



Land scarcity impedes sustainable input intensification in smallholder irrigated agriculture

Evidence from Egypt

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ABSTRACT

Increasing population pressure and population density in many African countries are inducing land scarcity and land constraints. These increasing land constraints are expected to trigger various responses and adaptation strategies, including agricultural intensification induced by land scarcity, as postulated by the Boserup hypothesis. However, most empirical evaluations of the Boserup hypothesis come from rainfed agriculture and mostly from Sub-Saharan Africa (SSA), where application of improved agricultural inputs remains historically low. Agricultural intensification practices as well as the relevance of the Boserup hypothesis in irrigated agriculture and in contexts where application of improved inputs is high remains unexplored. Furthermore, while much of the debate on the topic in Africa has focused on how to boost agricultural intensification, there is scant evidence on whether evolving agricultural intensification practices in some parts of Africa are sustainable, yield-enhancing, and optimal.

In this paper we investigate the implication of land scarcity on agricultural intensification and the relevance of the Boserup hypothesis in the context of Egypt, where agriculture is dominated by irrigation and input application rates are much higher than SSA. We also examine whether evolving agricultural intensification practices induced by land scarcity are agronomically appropriate and yield-enhancing. We find that land scarcity induces higher application of agricultural inputs, mainly nitrogen fertilizers, sometimes beyond the level that is agronomically recommended. More importantly, land scarcity increases overapplication of nitrogen fertilizer relative to crop-specific agronomic recommendations. This implies that land constraints remain as important challenges for sustainable agricultural intensification. Finally, we find suggestive evidence that such overapplication of nitrogen fertilizers is not yield-enhancing, but, rather, yield-reducing. We also document that land scarcity impedes mechanization of agriculture. Our findings have important implications to inform appropriate farm management and sustainable intensification practices. Furthermore, our results can inform long-term policy responses to land scarcity.

1 INTRODUCTION

The demographic dynamics and increasing population pressure in many African countries are inducing land scarcity in rural areas. While rural populations in most of the world continue to decline, they continue to increase in many African countries, including in those land-constrained countries with no surplus agricultural land or with limited potential for expansion of cultivable land frontiers (Chamberlin et al. 2014; Jayne et al. 2014; Headey and Jayne 2014). Because of this increase in overall population and/or localized population density, average farm and plot sizes are dwindling in most of the populous countries in Africa. Many studies identify several responses by both households and governments to the increasing population pressure and population density in Africa. The most common responses include: agricultural intensification in terms of usage of higher level of improved inputs and continuous cultivation of plots; expansion of land frontiers and conversion of forests into cultivation; diversification out of agriculture; migration into urban areas; and reduction in fertility rates (Chamberlin et al. 2014; Jayne et al. 2014; Headey and Jayne 2014; Liu and Yamauchi 2014). Increasing population pressure is also linked with the rise of land rental markets and changes in farm structures (e.g., Abay et al. 2020).

Agricultural intensification, in the form of higher application of agricultural inputs and increasing labor-land ratios, is the most debated response to population pressure. Much of the discussion and debate on agricultural input intensification revolves on whether the Boserup (1965) hypothesis, which argues that population growth induces agricultural intensification, holds or not. The debate on whether intensification is happening in general as well as the relevance of the Boserup hypothesis in African agriculture remains far from settled. More broadly, several studies invoke the low agricultural productivity in many African countries as indicating that intensification is not happening at sufficient levels and with consistent patterns (Binswanger-Mkhize and Savastano 2017). Several recent studies fail to find evidence to support the Boserup hypothesis in Africa (Holden and Yohannes 2002; Binswanger-Mkhize and Savastano 2017), while some other studies find evidence in favor of this hypothesis (e.g., Pender and Gebremedhin 2007; Headey et al. 2014; Josephson et al. 2014; Ricker-Gilbert et al. 2014; Abay et al. 2020). Meanwhile, other studies show nonlinear relationships between population density and agricultural intensification: a positive relationship up to a certain level of population density and reversal afterwards (Jayne and Muyanga 2012; Hadush et al. 2019).

Despite several studies showing empirical evidence in support of or against the Boserup hypothesis in Africa, almost all of them come from rainfed agriculture and mostly from sub-Saharan Africa (SSA). Historically, application of improved agricultural inputs, including chemical fertilizers and high-yield crop varieties, remained low in SSA and, hence, much of the debate has focused on why agricultural intensification is not happening and how to increase it (Binswanger-Mkhize and Savastano 2017). Yet, whether existing agricultural intensification practices are sustainable, agronomically appropriate, and economically yield-enhancing remains unexplored. Understanding the implication on sustainable agricultural intensification of looming land scarcity in many African countries is crucial to inform broader agricultural and rural development policies.

In particular, the relevance of the Boserup input intensification hypothesis remains unknown in the context of irrigated agriculture and the Middle East and North African (MENA) region, where water and land resources are continuously dwindling. Compared to rainfed agriculture, smallholder

irrigation agriculture involves different farming techniques and smallholders face slightly different constraints and farming environment.¹

In this paper, we revisit the relevance of the Boserup hypothesis in the context of Egypt where: (i) ever-increasing population growth is threatening water and land resources; (ii) agriculture is mainly dependent on irrigation, given the nearly complete absence of rainfall; (iii) agricultural yields and input application rates are high on a global scale; and (iv) fertilizer and input subsidies are important input policy instruments that are meant to trigger agricultural intensification. While much of the debate on agricultural intensification in Africa has focused on how to boost the process, there is scant evidence on whether evolving intensification in some parts of Africa are sustainable, yield enhancing, and optimal. We thus further examine whether agricultural input intensification, induced by land scarcity, is consistent with agronomic recommendations and profit maximization objectives. This is particularly crucial in the context of Egypt where farmers are shown to be using above recommended rates of chemical fertilizers (Kurdi et al. 2020), with important implications for soil, water, and environmental health. This paper therefore serves dual objectives of assessing the relevance of the Boserup hypothesis and whether such potential intensification is consistent with agronomic recommendations and yield (profit) maximization objectives.

The case of Egypt offers an interesting case study for testing the Boserup hypothesis and the sustainability of evolving agricultural intensification practices. This is particularly interesting since more than half of Egypt's population (57 percent) live in rural areas (World Bank 2018), where poverty rates are highest (Ghanem 2014). From 1994 to 2020, Egypt's population grew by 67 percent, from 60 million to more than 100 million people (Maged 2020). Such population growth poses serious challenges to the country's scarce and non-renewable resources, one of which is land, particularly in densely populated areas. About 97 percent of the population live in the Nile Valley and the Delta, where average population densities are 1,435 inhabitants per square kilometer (MWRI 2005). Meanwhile, population density drops to around 1.2 inhabitants per square kilometer in the desert (FAO 2016). Of Egypt's approximate area of one million square kilometers, only 4 percent of the country's land is cultivated, with arable land constituting 73 percent of the cultivated land area (FAO 2016). The average farm size has declined in Egypt from 6.1 feddans in 1950, to 3.8 feddans in 1960, and to 2.2 feddans in 2010 (Aboulnaga et al. 2017).² In addition, land parcels are expected to continue to fragment due to Muslim inheritance laws and urban expansion. All these factors have prompted the government to reclaim additional land in the desert. The government plans on reclaiming 4 million feddans of land, starting with a current first phase plan of reclaiming 1.5 million feddans (Sharaky et al. 2018).³

We find that land scarcity and, hence, smaller plot sizes induce higher application of agricultural inputs, mainly nitrogen fertilizers. More importantly, land scarcity increases overapplication of nitrogen fertilizer relative to crop-specific agronomic recommendations. We find that smaller plots are more likely to receive above recommended levels of nitrogen fertilizer. This implies that land constraints remain a serious impediment and a challenge for sustainable agricultural intensification. Finally, we find suggestive evidence that such overapplication of nitrogen fertilizers is not yield-enhancing, but, rather, is yield-reducing. This is consistent with studies showing that the overall impact and the marginal returns to fertilizers decline with their overuse (e.g., World Bank 2007). We also show that land scarcity impedes mechanization of

¹ For instance, smallholder farmers in the MENA region struggle to compete with large and medium-scale commercial holders. Furthermore, smallholder face important credit and liquidity constraints which can affect their intensification decisions.

