remain the same for each combination of farm-activity set and agro-ecological zone. However, some differences can be observed.

In terms of crop-portfolio, the farm-activity sets are naturally determined by the main staple crop(s) and perennial based on which they were categorized. The crop-portfolio also largely holds between agro-ecological zones. In the arid-pastoral zone, the amount of land allocated to sesame and millet increased somewhat, whereas this remained relatively stable in the drought-prone and moisture reliable zone. The difference in the arid-pastoral zone can be explained by the lack of observations in the ERSS for this zone.

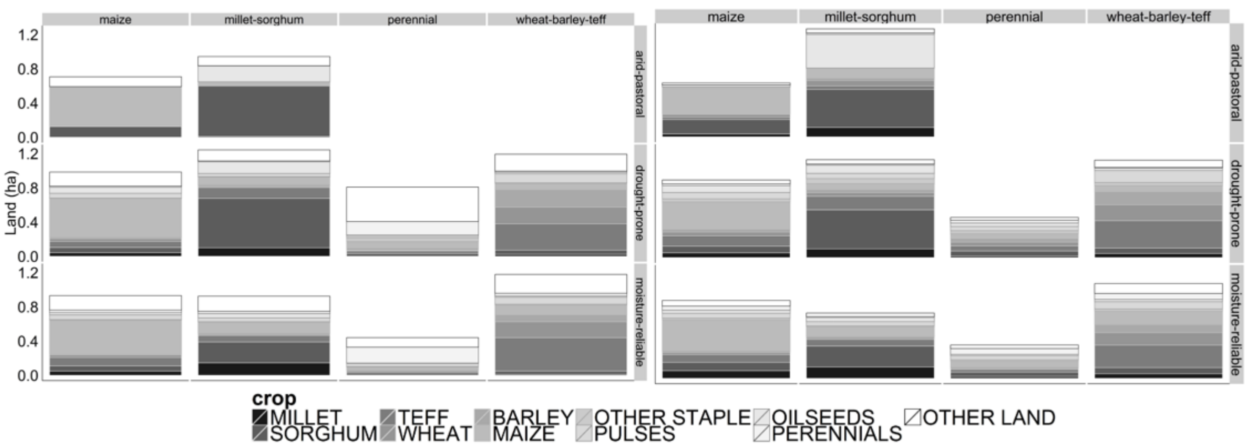

Figure 6 Comparison of land allocation by crop by farm-activity set and agro-ecological zone between the household survey data (left) and the household survey data harmonized with national statistics (right).

If we look at animals and their products in Figure 7, larger differences between activity-set and agro-ecological zone can be observed. The largest amount of livestock in the arid-pastoral and drought-prone zone is observed for the activity-set livestock. However, also maize and millet-sorghum have a relatively large amount of sheep and goats in the arid-pastoral zone (between four and seven). The number of cattle, and their product milk stays relatively constant between agro-ecological zone and farm-activity set (between 3 and 5). This might be because a limited number of cattle is necessary for agricultural purposes. The largest amount of milk production occurs in the arid-pastoral zone, and within that for the activity-set livestock. Each combination of activity-set and agro-ecological zone has at least some poultry and egg production. Generally, more poultry and eggs are produced in the drought-prone and moisture-reliable zone and within that mostly for the activity-set millet-sorghum.

