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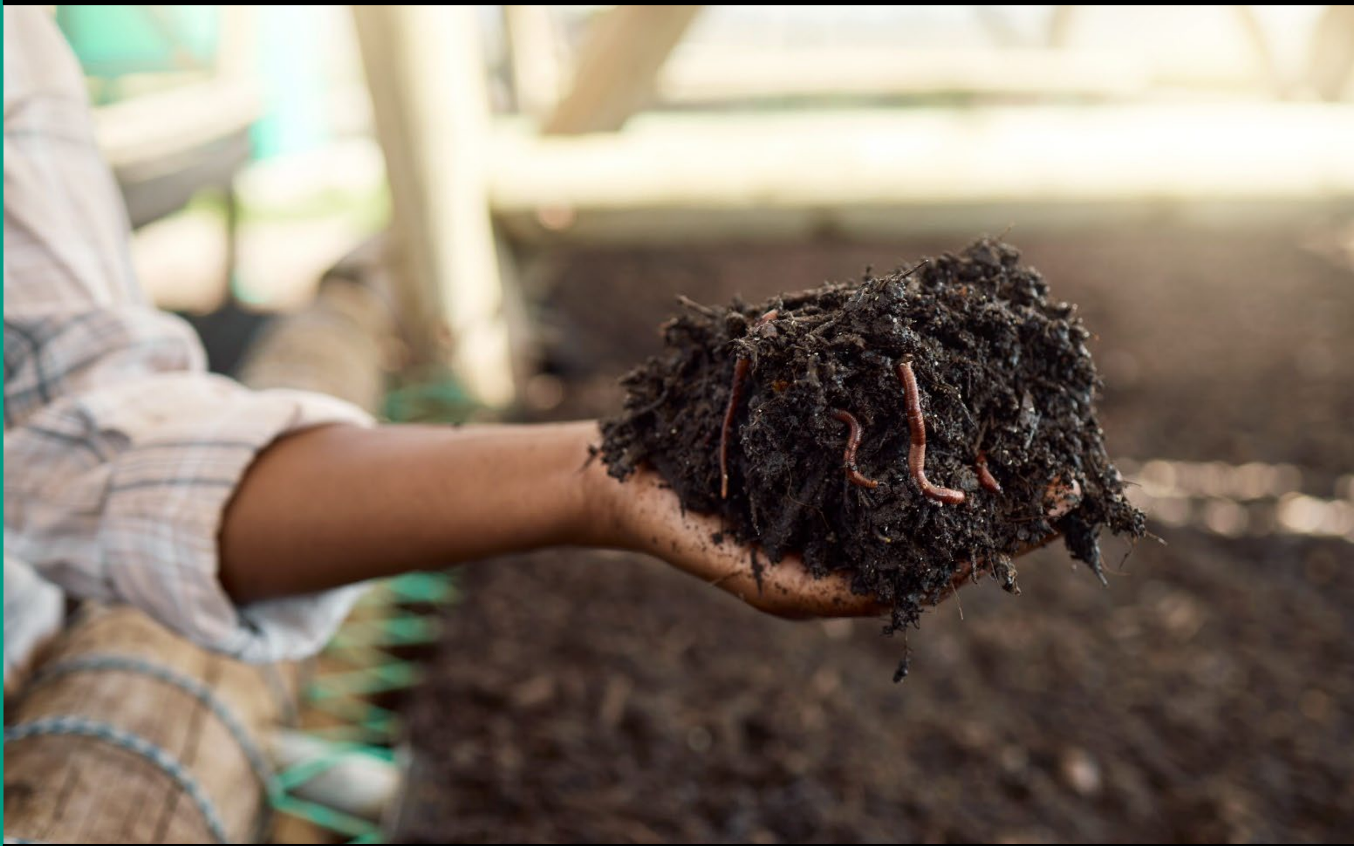

Norwegian University of Life Sciences
Centre for Land Tenure Studies

Centre for Land Tenure Studies Working Paper 01/25
ISBN: 978-82-7490-331-9

# Fertilizer Use Intensification and Manure Use: The case of Tigrai, northern Ethiopia

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## Abstract

There has been an increase in fertilizer use among farmers in the semi-arid Tigray region of Ethiopia during 2006-2015. Our household panel data covering nine years show that the average fertilizer adoption rate had increased from about 31% of plots in 2006 to almost 67% in 2015. Likewise, fertilizer use intensity increased from 28.6 kg/ha in 2006 to 88.5 kg/ha in 2015. Our study aims to explain the increase in fertilizer use and assess how it is associated with changes in manure use. This study is vital given the vast literature on low adoption and fertilizer use in Africa and the scanty literature on the relation between inorganic and organic fertilizers. We use panel data of farm household plots in three rounds (2006, 2010, and 2015) and estimate a correlated random effects double hurdle model with the control function approach to handle endogeneity. We analyze by splitting our sample by population density, market-access, and irrigation. The results show fertilizer use was higher in densely populated areas and areas with good market-access while its intensity was increasing in less densely populated areas, areas with good market-access, and non-irrigated plots. On the implication of increased uptake in fertilizer to manure use, our results suggest that the two inputs appear to be substitutes at the extensive margin. Moreover, with good market access, there seems to be complementarity between the two inputs at the extensive margin and substitution at the intensive margin.



**Key words:** Input demand, fertilizer, organic manure, semi-arid smallholder agriculture, crop-livestock system, Ethiopia.

**JEL codes:** Q12, Q16.

# 1. Introduction

Modern agricultural technology adoption and use has been very low throughout Africa (Abebaw & Haile, 2013; Dadi et al., 2004; Holden & Lunduka, 2012; Kassie et al., 2013). For example, Crawford et al. (2006) showed that the average fertilizer use in Africa was only 9 kg/ha. However, recent studies indicate that there was an increase. Average fertilizer use for six countries (Ethiopia, Malawi, Niger, Nigeria, Tanzania, and Uganda) is 57 kg/ha, and the ratio of plots covered with fertilizer varies between 40% in Nigeria, half in Ethiopia, and two-thirds in Malawi (Sheahan & Barrett, 2017). Holden (2018) shows that the fertilizer use landscape in Africa is undergoing substantial changes, and several countries are seeing an increase in fertilizer use. Recent studies in Ethiopia indicate that fertilizer is used on 80% of the plots while intensity is around 38 kg/ha (Tefera et al., 2020).

