Received: 19 February 2024 | Revised: 5 November 2024 | Accepted: 15 November 2024

DOI: 10.1111/1477-9552.12621

ORIGINAL ARTICLE

JAE Journal of Agricultural Economics

Farm size and agricultural productivity of nutritious foods: Evidence from Ethiopia

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Funding information
Fonds Wetenschappelijk Onderzoek, Grant/Award Number: 30784531; European Commission, Grant/Award Number: 861932

Abstract

Agri-food systems are transforming quickly in Africa. An important issue in the transformation process of agricultural production is the role of small farms. While many authors have looked at this question, one aspect that has received little attention is the role of small farms in the production of nutritious foods, an important topic given the low availability and relatively high prices of nutritious foods and the consequent low level of nutrition security in the continent. Using a unique large-scale dataset from Ethiopia—one of the largest countries in Africa that has been transforming rapidly—we look at the production of vegetables and dairy products. We find a strong association between farm size and partial productivity measured in terms of output, value of outputs and profit per hectare/cow, with productivity twice to four times as high for larger farms. These farms have substantially higher input expenditures as well as differences in farm technologies compared to small ones. Our findings have important implications for the debate on the role of small farms and nutritional improvements in the continent.

KEYWORDS

dairy, Ethiopia, farm size, horticulture, productivity

JEL CLASSIFICATION

O13, Q12, Q18

1 | INTRODUCTION

Agri-food systems are transforming quickly in Sub-Saharan Africa (SSA), driven by policy change, infrastructure development, income growth and urbanisation (AGRA, 2019). While food security problems in SSA are therefore becoming less of an issue than a few decades ago—although progress has stagnated in recent years (World Bank, 2022)—nutrition security, linked to low levels of dietary diversity, is still an imminent concern. This low diet diversity is partly explained by low availability and high prices of most nutritious foods such that a significant part of the population in the continent cannot afford a nutritious diet (Bai et al., 2021; Hirvonen et al., 2020; Masters et al., 2018). While agricultural transformation has been well documented for staple foods in SSA (Badiane et al., 2021), much less is known on how this transformation is playing out in the production of nutritious foods. This is an understudied and important topic and improved insights might better guide these incipient agricultural and nutrition transformation processes in the continent.

An important issue for agricultural transformation, particularly in low- and middle-income countries, is the role of small farms (Collier & Dercon, 2014; Deininger & Byerlee, 2012; Diao et al., 2023). For the past decades, agricultural economists have documented an inverse relationship between farm size and productivity (e.g. Barrett, 1996; Barrett, Carter, & Timmer, 2010; Henderson & Isaac, 2017; Schultz, 1964; Sen, 1962; Sender & Johnston, 2004). Consequently, there has remained a policy preference for smallholder farming in these countries (e.g. Barrett, Bellemare, & Hou, 2010; Hazell et al., 2010). However, as agricultural sectors transform, there is a seemingly steady emergence of better performing medium-scale farms in many regions in SSA (Jayne et al., 2016).

Nevertheless, there is no clear evidence on the relationship between farm size and productivity, overall as well as for various commodities. Understanding these size-productivity relationships matter greatly for improved policy formulations towards agricultural and nutritional transformation in Africa. While some recent studies have focused on measurement issues of this relation (Abay et al., 2021; Ayalew et al., 2023; Chen et al., 2022; Desiere & Jolliffe, 2018; Kosmowski et al., 2021), others show that there is no unambiguous inverse relationship between farm size and productivity, but it is in fact U-shaped or increasing when accounting for the largest farm sizes (over 10 ha) (Aragón et al., 2022; Foster & Rosenzweig, 2022; Muyanga & Jayne, 2019; Omotilewa et al., 2021). Nonetheless, most of the studies in this area have only focused on staple crops (e.g. Abay et al. (2019), wheat; Ali & Deininger (2015), grains and tubers; Carletto et al. (2013), maize).

In this paper, we focus on two important sectors of nutritious food production in Ethiopia: the horticulture and dairy sectors. Although staple crops are essential when considering hunger and undernourishment, we see increasing concerns regarding the triple burden of malnutrition in SSA, highlighting increasing micronutrient deficiencies and instances of hidden hunger. Here, food items such as vegetables and dairy are essential as they contain many nutrients that are generally under-consumed in the region (vitamin C, folate, iron and calcium). Ethiopia is an interesting case study given the size of the country—the second most populous country in Africa—and the important rapid transformation processes that have taken place in the last two decades (World Bank, 2016). Additionally, Ethiopian children consume one of the least diverse diets in SSA (Hirvonen, 2016). While growth in the agricultural sector overall has been well documented (Abate et al., 2015; Bachewe et al., 2018; Dorosh & Minten, 2020), much less is known on the production of nutritious foods. Recent studies have shown that there has been significant growth in production while productivity has been stagnant in nutritious foods (Bachewe & Minten, 2021; Minten, Habte, et al., 2020), but there have been no studies that investigate the important relationship between farm size and these transformation processes.

We contribute to the literature in three ways. First, we rely on unique surveys where farm samples were designed to ensure that they cover the rapidly transforming dynamic commercial areas in the country and that the largest farms were purposefully included in the sample, often a problem for these types of studies (Burkitbayeva et al., 2021; Jayne et al., 2016). Second, we study two agricultural subsectors that produce nutritious foods, which are mostly overlooked in existing studies of agricultural transformation in Africa. Third, we rely on several measures of productivity (yields, gross value and profit per unit of land/animal[1])—as several studies have pointed out the importance of deviating away from simply using yield measures (Aragón et al., 2022; Helfand & Taylor, 2021; Omotilewa et al., 2021)—and study underlying mechanisms for productivity differences.

Our findings indicate the importance of farm size on the (partial) productivity of nutritious commodities, with bigger farms having significantly higher yields, value of outputs and profits than smaller ones. We further show that these differences are large with productivity often twice to four times as high on these bigger farms, much larger than differences seen in other studies on staple food production. Additionally, larger farms invest more, with noticeable differences in input expenditures per ha/cow and farm technologies employed (e.g. hybrid seeds in the vegetable sector, and cross-bred cows in the dairy sector). We further find a strong S-shaped relationship between farm size and productivity suggesting that farm consolidation in the vegetable and dairy sector is less likely to lead to productivity dips as would be the case with a U-shaped relationship noted in other situations (e.g. Foster & Rosenzweig, 2022). Since a large share of the farms in our sample produce for commercial purposes, these findings positively support efforts to transform agricultural production away from subsistence farming.

These findings also have important implications for the nutrition debate. As the last decade has shown a considerable increase in the price of nutritious foods in Ethiopia (Ameye et al., 2021), it seems that the productivity gains from larger farm sizes (increased supply and accessibility), paired with a potential decline in the prices of these foods, could greatly benefit consumers and thus raise the opportunity for a more diversified diet and reduced malnutrition. This is especially important in Ethiopia where diet diversity of consumers is shown to be low, and many poor households are simply unable to afford nutritionally rich foods (Baye & Hirvonen, 2020; Warren & Frongillo, 2017). Recognising the importance of the potential role of these larger commercial farms for nutritious food production by improving accessibility, in helping to bring food prices down, in increasing employment opportunities, in fostering a more commercialised landholding system and food value-chain, and in contributing to the more widespread adoption of improved technologies to smallholders, might therefore be good for consumers and smallholders alike (Ali et al., 2019; Collier & Dercon, 2014). Appropriate business environments for such larger farms to flourish are therefore called for, while improving rural development and off-farm opportunities for smallholder farmers transitioning out of the sector.

2 | STRUCTURAL CHANGES IN ETHIOPIA'S AGRICULTURAL SECTOR

At 35% of GDP, compared to 20% for SSA as a whole, agriculture—and the agri-food system overall—still makes up a significant part of the Ethiopian economy (Dorosh & Minten, 2020; World Bank, 2023). Significant changes in the agri-food system have been noted over the last decade, with important increases in the use of chemical fertilisers and improved seeds on the production side, the rapid growth of the trade, processing and food service sector midstream,

[1]Due to data limitations on inputs and capital, we are unable to construct a reliable measure of total factor productivity (TFP). However, we carry out this exercise and present the results in Section 7, robustness checks.

and an important change in food consumption habits downstream in the value-chain (Dorosh & Minten, 2020).

The livestock sector has shown substantial changes over time. Livestock production at the national level showed high growth rates—livestock output increased by 5.8% per year—over the period 2005–2016. However, that growth came mostly from an increase in the numbers of livestock and input use, while improvements in production methods contributed little (Bachewe et al., 2020). Adoption of improved breeds and improved feeds increased, but started from a low base, while reliance on commercial feed markets increased as well. In the dairy sector in particular, significant transformations were noted, especially so in rural–urban value chains (Minten, Habte, et al., 2020). For example, a tripling of the number of processing firms was noted over the last decade, indicating the increasing investments and modernisation in this area.

The horticultural sector is also characterised by significant changes. Relying on national data on the horticultural sector over a 15-year period, it has been shown that the output of vegetables and fruits doubled over that period (Bachewe & Minten, 2021). However, this was mostly linked to growth in cultivated area. High-yielding varieties of fruits and vegetables were not widely adopted. There is however significant spatial variability. In a study of an important vegetable production cluster in the Central Rift Valley of Ethiopia, big increases in vegetable output were seen in the 2010s, driven by increased urban demand and a significant increase in irrigation and rapid intensification of vegetable production (Minten, Mohammed, & Tamru, 2020).