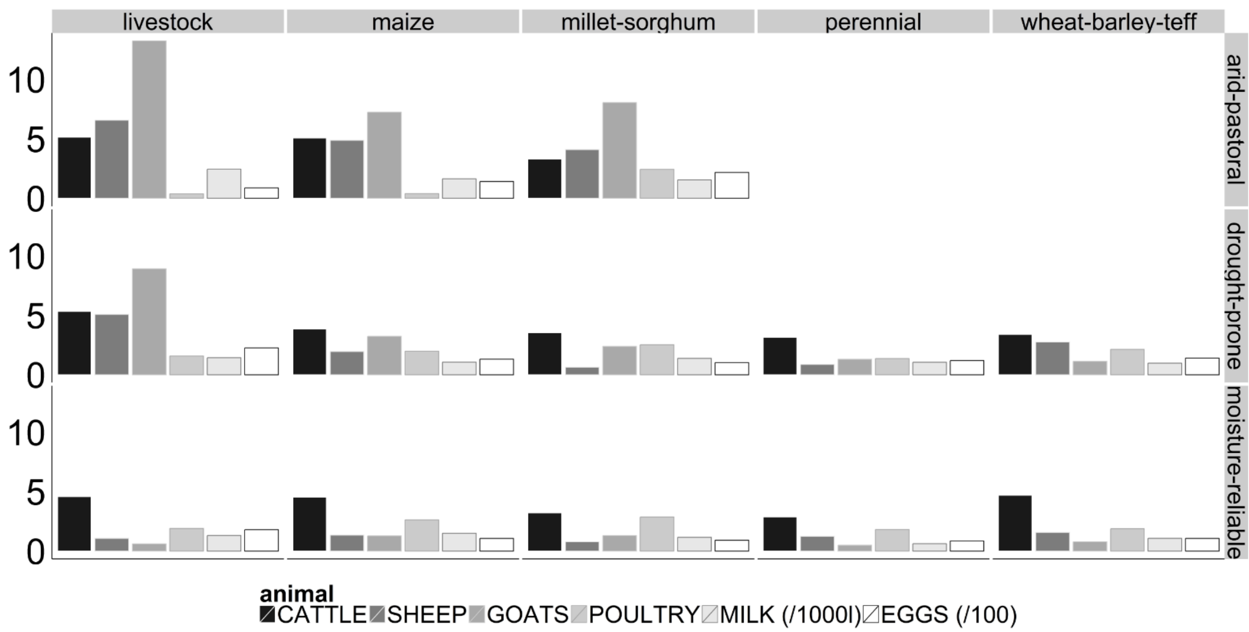

Figure 7 Comparison of number of animals and their main products by farm-activity set and agro-ecological zone.

5.1.2 Current food-security and poverty status

The combination of crop and livestock activities can be added together in order to determine the poverty and food-security status by agro-ecological zone and activity-set, given the current level of intensification. Figure 8 depicts the revenue and costs for all crop and livestock activities separately, as well as the resulting total profit and the kcal per person per day that can be derived from the main staple crops.

In terms of livestock activities, maize in the drought-prone and moisture-reliable zone, livestock and millet-sorghum in the arid-pastoral zone and perennial in moisture-reliable zone show much larger revenues obtained from livestock production than the other AEZ-activity set combinations. For livestock and millet-sorghum in the arid pastoral zone this is mostly due to the larger amount of livestock. For maize and perennials this is mostly due to the share of sales in the total production of livestock activities. In general, it can be seen that with a higher revenue of livestock activities, also higher costs of livestock activities occur. Costs of livestock activities are always lower than their revenues; however, high costs are especially observed for livestock and millet-sorghum in arid-pastoral zone. In terms of crop activities, the highest revenues are observed for maize in the arid-pastoral zone, perennials in the drought-prone zone and wheat-barley-teff in the moisture-reliable zone. For wheat-barley-teff this goes together with a higher input use and therefore high costs. For perennials, this is mostly due to the production of cash crops that can be sold at the market. Adding revenues and costs together results in total profits from farming activities. These are highest for maize in the arid-pastoral zone, perennial in the drought-prone zone and wheat-barley-teff in the moisture-reliable zone, which is directly related to their large revenues in crop activities. Only wheat-barley-teff in the moisture reliable zone has a profit of $385 per year, which is just above the $1/day line. Lastly, the kcal/person/day are calculated based on the total of staple crops and pulses produced on farm. Only the activity-set wheat-barley-teff produces above 2000 kcal/person/day. After wheat-barley-teff, millet-sorghum and maize produce the largest amount of kcal/person/day; between 500 and 1300. However, it can be reasonably assumed that their staple food production must be supplemented by other production or through market transactions. The activity-set perennial also buys from the market, likely in return for their sale of cash crops.