Studies on the interaction between fertilizer and manure show mixed results. Some studies show a complementarity between the two (Ahmed et al., 2017; Hassen, 2018; Holden & Lunduka, 2012; Marenya & Barrett, 2007). Other studies show substitutability between fertilizer and manure (Kassie et al., 2015; Teklewold et al., 2013). These studies show contradicting outcomes and focus on the probability of adopting one of the technologies (say fertilizer), given the other is adopted (manure, in this case). It is essential to distinguish between the extensive and intensive margins when assessing how fertilizer and manure interact. Regarding the crowding in or crowding out discussion, Alabi et al. (2016) show that the intensity of subsidized fertilizer use crowds out organic fertilizer in Nigeria, while Holden and Lunduka (2012) show a weak positive correlation between subsidized fertilizer and manure (no crowding out) in Malawi.

In our study area, where crop and livestock production are well integrated with smallholder agriculture, fertilizer use has been increasing consistently between 2006 and 2015, while there was a reduction in manure use, especially from 2010 to 2015. Thus, the research questions this study aims to answer are: 1) What are the main drivers of the observed increase in fertilizer use and intensity of use in our study area between 2006 and 2015? 2) Does this differ between the extensive and intensive margins? 3). How does this look across areas with low versus high population density, good versus poor market-access, and on land without and with irrigation? and 4) How are the changes in fertilizer use associated with changes in manure use? More specifically, do we observe complementarity or substitutability between the two inputs? We hypothesize that fertilizer and manure are more likely complements at the extensive margin and substitutes at the intensive margin.

This study contributes to the literature in two important ways. First, it contributes to understanding the reasons behind the recent rise in fertilizer uptake in Ethiopia's semiarid northern highlands by analyzing three rounds of household-farm plot panel data from the Tigray region that cover the years 2006, 2010, and 2015. Our data indicate that manured plots decreased from 24% in 2006 to 21% in 2015, while fertilized plots increased from 31% to 67% in our sample. Also, over this period, the average amount of manure used on manured land decreased from 934 kg/ha in 2006 to 436 kg/ha in 2015, while that of fertilizer increased from 28 kg/ha to 87 kg/ha on fertilized land.

Second, to our knowledge, this is the first study to investigate the heterogeneity in manure and fertilizer use across high and low-population density areas, across good and poor market-access areas, and on land without and with irrigation in an integrated crop-livestock system in a semiarid area. Our study contributes to understanding the evolution and intensification of smallholder farming systems in Africa. We hypothesize that fertilizer use and intensification are more likely in densely populated areas, areas with good market access, and irrigated land because the marginal returns to fertilizer are assumed to be higher in these cases. We hypothesize that the use of manure is driven by livestock ownership, which again is influenced by fodder availability and the opportunity cost of time. Thus, we suggest that livestock and manure are relatively more important in land-abundant (low population density areas) and areas with poorer market access (low opportunity cost of time), complicating fertilizer and manure interactions.

## 2. Literature review

Explaining the use of improved technology by rural farmers has been the focus of many studies. For a review of earlier studies on this topic, see Doss (2006), while Holden (2018) reviews more recent studies focusing on fertilizer use in sub-Saharan Africa. One area of focus of studies on fertilizer use by rural farmers in developing countries has been identifying the main factors determining fertilizer use. These studies are motivated mainly by the need to explain why fertilizer use is low in Africa and very high in Asia. Findings of some of the studies along this line point out that household and farm-level features are essential (Alene et al., 2000; Asfaw & Admassie, 2004; Asfaw et al., 2011; Knight et al., 2003). Other studies stress that endowment and liquidity-related factors (Abebe et al., 2013; Langyintuo & Mungoma, 2008; Regassa et al., 2023; Shiferaw et al., 2009; Zerfu & Larson, 2010) and institutional factors are essential in the adoption of technology by rural farmers (Abebaw & Haile, 2013; Isham, 2002; Ketema & Kebede, 2017; Krishnan & Patnam, 2013; Moser & Barrett, 2003) Besides these, relatively more recent literature stressed that risk-related issues are crucial (Alem et al., 2010; Dercon & Christiaensen, 2011; Holden & Westberg, 2016; Mukasa, 2018).

Farm input subsidy programs (FISPs) have also been another important driver of fertilizer use. Holden (2018, 2019) and Jayne et al. (2018) review studies on this topic. These reviews show that though first-generation input subsidy programs (from the 1970s to 1990s) failed in Africa, second-generation subsidy programs proliferated driven by the 'Malawi miracle.' FISPs became more politically popular based on theories on externality, market failure, new technology and learning by doing, poverty trap, and market-smart subsidy arguments. These literature reviews also indicate that poor market access (limited investments in infrastructure), low water availability (limited investments in irrigation), and poor soil quality limit fertilizer use, fertilizer use efficiency, and profitability in SSA.

Studies on the interaction between fertilizer and manure show mixed results; see Table 1 below for an overview. We find seven studies in a similar area of interest to ours. The relevance of the studies is based on whether the studies considered the fertilizer and manure use decisions jointly or assessed a multitude of technologies that include fertilizer and manure use among them. Only two of these studies, namely, Alabi et al. (2016) (Nigeria) and Holden and Lunduka (2012) (Malawi), have explored fertilizer use and manure use both at the extensive and intensive margins using panel data (see Table 1). The rest explored the extensive margin only. Although Alabi et al. (2016) use panel data, its period is very short (before and after harvest in one production season). To our knowledge, the study by Holden and Lunduka (2012) is the only one examining the relationship between fertilizer use and manure use at both margins. They found that fertilizer use intensity positively correlated with manure use at the extensive and intensive margins. However, they also found that the fertilizer price positively correlated with the probability and intensity of manure use. But the response elasticity was much higher for the intensity of manure use. The responses are likely sensitive to important contextual factors. Our study allows an assessment of the external validity of these findings in a smallholder crop-livestock farming system where livestock has a more important role than in Malawi. With three survey rounds covering changes over nine years in a semi-arid environment in Ethiopia and a sample stratified to cover substantial variation in population pressure and market-access, and without and with access to irrigation, our study should give valuable insights about how farmers combine or substitute fertilizer and manure across a variety of contexts.