In terms of consumption, Figure 1 shows that per capita consumption of nutrient-rich foods, such as horticultural products—fruits and vegetables—and animal-sourced foods, have been increasing rapidly over time in Ethiopia, as found in national consumption level assessments. The share of real spending on the consumption of fruits and vegetables in the food basket doubled, from 4.5% in 2006 to 9% in 2016, while that of animal-source foods increased by almost 50%. Wolle et al. (2020) showed more recently that 19% of food expenditures of residents in Addis Ababa was attributed to vegetables. While these findings illustrate that there are significant improvements in budgets devoted to nutritious foods over time, part of that increase has been driven by increased price levels of nutritious foods and overall diet diversity levels are still low and stunting levels high in Ethiopia (Baye & Hirvonen, 2020).

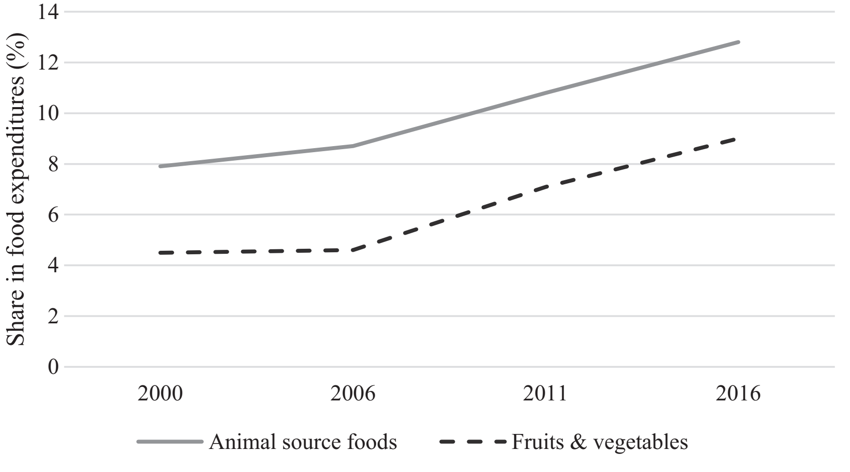

FIGURE 1 Consumption shares of nutritious food groups in the overall food basket of an average Ethiopian consumer.
Source: Authors' calculations based on CSA consumption data (HICES).

3 | DATA

To ascertain the size–productivity relationship in the dairy and horticultural sectors of Ethiopia, we rely on two primary datasets. First, the vegetable sector study uses a survey dataset purposefully collected to investigate vegetable production by smallholder and large-scale vegetable farmers. The survey was conducted in January and February 2020 in the East Shewa Administrative Zone in the Central Rift Valley of Ethiopia. Data on production and inputs used were collected on all vegetables harvested in the 12 months prior to the survey. To inform the sample selection and development of survey instruments, we collected preliminary information on several aspects of vegetable production from four woredas (districts): Dugda, Adame Tulu, Bora, and Lume. From each of these four woredas, we then selected those kebeles (the lowest administrative unit) that had more than 100 ha of irrigated land. This resulted in a total of 37 kebeles. For each kebele, a list of all vegetable cultivators was prepared, along with, among other information, the vegetable area they cultivate, their tenure status and use of irrigation. Out of all farmers in each kebele, 22 were randomly selected. This resulted in a sample of 814 farmers, out of which 805 farmers are included in the surveys. Vegetables included in our survey are tomatoes, onion, cabbage, green pepper and Ethiopian kale, important sources of vitamin C, folate and iron, which are often under-consumed in many regions of Sub-Saharan Africa.

Second, we use data from a survey on the dairy sector. The data includes 870 milk-producing households located in and around Addis Ababa, the capital city—30 urban, 240 suburban and 600 rural producers—were surveyed. The 600 rural dairy producers were surveyed in the two major rural dairy production zones around Addis Ababa, that is, North and West Shewa. To construct the sampling scheme in these rural areas, all woredas and kebeles in the two production zones were ranked and selected according to their remoteness from Addis Ababa, as measured by the travel time using the road network (Minten, Habte, et al., 2020).[2] Three kebeles were selected per woreda. In each of the selected kebeles, a census was conducted on households with at least one cow in milk production. Ten households were then randomly selected that had one or two cows in milk, and another 10 households were randomly selected that had three or more cows in milk. A similar procedure was followed for the farmers located in sub-urban areas ('Oromia Special Zone surrounding Addis Ababa') which resulted in 240 interviews. Finally, a census of dairy producing farms was conducted in Addis Ababa. From this census, 30 small-scale dairy producing households were randomly selected to be interviewed for the household survey. We also interviewed 13 commercial farms, defined as those having more than 25 cows, which were in the survey zones but not in the selected woredas. Data collection took place between 22 January and 15 February 2018. Data were collected on daily milk yields and input expenditures for cows at different stages of the lactation cycle. These data were then aggregated to average annual yields and annual profits considering the length of typical lactation cycles of cows.

[2]The number of woredas retained from each quartile for the survey was proportional to the number of cows. In the closest quartile, four woredas were randomly selected, while in the remaining three quartiles, two woredas were selected. Next, three kebeles (the sub-district administrative unit) were selected randomly in each of these woredas, depending on their location regarding the main road. In the two closest woreda quartiles, two kebeles located close to the main road, and one kebele without access to the road were chosen; while in the furthest two woreda quartiles, three kebeles were randomly selected without considering road access.

4 | ESTIMATION STRATEGY

4.1 | Establishing the relationship between farm size and productivity

In order to establish the general size–productivity relationship for our dairy and vegetable sample, free from specification assumptions, we plot non-parametric regressions between farm size and three measures of productivity: yield (output per hectare/cow), value of output per hectare/cow and profit per hectare/cow.[3] We use partial-productivity measures to (1) allow comparisons to the existing literature on the size–productivity relationship of staple foods and (2) because these measures are clearly calculated and interpretable.[4] We are aware of the measurement error concerns associated with self-reported yield and area measures as referred to in, for example, Gourlay et al. (2019) and Ayalew et al. (2023). Although measurement error will likely exist, several characteristics specific to our sample may limit their extent: (1) The farms in our vegetable survey are largely commercial, selling on average 91% of their produce and due to this market participation—as transactions are negotiated based on careful assessments of quantities—more knowledgeable on production and sales, thus increasing reliability of yield and farm area knowledge. Farm size (area) is often annotated in contracts or rental agreements on the land. During data collection, we observed that farmers were well aware of the area and yield of their plots. (2) The number of cows and production of dairy is relatively low for smallholder farmers—making it easy to track—and readily monitored by larger commercial farms. Further, we run several robustness checks in Section 7 to test the sensitivity of our results.

Succeeding the polynomial associations, we follow previous studies (e.g. Assunção & Braido, 2007; Barrett, Bellemare, & Hou, 2010; Muyanga & Jayne, 2019) to empirically confirm this relationship:

$$Y_i = \beta_0 + \beta_1 A_i + \beta_2 A_i^2 + \varepsilon_i \tag{1}$$

where Y_i is the outcome variable measuring productivity (yield, value of output per hectare/cow and profit per hectare/cow). The main explanatory variables of interest are the farm size (A_i) and its square (A_i^2). The quadratic term is added to determine the shape of any curvature and turning point, if any, in the estimated function. For the vegetable sector, we use area cultivated as a measure of farm size. For dairy, farm size is determined by size of the herd.

Subsequently, we re-estimate the equation also controlling for household characteristics. This estimation follows the equation:

$$Y_i = \beta_0 + \beta_1 A_i + \beta_2 A_i^2 + \beta_3 \boldsymbol{C}_i + \varepsilon_i \tag{2}$$

where $\boldsymbol{C}_i$ captures household level controls such as the gender, age and education of the household head, as well as household size.

[3]To calculate profits, we took the total variable cost of production per hectare/cow and calculated total revenues by multiplying total output by price obtained. Profits are then calculated as sales revenue minus the reported total costs. Note that fixed costs are not included in these calculations. Important to consider is that large farms likely have higher fixed costs to smaller farms which could reduce profits as farm size increases.

[4]To complement the use of partial productivity measures, we also calculate a measure of total factor productivity (TFP). Due to data limitations on the cost of all inputs and capital, we believe this measure to be a rough estimation. However, results of the TFP analyses are provided in Section 7, robustness checks.

4.2 | Input expenditures and modern technologies

Once we determine the non-parametric relationship between farm size and agricultural productivity for our vegetable and dairy sample, we also assess important differences between small and large farms that are associated with productivity. We hypothesise that there are two main factors which appear differently for small and larger farms. The first is input expenditures. We assume that large farms generally invest more in farming inputs such as agro-chemicals, irrigation, fertilisers, or feed and medicines. The second is farming technologies. For vegetables, hybrid crops are often more efficient and better protected against pests, drought and stresses that could decrease overall yields. Figure 2 motivates these hypotheses as total cost of modern inputs such as fertilisers, herbicides and pesticides, and the share of improved seeds used all increase with farm size in our sample.

In the case of the dairy sector, there is also a vast difference between traditional and cross-bred cows. For example, the lactation period for a cross-bred cow is 1.5–2 times longer than that of a traditional cow, therefore increasing the ability of achieving higher milk yields. As seen for the vegetable sector, Figure 3 shows that the total cost of modern inputs—such as expenses on modern feed, medicine and veterinary care—as well as the share of cross-bred cows increase with farm size. Although we cannot causally test these mechanisms due to the limitations of cross-sectional data, these hypotheses are consistent with the literature. For example, Muyanga and Jayne (2019) find increased productivity in large farms partly due to mechanisation and intensity of input use. Similarly, Foster and Rosenzweig (2022) explain the rising upper tail of farm productivity by farm machine capacity with operational scale.