² A feddan is a unit of area commonly used in Egypt equivalent to 0.42 hectares or 1.03 acres.

³ The additional 1.5 million feddans will increase agricultural land by 20 percent, from 8 to 9.5 million feddans. In addition, this plan will increase the country's populated area to 10 percent (SIS 2020).

agriculture. This is intuitive given the economies of scale associated with mechanization and the costs of machinery use (e.g., Foster and Rosenzweig 2017; Otsuka et al. 2013; Takeshima 2017).

Our findings have important implications for informing appropriate farm management and sustainable intensification practices in Egypt and beyond. We highlight that land constraints induced by population growth can impede sustainable agricultural intensification in contexts where application of chemical fertilizers is already high. The overapplication of nitrogen fertilizers is likely to cause significant environmental damage, as documented in several European (e.g., Sutton et al. 2011; Sterner et al. 2019) and Asian (Zhang et al. 2013) countries. The evidence that overapplication of nitrogen fertilizers is yield-reducing is particularly worth noting for several reasons. The evidence that inorganic fertilizer application rates substantially deviate from agronomic recommendations, and more so for smaller plots, imply the need to revitalize rural agricultural extension systems to ensure sustainable intensification. As farmers appear to be losing yield gains because of overapplication of chemical fertilizers, improving their awareness about optimal fertilizer application can improve farmers' input management practices and the profitability of use of agricultural inputs. Smaller plots are likely to be managed by poorer farmers, implying that improving the effectiveness of agricultural extension systems can particularly benefit the rural poor.

More broadly, our findings highlight that looming land constraints in some African countries may pose important challenges for sustainable agricultural intensification. In contexts where agricultural productivity growth cannot be achieved by further intensification, policy makers and individuals may need to consider other responses to land scarcity, including diversification out of agriculture and migration into less populated or urban areas. This is particularly relevant in the context of Egypt, where some smallholders are parttime farmers who already generate a substantial share of their income from non-farm activities (El-Enbaby et al. 2016).

The rest of the paper is organized as follows. Section 2 provides a review of input intensification theories and empirics. Section 3 describes the context of agriculture in Egypt and the data. Section 4 outlines the methodology of our analysis. Section 5 presents our empirical results, and Section 6 presents results for other inputs and robustness exercises. Section 7 provides a discussion of our main findings and concluding remarks.

2 REVISITING INPUT INTENSIFICATION IN AFRICA: A REVIEW

In most of Africa, the amount of land is diminishing while population continues to grow. In particular, the rural population in Africa continues to increase, while it is shrinking in many regions of the world (Jayne et al. 2014). This is the case even in those countries with limited underutilized land and water resources, which adds pressure on farming systems and makes it necessary to increase productivity growth without relying on area expansion. Theoretically, land intensification is one of the important responses to increasing population growth and density, as mentioned earlier. Yet, empirical evidence on the relevance of the Boserup intensification hypothesis remain inconclusive and much of the empirical evidence on agricultural intensification comes from only a few populous countries. Besides several country-specific studies, three recent multi-country studies investigate agricultural input intensification practices and the relevance of the Boserup hypothesis in Africa (e.g., Binswanger-Mkhize and Savastano 2017; Sheahan and Barrett 2017; Abay et al. 2020). Both Sheahan and Barrett (2017) and Abay et al. (2020) show that the Boserup hypothesis holds across several countries, including Ethiopia, Malawi, Nigeria, Tanzania and Uganda. On the other hand, Binswanger-Mkhize and Savastano (2017) argue that agricultural intensification practices in Africa remain weak and are only partially consistent with the Boserup hypothesis.

Other country-specific studies within Africa, which mostly come from areas with high rural population density, shed more light on agricultural intensification practices. Ethiopia is one of the countries characterized with small farm sizes that continue to decline, leaving young farmers cultivating substantially less land than previous generations did, particularly in the Ethiopian highlands. Such smaller farm sizes are associated with higher rural population density, and this has positively affected input demand (Pender and Gebremedhin 2007; Headey et al. 2014; Josephson et al. 2014).⁴ For instance, a village-level analysis by Headey et al. (2014) show that young rural households in Ethiopia that face severe land constraints tend to apply more fertilizer, improved seeds, pesticides, and herbicides, compared to other inputs, such as plowing.

In Kenya, population density is negatively related to farm size and positively related to land intensification (Muyanga and Jayne 2014). But several studies show that the Boserup hypothesis does not necessarily apply across the whole population density and land scarcity spectrum. Kopper and Jayne (2019) differentiate between areas of low agro-ecological potential and high agro-ecological potential in terms of how households respond to changes in input prices. In the former, households respond to higher land prices by cultivating less land and applying fertilizers more intensively. In the latter, there is no adjustment to the quantity of cultivated land in response to input price changes. They also found that households with better market access tend to be more responsive to land price changes compared to those with poor market access conditions.

Other African countries display heterogenous trends. Malawi, for instance, is an interesting case where higher population density is also associated with smaller farm sizes, lower real agricultural wage rates, and higher real output (maize) prices (Ricker-Gilbert et al. 2014). The case of Ghana is different from Ethiopia, Kenya, and Malawi. Nin-Pratt and McBride (2014) found no correlation between population density and input intensity in Ghana, and thereby conclude that there is no evidence of an Asian-style Green Revolution in the country. Instead, there has been increasing demand for mechanized farming operations, particularly plowing, even among smallholders (Diao et al. 2014).

Moving to the MENA region, some countries have been experiencing agricultural intensification. In Morocco, some studies show that farmers sometimes over-apply fertilizers while using drip-irrigation, following practices from gravity fed irrigation systems (FAO 2012). Another study in Morocco and Tunisia concluded that oasis agriculture in the Maghreb involves more intensive cultivation over time (De Haas 2001). The study identified both vertical and horizontal intensification taking place, which, respectively, refer to: a) intensification of agricultural production and increasing the use of motor pumps, and b) extending agriculture in the desert using motor pumping only (De Haas 2001).⁵ Nevertheless, agricultural intensification studies on the MENA region remain scant, and our paper aims to fill this research gap.