TABLE 1 Literature on the relationship between fertilizer and manure use

| S.N. | Authors | Probability of Use/Intensity | Data | Method | Key finding |
|---|---|---|---|---|---|
| **1** | Alabi et al. (2016) | Both | Household level panel data before and after harvest season in 2010/11 from the Nigeria General Household Survey that covers 5000 farming | IV probit and IV Tobit | Inorganic fertilizer subsidy crowds out organic fertilizer use at extensive and intensive margins. |
| **2** | Morgan et al. (2019) | Probability of use only | Two panel data sets from nationally representative surveys of smallholder farm households. The first is a three-wave panel for the 1999/00, 2002/03 and 2006/07 agricultural years. The second data set is for the 2010/11 and 2013/14 agricultural years. | CRE probit | The maize fertilizer subsidy program has no statistically significant effect on manure use. |
| **3** | Holden and Lunduka (2012) | Both | Panel data of 450 HHs from three rounds of survey (2006, 2007, and 2009) in two districts of Malawi | CRE probit and CRE Tobit. | Fertilizer uses crowds in manure at extensive and intensive margins. |
| **4** | Hassen (2018) | Probability of use only | Panel data from two rounds (2013 and 2015) in the Southern Zone of Tigray. A rainfall-stressed area with frequent droughts. He took 297 smallholder crop-livestock mixed system farm households with 634 plots. | CRE ordered probit & IV Ordered probit | Fertilizer use is likely to continue in manured plots (i.e., complementarity) |
| **5** | Ahmed et al. (2017) | Probability of use only | Cross-sectional data of 355 smallholder rain-fed maize-growing households with 480 plots in eastern Ethiopia. | Multivariate probit | There is substitutability between inorganic fertilizer use and manure use. |
| **6** | Kassie et al. (2015) | Probability of use only | Cross-sectional survey data in 2010 of 5779 HHs and 9837 maize plots in Ethiopia, Kenya, Malawi and Tanzania | Multivariate probit | Manure and fertilizer are substitutes in Ethiopia and Malawi |
| **7** | Teklewold et al. (2013) | Probability of use only | Cross-sectional data of 898 HHs and 4,050 plots in 2010. They took maize plots only (1,616 plots) | Multivariate probit & ordered probit models | The likelihood of inorganic fertilizer use decreases on manured plots (substitutability) |

## 3. Analytical Framework and Hypotheses

Agricultural production functions capture the relationships between outputs and inputs such as fertilizer, manure, labor, traction power, seeds, etc. Knowing that crop growth depends on the supply of nutrients, water, light, and advantageous temperatures, fertilizer and manure can be alternative sources of mineral nutrients that help enhance soil fertility. The soil organic matter (SOM) content in the soil also matters for soil quality (soil structure and nutrient availability) and plant growth (Dieckow et al., 2005; Loveland & Webb, 2003). Organic manure contributes to the SOM and soil structure, which may enhance the water-holding capacity of soils and release nutrients that enhance plant growth (Antil & Singh, 2007; Maillard & Angers, 2014). SOM can also improve the plant's ability to utilize nutrients from inorganic fertilizer, which may explain potential synergies between combining organic manure and fertilizers (Lima et al., 2009). Some types of organic manure may also be low in some types of nutrients (e.g., Nitrogen (N)), and the supply of N through fertilizer may give a more balanced nutrient supply that can enhance the nutrient release and thereby plant growth (Menšík et al., 2018). Therefore, these factors suggest that organic manure and fertilizer complement each other at an extensive margin. On the other hand, with an abundant supply of nutrients from organic manure and fertilizer, they may become substitutes. Overall, organic manure and fertilizer are more likely complements at the extensive margin, especially on poor soils, and are more likely substitutes on the intensive margin and fertile soils.

The decisions in a given production year regarding the use of inputs are assumed to emanate from the farmer's maximization of expected utility, given the information and resources available and the constraints faced when making these decisions. As farm households are both production and consumption units and production and consumption decisions are inter-related due to market imperfections, input use decisions are influenced by market-access constraints as well as household resource endowments such as land, livestock, and family labor, and current and anticipated future weather conditions, yields, market prices, and consumption needs (Sadoulet et al., 1996). An important implication of the imperfect market conditions is that local heterogeneity in population density, market access, and access to irrigation can also affect the use of inputs such as fertilizer and manure.

Based on the discussion so far, we launch the following hypotheses:

H1. Manure use is constrained by the household's livestock endowment, which depends on fodder access, rainfall (drought), and the opportunity cost of time (family labor availability and off-farm employment opportunities) rather than direct input substitution.

H2) Fertilizer use (extensive margin) and fertilizer use intensity (intensive margin) are higher in densely populated areas than in low-population density areas.

H3) Fertilizer use and fertilizer use intensity are higher in areas with good market access than in areas with poor market access.

H4) Fertilizer use and fertilizer use intensity are higher on irrigated land than on rainfed land.

H5a) Manure and fertilizer are complementary inputs at the extensive margin.

H5b) Manure and fertilizer are substitutes at the intensive margin.

## 4. Data and Empirical Strategy

### 4.1 Sampling strategy and data

This study collected data from 11 *woredas*[1] in the Tigray region, northern Ethiopia. We utilize the three last rounds of panel data collected by the Norwegian University of Life Sciences in collaboration with Mekelle University. The initial baseline survey (1998) was a stratified sub-

[1] A *woreda* is a middle level administrative unit (district) which is below the regional level administration and above the *tabia* (community) level administration.

sample of a survey sample made by the International Food Policy Research Institute. The stratification is used to enlarge the sample variation in population density and market access while retaining the zonal representativeness within the highland areas of the Tigray region and containing communities without and with access to irrigation (Hagos, 2003).