To gauge whether higher input expenditures and improved farm technologies are associated with productivity, which increases with farm size, we add several matrices to the previously run regressions. These regressions will follow the form:

$$Y_i = \beta_0 + \beta_1 A_i + \beta_2 A_i^2 + \beta_3 \boldsymbol{C}_i + \beta_4 \boldsymbol{X}_i + \varepsilon_i \tag{3}$$

where $\boldsymbol{X}_i$ contains variables related to input expenditures—total labor use, cost of fertiliser, irrigation, agro-chemicals, feed and veterinary care—and modern technologies—share of hybrid seeds, share of cross-bred cows, use of artificial insemination and agricultural extension information.

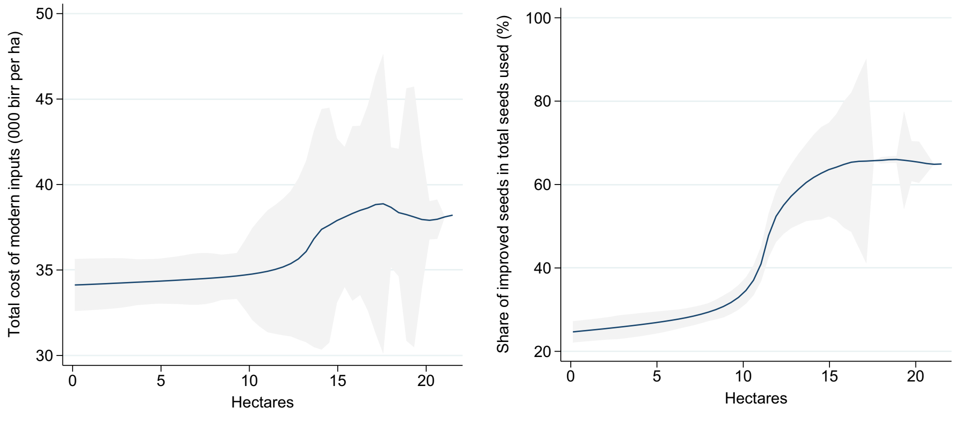

FIGURE 2 Non-parametric associations between input expenditures and modern technology and farm size in the Ethiopian vegetable sector.
Source: Authors' depiction of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

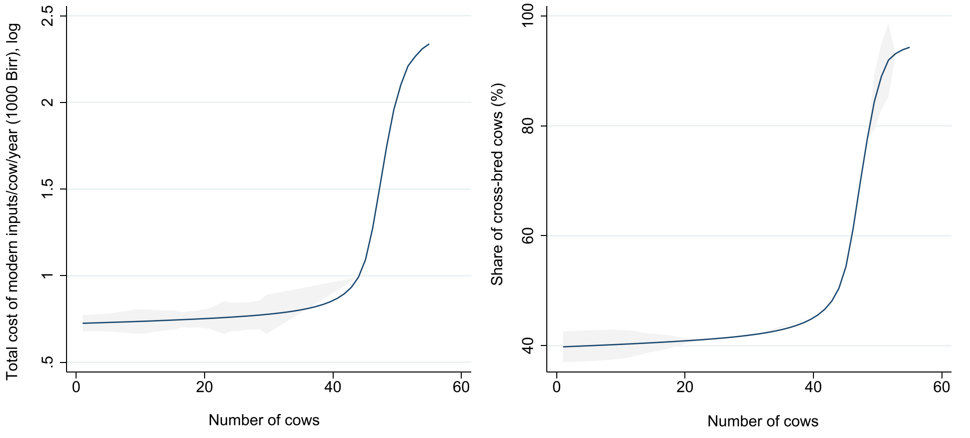

FIGURE 3 Non-parametric associations between input expenditures and modern technology and farm size in the Ethiopian dairy sector.
Source: Authors' depiction of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).

5 | THE VEGETABLE SECTOR

5.1 | Descriptive results

First, we plot the relationship between farm size and our three measures of productivity: output per hectare, value of output per hectare and profit per hectare. Contrary to previous studies conducted primarily on cereals and other staple crops, we find a strong and positive relationship between farm size and productivity for vegetables (Figure 4). For yield, we see a small dip in productivity for farms larger than 15 ha, although confidence intervals widen past this point. In terms of value and profit per hectare, productivity rises similarly, only levelling off slightly for farms larger than 20 ha.

Contrary to the inverse- or U-shaped relationship generally found by agricultural economists for staple crops, our findings are more consistent with the firm size–productivity literature in manufacturing, where the standard model of market equilibrium with endogenous entry and heterogeneous firms, for example, as in Hopenhayn (1992), produces a positive relationship as highly productive firms hire more variable inputs and operate at a larger scale. Interestingly, the slowing in productivity for larger farms also mimics the transition literature, where productivity for larger farms stagnates due to difficulties in labour monitoring/supervision (Mathijs & Swinnen, 2001).

As small and large farms evidently differ in terms of productivity, we also hypothesise a difference in farm structure and characteristics. Table 1 compares several characteristics for small farms, representing 90% of the farms in our sample, and large farms, representing the remaining 10%. We choose to determine small farms by the majority of our smallholder sample rather than use an arbitrary cut-off of 1 or 2 ha to define small farms—especially as we prefer to use a continuous variable of farm size in our regression analysis instead of a dummy-differentiator. Further, Ethiopia has particularly small farm sizes, which we wish to capture in these distinctions.

We find that farmers operating large farms are on average mostly male, younger and more educated in terms of educational attainment and literacy. Large farm yields are almost twice as much compared to small farmers, leading to a value of output and profits that are more than double. On average, smaller farmers operate just under 1 ha, whereas larger farms cultivate around 8 ha. Related to this, we see that large farms generally have more plots and that the

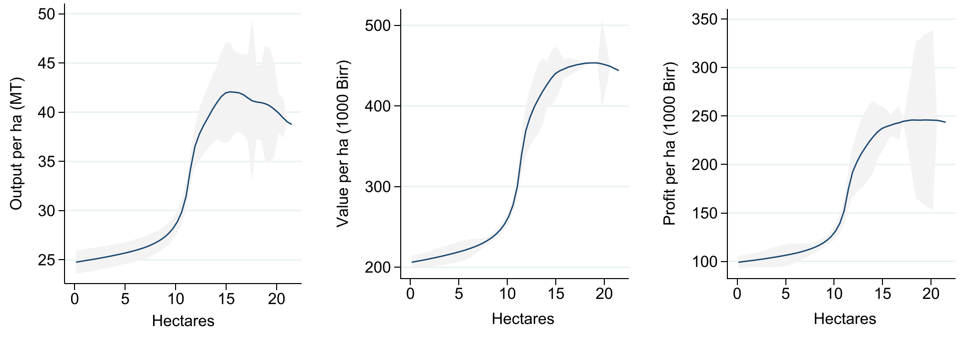

FIGURE 4 Non-parametric associations between farm size and productivity in the vegetable sector.
Source: Authors' depiction of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020). Confidence interval at the 95% level.

average size of these plots is almost three times the average size of plots cultivated by smallholders. More specifically related to the type of vegetable farming, we see that large farms also tend to grow different vegetables than smallholder farms. Nearly 60% of the total area of large farmers is sown to tomatoes, which is one of the costliest vegetables to produce. In contrast, the share of tomatoes in the total area of smallholders' farm production is 28%. The proportion of small and large farmers cultivating onion is closer together at 46% and 36.5%, respectively.

Further, large farms use more labour, although less labour per ha. Fertiliser, irrigation and hybrid seeds use is also much higher for larger farms. Nevertheless, smaller farms rely more on fertile soils and applied extension information. This includes input use, production and marketing information obtained from extension sources. There are no clear differences in farms' exposure to droughts, excess rainfall or disease. Lastly, larger farms are more closely situated to input retailers. This ensures smaller transportation costs and higher accessibility to 'modern' inputs. We must note that the farms in our sample are largely commercial, with over 91% of output sold on average. This is unlike the national average, where farmers sell less than 30% of their vegetables output (Bachewe & Minten, 2023). Particularly, large farms sell a slightly higher proportion of their outputs.

5.2 | Econometric results

5.2.1 | Productivity

Table 2 portrays the results for Equations (1) and (2) run for the three measures of productivity. We see that like in Figure 4, productivity in terms of yield, value of output and profits increases as farm size increases and then levels off or decreases slightly at the level of the largest farms. When we add in the household characteristics, as shown in Equation (2), we find that the estimates remain the same in terms of their implication, although with a slightly smaller magnitude. As land tenure rights in Ethiopia are relatively complex, the opportunity for farm size expansion is not readily available. This reduces possible endogeneity issues in the relationship where more productive farms may be the ones growing in size. The estimates of all equations imply that there exists a quadratic relationship between cultivated area of vegetables and productivity—measured as output, value or profits per hectare.[5] Likewise, Table A1 (in the Appendix A) shows similar results

[5]Specifications using only a linear area term perform inferior to those that include a quadratic area term while cubic terms are insignificant.

TABLE 1 Descriptive statistics for the vegetable sector.