To sum up, our brief review suggests responses to land constraints and, hence, agricultural intensification practices are likely to be shaped by existing environments and production potential. Although such responses in the MENA region remains largely unexplored, a couple of recent studies provide some suggestive pieces of evidence on responses to growing population and associated demand for food. A recent study by Fuglie et al. (2020) estimates that irrigated land increased by 45 percent in Egypt between 1961 and 2016, suggesting that irrigation expansion could be one immediate response to expand cultivable land. Similarly, water used in agriculture rose by 42 percent during the same period. Such expansions of irrigable land are likely to continue, as reflected in the recent “1.5 million feddans” initiative to expand cultivable land for the young.

⁴ Yet, this does not lead to a corresponding increase in staple crop yields (Josephson et al. 2014). Farm income is found to be declining as population density rises, leaving farmers stuck and unable to sustainably intensify.

⁵ De Haas (2001) also noted that vertical intensification is taking place through the increasing use of fertilizers and pesticides.

However, these responses are unlikely to sufficiently absorb the bulge of youth coming into Egypt's workforce or satisfy the growing demand for food. The continuously increasing pressure to increase agricultural yield on small plots is likely to trigger higher input intensification. Kurdi et al. (2020) show, for example, that fertilizer application rates in Egypt are much higher than agronomic recommendations.

Finally, the discourse and policy discussions on agricultural intensification in SSA has focused on how to increase agricultural intensification and less on how to ensure sustainable agricultural intensification. Despite the remarkable impacts of agricultural intensification in Asia, overapplication of agrochemicals and, hence, reducing the adverse environmental impact of agricultural intensification are major challenges (Zhang et al. 2013). As we discuss, agricultural intensification practices and overapplication of agrochemicals in Egypt resonates more with the Chinese case than with most of SSA.

3 CONTEXT AND DATA

3.1 Agriculture and farming systems in Egypt

The agriculture sector continues to play an important role in the Egyptian economy. Agriculture accounts for 12.1 percent of GDP, with the share going up to 18.2 percent if agro-processing industries are included. It also accounts for 5.6 percent of exports, while agro-processing accounts for 14.2 percent (El-Enbaby et al. 2016). In addition, nearly a quarter (23.8 percent) of the Egyptian population works in agriculture.⁶

Egyptian agriculture is characterized by two types of lands. The first is “old lands” which represent 85 percent of Egypt's agricultural lands, mostly located in the Nile Valley and Delta. These are dominated by smallholder farmers with the majority of landholdings being less than 5 feddans in area (Kheir El-Din and El-Laithy 2008). The second type are “new lands” which are reclaimed lands in the desert, larger in size, and on which are implemented more capital-intensive technologies (Kheir El-Din and El-Laithy 2008). Since Egypt's “old lands” cannot be expanded, improvements in agricultural productivity are the only way to increase agricultural output.

Apart from land constraints, Egypt also faces water scarcity. Egypt gets 96 percent of its water from the Nile river (Sims 2015), with agriculture consuming 86 percent of the country's water supply (Al-Saidi et al. 2016). This makes both the country and the agricultural sector heavily dependent on Nile water.⁷ Most agricultural land in Egypt is irrigated, particularly using flood irrigation, while less than 2 percent of cultivated land is rainfed (Kassim et al. 2018). Irrigation of old lands relies on gravity and water lifting systems with the water then being run through canals (FAO 2005). It then gets distributed along branches and into tertiary canals (*mesqas*). The water then reaches the fields through quaternary channels (*marwas*) according to a rotation schedule (FAO 2005). Water is delivered to farmers free of charge (Kassim et al. 2018). For the new lands, water reaches the field from a cascade of pumping stations from the main canal. Sprinkler or drip irrigation is used, as the law bans surface irrigation on such land (FOA 2005).

In absolute terms, the agricultural land area has been increasing in Egypt. Fuglie et al. (2020) estimates that between 1961 and 2016, irrigated land increased by 45 percent and water used in

⁶ These shares are higher than many other middle-income countries, despite the fact that the share of agriculture value added and employment in agriculture have been declining in Egypt, following the country's economic transformation (El-Enbaby et al. 2016).

⁷ Some water is also supplied from groundwater via the Nile Aquifer and the Nubian Sandstone Aquifer, which allows the reclamation of lands into the Eastern and Western Deserts, which the government is promoting to make up for declining agricultural land per capita around the Nile Valley (Kassim et al. 2018; Sims 2015; Gouda 2016).

agricultural rose by 42 percent. Over this 55 year period, crop output rose by 307 percent, at an average rate of 2.4 percent annually. The authors also estimate that increases in crop net yield (technical change) accounted for 44 percent of total crop output growth, while intensification of other inputs per hectare harvested accounted for 13 percent.

3.2 Data source and description

This paper utilizes a unique farm household survey targeting smallholder farmers in six governorates in Upper Egypt. Data was collected in Assiut, Beni-Suef, Luxor, Menya, Qena, and Sohag between April and May 2018. In addition to regular household survey modules, the survey had an extensive agricultural module which covered agricultural assets, livestock, agricultural land, agricultural inputs, and crop output. Farming activities were surveyed for the summer 2017 and the winter 2017/18 seasons. For the purpose of this study, we focus on the winter sample to avoid a longer recall period.

The survey was administered to 2,246 farm households. The data was collected with the original purpose of evaluating the impact of a development project funded by the United States Agency for International Development (USAID) that targeted smallholder farmers with the aim of increasing their agricultural incomes and their food security through several components, one of which was forward contracts. For the evaluation's treatment arm, a random sample was selected out of the program beneficiaries, or more specifically, out of the farmers who signed an individual project-facilitated forward contract with a buyer or committed to a facilitated forward contract between the representing association and a buyer for the sale of horticultural crops. A counterfactual was then constructed through a random walk method to randomly select non-beneficiary horticulture-based smallholder farm households. Membership in both groups was restricted to smallholder farmers owning less than 10 feddans of land and having cultivated horticultural crops. More details about the sampling design and the sample can be found in El-Enbaby et al. (2019).

Even though the sample is not nationally representative, it provides an appropriate sample for studying farmers' intensification decisions since such decisions are only faced by smallholder farmers in the old lands, which represents the majority of the cropped area in Egypt (Kheir El-Din and El-Laithy 2008), in contrast to the newly reclaimed lands which generally exceed 10 feddans per farm. In Upper Egypt, 89 percent of landholdings are less than five feddans (Kheir El-Din and El-Laithy 2008), which is comparable to the 84 percent in our data (Table 1).

Table 1 provides summary statistics for key household and field plot characteristics of the sample. As shown, 98 percent of households in the sample are male-headed. The average age of the head is 47 years. About half of household heads have basic education or more, and about one fifth participate in non-agricultural activities. On average, households consist of 5.2 members. In terms of farming, 77 percent of surveyed fields are in the old lands, while the rest are in the new lands. The average total farm size of the surveyed households is 2.77 feddans. The average plot size is 1.56 feddans. Irrigation water is available five days a week for less than half of the farmers.