The survey started in 1998 with 400 households from 16 *tabias*[2], taking 25 households from each *tabia*. Follow-up surveys of these households took place in 2001, 2003, 2006, 2010 and 2015. We expanded the sample by adding one more *tabia* in 2010 and three more *tabias* in 2015. Table 2 gives the sample breakdown in the last three survey rounds we utilized in this study.

TABLE 2 Break down of sample households and plots

| Year | # of HHs | | | Population density | | Market-access | | # of plots |
|---|---|---|---|---|---|---|---|---|
| | Sample | Available | Attrition | High | Low | Good | Poor | |
| 2006 | 400 | 359 | 41 | 227 | 132 | 173 | 186 | 1,856 |
| 2010 | 512 | 483 | 29 | 291 | 192 | 241 | 241 | 2,276 |
| 2015 | 695 | 624 | 71 | 311 | 313 | 350 | 274 | 2,725 |

Source: MU and NMBU survey

We carried out each survey round from June to September to avoid bias due to seasonality. A questionnaire with predominantly the same structure and questions was used in all the rounds to avoid bias due to the lack of comparability of survey instruments. The data included household characteristics, consumption expenditure, asset ownership, land use, and input use at the farm plot level. Plot sizes were measured with GPS. The Ethiopian Meteorology Institute branch office in Mekelle provided rainfall data from local rainfall stations.

### 4.2. Empirical strategy

In our assessment of farm plot level fertilizer and organic manure use at the extensive and intensive margins, given our research questions and hypotheses, we have identified the

[2] A *tabia* is the lower level administrative unit just below the *woreda*.

following key variables of interest: Dependent variables: a) Use/non-use of fertilizer at farm plot level by survey round, b) Use/non-use of organic manure at farm plot level by survey round, c) Intensity of fertilizer use at farm plot level (kg/ha), and d) Intensity of organic manure use at farm plot level (tons/ha).

We investigate the importance of the key explanatory variables by running split sample models for areas with low versus high population density, for areas with good versus poor market access, and for irrigated versus rainfed farm plots. We test the robustness of the results by running models without and with additional control variables, which are plot level, household level, and village level variables.

Since we use three-panel data rounds and face households' attrition from survey round to survey round (see Table 2), attrition bias can become a problem in our estimated models. Thus, we estimate the attrition probit and include the inverse Mill's ratio in the manure and fertilizer regressions that we estimate (Miller & Wright, 1995; Moffit et al., 1999). For details, see Table A1 in the Appendix.

We want to explore factors that drive the observed increase in fertilizer use and intensity in our study area and assess whether fertilizer use has substituted for (crowded out) the use of manure. The primary source of manure in our study area is animal dung, which is collected mainly from animal barns around the homestead. Mostly, animal dung is dried near the homestead and then transported to farm plots. Since transporting manure is labor-intensive and cumbersome, households may prefer to apply it on nearby plots unless far away plots are so degraded that manuring them becomes urgent. Fertilizer use on a given plot may be conditioned by whether manure has been applied on that plot, as the transportation of fertilizer with its much higher nutrient concentration is less labor-demanding. This implies a sequential decision-making process, with the manure use decision coming before the fertilizer use decision, as manure is applied on cropland before the crop is planted, while fertilizer is typically applied after planting. Manure use can, therefore, influence fertilizer use recursively. Thus, we model this decision process as a recursive system of equations as follows.

First, we specify the manure equation:

$$M_{qjit} = \delta_q + \beta_{qk} X_{jit} + \alpha_{qk} \bar{X}_{ji} + v_{qjit} \qquad (1)$$

where $M_{qjit}$ represents the use (dummy indicator for use) of or intensity of use (*log*(ton/ha)) of manure on plot $j$ of household $i$ in year $t$ in split sample $q$ where we split the sample by population density, market-access, or irrigation status. We split *tabias* into high- and low-density areas based on population density before estimation. Alternatively, we split *tabias* into good (if the nearest market is less than 10 kilometers from the *tabia* center) and poor market access for separate estimation. Finally, we split plots by irrigation status, which are estimated separately. While using one split at a time, we include the other split indicators as dummy variables. Our limited sample size does not provide the statistical power to disaggregate further.

Our key variables of interest in the $X_{jit}$ vector of variables with means $\bar{X}_{ji}$ in the manure models are in addition to the year dummies and sample splits, the total livestock per hectare of cultivated land (TLU/ha), distance of the plot from the homestead in walking hours (*distplot*), number of adult members in the household per hectare of cultivated land (adult/ha), and the availability of off-farm work access to the household head (*off-farm*). Livestock are the direct source of manure; hence, TLU/ha should positively correlate with manure use and intensity. Conversely, distance to plot should be negatively correlated with manure use and intensity as manure is mostly prepared around the homestead and is heavy to transport. We hypothesize that the availability of labor will be positively correlated with manure use and intensity as manure is labor-intensive in preparation, storage, and use. Availability of off-farm work access is hypothesized to be negatively correlated with manure use as it proxies the opportunity cost of labor used in manure. As additional control variables we include rainfall as it is directly related to plant growth and animal feed availability[3] (Maleko et al., 2018). We also expect the likelihood of use of manure and its intensity to be lower on plots that are rented compared to own plots as the effect of manure lasts more than a year, but rental contracts are short-term by law.

To estimate the fertilizer models, first, we estimate equation (1) for each category ($q$) and obtain predicted values of the probability of manure use on a plot (from the hurdle equations) and the predicted value of the log (tons/ha of manure used) in equation (1). In this setup, we assume the farmers know the manure use and intensity before making fertilizer use decisions. Thus, we estimate and predict manure use and include the predicted variables when estimating the fertilizer models. Therefore, the fertilizer models we estimate are specified as follows.

$$F_{jitq} = \pi_q + \rho_q T + \gamma_q \widehat{M}_{jitq} + \theta_{qk} X_{jitq} + \sigma_q \bar{X}_{jiq} + \varepsilon_{jitq} \qquad (2)$$

where $F_{jitq}$ represents the use (dummy indicator for use) of or intensity of use (log(kgs/ha)) of fertilizer on plot $j$ of household $i$ in year $t$ in split sample $q$

Our key coefficients of interest across all split sample regressions are $\rho_q$ and $\gamma_q$. The first ($\rho_q$) are coefficients of the year dummies, allowing us to compare the fertilizer use trends and intensity across the split samples over time. The second ($\gamma_q$) show us whether fertilizer and manure are complements or substitutes across the split sample groups.