	Smallholders (90% of farmers)		Larger farms (10% of farmers)		All farmers		*T*-test small versus large farms
	Mean	SD	Mean	SD	Mean	SD	
Gender of head of household (=1 if male)	0.95	0.2	0.99	0.1	0.96	0.2	
Age of head of household	40.9	13.5	38.6	8.3	40.7	13.0	
Household size	5.5	2.3	5.6	2.5	5.5	2.3	
Education of head of household							
Illiterate	18.3	38.7	4.9	21.7	16.9	37.5	***
Primary (1–5)	32.5	46.9	24.4	43.2	31.7	46.6	
Middle (6 & 7)	16.7	37.4	14.6	35.6	16.5	37.2	
High school (9–12)	27.2	44.6	46.3	50.2	29.2	45.5	***
Tertiary	5.3	22.3	9.8	29.9	5.7	23.2	*
Yield (MT/ha)	24.0	17.1	40.3	16.2	25.7	17.7	***
Value of output (Thousand birr/ha)	196.0	135.2	414.4	159.3	218.0	152.6	***
Profits (Thousand birr/ha)	92.7	102.7	225.5	149.3	106.3	115.4	***
Area in ha	0.9	0.8	7.9	4.3	1.6	2.6	***
Labour use (person/days)	217.4	301.9	2084.1	2836.9	407.5	1100.8	***
Labour use per ha (person/days/ha)	301.2	701.3	255.7	264.0	296.5	670.0	
Chemical fertiliser used (kg)	704.3	997.2	8072.3	5551.8	1454.8	2995.2	***
Chemical fertiliser used per ha (kg/ha)	688.3	458.3	1041.6	504.0	724.3	475.1	***
Agrochemical users (percent)	95.2	21.5	91.5	28.1	94.8	22.3	
Seed type users (percent)	22.8	38.7	60.8	35.7	26.6	40.1	***
Variable cost of irrigation (000 birr)	9.1	12.6	95.1	104.4	17.8	43.8	***
Variable cost of irrigation per ha (000 birr/ha)	10.4	8.3	11.4	8.2	10.5	8.3	
Cultivating fertile soil (percent)	60.8	47.6	47.9	48.8	59.5	47.9	**
Experience cultivating vegetables (years)	10.3	8.5	10.3	4.8	10.3	8.2	
Applied extension information (per cent)	29.7	45.7	22.0	41.6	28.9	45.4	

TABLE 1 (Continued)

	Smallholders (90% of farmers)		Larger farms (10% of farmers)		All farmers		*T*-test small versus large farms
	Mean	SD	Mean	SD	Mean	SD	
Plot affected by drought or excess rainfall (per cent)	20.5	39.1	21.3	39.1	20.6	39.1	
Plot suffered from diseases (per cent)	41.4	47.6	41.4	46.8	41.4	47.5	
Distance to nearest coop selling inputs (km)	31.6	32.1	19.0	22.4	30.3	31.5	***

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

Note: The cut-off of the largest 10% of farms falls at about 4 ha.

***$p<0.01$, **$p<0.05$ and *$p<0.1$.

TABLE 2 Regression results of the size–productivity relationship among vegetable producers in Ethiopia, household level.

	Yield (MT/ha)		Value of output (Thousand birr/ha)		Profits (Thousand birr/ha)	
	(1)	(2)	(1)	(2)	(1)	(2)
Area in hectares (ha)	4.615***	4.171***	64.007***	61.424***	34.918***	33.614***
	(0.533)	(0.537)	(4.055)	(4.099)	(3.364)	(3.397)
Area in hectare squared (ha^2)	−0.205***	−0.185***	−2.736***	−2.620***	−1.440***	−1.381***
	(0.036)	(0.036)	(0.278)	(0.277)	(0.230)	(0.230)
Constant	20.280***	22.200***	142.171***	171.706***	64.287***	127.424***
	(0.807)	(3.767)	(6.126)	(28.992)	(5.092)	(23.841)
Household characteristics	No	Yes	No	Yes	No	Yes
Explanatory mechanism variables	No	No	No	No	No	No
Adjusted R2	0.113	0.139	0.312	0.328	0.170	0.190
Number of observations	805	805	804	804	805	805
Turning point (ha)	11.3	11.3	11.7	11.7	12.1	12.2

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

Note: Columns with headings of (1) provide results of Equation (1) and those with (2) results of Equation (2). Full regression results for Equation (2) can be found in Table A2.

***$p<0.01$, **$p<0.05$ and *$p<0.1$.

when running Equations (1) and (2) disaggregated at the vegetable level. These regressions include vegetable dummies for onions, cabbage, green pepper and Ethiopian kale, as well as interaction terms between area and type of vegetable. Tomatoes are the omitted category and the most productive vegetable type in our sample.

The results indicate that vegetable productivity first increases and then declines slightly. The inflection point, where productivity starts declining varies according to the specification, data aggregation and productivity measure used. When comparing inflection points, we find that the pair of specifications that include/exclude variables representing household characteristics provide the same inflection point—indicating that effects of those variables on the area at which productivity is maximised is negligible.[6] Here, we find that the maximally productive farm lies between 11.3 and 12.2 ha depending on the productivity measure used. Note that as farm size increases, sample size decreases significantly. Therefore, it may be that once the maximum/turning point is reached, that productivity levels off but does not necessarily decrease much.

Interpreting results from Equation (2), we further see that productivity is not associated with the gender of vegetable farmers. However, unlike the share (about one quarter) of female heads among rural households nationwide (see e.g., Bachewe et al., 2018), this dataset is dominated by male household heads. Household/family size is also not associated with productivity. Household head education is positively associated with productivity in all equations. In addition to the direct positive effect of increased literacy on productivity, education has other externality effects that impact productivity, including increasing farmers' openness to using new inputs and methods of farm management. We also see that younger farmers are more productive. There is seemingly more than one pathway for this relationship. Younger generations are generally open to adopt modern varieties given they are less risk-averse than older farmers. They might also be more likely to use the internet and smartphones to access information on methods of production, inputs and other productivity-increasing information.

5.2.2 | Input expenditures and modern technologies

After establishing the relationship between productivity and farm size, we aim to determine whether there are differences between smaller and larger farms linked to productivity. The results are presented in Table 3. First, we find that modern inputs like the use of hybrid or improved seeds, fertiliser and irrigation are positively associated with productivity of vegetable farms. Particularly, a higher use of improved seed varieties is strongly correlated with increased productivity. These findings are strengthened by the regression results in Table A3, where we see that total cost of modern input use and share of improved seeds used increase and then decline with farm size in the same way as productivity, as measured by yield, value and profits per hectare.

Labour use per hectare is not significantly associated with productivity. Farmers' experience cultivating vegetables is positively associated with profit per hectare while quality of soil is positively associated with yields. Vegetable productivity is lower if fields are adversely affected by drought, excess rainfall or disease. Access to extension services negatively affects profits while higher distances to input selling cooperatives negatively affect yields. Note that the vegetable-producing enclave covered in this study is easily accessible by road transportation, unlike what is observed in the remaining parts of the country (e.g. see Bachewe et al., 2018; Minten, Dereje, et al., 2020), so cooperatives are relatively available to all farms in the sample.

Overall, we find that there is a significant drop in the magnitude of the coefficients representing the size–productivity relationship when explanatory variables are included in the regressions. We can see that about a third of the relationship observed can be explained by farm inputs and technology adoption. The data for Table 3 are run at the household level, as the household represents the unit operating the farm. The analyses we run using vegetable-level disaggregated data provides similar results (Table A4).

[6]However, log-likelihood tests indicate that all specifications that include household characteristics perform better relative to those that omit those variables.

TABLE 3 Regression results including input expenditures and the adoption of modern farm technology in the vegetable sector, household level.

	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)
Area in hectares (ha)	2.948***	48.999***	27.822***
	(0.534)	(3.821)	(3.440)
Area in hectare squared (ha^2)	−0.130***	−2.042***	−1.115***
	(0.035)	(0.250)	(0.225)
Gender of head of household (1 = male)	0.680	11.077	−20.284
	(2.737)	(19.874)	(17.646)
Age of head of household head	−0.150***	−0.862**	−1.177***
	(0.051)	(0.367)	(0.331)
Education of head of household	0.701	2.745	1.583
	(0.530)	(3.787)	(3.415)
Household size	0.104	−1.899	−0.925
	(0.257)	(1.838)	(1.659)
Cost of fertiliser per ha (thousand birr)	0.227***	4.518***	2.343***
	(0.087)	(0.618)	(0.558)
Cost of agro-chemicals per ha (thousand birr)	0.072	1.924***	0.948***
	(0.051)	(0.366)	(0.330)
Share of improved seeds (%)	9.642***	67.943***	25.514***
	(1.494)	(10.686)	(9.633)
Variable cost of irrigation per ha (thousand birr)	0.264***	0.884*	0.531
	(0.069)	(0.490)	(0.443)
Total labour use per ha (person/days)	0.000	0.007	0.003
	(0.001)	(0.006)	(0.005)
Soil quality (=1 if fertile)	3.751***	8.868	5.126
	(1.146)	(8.192)	(7.390)
Experience cultivating vegetables (years)	0.029	0.518	0.843*
	(0.072)	(0.513)	(0.463)
Applied extension information	0.287	−8.572	−13.203*
	(1.238)	(8.846)	(7.983)
Affected by drought or excess rainfall	−3.975***	−31.378***	−26.761***
	(1.443)	(10.328)	(9.305)
Suffered from diseases	−3.141***	−13.183	−17.082**
	(1.188)	(8.490)	(7.661)
Distance to nearest coop selling inputs	−0.030*	−0.031	−0.077
	(0.018)	(0.129)	(0.116)
Constant	18.170***	106.126***	105.892***
	(3.845)	(27.704)	(24.791)
Adjusted R2	0.258	0.491	0.275
Number of observations	805	804	805

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).
Note: ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.