Table 1: Household and plot characteristics, summary statistics

| Variables | Mean | Standard deviation |
|--|--------|--------------------|
| Household characteristics | | |
| Male household head, 0/1 | 0.98 | 0.13 |
| Age of household head, years | 47.40 | 12.85 |
| Education of household head – has prep education or more, 0/1 | 0.51 | 0.50 |
| Household size, members | 5.21 | 2.06 |
| Household head participates in non-agricultural occupations, 0/1 | 0.21 | 0.41 |
| Farm size, feddan | 2.77 | 3.21 |
| Livestock assets (TLU) | 2.12 | 1.85 |
| Plots cultivated, number | 2.06 | 1.16 |
| Plots owned, number | 1.51 | 1.32 |
| Household planted wheat, 0/1 | 0.74 | 0.44 |
| Total consumption, EGP per capita (monthly) | 689.91 | 355.98 |
| Plot characteristics | | |
| Plot owned, 0/1 | 0.68 | 0.47 |
| Size of the plot, feddan | 1.56 | 1.90 |
| New lands (desert), 0/1 | 0.23 | 0.42 |
| Irrigation water available at least every five days, 0/1 | 0.48 | 0.50 |
| Observations | 4379 | |

Source: Analysis of 2018 baseline survey of smallholder farmers in Upper Egypt.

Note: Tropical Livestock Unit (TLU) values are computed using the following arithmetic formula: TLU = camels + (0.7*cattle) + (0.8*horses) + (0.5*donkeys) + (0.5*mules) + (0.1*sheep) + (0.1*goats) + (0.01*chicken).

Table 2 presents for households in the survey sample the average crop-specific usage of nitrogen fertilizers, the largest sources of nutrients in Egypt. The amount of nitrogen fertilizer applied by the sample households to their crops exceeds the requirements for all crops, except for tomatoes. For some crops, such as fennel, the amount of over-application is small. Yet, for others, there exists substantial over-application of nitrogen. Comparing application of nitrogen fertilizer to wheat in this sample to that of a sample of wheat farmers in China, it becomes apparent that overapplication by Egyptian farmers exceeds that of Chinese farmers (Zhang et al. 2013).⁸

Table 2: Crop-specific nitrogen fertilizer recommendations and use in the old lands, kg/feddan

| Crop | Nitrogen fertilizer | |
|-------------|---------------------|---------|
| | Recommended | Applied |
| Wheat | 75 | 141.5 |
| Sugar beets | 90 | 146.2 |
| Green beans | 70 | 173.0 |
| Onions | 120 | 188.8 |
| Garlic | 120 | 167.6 |
| Potatoes | 180 | 190.2 |
| Tomatoes | 250 | 158.3 |
| Basil | 100 | 123.6 |
| Fennel | 100 | 105.6 |
| Clover | 15 | 71.7 |

Source: Analysis of 2018 baseline survey of smallholder farmers in Upper Egypt. Fertilizer requirements are based on Ministry of Agriculture and Land Reclamation (MALR) recommendations for the old lands (MALR 2015).

Over-application of nitrogen fertilizers may be related to the government's nitrogen fertilizers subsidy. It is perceived that the government is subsidizing nitrogen fertilizers to promote wheat

⁸ Average application of synthetic nitrogen fertilizer in the China wheat farmer sample was 197 kg per hectare, which is equivalent to 82.7 kg per feddan.

cultivation, since it requires nitrogen-based more than phosphate-based fertilizers, in contrast to horticultural crops (Kassam and Dhehibi 2016). Subsidizing nitrogen fertilizers is done indirectly through subsidizing natural gas, which is used in the production of the fertilizers; and directly through requiring that producing companies sell part of their production to agricultural cooperatives at a fixed price that is below the market price (Kurdi et al. 2020). Each season, farmers receive a pre-set quantity of subsidized nitrogen fertilizer based on their land holding size and the crops they cultivate.

As Table 3 shows, 65 percent of plots are receiving amounts of nitrogen above the recommendations for nitrogen fertilizer application. Yet, over-application of non-subsidized nitrogen is more than subsidized nitrogen. This shows that farmers behavior may not be completely driven by the subsidy alone, which makes it interesting to investigate other factors that may be driving this behavior. One possible scenario is intensification, whereby farmers feel pressured to increase their productivity due to land scarcity.

Table 3: Fertilizer use, summary statistics

| Variables | Mean | Standard deviation |
|--|--------|--------------------|
| Total nitrogen fertilizers, kg/feddan | 130.20 | 85.76 |
| Non-subsidized nitrogen fertilizers, kg/feddan | 99.02 | 85.34 |
| Subsidized nitrogen fertilizers, kg/feddan | 31.18 | 50.25 |
| Overapplication of total nitrogen fertilizer, 0/1 | 0.65 | 0.48 |
| Overapplication of non-subsidized nitrogen fertilizer, 0/1 | 0.49 | 0.50 |
| Overapplication of subsidized nitrogen fertilizer, 0/1 | 0.15 | 0.36 |

Source: Analysis of 2018 baseline survey of smallholder farmers in Upper Egypt.

4 EMPIRICAL ESTIMATION STRATEGY

To quantify farmers' response to land scarcity and associated yield responses, we estimate alternative empirical specifications characterizing input demand and production functions. To understand the impact of land scarcity on input application rates, we estimate the following input demand function that quantifies the response of input demand functions to land scarcity.

$$D_{hp} = \alpha_h + \beta_1 \text{Log}(\text{plot size})_{hp} + \beta_2 X_{hp} + \alpha_c + \varepsilon_{hp} \quad (1)$$

where D_{hp} stands for application of fertilizer and other inputs per feddan for each plot (p). As nitrogen fertilizer remains the dominant chemical fertilizer in Egypt, we focus on input intensification associated with nitrogen fertilizer application. However, we use alternative sources of nitrogen fertilizers, including subsidized and non-subsidized nitrogen fertilizers, to uncover the implication of differential access to various types of fertilizers. Thus, D_{hp} represents both continuous and binary indicator values to capture intensive and extensive margins of fertilizer use. α_h stands for farmer-specific effects, captured by household fixed effects, which are expected to control for potential heterogeneities in farm management and input use practices. Plot size is the main variable of interest, capturing land scarcity or abundance. β_1 quantifies farmers' response to land constraints or simply the impact of land scarcity (abundance) on agricultural intensification. β_1 can be interpreted as the change in input demand associated with a marginal change in plot size and is the Boserup intensification parameter of interest. Rejection of the null hypothesis in favor of $\beta_1 < 0$ confirms the relevance of the Boserupian hypothesis. X_{hp} captures additional plot-level characteristics that may affect demand for agricultural inputs and associated intensifications. α_c stands for crop fixed effects, which can capture differences in fertilizer and other input requirements across different crops. ε_{hp} absorbs other unobserved factors that may generate variations in demand for agricultural inputs and associated intensification decisions.

To examine whether land constraints are inducing overapplication of nitrogen fertilizers and, hence, impede sustainable agricultural intensification, we generate indicator variables for those plots where nitrogen fertilizer application rates are higher than agronomic recommendation rates of the Ministry of Agriculture and Land Reclamation (MALR). For each plot, we create a dummy variable that takes a value of 1 for those plots where nitrogen application rates are higher than the crop-specific recommendations discussed in Section 3. We then estimate the following slightly different version of equation (1):

$$ON_{hp} = \alpha_h + \delta_1 \text{Log}(\text{plot size})_{hp} + \delta_2 X_{hp} + \alpha_c + \varepsilon_{hp} \quad (2)$$

where ON_{hp} now stands for an indicator variable that takes a value of 1 for those plots where nitrogen fertilizer is overapplied and 0 otherwise. Remaining notations are as described in equation (1). If land constraints induce overapplication of nitrogen fertilizer, we expect a statistically significant and negative value of δ_1 . We note that as we are controlling for farmer fixed effects, the estimations in equations (1) and (2) exploit within farm variations in plot size. The additional controls as well as crop fixed effects in equation (2) help to minimize potential unobserved heterogeneity that may confound our estimations.