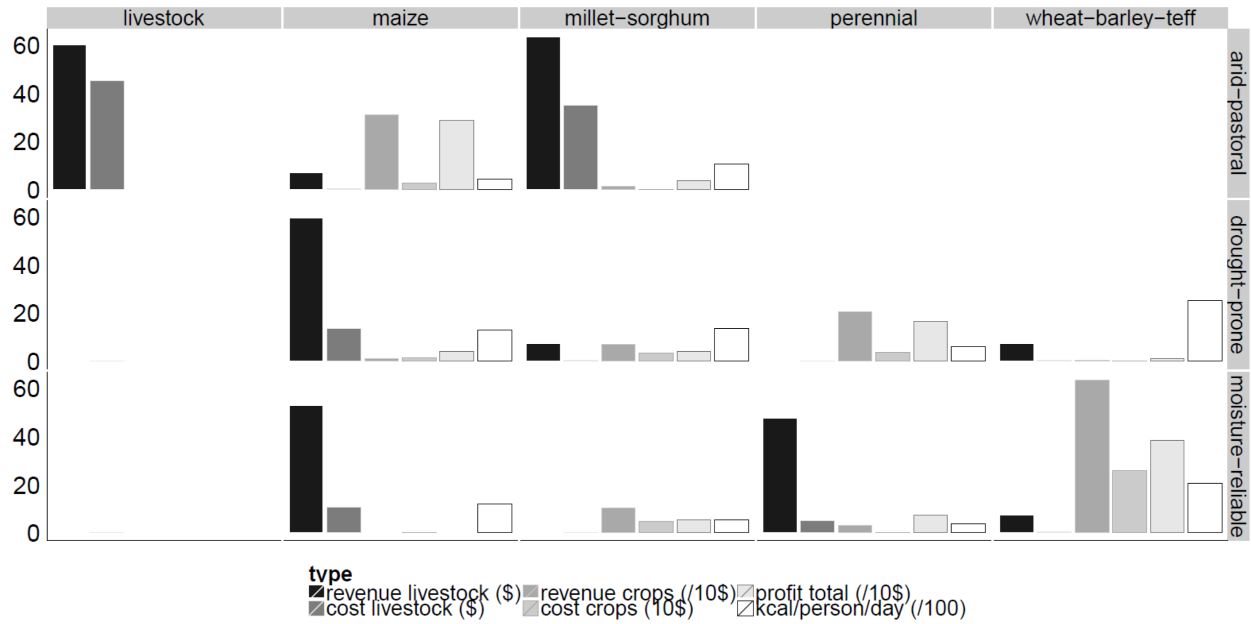

Figure 8 Revenue and costs for livestock and crop production respectively, total profit and kcal per person per day from main staple food production.

6. DISCUSSION AND CONCLUSIONS

6.1 Discussion

Farmer's production activities are strongly dependent on the bio-physical conditions in which they operate. Livestock-keepers dominate in the arid-pastoral zone along the border with Somalia. They have the largest amount of livestock, leading to the highest milk production. Farm activity-sets in the arid pastoral zone have the largest revenues and costs for livestock activities. Compared with the other activity-sets livestock systems have the lowest profits, which is due to a lack of land and poor biophysical conditions. These conditions are likely to worsen and have already led to an alteration of livestock composition in favor of camels and small ruminants instead of cattle in dry, arid areas (Kassahun et al., 2008).

Millet-sorghum also dominates in the arid-pastoral AEZ as well as the Northern half of Ethiopia. It almost always has sorghum as a main crop, and also produces some sesame in the arid-pastoral zone. They have a relatively large amount of sheep and goats, as well as poultry and egg production. This leads to high costs for livestock production and therefore relatively low profits. Because of a lack of land and poor biophysical conditions they produce between 500 and 1300 kcal/person/per day in staple crops. Legesse et al. (2010) report an annual profit per animal ranged from 20 to 37 Ethiopian Birr; and a larger share of the revenue coming from crop activities. They also report that the largest part of milk and milk products is sold by peri-urban instead of rural farmers.

Maize spreads out over the whole of Ethiopia, but mostly occurs in the drought-prone and moisture reliable zones where it has some cultivation in pulses and oilseeds besides maize production, leading to larger revenues and profits. Instead, it focuses more on sheep and goats in the arid-pastoral zone. Generally, they produce between 500 and 1300 kcal/person/day, making it necessary to buy and sell at the market. Due to an increased population density and resulting decline in cattle numbers per capita, maize cultivation and camel husbandry is adopted in more areas (Legesse et al., 2010).

Wheat-barley-teff is limited to the moisture reliable and drought-prone zone and dominant in the highlands. They have the highest revenues and total profits among farm activity sets and wheat-barley-teff in the moisture-reliable zone is the only combination where profits exceed $1/day. Moreover, wheat-barley-teff is the only activity-set producing more than 2000 kcal/person/day.

Perennials are spatially very limited, occurring only in specific locations in the moisture-reliable and drought-prone zone. They generate high revenues and profits from the cultivation of cash-crops. This comes at the cost of their staple crop production; they only produce around 500 kcal/person/day, making it necessary to buy and sell via the market. To cope with increased food insecurity and declining farm sizes, farmers started to increase the cultivation of tree and shrub species, Chat in particular. This increased farm income and crop-livestock integration (Mulatu and Kassa, 2001).