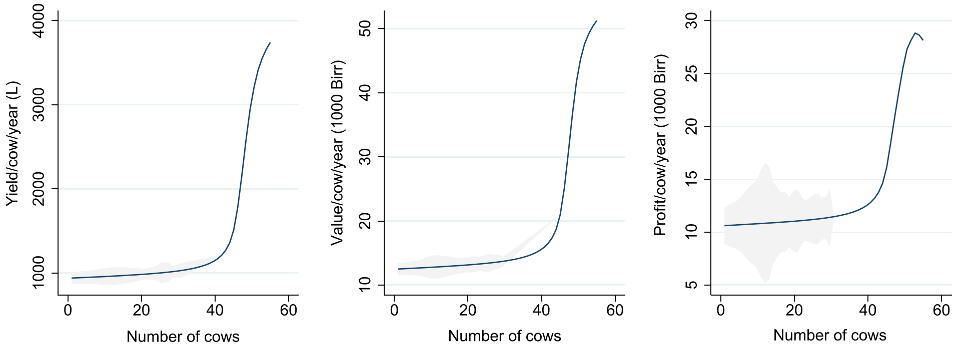

FIGURE 5 Non-parametric associations between farm size and productivity in the dairy sector.
Source: Authors' depiction of data from the Dairy Value Chain Survey in Ethiopia (2018).

6 | THE DAIRY SECTOR

6.1 | Descriptive results

Similar to the vegetable sector, we plot the relationship between farm size in terms of number of cows and our three measures of productivity: output per cow (litres/year), value of output per cow per year and profit per cow per year. Again, we find that the relationship between farm size and productivity for dairy is generally positive, although there is no discernible turning point or stagnation in productivity for larger farms in our sample, except slightly for our profit measure (Figure 5). The Ethiopian dairy sector is still characterised by a predominantly smallholder system with the majority of farmers owning 1, 2 or 3 cows. Here, we predict that we are yet to reach a scale of farm size where productivity declines; again, due to monitoring or management issues.

We also find that small and larger farms differ significantly in terms of several key characteristics. Table 4 compares several characteristics for small dairy farms, representing 90% of the farms in our sample, and large farms, representing the remaining 10%. Contrary to the vegetable sector, larger dairy farms are run by older household heads, although with still a higher educational attainment. Larger farms have an average of 14 cows, compared to 2.4 cows for smaller farms. As seen from Figure 5, yield, value and profits per cow are about three times higher for larger farms.[7] As expected, the use of modern inputs and technologies such as share of cross-bred cows, cost of feed and share of artificial insemination users is also higher for larger farms. Lastly, we find that larger farms are generally situated closer to cooperatives, reducing transportation costs and increasing access to inputs.

The farmers in our dairy sample differ from our vegetable farmers mainly in terms of commercialization. The smaller farms (who often happen to be located in more remote areas and mostly own local cows) tend to auto-consume a considerable share of their milk as compared to the bigger ones, often located in close proximity to urban centres (Minten, Habte, et al., 2020). This is also the case for those more remote farms who tend to produce the relatively more storable dairy product types (i.e. butter and cheese). By doing so, they can still consume 'whey' which is a by-product that otherwise would not have been produced had they sold out the fresh milk (Minten, Habte, et al., 2020; Vandercasteelen et al., 2021).

[7]In our dataset, there are seven farms with more than 40 cows. These larger farms have significantly different dairy production practices, leading to higher productivity and profitability per cow, driving partly the large observed difference seen between large and small farms.

TABLE 4 Descriptive statistics for the dairy sector.

	Smallholders (90% of farmers)		Larger farms (10% of farmers)		All farmers		*T*-test small versus large farms
	Mean	SD	Mean	SD	Mean	SD	
Gender of head of household (=1 if male)	0.90	0.29	0.95	0.21	0.91	0.29	
Age of head of household	48.5	13.8	54.6	13.2	48.8	13.9	***
Household size	6.0	2.1	7.0	2.6	6.0	2.1	***
Education of head of household							
Illiterate	0.43	0.49	0.34	0.48	0.43	0.49	
Primary (1–5)	0.33	0.47	0.21	0.41	0.33	0.47	*
Middle (6 & 7)	0.09	0.29	0.02	0.15	0.09	0.29	
High school (9–12)	0.09	0.29	0.34	0.48	0.11	0.31	***
Tertiary	0.03	0.18	0.07	0.26	0.04	0.19	
Yield (Lt/cow/year)	821.6	39.7	2405.7	198.4	966.8	43.3	***
Value of output (Thousand birr/cow/year)	10.6	14.9	35.7	27.5	12.9	18	***
Profits (Thousand birr/cow/year)	9.5	32.1	24.5	58.9	10.8	35.6	***
Number of cows	2.5	1.3	14	10.7	3.5	4.7	***
Labour use (person days/year)	114.5	75.1	160.5	129.1	118.6	82.5	***
Labour use per cow (person days/cow/year)	56.8	48.5	13.5	9.9	53.0	48.0	***
Share of crossbreed cows	0.4	0.4	0.8	0.4	0.4	0.5	***
Share of artificial insemination users	0.3	0.5	0.6	0.5	0.4	0.5	***
Share of vaccinated cows	0.8	0.4	0.9	0.2	0.8	0.4	***
Variable cost of feed per HH (000 birr)	26.0	19.2	67.1	46.6	31.2	27.2	***
Variable cost of feed per cow (000 birr/cow)	0.8	1.3	2.5	2.6	0.9	1.5	***
Variable cost of modern inputs per cow (000 birr/cow)	2.0	6.4	9.5	16.3	2.6	8.1	***
Access to extension information (percent)	0.87	0.34	0.96	0.19	0.88	0.33	**
Share of cows that had diseases	0.1	0.3	0.1	0.3	0.1	0.3	
Travel time to nearest coop (min)	79.3	71.8	37.1	38.5	75.4	70.5	***

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).
Note: ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.

6.2 | Econometric results

6.2.1 | Productivity

Table 5 portrays the results for Equations (1) and (2) run for the three measures of productivity in the dairy sector. Due to the fact that the largest farms are generally run by managers instead of households, we do not have household characteristics for the owner of these farms in our sample. As we do not want to exclude the largest farms due to missing values in the regressions, we have taken woreda (district) averages for household characteristics of the largest 10% of farms that have this data. Household characteristics are expected to be less important for these farms precisely as they are often run by managers or owned by an enterprise.

We see that like in Figure 5, productivity in terms of yield, value of output and profits increases as farm size increases and then levels off or decreases slightly at the level of the largest farms. The squared term, however, is less pronounced in the dairy sector than in the vegetable sector. When we add in the household characteristics (full Table A5 in Appendix A), Equation (2), we find that the estimates remain the same in terms of their implications, although with a higher magnitude (column 2). Controlling for household characteristics, where age and education positively impact productivity and household size has negative effects, increases the overall relationship between farm size and yield, value of output and profits, although the coefficient for farm scale becomes less significant for yield.

6.2.2 | Input expenditures and modern technologies

After establishing the relationship between productivity and farm size, we further assess whether input expenditures and modern technologies, more commonly used by larger farms, affect productivity (Equation (3)). Overall, we find that the coefficients for farm size, as measured by number of cows, decrease drastically and lose significance once these factors are added (Table 6). Higher spending on inputs is positively associated with an increase in yield and value of dairy. This may have adverse effects on profits however, as increasing costs beyond an optimum point will reduce these. Further, as is expected for the dairy industry, productivity in

TABLE 5 Regression results of the size-productivity relationship among dairy producers in Ethiopia.

	Yield (litre/cow/year)		Value of output (Thousand birr/cow)		Profits (Thousand birr/cow)	
	(1)	(2)	(1)	(2)	(1)	(2)
Total number of cows	44.690***	66.06*	0.028***	0.207***	25.330***	25.810***
	(36.470)	(36.930)	(0.472)	(0.477)	(19.990)	(20.660)
Number of cows, squared	5.048**	2.303***	0.0989***	0.0661**	0.011***	0.022***
	(2.337)	(2.336)	(0.031)	(0.031)	(2.011)	(2.038)
Constant	603.7***	652.8***	8.344***	8.119***	−13.750***	−23.950***
	(80.660)	(173.900)	(1.101)	(2.146)	(32.620)	(48.400)
Household characteristics	No	Yes	No	Yes	No	Yes
Explanatory mechanism variables	No	No	No	No	No	No
Adjusted R2	0.046	0.142	0.051	0.162	0.065	0.068
Number of observations	835	835	802	802	784	784

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).
Note: ***$p<0.01$, **$p<0.05$ and *$p<0.1$.

TABLE 6 Regression results including input expenditures and the adoption of modern farm technology in the dairy sector.

	Yield (litre/cow/year)	Value of output (Thousand birr/cow)	Profits (Thousand birr/cow)
Total number of cows	−7.384	−0.703*	24.6
	(29.180)	(0.386)	(21.000)
Number of cows, Number of squared	3.345*	0.0785***	0.0057
	(1.849)	(0.025)	(2.070)
Gender of head of household	28.95	−0.984	−12.19
	(82.120)	(1.126)	(18.620)
Age of head of household	2.275	0.0488**	0.481
	(1.964)	(0.025)	(0.621)
Education of head of household	156.3***	2.328***	−7.16
	(35.860)	(0.458)	(6.262)
Household size	−36.54**	−0.3	2.12
	(14.920)	(0.189)	(4.328)
Total labour use per cow person hours/days	−26.85	−0.481	−2.516
	(29.700)	(0.391)	(10.380)
Total cost of inputs per cow thousand birr	51.49***	0.634***	0.937
	(9.196)	(0.123)	(1.623)
Share of cross-bred cows	1.039***	11.87***	45.78
	(88.070)	(1.112)	(31.130)
Use of artificial insemination yes = 1	256.7***	3.944***	−32.14
	(77.510)	(0.975)	(26.540)
Access to extension service yes = 1	49.87	0.335	−3.507
	(71.540)	(1.037)	(13.940)
Number of calvings	23.46*	0.249*	4.921
	(12.320)	(0.138)	(3.038)
Suffered from cow diseases	146.4	1.76	−51.44
	(126.800)	(1.570)	(38.320)
Distance to nearest coop	−0.204	−0.00689	0.03
	(0.371)	(0.005)	(0.100)
Constant	−2.938	1.362	−38.51
	(225.900)	(2.823)	(69.500)
Adjusted R2	0.433	0.45	0.081
Number of observations	835	802	784

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).
Note: $^{***}p < 0.01$, $^{**}p < 0.05$ and $^{*}p < 0.1$.

terms of yield and value of output increases with the number of calvings and use of artificial insemination. Dairy cows produce milk more consistently if pregnancies follow closely together. Lastly, having a higher share of cross-bred cows, who are generally in-milk for a longer time than traditional cows, also increases farm productivity. These findings are strengthened by the regression results in Table A6, where we see that total cost of modern input use and share of cross-bred cows increase with farm size in the same way.