Finally, to quantify yield responses associated with fertilizer application and potential overapplication of nitrogen fertilizers, we estimate the following empirical specification.

$$\log(y_{hp}) = \alpha_h + \gamma_1 \text{Log}(\text{plot size})_{hp} + \gamma_2 D_{hp} + \gamma_3 ON_{hp} + \gamma_4 X_{hp} + \alpha_c + \varepsilon_{hp} \quad (3)$$

Where y_{hp} now stands for yield (output per hectare of land) and all remaining terms are as described in equation (1) and (2). γ_2 in equation (3) captures the productivity impact of nitrogen fertilizers, while γ_3 identifies the impact of potential overapplication in nitrogen fertilizers. These parameters are meant to detect potential yield gains (losses) associated with applying nitrogen fertilizers. Both parameters can inform us whether farmers' chemical fertilizer applications are productivity-enhancing or not.

We also extend the empirical specification in equation (3) by including interaction terms across several agricultural inputs. We then compute marginal contributions associated with agricultural inputs, mainly nitrogen fertilizer, and whether the marginal returns decline or increase with plot size. This helps to confirm whether land scarcity and associated input intensification patterns are affecting marginal returns associated with agricultural inputs.

For simplicity, we estimate linear models where some of our outcomes assume a binary nature. Plots managed by the same farmer are expected to share some unobserved effects arising from similar farm management. Thus, we cluster standard errors at household level. We conduct several robustness exercises involving estimation of slightly different versions of equations (1) to (3). For instance, our main sample includes intercropped plots, implying that some crops may receive higher levels of inputs than others, which may drive some of our estimations. We thus estimate our models restricted to mono-cropped plots. Theoretically, one could argue in favor of testing the Boserup's hypothesis at the farm rather than the plot level, which we did in some of our robustness exercises by aggregating the plot-level variables. However, such estimation requires strong assumptions about plot-level variations in input use and farm management practices and decisions.

5 RESULTS AND DISCUSSION

5.1 Land constraints and agricultural intensification

In Table 4, we report the impact of plot size on fertilizer application per unit of land. As noted in section 3.2, farmers can acquire nitrogen fertilizers through government subsidies and from commercial fertilizer market. Farmers with varying farm size and tenure status are likely to have differential access to subsidized fertilizers. Farmers' access to subsidized nitrogen fertilizers is administered through agricultural cooperatives and is a function of the size of their landholding and the crops they cultivate during the season. Plot owners have relatively easier access to subsidized fertilizer than tenants, as the latter are required to provide their rental contract and obtain their landlords' consent to receive any subsidized fertilizer. Farmers' input management practices may also vary across subsidized and non-subsidized fertilizers. We, thus, examine total nitrogen application as well as application of subsidized and non-subsidized nitrogen fertilizers separately. Because of these contexts, we control for households fixed effects, crop fixed effects as well as additional plot-level controls, including plot ownership and cropping pattern.

Table 4: Land constraints and agricultural intensification, nitrogen fertilizers

| | (1) | (2) | (3) | (4) | (5) | (6) |
|------------------------------|-----------------------------|-----------------------------|--------------------------------------|--------------------------------------|----------------------------------|----------------------------------|
| | Total nitrogen (kg/ feddan) | Total nitrogen (kg/ feddan) | Non-subsidized nitrogen (kg/ feddan) | Non-subsidized nitrogen (kg/ feddan) | Subsidized nitrogen (kg/ feddan) | Subsidized nitrogen (kg/ feddan) |
| Log (plot size) | -30.594*** (6.264) | -33.994*** (6.077) | -19.019*** (5.501) | -25.581*** (6.216) | -11.575*** (3.268) | -8.414*** (2.971) |
| Plot owned | | 3.237 (4.154) | | -13.155** (5.027) | | 16.392*** (4.258) |
| New land | | -12.283 (19.417) | | 14.520 (12.855) | | -26.803** (11.214) |
| Irrigated water availability | | 3.367 (16.631) | | -2.836 (16.038) | | 6.203 (7.529) |
| Intercropped field | | 19.454*** (5.002) | | 20.350*** (5.247) | | -0.896 (2.918) |
| Constant | 140.932*** (3.649) | 132.279*** (9.258) | 99.618*** (3.061) | 98.738*** (7.443) | 41.315*** (1.813) | 33.541*** (7.241) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.359 | 0.363 | 0.234 | 0.241 | 0.170 | 0.186 |
| Observations | 4,379 | 4,379 | 4,379 | 4,379 | 4,379 | 4,379 |

Notes: Standard errors, clustered at household level, are given in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Source: Analysis of 2018 baseline survey of smallholder farmers in Upper Egypt

The results in Table 4 and hence the Boserup intensification parameter of interest show that smaller plots receive higher amount of nitrogen fertilizer, and this holds for all types of nitrogen fertilizers. For instance, columns (1) and (2) indicate that a one percent increase in plot size is associated with 0.31 to 0.35 kg/feddan reduction in nitrogen application. This is considered a substantial response in the intensity of use of chemical fertilizers. Given that most farmers are likely to rely on non-subsidized nitrogen fertilizer, the response to land constraints is therefore more pronounced in non-subsidized fertilizer than on subsidized fertilizers. These results in Table 3 suggest that the Boserup hypothesis extends to irrigated agriculture, a dominant farming system in most of the MENA region.

The remaining estimates in Table 3 indicate theoretically intuitive findings. As shown by Kurdi et al. (2020), owned plots receive higher amounts of subsidized nitrogen fertilizer and receive less

amounts of commercial fertilizers. This is mainly driven by the differential access to subsidy between owned and rented fields. We also find that intercropped fields receive higher amounts of nitrogen fertilizers. In our robustness exercise, we exclude intercropped fields to probe if intercropping confounds some of our estimations.

5.2 Land constraints and overapplication of chemical fertilizers

In this section, we examine whether the input intensification responses in Table 4 are consistent with agronomic recommendations. This is an important exercise to understand whether the potential increase in nitrogen application driven by land scarcity is needed or agronomically recommended to boost agricultural productivity. For this purpose, we employ crop-specific agronomic recommendations from MALR to examine whether land scarcity is inducing overapplication of nitrogen fertilizers per unit of land. For this purpose, we create indicator variables for those fields where the crop-specific application of nitrogen fertilizer is higher than recommended by MALR. We also compute a relative deviation between the nutrient recommendations and farmers' actual fertilizer applications. We then estimate equation (2) with the dependent variable being an indicator variable for those plots receiving above recommendation fertilizers as well as a continuous variable showing the deviation between actual and recommended fertilizer use. We estimate these equations for all types and sources of nitrogen fertilizers. Table 5 provides results based on the indicator variable for overapplication, while Table 6 reports results based on the continuous measure of deviation between actual and recommended fertilizer.