The $X_{jit}$ vector of variables with means contains the same variables as in the manure use models plus whether the household head has accessed credit and the deflated price/kg of fertilizer[4]. $\bar{X}_{ji}$ (the time mean of the control variables) in the manure and fertilizer models to account for

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[3] We have a dummy for the rainfall condition of *tabias* which equals one if the *tabia* received less than average rainfall based on 12-year rainfall data for all *tabias* and zero otherwise.

[4] To deflate the *tabia* level market price of fertilizer, we used average consumer price index inflation data from the Annual Economic Report of the National Bank of Ethiopia for the years 2005/6, 2009/10 and 2014/15. We did this because we could not find producer price index.

plot- and household-level unobserved heterogeneities using the correlated random effects model (Mundlak, 1978; Wooldridge, 2019). This approach is commonly used in limited dependent variable models as fixed effects models cause the incidental parameter problem.

We use the double hurdle model for estimation as it is more flexible than the censored Tobit model (Cragg, 1971). We also tested these alternative model specifications against each other using Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The result shows that the double hurdle models fit our data better (see Table B1 in the Appendix).

## 5. Results and Discussion

First, we assess the general trends in fertilizer and manure use (2006-2015). Next, we explore differences in our key variables based on the sample splitting categories using statistical tests of sample mean difference. Finally, we present the econometric results based on the sample splitting categories.

### 5.1 Trends in fertilizer and manure use

Table 3 shows that fertilizer use increased from 31.4% of cultivated plots in 2006 to 58.7% in 2010 and 66.8% in 2015. Fertilizer use increased from 27.6 kg/ha in 2006 to 49.7 kg/ha in 2010 and 86.5kg/ha in 2015. Manure use increased from 24.1% of plots in 2006 to 29.4% in 2010 and then declined to 20.8% in 2015. Manure use intensity decreased from 9.4 tons/ha in 2006 to 9 tons/ha in 2010 and 4.4 tons/ha in 2015. The proportion of plots receiving fertilizer and manure increased from 2006 to 2010 but declined from 2010 to 2015.

The sample splitting categories in Table 4 show that high-density areas have a higher proportion of plots with fertilizer and manure and higher use intensity for both inputs in 2006 and 2010. In 2015, the difference in intensity was reduced.

TABLE 3 General trends in fertilizer and manure use and proportion of plots by sample splits (population density, market distance, and irrigation)

| ***Year*** | ***Use (% of plots)*** | | | ***Intensity (kg/ha)*** | | ***% of plots in areas with*** | | ***Irrigated plots (%)*** |
|---|---|---|---|---|---|---|---|---|
| | Fertilizer | Manure | Both | Fertilizer | Manure | High-density | Good market | |
| **2006** | 31.4 | 24.1 | 6.6 | 27.6 | 934.9 | 63.5 | 50.0 | 3.0 |
| **2010** | 58.7 | 29.4 | 18.7 | 49.7 | 898.3 | 59.5 | 51.3 | 11.6 |
| **2015** | 66.8 | 20.8 | 15.5 | 86.5 | 435.3 | 53.4 | 62.7 | 10.2 |

Source: MU and NMBU survey

A comparison by market access yields mixed results. In 2006, fertilizer and manure use rates were higher in poor market-access areas. The intensity of fertilizer use was higher in good market-access areas, while that of manure use was higher in poor market-access areas. In 2010, fertilizer use rate (the extensive margin) and kg/ha of fertilizer (the intensive margin) were higher in good market-access areas. There was no statistically significant difference in manure use at the extensive and intensive margins. In 2015, the fertilizer use rate and intensity were higher in good market-access areas, while the manure use rate was higher in poor market-access areas. There was no statistically significant difference in terms of manure use intensity.

When we look at irrigation, there was a higher manure use rate and intensity of use on irrigated plots in 2006. In 2010 and 2015, irrigated plots showed a higher fertilizer use rate.

TABLE 4 Trends in fertilizer and manure use by population density, market access, and irrigation

| *Year* | *Variables* | *Population density* | | | *Market access* | | | *Irrigated plots* | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *Low* | *High* | *t-value* | *Poor* | *Good* | *t-value* | *No* | *Yes* | *t-value* |
| **2006** | Fertilizer (%) | 22.6 | 36.4 | -6.26*** | 38.4 | 24.4 | 6.58*** | 31.4 | 29.1 | -0.37 |
| | Manure (%) | 19.5 | 26.8 | -3.58*** | 30.2 | 18.1 | 6.13*** | 23.8 | 34.6 | -1.83* |
| | Fertilizer (kg/ha) | 22.6 | 30.4 | -1.877* | 19.9 | 35.2 | -3.86*** | 26.1 | 74.8 | -4.17*** |
| | Manure (kg/ha) | 580.3 | 1139 | -2.93*** | 1298.5 | 571.2 | 3.97*** | 950.2 | 431.5 | 0.96 |
| | ***Obs.*** | ***628*** | ***1178*** | | ***928*** | ***928*** | | ***1801*** | ***55*** | |
| **2010** | Fertilizer (%) | 53.3 | 62.3 | -4.28*** | 54.8 | 62.3 | -3.66*** | 56.8 | 73.1 | -5.10*** |
| | Manure (%) | 30 | 28.9 | 0.533 | 28.6 | 30.1 | -0.76 | 29.7 | 26.7 | 0.93 |
| | Fertilizer (kg/ha) | 34.5 | 60.1 | -5.67*** | 36 | 62.7 | -6.05*** | 48.6 | 58.3 | -1.39 |
| | Manure (kg/ha) | 668.5 | 1054.4 | -2.66*** | 938.3 | 860.2 | 0.55 | 925.4 | 691.4 | 1.05 |
| | ***Obs.*** | ***980*** | ***1296*** | | ***1108*** | ***1168*** | | ***2012*** | ***264*** | |
| **2015** | Fertilizer (%) | 61.7 | 71.2 | -5.28*** | 59.9 | 70.9 | -5.94*** | 66.1 | 72.9 | -2.30** |
| | Manure (%) | 17.6 | 23.7 | -3.93*** | 25.2 | 18.2 | 4.40*** | 21.2 | 17.3 | 1.51 |
| | Fertilizer (kg/ha) | 83 | 89.6 | -1.281 | 73.6 | 94.2 | -3.918 | 86 | 91.3 | -0.64 |
| | Manure (kg/ha) | 413.7 | 454.3 | -0.44 | 384.8 | 465.5 | -0.84 | 437.7 | 417.8 | 0.13 |
| | ***Obs.*** | ***1362*** | ***1363*** | | ***1176*** | ***1549*** | | ***2448*** | ***277*** | |