6.2 Future food-security and poverty status

Dramatic increases in population and corresponding difficulties in access to land suitable for agricultural activities are prevalent throughout Ethiopia and are likely to persist as rural population densities continue to increase (Josephson et al., 2014). To assess the amount of future land needed for food consumption, we calculate the area of land by person currently used to produce for own consumption. Figure 9 shows this area as a share of the total cropland and natural land available, given the projected increase in population by woreda for 2030, under the condition that yields stay constant (left) and yields increase towards the highest level of intensification (right). The dark areas, indicating increasing pressure on land, mostly occur in the moisture-reliable and drought-prone zone for the activity-set wheat-barley-teff. This is likely due to the fact that this activity-set produces the largest amount of kcal/person/day. They largely disappear between the base-year yields and the scenario with intensification. However, even with an increased intensification, pressure on land remains high in some areas.

Closing the part of the yield gap that is due to an inadequate fertilizer-yield relationship alone is therefore likely to not be enough to alleviate pressure on land use. Other technologies such as improved water availability may help to alleviate poverty and food insecurity. Moreover, the increased population growth depicted in Figure 9 will impact other factors, such as input and output prices and agricultural wage rates.

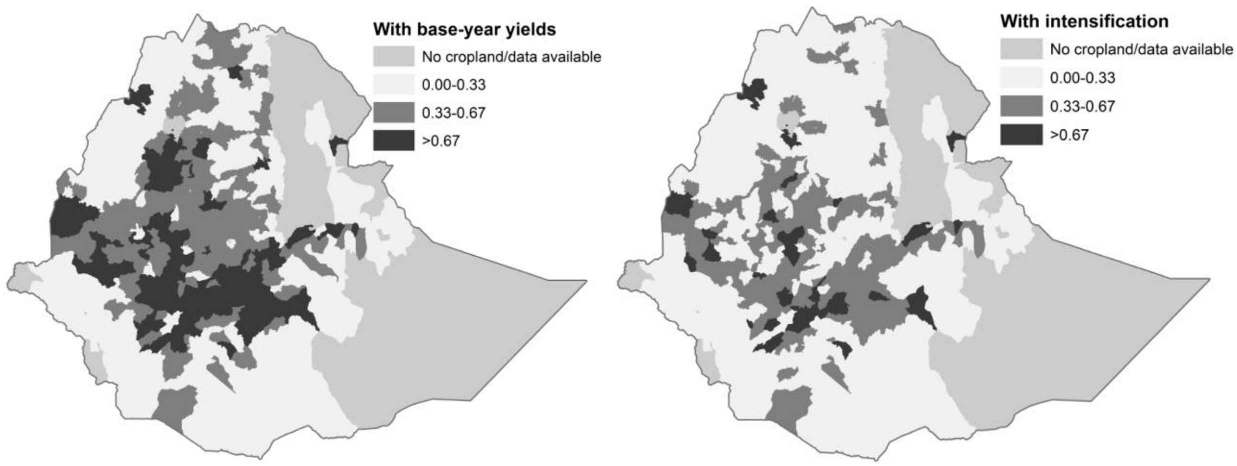

Figure 9: Land used to produce the products for own consumption, specified as a ratio of total cropland and natural land available, given the yields of the base year (left) and the high-intensity yield (right).

6.3 Conclusions

Ethiopia's agricultural sector is highly diverse and subject to change due to different factors relating to climate change and technological progress. To analyze the impact of these factors on poverty and food security, it imperative to properly reflect what defines farmer's production choices, where which types of farming systems are located where and what type of investments at which location would have the largest impact. This paper aimed to do so by developing a methodology that established country-wide farm typologies allowing for both a spatial and temporal analysis of the evolution of farming systems in Ethiopia. The typology focused on the agro-ecological zone, farm size, main activity set and degree of intensification; allowing to account for the diversity within smallholder farming systems and their interplay with large-scale commercial farms.

A novel methodology is proposed that makes use of household survey data to categorize smallholder farming systems, extrapolate the occurrence of each system on a woreda level using a multinomial logit-regression and harmonize their production activities using census data. Compared with other typologies that commonly only focus on the spatial distribution of farming systems, this methodology fills the resulting typology with data, allowing for the analysis of income and food security on different farming systems.

It is generally concluded that livestock-oriented systems are less profitable than crop-oriented systems, which may be due to their access to markets. These systems are also the most prone to food-insecurity. To illustrate the use of this novel methodology, we evaluated the effect of increased input intensification on future food security in Ethiopia. Increased input intensification is one way to reduce pressure on land use, but has to go together with other methods to fully alleviate poverty and food security in light of the increased population.

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