Table 5: Land constraints and overapplication of chemical fertilizers, dummy variable

| | (1) | (2) | (3) | (4) | (5) | (6) |
|------------------------------|---|---|--|--|---|---|
| | Overappli- cation of total nitrogen | Overappli- cation of total nitrogen | Overappli- cation of non- subsidized nitrogen | Overappli- cation of non- subsidized nitrogen | Overappli- cation of subsidized nitrogen | Overappli- cation of subsidized nitrogen |
| Log (plot size) | -0.105*** (0.024) | -0.098*** (0.029) | -0.077*** (0.027) | -0.082** (0.031) | -0.065*** (0.020) | -0.045** (0.022) |
| Plot owned | | 0.034 (0.024) | | -0.052 (0.033) | | 0.077** (0.030) |
| New land | | -0.150 (0.093) | | -0.024 (0.101) | | -0.125 (0.077) |
| Irrigated water availability | | 0.113 (0.094) | | 0.039 (0.084) | | 0.086 (0.052) |
| Intercropped field | | 0.014 (0.037) | | 0.008 (0.036) | | -0.030 (0.033) |
| Constant | 0.787*** (0.023) | 0.739*** (0.045) | 0.549*** (0.022) | 0.567*** (0.045) | 0.213*** (0.013) | 0.160*** (0.044) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.242 | 0.244 | 0.149 | 0.151 | 0.055 | 0.062 |
| Observations | 4,379 | 4,379 | 4,379 | 4,379 | 4,379 | 4,379 |

Notes: Standard errors, clustered at household level, are given in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

The estimates in Table 5 and 6 show that land scarcity induces overapplication of nitrogen fertilizers. For instance, the first two columns of Table 4 suggest that a 1 percentage point increase in plot size is associated with a 0.1 percentage point reduction in the probability of overapplication of nitrogen fertilizer. Similarly, the results in Table 5 suggest that land scarcity is associated with a positive deviation in fertilizer application, smaller fields receive above the recommended levels of nitrogen fertilizers. These findings are consistent across all types of fertilizers and the alternative construction of the variables.

Table 6: Land constraints and overapplication of chemical fertilizers, deviation from recommendations

| | (1) | (2) | (3) | (4) | (5) | (6) |
|------------------------------|--|--|---|---|---|---|
| | Deviation from recommendation (total nitrogen) | Deviation from recommendation (total nitrogen) | Deviation from recommendation (non-subsidized nitrogen) | Deviation from recommendation (non-subsidized nitrogen) | Deviation from recommendation (subsidized nitrogen) | Deviation from recommendation (subsidized nitrogen) |
| Log (plot size) | -0.675*** (0.147) | -0.627*** (0.161) | -0.497*** (0.150) | -0.490*** (0.163) | -0.178* (0.090) | -0.137 (0.086) |
| Plot owned | | 0.284* (0.144) | | -0.011 (0.194) | | 0.295** (0.129) |
| New land | | -0.340 (0.447) | | -0.026 (0.451) | | -0.315* (0.185) |
| Irrigated water availability | | -0.015 (0.553) | | 0.019 (0.497) | | -0.034 (0.247) |
| Intercropped field | | -0.006 (0.238) | | -0.030 (0.231) | | 0.024 (0.151) |
| Constant | 0.747*** (0.152) | 0.640** (0.283) | 0.186 (0.138) | 0.202 (0.257) | -0.439*** (0.050) | -0.562*** (0.191) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.332 | 0.333 | 0.277 | 0.277 | 0.057 | 0.062 |
| Observations | 3,969 | 3,969 | 3,969 | 3,969 | 3,969 | 3,969 |

Notes: Standard errors, clustered at household level, are given in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

These findings imply that land scarcity not only induces intensification of nitrogen fertilizer, but also encourages overapplication of chemical fertilizers. This sheds new light on the extent of land scarcity and the associated Boserup type of intensification, which, in our context, leads to fertilizer use beyond a level that is agronomically recommended. Intuitively, this result suggests that land constraints can impede the sustainable intensification of agricultural input use.

While the evidence that land scarcity increases input intensification is not new, our finding that such scarcity can lead to overapplication of chemical fertilizers is noteworthy for efforts that aim to improve farm management practices and extension services. Overapplication of nitrogen fertilizer is inefficient from an economic cost-benefit perspective because agronomic recommendations are associated with best practices and maximum yield gains. Overapplication implies that farmers may be incurring additional costs of fertilizer with little gain in yields (Yadav et al. 1997; Ju et al. 2009). In some cases, overapplication of nitrogen fertilizer may further reduce yield and the marginal contribution of inputs (World Bank 2007), a hypothesis we empirically probe in our next section. In terms of farm management practices, the substantial deviation between actual fertilizer application and agronomic recommendations highlights the need to improve the effectiveness of rural agricultural extension services. The limitation of extension systems in Egypt and potential implications are documented by some studies (e.g., Dhehibi et al. 2018; McDonough et al. 2015; Kurdi et al. 2020). Revitalizing the effectiveness of the extension sector and associated R&D investments can optimize levels of nitrogen fertilizer application by farmers and improve farmers' input management practices in general.

Overapplication of nitrogen fertilizers can adversely affect human, soil, water, and environmental health. The environmental impact of overapplication of inorganic fertilizers is well-documented in several European (Sutton et al. 2011; Von Blottnitz et al. 2006; Van Grinsven et al. 2013; Sterner et al. 2019) and Asian (Zhang et al. 2013) countries. Indeed, some cost-benefit analyses suggest that in some contexts the adverse health and environmental impacts of nitrogen

fertilizers may outweigh the economic gains from nitrogen fertilizer application (van Grinsven et al. 2013). Sutton et al. (2011) estimate that excess nitrogen application in the European Union is associated with an environmental cost of between €70 and €320 billion per year. Other studies from China show that the environmental cost and impact associated with nitrogen fertilizer application in China is even higher than it is for the European Union (Zhang et al. 2013).

5.3 Land constraints, agricultural intensification, and yield

To probe the implication of fertilizer overapplication on agricultural yields, we estimate equation (3), which characterizes agricultural yield as a function of field size and nitrogen fertilizer (over)applications. Unfortunately, we do not have yield information for all fields in our sample, as a large share were not yet harvested at the time of the survey. However, we have about 1,600 plots with complete yield information. We use this to generate suggestive evidence on the implications of fertilizer overapplication, presented in Table 7.