Significance levels: * 10%, ** 5%, *** 1%.

## 5.2 Econometric Results

The probit regression of sample attrition shows that attrition is correlated with some household features, endowments, and zones of household residence (see Table A1 in the Appendix). To correct for non-random attrition, we included the Inverse Mills Ratio (IMR) from the attrition probit model in all the following models (see Tables 5 and 6). The IMR was significant in many models and thus should control for attrition bias. We used bootstrapping to correct the standard errors for the predicted IMR.

### 5.2.1 Manure use and intensity of use

Table 5 presents the econometric model results for the manure use and intensity. Market access has opposite effects on the likelihood and intensity of manure use in low-density versus high-density areas. Good market access increases the likelihood of use of manure in low-density areas but is associated with lower intensity of use. In low-density areas with good market access, the likelihood of manure use is lower, but the intensity of use is higher. Market access, therefore, seems to stimulate concentration of manure use, probably for more market-oriented production. From 2006 to 2010 and 2015, manure use intensity increased only on irrigated plots. While manure use and intensity overall increased from 2006 to 2010, it declined substantially from 2010 to 2015. The El Nino drought in 2014-15 is an important reason for this as it has negatively affected fodder and livestock production. There was a marked decrease in livestock/ha across all areas from 2010 to 2015 (see Table E1 in the Appendix). The drought in 2014-15 was so severe that 43% of households had to sell their livestock and 55% needed drought related support from the government (Holden & Tilahun, 2024). Various literature have documented the negative effect of drought on livestock in the context of climate change; see, for example, Cheng et al. (2022) and Thornton et al. (2009) for a review of such literature. Selling of livestock is a well-known coping strategy associated with drought in Ethiopia (Alemayehu & Bewket, 2017; Gebregziabher & Holden, 2011; Holden & Shiferaw, 2004). The

2015 year dummy is negatively and significantly related to manure use in low-density, poor market access, and non-irrigated plots, and with manure use intensity in high-density, poor market access, and non-irrigated plots. We must remember this when we assess the relationship between manure use and fertilizer use. The results for the livestock and labor endowment variables were mixed and less clear, demonstrating complex heterogeneities in the data.

Table 5 Manure use rate and intensity (CRE double hurdle models)