7 | ROBUSTNESS CHECKS

7.1 | Outlier analysis

As recent literature—for example, Gourlay et al. (2019) and Ayalew et al. (2023)—point to important measurement errors in plot area and yield, we run a bounding exercise to test whether our results hold when removing 2%, 5% and 10% of the smallest and largest farms in our sample. This will allow us to determine whether the smallest farms or the largest farms in our sample may be driving the positive relationship between farm size and productivity.

Tables A7–A9 (in Appendix A) display the results of the regressions run for the vegetable sector, without controls, with household controls and adding in explanatory mechanisms, respectively. From Table A7, we can see that there remains a strong positive relationship between farm size and yield, value of output and profits when removing 1%, 2.5% and 5% of farms from the upper- and lower tail of farm size. Interestingly, the negative and statistically significant coefficient for area squared also remains, meaning that even with the removal of the largest farms in our sample, there seems to remain a downturn in productivity at the upper end of farm size. Similar results are observed from Table A8 when controlling for household characteristics. Lastly, Table A9 shows that input expenditures on fertilisers and irrigation, as well as a higher use of improved seed varieties positively affect productivity. Including these factors reduces the magnitude of our coefficients on farm size and farm size squared, but slightly less so than in Table 3.

Tables A10–A12 show our regression results from this bounding exercise in the case of the dairy sector. Again, we find that the positive relationship between farm size and productivity holds, with even stronger magnitudes than observed in Tables 5 and 6. These findings are consistent with the observation that the strongest positive relationship between farm size and productivity takes off at a scale of about 40 cows and above. As these farms are predominantly commercial farms, it is important to note that the positive relationship between farm size and productivity may be influenced by the nature of the farm, that is, whether for subsistence or commercial purposes, rather than simply the size.

Note that this bounding exercise places equal importance on measurement error for the smallest and largest farms. It may however be that only smaller or larger farms systematically under- or over-report farm size or yield. Gourlay et al. (2019) find that over-reporting of production by smaller farms partly explains the inverse relationship previously found in the literature. We also believe that small farmers in the surveyed vegetable growing areas can underreport input use compared to commercial farmers.[8] If we hold this true for our sample, then the positive relationship observed in our study would only be further strengthened if accounting for the reporting errors of smaller farmers. The positive relationship between (partial) productivity and farm size in our analysis could only be impacted by a very large underestimation (overestimation) of production by smaller (larger) farms in our sample. As the literature mainly highlights measurement error in the opposite direction, we believe our results to be less sensitive to these errors.

[8]Large farmers rent-in most of their land. Land sizes are not only included in contracts but also serve as a unit of measure of variable input use—including number of labourers. Subsistence farmers use relatively more family labour, which is more difficult to accurately recall and measure. Moreover, unlike subsistence farmers, who use part or their produce for consumption, large farmers sell almost all of their produce and therefore can recall output volumes with less error. Similarly, large farmers sell outputs in large volumes and are well connected with wholesalers, making them less prone to recalling errored prices.

7.2 | Sensitivity analysis

Besides measurement error, another factor affecting studies on farm productivity is the presence of unobserved variables at the plot (e.g. soil quality), household (e.g. ability or effort) or community level (e.g. market failures). As our data are cross-sectional, our ability to control for unobservable variables is limited. Therefore, we test the sensitivity of our key independent variable (farm size: area and number of cows and the squared terms) following methods proposed by Diegert et al. (2022), Oster (2019) and Masten and Poirier (2023). These studies define a set of sensitivity parameters which index relaxations of the assumption that the covariate of interest is uncorrelated with any unobserved variables. A Stata code (regsensitivity) developed by Diegert et al. (2022) implements all three methods for given values of the three parameters β ($\overline{r_X}$, $\overline{r_y}$, $\overline{c}$) whereby $\overline{r_X}$ is a ratio of mean function of the omitted variables over observed variables whereby $\overline{r_X} = 0$ is the case of no unobserved variables. Similarly, $\overline{c}$ is a ratio of variance functions of omitted variables over observed variables while $\overline{r_y}$ is a limit function of the dependent variable, expressed as a function of the variable of interest/area, other controls and unobservables. This method tests the sensitivity of only one variable at once.

Table 7 presents the results of our sensitivity tests conducted separately on area and area squared. The entries in the table indicate the breakdown point or the value of $\overline{r_X}$ at which the coefficients on area or area square change their sign (from + and – to – and +, respectively). The results are presented for values of $\overline{c}$ ranging from 0.1, when the omitted variables have the lowest variation relative to observed variables, to 1, when the variation in the two groups of variables is equal. The results indicate that if the omitted variables have less variation ($\overline{c} =$ 0.1), then the area coefficient in the yield equation will breakdown if the value of $\overline{r_X} = 88\%$, which means the coefficient of area will change sign (become negative) if the weight of omitted variables is over 88% of the observed variables. At $\overline{c} = 0.1$, the breakdown point of the coefficient on area is 171% and 122% in the value and profit per hectare equations, respectively. If we assume that the variation in the omitted variables is the same as the observed variables (or $\overline{c} = 1$), then the breakdown points are lower across the board, at 69%, 90% and 81% in the respective equations, relative to when the variation in the omitted variables is less important. Generally, the analyses pertaining to area squared have implications similar to those discussed above.

Figure 6 further provides results of the sensitivity analyses conducted assuming different values of $\overline{c}$ and $\overline{r_X}$. These graphs are consistent with what was observed in Table 7, and importantly, the coefficients estimated possess signs that are robust across a wide range of assumptions on the relative weight of omitted variables.

For the dairy sector, we find that the weight of unobservable factors over observable variables is much smaller before they gain importance, meaning that there is more chance

TABLE 7 Results of sensitivity analyses for area and area squared for different assumptions on $\overline{c}$.

	Breakdown point					
	Area (ha)			Area squared		
Value of cbar ($\overline{c}$)	Yield	Value	Profit	Yield	Value	Profit
0.1	88%	171%	122%	85%	162%	109%
0.25	80%	139%	105%	77%	133%	96%
0.5	72%	109%	89%	70%	105%	83%
1	69%	90%	81%	68%	89%	77%

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

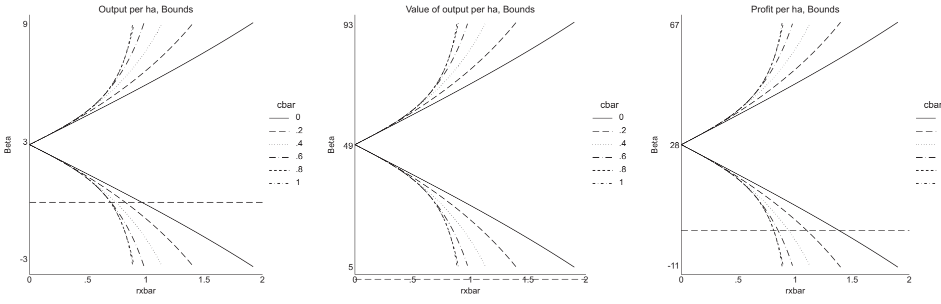

FIGURE 6 Results of sensitivity analyses for area and area squared for different assumptions on $\bar{c}$ and $\overline{r_X}$.
Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

TABLE 8 Results of sensitivity analyses for number of cows and number of cows squared for different assumptions on $\bar{c}$.

	Breakdown point					
	Total number of cows			Number of cows squared		
Value of cbar	Yield	Value	Profit	Yield	Value	Profit
0.1	4%	21%	43%	23%	44%	12%
0.25	4%	21%	42%	23%	42%	12%
0.5	4%	21%	41%	23%	42%	12%
1	4%	21%	41%	23%	42%	12%

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).

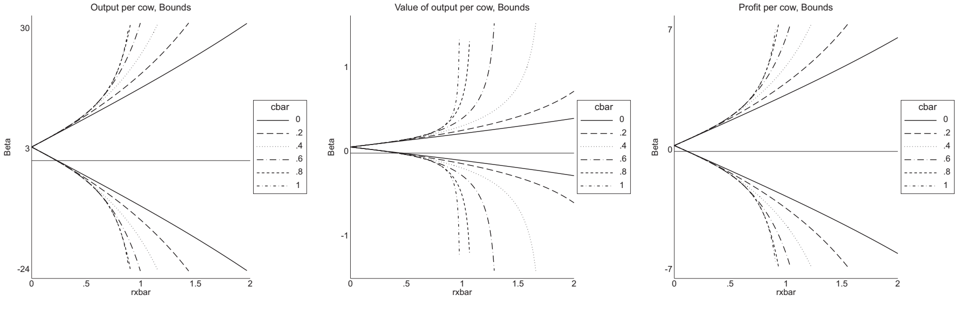

FIGURE 7 Results of sensitivity analyses for number of cows and number of cows squared for different assumptions on $\bar{c}$ and $\overline{r_X}$.
Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).

to exert influence on the relationship between farm size and productivity than observed for the vegetable sector (Table 8). However, we see that the percentages remain relatively robust with an increasing $\bar{c}$. These observations are confirmed in Figure 7, where we see a relatively small spread in the bounds produced for changing values of $\bar{c}$, especially for value and profit per cow.