Table 7: Land constraints, fertilizer application, and yield

| | (1) Yield (ton/feddan) | (2) Yield (ton/feddan) | (3) Yield (ton/feddan) | (4) Yield (ton/feddan) | (5) Yield (ton/feddan) | (6) Yield (ton/feddan) |
|------------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|
| Log (plot size) | 0.623** (0.274) | 0.817*** (0.292) | 0.374 (0.239) | 0.605** (0.247) | 0.508* (0.297) | 0.629** (0.281) |
| Nitrogen fertilizer (kg/feddan) | 0.009** (0.004) | 0.009** (0.004) | 0.005 (0.005) | 0.005 (0.005) | 0.016** (0.007) | 0.015* (0.008) |
| Overapplication | -1.110** (0.484) | -1.181** (0.530) | -0.750 (0.592) | -0.755 (0.619) | -1.310 (0.977) | -1.326 (0.990) |
| Plot owned | | 0.777 (0.610) | | 0.901 (0.589) | | 0.640 (0.646) |
| New land | | -1.844 (1.439) | | -1.862 (1.393) | | -1.255 (1.554) |
| Irrigated water availability | | 0.461 (1.154) | | 0.493 (1.201) | | 0.182 (1.143) |
| Constant | 0.964** (0.411) | 0.639 (0.875) | 1.390*** (0.388) | 0.819 (0.882) | 0.990** (0.413) | 0.783 (0.828) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.695 | 0.697 | 0.691 | 0.693 | 0.695 | 0.696 |
| Observations | 1594 | 1594 | 1594 | 1594 | 1594 | 1594 |

Notes: The first two columns use total nitrogen fertilizer applications; the next two columns are based on non-subsidized nitrogen fertilizers while the last two columns employ subsidized nitrogen fertilizers. Standard errors, clustered at household level, are given in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

The results in Table 7 show positive marginal returns to agricultural inputs, mainly land and nitrogen fertilizer. The first-row results show that yield increases with plot size. This contrasts with several studies documenting an inverse size-productivity relationship in Africa, although those studies come from rainfed agriculture (e.g., Larson et al. 2014; Carletto et al. 2015; Barrett et al. 2010; Ali and Deininger 2015; Khataza et al. 2019; Julien et al. 2019).⁹ However, some of the explanations for inverse size-productivity relationship are likely to reverse in the context of irrigated agriculture. For instance, the scale of irrigation may encourage further investments in agricultural inputs that can improve overall agricultural productivity. Similarly, and as expected, nitrogen fertilizers are associated with a positive marginal yield contribution. However, overapplication of nitrogen fertilizers leads to significant yield reduction, as reflected by the negative impact of the

⁹ Other recent studies (e.g., Desiere and Jolliffe 2018; Abay et al. 2019; Gourlay et al. 2019) show that evidence for such inverse size-productivity relationships may actually be driven by measurement error in land area and production data.

overapplication dummy. This implies that nitrogen fertilizers are yield-increasing up until some level, but can adversely affect yield when applied beyond agronomic recommendations.

6 OTHER INPUTS AND ROBUSTNESS EXERCISES

To assess the implication of land scarcity on application of other inputs we consider three additional inputs – total cost of hired labor, machinery use for land preparation, and pesticide usage. As in many other household surveys, our labor data are likely to suffer from measurement errors, but the results in the columns (1) and (2) of Table 8 show that smaller plots receive higher amount of labor per unit of land, implying that operating smaller plot is relatively costly. The results in columns (3) and (4) suggest that land scarcity impedes mechanization of agriculture. This is intuitive given the economies of scale associated with mechanization and cost of machinery use (e.g., Otsuka et al. 2013; Foster and Rosenzweig 2017; Takeshima 2017). The last two columns in Table 7 suggest similar evidence on the impact of land scarcity on pesticide use, implying that the Boserup intensification hypothesis extends to other chemical inputs. As pesticides are also known for their adverse health impacts (e.g., Sheahan et al. 2017), agricultural intensification induced by land scarcity can have important health implications.

Table 8: Application of other inputs

| | (1) | (2) | (3) | (4) | (5) | (6) |
|------------------------------|----------------------------------|----------------------------------|---------------------|----------------------|-------------------------|-------------------------|
| | Log (cost of hired labor/feddan) | Log (cost of hired labor/feddan) | Machinery use | Machinery use | Pesticide (kg/l/feddan) | Pesticide (kg/l/feddan) |
| Log (field size) | -0.832*** (0.040) | -0.839*** (0.037) | 0.028*** (0.010) | 0.023** (0.011) | -0.540*** (0.182) | -0.585*** (0.202) |
| Field owned | | 0.005 (0.019) | | -0.050*** (0.014) | | 0.023 (0.118) |
| New land | | 0.158 (0.111) | | -0.038 (0.040) | | 0.653* (0.373) |
| Irrigated water availability | | 0.193** (0.085) | | -0.047 (0.044) | | 0.316 (0.247) |
| Intercropped field | | -0.015 (0.029) | | 0.013 (0.016) | | 0.012 (0.148) |
| Constant | 10.137*** (0.006) | 10.007*** (0.049) | 0.913*** (0.004) | 0.972*** (0.030) | 0.482*** (0.031) | 0.168 (0.159) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.839 | 0.843 | 0.102 | 0.117 | 0.176 | 0.178 |
| Observations | 3,738 | 3,738 | 4,378 | 4,378 | 4,378 | 4,378 |

Notes: Standard errors, clustered at household level, are given in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.
Source: Analysis of 2018 baseline survey of smallholder farmers in Upper Egypt

We also conduct two additional exercises to probe the robustness of our results against alternative scenarios and threats to identification. First, intercropping of fields confounds allocation of fertilizer inputs across crops. To circumvent this intercropping effect, we exclude intercropped plots and re-estimate our empirical specifications. The results of this analysis in Appendix Tables A1 to A3 strongly confirm the main findings on the impact of land scarcity. Although the sample size for the analyses in Tables A1 to A3 are substantially smaller than the full sample used in Tables 4 to 6, the size of the impacts are comparable across all specifications. These findings reinforce our hypothesis that land scarcity is inducing overapplication of chemical fertilizers.

Second, one could argue that the Boserup intensification hypothesis should be tested at farm-level. Testing the Boserup hypothesis at farm level requires aggregating inputs across plots and

invoking some important assumptions to facilitate such aggregation. Such farm-level aggregation requires imposing that a single household member makes management decisions over all plots or intra-household decision-making are fully cooperative (i.e., Pareto efficient), an assumption that has been disputed in the context of Africa (e.g., Udry 1996). From an econometric point of view, farm-level testing of Boserup hypothesis in our context would only rely on cross-sectional variations and, hence, are not likely to reflect causal relationships.

7 CONCLUDING REMARKS

The looming population pressure in many African countries is creating acute land scarcity in many parts of rural Africa. In response to these increasing land constraints, governments are responding and adapting in various ways. Agricultural intensification remains one of the responses documented in many African countries (Chamberlin et al. 2014; Jayne al. 2014; Headey and Jayne 2014; Liu and Yamauchi 2014). In particular, several studies show evidence both in favor and against the Boserup hypothesis, which links land scarcity with increased agricultural intensification. However, much of the debate is on whether intensification is happening and the relevance of the Boserup hypothesis in African agriculture uses evidence from rainfed farming systems in SSA, where application of modern agricultural inputs remains low. Agricultural intensification patterns and the relevance of the Boserup hypothesis in contexts where the application of improved inputs already is high and where farming is done under irrigation remain unexplored. Furthermore, the sustainability of evolving agricultural input intensification practices in some African countries have not been investigated and scrutinized.

In this paper, we bring fresh insights to this debate by investigating the implication of land scarcity on agricultural intensification and the relevance of the Boserup hypothesis in the context of Egypt, where agriculture is dominated by irrigation and agricultural yields and input application rates are much higher than in SSA. We also examine whether evolving agricultural intensification practices induced by land scarcity are agronomically appropriate and yield-enhancing. Such dual objectives of assessing the relevance of the Boserup hypothesis and the sustainability of agricultural intensification practices can inform appropriate farm management and fertilizer applications practices in Egypt and beyond.