| **Sample split by** | **Population density** | | **Market Access** | | **Plot is irrigated** | |
|---|---|---|---|---|---|---|
| | **High** | **Low** | **Good** | **Poor** | **Yes** | **No** |
| **Log of tons of manure/ ha** | | | | | | |
| Year 2010 dummy | -0.248 | 0.248** | 1.011*** | 0.341*** | 2.453*** | -0.070 |
| | (0.169) | (0.111) | (0.150) | (0.111) | (0.246) | (0.074) |
| Year 2015 dummy | -1.260*** | 0.112 | -0.085 | -0.269** | 1.198*** | -0.397*** |
| | (0.158) | (0.118) | (0.142) | (0.128) | (0.233) | (0.078) |
| Population density (1=high) | | | 0.274** | 0.351** | 0.138 | 0.301*** |
| | | | (0.126) | (0.139) | (0.113) | (0.076) |
| Market access (1=good) | 0.612*** | -0.251** | | | 0.081 | 0.148** |
| | (0.114) | (0.114) | | | (0.106) | (0.060) |
| Plot is irrigated (1=yes) | -0.557*** | 0.395*** | 0.019 | -0.013 | | |
| | (0.178) | (0.124) | (0.150) | (0.141) | | |
| TLU/ ha | 0.313 | 0.084 | 0.627** | 0.359* | -0.255 | 0.227 |
| | (0.224) | (0.224) | (0.296) | (0.189) | (0.195) | (0.176) |
| Distance to plot | 0.205** | -0.136** | 0.167 | -0.021 | 0.012 | -0.000 |
| | (0.091) | (0.064) | (0.105) | (0.071) | (0.170) | (0.049) |
| # of adults in the HH/ha | 0.003 | -0.004* | 0.020*** | 0.001 | -0.005 | 0.003 |
| | (0.002) | (0.002) | (0.004) | (0.002) | (0.003) | (0.002) |
| Off-farm work access dummy (1=yes) | 0.234 | -0.101 | 0.214 | 0.033 | 0.143 | -0.239** |
| | (0.194) | (0.130) | (0.156) | (0.116) | (0.154) | (0.099) |
| Plot is rented in (1=yes) | 0.277 | -0.433** | -0.152 | -0.116 | 0.106 | 0.233* |
| | (0.210) | (0.194) | (0.199) | (0.183) | (0.233) | (0.126) |
| Tabia receives below average rainfall (1=yes) | -0.105 | -0.201 | 0.171 | -0.520*** | -0.363*** | -0.400*** |
| | (0.093) | (0.124) | (0.126) | (0.081) | (0.129) | (0.070) |
| Attrition IMR | 0.159 | 0.073 | 0.406*** | 0.430*** | -0.565*** | 0.244*** |
| | (0.166) | (0.100) | (0.112) | (0.107) | (0.120) | (0.071) |
| Time mean of variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | 0.310 | -0.542* | -2.441*** | -0.314 | -2.793*** | -0.051 |
| | (0.441) | (0.308) | (0.413) | (0.378) | (0.560) | (0.232) |
| Sigma constant | 1.069*** | 1.163*** | 1.365*** | 1.280*** | 0.446*** | 1.274*** |
| | (0.058) | (0.036) | (0.050) | (0.051) | (0.032) | (0.031) |
| **Manure Use (1=plot received manure)** | | | | | | |
| Year 2010 dummy | 0.095 | -0.357 | -0.641** | -2.595* | -11.795 | 0.040 |
| | (0.189) | (0.361) | (0.321) | (1.408) | (145.345) | (0.167) |
| Year 2015 dummy | 0.696*** | -1.844*** | 0.597 | -1.855** | -11.046 | -0.285* |
| | (0.231) | (0.429) | (0.408) | (0.926) | (145.344) | (0.172) |
| Population density (1=high) | | | -1.322*** | -3.474** | 0.709** | -9.453 |
| | | | (0.307) | (1.421) | (0.275) | (87.389) |
| Market access (1=good) | -0.997*** | 2.308*** | | | -0.291 | -1.156*** |
| | (0.179) | (0.446) | | | (0.256) | (0.184) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Plot is irrigated (1=yes) | 0.470 | -1.796*** | 0.144 | -0.187 | | |
| | (0.311) | (0.390) | (0.365) | (0.556) | | |
| TLU/ ha | 0.251 | 3.691*** | -0.023 | -0.441 | 0.986 | 0.207 |
| | (0.200) | (0.900) | (0.431) | (0.470) | (0.769) | (0.249) |
| Distance to plot | -0.038 | 1.436*** | -0.266 | 3.156** | 0.708** | -0.083 |
| | (0.091) | (0.262) | (0.209) | (1.590) | (0.314) | (0.110) |
| # of adults in the HH/ha | -0.007*** | 0.025*** | -0.036*** | -0.007 | -0.019** | -0.013*** |
| | (0.002) | (0.007) | (0.008) | (0.007) | (0.009) | (0.002) |
| Off-farm work access dummy (1=yes) | -0.382* | -0.124 | -0.015 | 4.109 | 1.215*** | -0.438** |
| | (0.200) | (0.476) | (0.539) | (3.343) | (0.453) | (0.199) |
| Plot is rented in (1=yes) | -0.087 | 2.797*** | 0.853** | 0.441 | -0.589 | -0.031 |
| | (0.243) | (0.751) | (0.435) | (0.929) | (0.611) | (0.274) |
| Tabia receives below average rainfall (1=yes) | 0.016 | -3.480*** | -0.419 | 0.835* | -0.497 | 0.522*** |
| | (0.102) | (0.552) | (0.303) | (0.469) | (0.339) | (0.154) |
| Attrition IMR | -0.189 | 1.114*** | -0.501* | -1.454*** | 1.588*** | -0.762*** |
| | (0.181) | (0.402) | (0.304) | (0.528) | (0.387) | (0.190) |
| Time mean of variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | 0.782* | 3.578** | 7.310*** | 4.812*** | 13.745 | 11.037 |
| | (0.455) | (1.419) | (1.550) | (1.585) | (145.350) | (87.393) |
| ***Observations*** | 3896 | 2807 | 3660 | 3229 | 569 | 6243 |

Bootstrapped standard errors in parentheses, clustered at household level. Significance levels: * 10%, ** 5%, *** 1%.

### 5.2.2 Fertilizer use and intensity of use

Table 6 presents the fertilizer use and intensity models where manure use has been predicted based on the manure models above. Fertilizer use intensity increased over the years in low-density areas without a significant increase in the likelihood of fertilizer use. This indicates a concentration of fertilizer use in such areas. In high-density areas, we see an opposite trend: the likelihood of fertilizer application has increased while the intensity of use has declined significantly. The intensity of fertilizer use also increased over time in areas with good market access but much less in areas with poor market access. Fertilizer use intensity increased significantly over time on non-irrigated land but not on irrigated land. Fertilizer use on irrigated land was high already in 2006 (74.8 kg/ha).

Table 6 Fertilizer use rate and intensity (CRE double hurdle models)