7.3 | Total factor productivity analysis

To investigate whether farm size is positively related to productivity among vegetable and dairy farmers in Ethiopia, we focus on several partial productivity indicators (yield, value and profit). However, partial productivity measures often include certain inputs, primarily land, in output calculations and may overlook potential input substitution possibilities. Total factor productivity (TPF), defined as the rate of transformation of total inputs into total outputs (Diewert & Nakamura, 2002), is typically preferred as a more complete productivity measure, encompassing all outputs relative to all inputs, unlike partial productivity indices (e.g. yields) which measure outputs per area/cow. However, TFP is challenging to calculate due to the detailed data required on all inputs and outputs, a common limitation in many studies.

To provide an approximate measure of TFP in our study, which uses a cross-sectional dataset, we follow the approach by Helfand and Taylor (2021), Diewert and Nakamura (2007, 2002) and Carlaw and Lipsey (2003), who define TFP through the following index:

$$\text{TFP}_i = \frac{\text{Outputs}_i}{\text{Inputs}_i} = \frac{\sum_{j=1}^{J} p_j y_j}{\sum_{k=1}^{K} w_k m_k}$$

Whereby farmers are indexed by i, inputs are indexed by k ($k = 1, 2, \ldots K$) and outputs by j ($j = 1, 2, \ldots J$). This study investigates whether there exist differences in TFP of farmers as a function of farm size, I. If there are differences in TFP across farm size, then $\frac{\partial \varphi(\text{TFP})}{\partial I} \neq 0$. Particularly, $\varphi(\text{TFP}) / \partial I > 0$ implies that TFP increases with farm size.

While a TFP index is appealing, practical implementation presents several challenges, which is why TFP assessments are not included in our main analysis. First, TFP measures are theoretically comprehensive, accounting for all inputs influencing output quantities. However, it is difficult to value and incorporate all inputs/factors affecting the production process—such as rainfall, critical in Ethiopia's agriculture, and other inputs that are not well measured in most farm surveys, such as organic fertiliser. Fixed inputs also pose challenges in these analyses. Although our sensitivity analyses suggest omitted variables are less concerning, especially in the vegetables sector, TFP estimates could still be biased if omission correlates with farm size (heteroscedastic). Second, TFP indices typically rely on prices to aggregate differently measured inputs and outputs for productivity comparisons across firms and industries. However, imperfect and absent input markets complicate TFP measurement in low-income settings like Ethiopia. Third, a TFP index may be biased if self-provided inputs (e.g. seeds, family labour), critical for smallholders in these settings, are not accurately imputed into cost calculations. A fourth issue, closely related to the first, is incomplete data on TFP components. Particularly, our dataset lacks prices for all inputs, relying instead on farmers' recall for the total input costs while we compute the value of outputs using farmers' recall data on outputs and prices. The reliance on different output and [implicitly] input prices can lead to inaccurate TFP measures. Accordingly, we calculate the TFP index of farmer i in this study as:

$$\text{TFP}_i = \frac{\text{Value of output}_i}{\text{Costs of production}_i}$$

A summary of the TFP index of vegetable producers calculated in this manner averaged 2.09 (with standard deviation (SD) of 1.05) across all farmers; 2.08 (with SD of 1.1) for smallholders; and 2.19 (with SD of 0.7) among larger farms. The respective averages are slightly different (1.9, 2.3 and 1.9) when considering only tomatoes and onions, in which commercial farmers are dominant. These numbers indicate that, despite the multitudes of problems highlighted above,

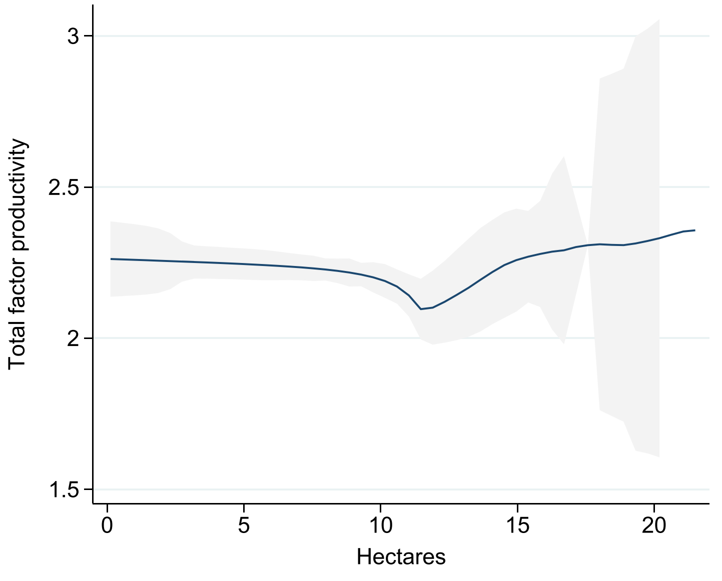

FIGURE 8 Non-parametric associations between farm size and TFP in the vegetable sector.
Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

our analyses provide values close to the TFP estimates ranging between 1 and 2 expected from such an exercise (Carlaw & Lipsey, 2003; Diewert & Nakamura, 2007, 2002; Helfand & Taylor, 2021); particularly in Ethiopian agriculture (Bachewe et al., 2018, 2020).

Results of the TFP analyses for vegetable farmers are further summarised in Figure 8. The figure shows a constant relationship between farm size and TFP with no seemingly significant differences in productivity with farm size. However, findings from the regression analysis, presented stepwise in Table 9, show a significant pattern of initial decline, followed by an increase. This U-shaped relationship mimics similar relationships found in, for example, Foster and Rosenzweig (2022). As expected, many of the explanatory variables included in the regression specification in column (3) are not significant, as the effect of modern technologies and inputs are now captured in the TFP measure.

In the case of the dairy farmers included in our sample, the TFP value averaged 3.40 (with SD of 5.03) across all farmers; 3.34 (with SD of 5.12) across smallholders; and 3.99 (with SD of 3.99) among larger farms. The relationship between farm size and TFP is less consistent. Figure 9 presents the non-parametric association between number of cows and TFP. Here, we observe a slight increase up to farms with about 20 cows, a U-shaped relationship for farms between 20 and 40 cows and a recurring decline in TFP for farms with over ~43 cows. Nevertheless, these patterns have large confidence intervals which disables discernment of any clear patterns. From the regression analysis in Table 10, we find that there is first a strong and significant increase in TFP with farm size. However, TFP decreases again for larger farms. These findings are consistent with those observed from our partial productivity measures.

The findings from this TFP analysis should be interpreted cautiously due to data limitations. Nonetheless, it is noteworthy that our TFP results do not align perfectly with our findings from the partial productivity measures. Earlier, we found that modern technologies and increased input spending largely explained the positive relationship between farm size and land productivity and value of output. However, after factoring in these variables in the TFP analysis, the productivity differences between small and large farms become less pronounced.

TABLE 9 Regression results of the size–TPF relationship among vegetable producers in Ethiopia.

	TFP (1)	TFP (2)	TFP (3)
Area in hectares (ha)	−0.126**	−0.124**	−0.106*
	(0.051)	(0.052)	(0.055)
Area in hectare squared (ha^2)	0.008**	0.008**	0.007*
	(0.004)	(0.004)	(0.004)
Gender of head of household (1 = male)		−0.218	−0.204
		(0.285)	(0.284)
Age of head of household head		−0.013**	−0.017***
		(0.005)	(0.005)
Education of head of household		−0.026	−0.032
		(0.053)	(0.055)
Household size		0.035	0.042
		(0.026)	(0.027)
Cost of fertiliser per ha (thousand birr)			−0.000
			(0.000)
Cost of agro-chemicals per ha (thousand birr)			−0.002
			(0.009)
Share of improved seeds (%)			−0.008
			(0.005)
Variable cost of irrigation per ha (thousand birr)			−0.222
			(0.155)
Total labour use per ha (person/days)			0.008
			(0.007)
Soil quality (=1 if fertile)			0.173
			(0.119)
Experience cultivating vegetables (years)			0.010
			(0.007)
Applied extension information			−0.127
			(0.128)
Affected by drought or excess rainfall			−0.448***
			(0.150)
Suffered from diseases			−0.136
			(0.123)
Distance to nearest coop selling inputs			−0.002
			(0.002)
Constant	2.390***	2.963***	3.204***
	(0.077)	(0.366)	(0.399)
Adjusted R2	0.005	0.009	0.026
Number of observations	805	805	805

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).
Note: ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.

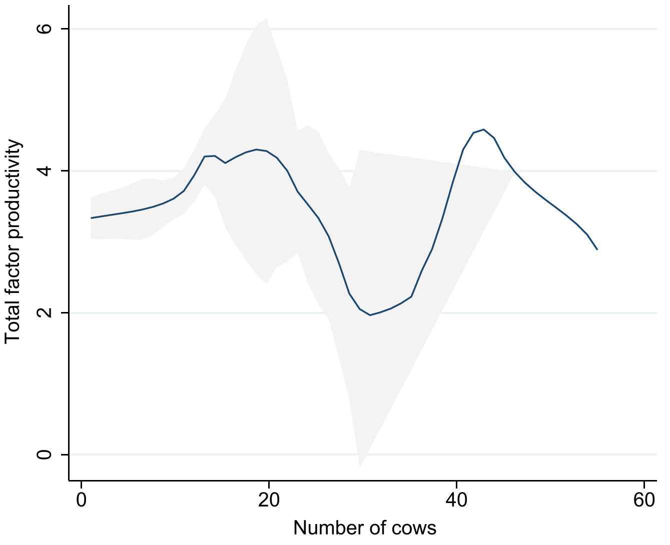

FIGURE 9 Non-parametric associations between farm size and TFP in the dairy sector.
Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).