We find that land scarcity induces higher application of agricultural inputs, mainly nitrogen fertilizers, sometimes beyond the level that is agronomically required and that plants can utilize. More importantly, land scarcity increases overapplication of nitrogen fertilizer, relative to crop-specific agronomic recommendations. We find that smaller plots are likely to receive above recommended levels of nitrogen fertilizer. Furthermore, land scarcity impedes mechanization. This implies that land constraints remain important challenges for sustainable agricultural intensification. Finally, we find such overapplication of nitrogen fertilizers is not yield-enhancing, but, rather, is yield-reducing. This is likely to reduce the overall impact and marginal returns to fertilizers.

While the evidence that land scarcity increases input intensification is not new, the additional evidence that such scarcity leads to overapplication of chemical fertilizers is noteworthy for guiding efforts to improve farm management and fertilizer use practices and extension services. Overapplication of nitrogen fertilizer is inefficient from an economic cost-benefit perspective, implying that farmers may be incurring additional costs of fertilizer with little gain in yields. The substantial deviation between actual levels of fertilizer application and agronomic recommendations of application highlights the need to improve the effectiveness of rural agricultural extension services. Improving farmers' nitrogen fertilizers applications by revitalizing the effectiveness of the extension sector and associated R&D investments could improve farmers' input management practices.

Our findings also have important implications for informing sustainable agricultural intensification practices in Egypt and beyond. We highlight that land constraints induced by population growth can impede sustainable agricultural intensification in contexts where application of chemical fertilizers already is high. As documented in several European and Asian countries, the overapplication of nitrogen fertilizers is likely to cause significant environmental damage. The evidence that smaller plots receive fertilizer amounts above recommended levels implies that agricultural extension services need to pay attention to fertilizer management on smaller plots to ensure sustainable agricultural intensification. This is particularly important as smaller plots are likely to be managed by poorer farmers, implying that improving the effectiveness of agricultural extension systems can particularly benefit the rural poor.

More broadly, our findings highlight that looming land constraints in some African countries may pose important challenges for sustainable agricultural intensification. Intuitively, our findings suggest that the increasing population pressure and population density in Africa may soon be a challenge for sustainable agricultural intensification and call for broader rural transformation strategies. In contexts where additional agricultural productivity growth cannot be achieved by further intensification, policy makers and individuals may need to consider other responses to land scarcity, including diversification of crops, e.g., from cereals to higher value crops like fruits and vegetables, or out of agriculture, including through fostering migration into less populated or urban areas. In Egypt, the majority of smallholders already earn a substantial share of their income from non-farm activities and the potential for agro-industrial development is large (El-Enbaby et al. 2016). Therefore, supporting smallholders on their way out of agriculture can be important elements of a broader rural transformation strategy.

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APPENDIX

Table A1: Land constraints and agricultural intensification, nitrogen fertilizers, monocropped plots only

| | (1) | (2) | (3) | (4) | (5) | (6) |
|------------------------------|-----------------------------|-----------------------------|--------------------------------------|--------------------------------------|----------------------------------|----------------------------------|
| | Total nitrogen (kg/ feddan) | Total nitrogen (kg/ feddan) | Non-subsidized nitrogen (kg/ feddan) | Non-subsidized nitrogen (kg/ feddan) | Subsidized nitrogen (kg/ feddan) | Subsidized nitrogen (kg/ feddan) |
| Log (plot size) | -36.030*** (6.134) | -35.229*** (6.476) | -26.158*** (6.991) | -27.807*** (7.133) | -9.872*** (2.604) | -7.422*** (2.741) |
| Plot owned | | 8.264 (5.100) | | -6.930 (5.768) | | 15.194*** (5.537) |
| New land | | 4.490 (13.455) | | 20.756 (12.637) | | -16.266** (6.255) |
| Irrigated water availability | | 0.055 (20.612) | | -3.941 (17.797) | | 3.996 (9.443) |
| Constant | 128.678*** (5.063) | 122.719*** (7.900) | 91.065*** (4.565) | 93.479*** (7.166) | 37.613*** (1.997) | 29.240*** (5.727) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.375 | 0.376 | 0.269 | 0.271 | 0.161 | 0.177 |
| Observations | 2,595 | 2,595 | 2,595 | 2,595 | 2,595 | 2,595 |

Notes: Standard errors, clustered at household level, are given in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Table A2: Land constraints and overapplication of chemical fertilizers, dummy variable, monocropped plots only

| | (1) | (2) | (3) | (4) | (5) | (6) |
|------------------------------|-------------------------------------|-------------------------------------|---|---|--|--|
| | Overappli- cation of total nitrogen | Overappli- cation of total nitrogen | Overappli- cation of non- subsidized nitrogen | Overappli- cation of non- subsidized nitrogen | Overappli- cation of subsidized nitrogen | Overappli- cation of subsidized nitrogen |
| Log (plot size) | -0.120*** (0.038) | -0.111*** (0.040) | -0.085** (0.038) | -0.087** (0.039) | -0.055** (0.021) | -0.046* (0.026) |
| Plot owned | | 0.051 (0.033) | | -0.007 (0.036) | | 0.055 (0.038) |
| New land | | -0.102 (0.125) | | 0.026 (0.107) | | -0.087 (0.098) |
| Irrigated water availability | | 0.126 (0.105) | | 0.029 (0.089) | | 0.088 (0.069) |
| Constant | 0.760*** (0.029) | 0.693*** (0.048) | 0.541*** (0.028) | 0.529*** (0.040) | 0.199*** (0.013) | 0.143*** (0.045) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.258 | 0.261 | 0.193 | 0.193 | 0.064 | 0.070 |
| Observations | 2,595 | 2,595 | 2,595 | 2,595 | 2,595 | 2,595 |

Notes: Standard errors, clustered at household level, are given in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

Table A3: Land constraints and overapplication of chemical fertilizers, deviation from recommendations, monocropped plots only

| | (1) | (2) | (3) | (4) | (5) | (6) |
|------------------------------|--|--|---|---|---|---|
| | Deviation from recommendation (total nitrogen) | Deviation from recommendation (total nitrogen) | Deviation from recommendation (non-subsidized nitrogen) | Deviation from recommendation (non-subsidized nitrogen) | Deviation from recommendation (subsidized nitrogen) | Deviation from recommendation (subsidized nitrogen) |
| Log (plot size) | -0.831*** (0.203) | -0.797*** (0.204) | -0.552*** (0.204) | -0.536** (0.201) | -0.279*** (0.092) | -0.261** (0.100) |
| Plot owned | | 0.341** (0.168) | | 0.189 (0.167) | | 0.152 (0.142) |
| New land | | 0.114 (0.488) | | 0.121 (0.430) | | -0.007 (0.238) |
| Irrigated water availability | | 0.068 (0.625) | | 0.090 (0.496) | | -0.022 (0.340) |
| Constant | 0.669*** (0.175) | 0.407 (0.277) | 0.111 (0.143) | -0.067 (0.237) | -0.442*** (0.075) | -0.526*** (0.183) |
| Crop fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| Household fixed effects | Yes | Yes | Yes | Yes | Yes | Yes |
| R-squared | 0.298 | 0.300 | 0.221 | 0.222 | 0.092 | 0.093 |
| Observations | 2,338 | 2,338 | 2,338 | 2,338 | 2,338 | 2,338 |

Notes: Standard errors, clustered at household level, are given in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

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