| Sample split by | Population density | | Market-access | | Plot is irrigated | |
|---|---|---|---|---|---|---|
| | **High** | **Low** | **Good** | **Poor** | **Yes** † | **No** |
| **Log of kgs of fertilizer/ha** | | | | | | |
| Year 2010 | -0.548** | 2.282*** | 1.922*** | 0.670* | -0.710 | 0.620*** |
| | (0.275) | (0.308) | (0.345) | (0.366) | (2.053) | (0.187) |
| Year 2015 | -1.657** | 4.329*** | 3.205*** | 0.674 | 1.718 | 1.149** |
| | (0.843) | (0.579) | (0.633) | (0.592) | (1.992) | (0.468) |
| Predicted log of tons of Manure/ha | 0.369 | -1.171 | -0.460** | -0.310 | 0.853 | -0.267 |
| | (0.435) | (0.809) | (0.189) | (0.828) | (0.981) | (0.588) |
| Population density (1=high) | | | 0.110 | 0.345 | 0.301* | 0.080 |
| | | | (0.076) | (0.256) | (0.166) | (0.160) |
| Market-access (1=good) | -0.098 | -0.129 | | | -0.630 | 0.119 |
| | (0.319) | (0.189) | | | (0.726) | (0.082) |
| Plot is irrigated (1=yes) | 0.288 | 0.403 | 0.024 | -0.175** | | |
| | (0.269) | (0.309) | (0.060) | (0.087) | | |
| Sample attrition IMR | 0.040 | 0.073 | 0.039 | 0.239 | -0.044 | -0.001 |
| | (0.101) | (0.080) | (0.096) | (0.297) | (0.124) | (0.131) |
| Time mean of variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | 2.703*** | 4.242*** | 4.894*** | 3.148*** | 6.004*** | 3.942*** |
| | (0.357) | (0.532) | (0.578) | (0.426) | (1.384) | (0.253) |
| Sigma_ constant | 0.772*** | 0.694*** | 0.774*** | 0.791*** | 0.754*** | 0.778*** |
| | (0.013) | (0.013) | (0.013) | (0.016) | (0.028) | (0.010) |
| **Fertilizer use (1=plot received fertilizer)** | | | | | | |
| Year 2010 | 0.939*** | -0.869** | -0.541 | -0.510 | -12.761 | -0.301 |
| | (0.331) | (0.371) | (0.434) | (0.315) | (10.010) | (0.184) |
| Year 2015 | 2.672** | -1.025 | -0.397 | -0.690 | -11.985 | -0.148 |
| | (1.194) | (0.663) | (0.745) | (0.600) | (11.091) | (0.456) |
| Predicted log of tons of Manure/ha | 0.038 | 0.569 | 0.380 | -1.079*** | -0.020 | 0.560 |
| | (1.351) | (0.809) | (0.308) | (0.415) | (1.832) | (0.468) |
| Predicted Manure Use (1=yes) | -0.912 | -0.134** | 0.226* | -0.283*** | -7.389 | 0.205 |
| | (0.831) | (0.064) | (0.135) | (0.106) | (6.724) | (0.153) |
| Population density (1=high) | | | 0.299** | -0.545** | 0.094 | 2.239** |
| | | | (0.124) | (0.266) | (0.186) | (1.022) |
| Market-access (1=good) | -0.204 | 1.132*** | | | -3.667 | 0.366*** |
| | (0.226) | (0.222) | | | (2.934) | (0.095) |
| Plot is irrigated (1=yes) | 0.616 | -0.196 | 0.140* | 0.206** | | |
| | (0.402) | (0.313) | (0.085) | (0.097) | | |
| Time mean of variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Constant | -0.967 | -0.557 | -0.613 | 0.551 | 20.550 | -4.143*** |
| | (1.108) | (0.563) | (0.552) | (0.578) | (14.506) | (1.256) |
| ***Observations*** | 3896 | 2902 | 3660 | 3229 | 589 | 6243 |

Bootstrapped standard errors in parentheses, clustered at household level. Significance levels: * 10%, ** 5%, *** 1%. †= results are without bootstrapped standard errors. 2)The attrition IMR is dropped in all the hurdle equations due to multicollinearity.

Table 4 shows that high-density areas have higher fertilizer use and intensity in all years. Thus, we can say that our population density (H2) hypothesis cannot be rejected at a given time. Over the years, the intensification of fertilizer use has been stronger in low-density areas and non-irrigated plots. Therefore, the Boserupian theory is relevant as households apply fertilizer on larger parts of their land over time. The results also show that the intensification of fertilizer use is catching up in low-density areas with larger per capita land[5] compared to high-density areas.

While the likelihood of fertilizer use was lower in good than in poor market access areas in 2006, this changed in 2010 and 2015, while fertilizer use intensity increased and remained higher in all years in good compared to poor market access areas (Table 4). Table 6 indicates that fertilizer use was more likely in low-density areas with good than poor market access and non-irrigated land with good than poor market access. These results imply that our market access (H3) hypothesis cannot be rejected. Therefore, market access seems to be a key player in explaining the expanding fertilizer use observed in our study area.

Table 4 provides evidence supporting our hypothesis H4 that fertilizer use and fertilizer use intensity are higher on irrigated land than on rainfed land. However, over the period studied, fertilizer use on non-irrigated land expanded more and was not far below that on irrigated land in 2015.

#### 5.2.3 How is the use of fertilizer and manure related?

Our hypothesis H5a stated that manure and fertilizer are complements at the extensive margin while hypothesis H5b stated that manure and fertilizer are substitutes at the intensive margin. Table 6 shows that predicted manure use is negatively correlated with fertilizer use in low population density areas (significant at 5% level) and areas with poor market access (significant

[5] Low-density areas have larger per capita land holding (1.53) compared to high-density areas (0.89).

at 1% level). In good market access areas, predicted manure use has a positive correlation with fertilizer use (significant at a 10% level only) while predicted manure use intensity has a negative correlation with fertilizer use intensity. For the other models, the coefficients are insignificant. The results, therefore, point in the direction of manure and fertilizer being substitutes rather than complements at the extensive margin in low population density areas and areas with poor market access. We, therefore, reject our H5a hypothesis for these areas. In good market-access areas we have complementarity at the extensive margin and substitution at the intensive margin. Therefore, we cannot reject our H5a and H5b hypotheses for such areas but have to do so for other areas.

The result in good market-access areas may indicate that households combine the two inputs across their plots (the extensive margin) and tend to use more fertilizer at a plot (the intensive margin) to maximize yield per plot. The substitution between the two inputs in low-density and poor market access areas may be a result of the decline in livestock/ha (see Table E1 in the Appendix) observed in the study area especially due to the drought in 2014-15.

## 6. Conclusion

This paper investigates possible explanations for the increased uptake of fertilizer observed in a semi-arid environment in northern Ethiopia, how it relates to manure use, and whether these inputs are complements or substitutes in crop production. We use panel data from three rounds between 2006 and 2015 of more than 600 smallholder farm households with more than 2700 plots. We tested the hypotheses that population density, market access, and irrigation are the main drivers of the increased fertilizer uptake, and that fertilizer and manure are complements at the extensive margin and substitutes at the intensive margin.

The results show higher fertilizer use and intensity in areas with high population density, but intensity has also increased substantially over time in low-density areas. Fertilizer use and intensity are higher in areas with good market access, and the intensity of use has increased more in areas with good market access. We found fertilizer and manure to be substitutes on the extensive margin in low-density areas and areas with poor market access. A severe drought in 2014/15 may have contributed to the loss of livestock in these areas and, thereby, a reduction in manure use, which may have been compensated with increased fertilizer use. Only in areas with good market access were the two inputs found to be complements at the extensive margin and substitutes at the intensive margin.

Generally, our results indicate that Ethiopia's focus on improving smallholder farmers' productivity through the provision of improved inputs, among others (Berhanu & Poulton, 2014; National planning commission, 2016), seems to have started to yield the desired result regarding fertilizer use intensification.

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