TABLE 10 Regression results of the size-TPF relationship among dairy producers in Ethiopia.

	TFP index	TFP index	TFP index
	(1)	(2)	(3)
Total number of cows	0.717***	0.679***	−0.138
	(0.207)	(0.214)	(0.197)
Number of cows. squared	−0.0314*	−0.0307*	−0.001
	(0.017)	(0.017)	(0.014)
Gender of head of household		−0.947	−0.636
		(0.711)	(0.636)
Age of head of household		0.019**	0.0115
		(0.015)	(0.014)
Education of head of household		0.143	0.0918
		(0.143)	(0.130)
Household size		0.134	0.134
		(0.102)	(0.089)
Total labour use per cow person hours/ days			−2.513***
			(0.288)
Total cost of inputs per cow thousand birr			−0.234***
			(0.089)
Share of cross-bred cows			0.544
			(0.550)
Use of artificial insemination yes = 1			−0.0633
			(0.627)
Access to extension service yes = 1			0.371
			(0.505)

TABLE 10 (Continued)

	TFP index (1)	TFP index (2)	TFP index (3)
Number of calvings			0.0808
			(0.062)
Suffered from cow diseases			0.139
			(0.512)
Distance to nearest coop			0.0036
			(0.003)
Constant	1.822***	0.883***	13.35***
	(0.351)	(1.031)	(1.838)
Adjusted R-squared	0.025	0.031	0.181
Number of observations	835	835	835

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (IFPRI, 2018).
Note: ***$p<0.01$, **$p<0.05$ and *$p<0.1$.

Although larger farms have the potential for greater outputs and profits, they face unique constraints that impact their success.

8 | CONCLUSION

The size–productivity relationship remains a contested topic among agricultural economists. From the early determination of a negative relationship favouring small farms to the recent findings of a U-shaped relationship, these interpretations have left ambiguity to the agricultural transformation process in SSA. Our study focuses on clarifying this relationship for the Ethiopian vegetable and dairy sector, key in the provision of nutritious foods. Contrary to the inverse- or U-shaped relationship generally found in agricultural economics, our findings are more consistent with the firm size–productivity literature in manufacturing forwarded by Hopenhayn (1992), showing a positive relationship.

The results in our analysis suggest a strong association between farm size and our three measures of (partial) productivity, with yields, value of outputs and profits of larger farmers being two to four times higher than smaller farms. These effects are larger and more positive than documented in other studies in SSA—for example, an analysis with commercial cereal farms in Ethiopia showed that yields obtained by larger farms were almost double those obtained by smallholders and that larger farms mostly only specialised in those crops where they might have comparative advantages relative to smallholders (Ali et al., 2019). Muyanga and Jayne (2019) also generally show lower effects of large farms in staple crop production than documented here. Our findings may be exacerbated by several characteristics more prevalent in our sample compared to regional and national averages, such as good market access, commercialisation and infrastructure, which are conducive to increasing productivity.

In the case of the production of nutritious foods, it seems that larger farms with higher levels of productivity also have higher input expenditures and superior farm technologies. Some of these technologies might be characterised by threshold capital investments that only bigger and richer farms are able to make, such as investments in private irrigation and hybrid seeds in the case of vegetable farms or cross-bred cows and artificial insemination for dairy farms. Such threshold effects have been identified before with farmers trying to access modern markets (e.g. Lu et al., 2016; Neven et al., 2009).

Overall, these findings have important implications for the debate on the role of small farms and nutritional improvements in the continent. Productivity gains from larger farm sizes, coupled with a potential decline in the prices of nutritious foods, could greatly benefit consumers by increasing access to a more diversified diet and addressing issues of malnutrition. To allow for these gains, appropriate business environments—such as physical security and secure tenure arrangements—for such larger farms to flourish will be necessary. Simultaneously, rural development and off-farm opportunities will bolster a transition that minimises losses for smallholder farmers.

ACKNOWLEDGEMENTS

We are grateful for the useful comments by participants at the CSAE conference in Oxford, 2023. We acknowledge funding from the Excellence of Science (EOS) Research Project 30784531 at the Research Foundation—Flanders (FWO) and the European Union's Horizon 2020 research and innovation programme under grant agreement No. 861932 (BATModel).

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Conducted surveys received ethical approval from IFPRI's Institutional Review Board (IRB #00007490; FWA #00005121): Vegetable Survey dossier number DSGD-19-1265 M, and Dairy Survey dossier number 17-11-01 (Temporary dossier for period of 1 year).

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How to cite this article: Ameye, H., Bachewe, F.N., Minten, B. & Tamru, S. (2025) Farm size and agricultural productivity of nutritious foods: Evidence from Ethiopia. *Journal of Agricultural Economics*, 00, 1–42. Available from: https://doi.org/10.1111/1477-9552.12621

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APPENDIX A

TABLE A1 Regression results of the size-productivity relationship among vegetable producers in Ethiopia, disaggregated at the vegetable level.

	Yield (MT/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Profits (Thousand birr/ha)
Area in hectare (ha)	3.495***	3.155***	39.698***	36.477***	20.484***	18.889***
	(0.656)	(0.651)	(6.929)	(6.900)	(4.801)	(4.798)
Area in hectare squared (ha^2)	−0.157***	−0.140***	−1.946***	−1.778***	−1.084***	−1.004***
	(0.040)	(0.040)	(0.423)	(0.421)	(0.293)	(0.293)
Gender of head of household		0.288		−25.228		1.268
		(2.685)		(28.478)		(19.800)
Age of head of household		−0.169***		−1.213**		−0.966***
		(0.045)		(0.482)		(0.335)
Education of head of household		1.335***		14.941***		5.282
		(0.476)		(5.045)		(3.508)
Household size		0.062		−1.293		−0.959
		(0.241)		(2.555)		(1.776)
Interaction of onion cultivation and area	−0.452	−0.446	4.379	4.498	7.878*	7.937*
	(0.588)	(0.579)	(6.207)	(6.138)	(4.301)	(4.268)
Interaction of cabbage cultivation and area	11.416***	10.852***	5.515	2.798	12.727	11.146
	(3.864)	(3.814)	(40.822)	(40.452)	(28.283)	(28.127)
Interaction of green pepper cultivation and area	−0.212	−0.608	20.648	17.255	−6.310	−7.540
	(1.601)	(1.584)	(16.912)	(16.795)	(11.717)	(11.678)
Interaction of Ethiopian kale cultivation and area	−4.977*	−4.268	−39.239	−33.734	−19.447	−15.405
	(2.765)	(2.727)	(29.210)	(28.926)	(20.238)	(20.112)
Vegetable_type==Onion	−21.868***	−21.965***	−194.172***	−195.040***	−100.632***	−101.992***
	(1.809)	(1.786)	(19.108)	(18.940)	(13.238)	(13.169)

(Continues)

TABLE A1 (Continued)

	Yield (MT/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Profits (Thousand birr/ha)
Vegetable_type==Cabbage	−12.626***	−12.459***	−264.518***	−264.635***	−126.274***	−126.330***
	(3.154)	(3.110)	(33.313)	(32.982)	(23.080)	(22.932)
Vegetable_type==Green pepper	−29.000***	−28.486***	−214.065***	−209.030***	−85.786***	−84.559***
	(2.332)	(2.317)	(24.639)	(24.574)	(17.071)	(17.086)
Vegetable_type==Ethiopian kale	−8.539***	−8.161***	−263.223***	−258.977***	−98.961***	−97.512***
	(2.238)	(2.210)	(23.641)	(23.437)	(16.379)	(16.296)
Constant	38.824***	42.758***	385.235***	439.600***	169.793***	204.462***
	(1.649)	(3.762)	(17.423)	(39.897)	(12.071)	(27.740)
Adjusted R2	0.296	0.317	0.289	0.305	0.140	0.153
Number of observations	1164	1164	1164	1164	1164	1164
Turning point, ha	11.16	11.30	10.20	10.26	9.45	9.41

Note: ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.

TABLE A2 Regression results of the size–productivity relationship among vegetable producers in Ethiopia.

	Yield (MT/ha)		Value of output (Thousand birr/ha)		Profits (Thousand birr/ha)	
	(1)	(2)	(1)	(2)	(1)	(2)
Area in ha	4.615***	4.171***	64.007***	61.424***	34.918***	33.614***
	(0.533)	(0.537)	(4.055)	(4.099)	(3.364)	(3.397)
Area in ha, squared	−0.205***	−0.185***	−2.736***	−2.620***	−1.440***	−1.381***
	(0.036)	(0.036)	(0.278)	(0.277)	(0.230)	(0.230)
Gender of head of household (=1 if male)		−0.289		−2.308		−25.869
		(2.934)		(22.716)		(18.568)
Age of head of household		−0.128**		−0.818**		−0.979***
		(0.052)		(0.397)		(0.329)
Education of head of household		1.796***		10.417**		5.309
		(0.546)		(4.162)		(3.456)
Household size		0.173		−1.687		−1.149
		(0.272)		(2.075)		(1.724)
Constant	20.280***	22.200***	142.171***	171.706***	64.287***	127.424***
	(0.807)	(3.767)	(6.126)	(28.992)	(5.092)	(23.841)
Adjusted R2	0.113	0.139	0.312	0.328	0.170	0.190
Number of observations	805	805	804	804	805	805
Turning point, ha	11.3	11.3	11.7	11.7	12.1	12.2

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).
Note: ***$p<0.01$, **$p<0.05$ and *$p<0.1$.

TABLE A3 Regression results of the relationship between modern inputs and farm area.

	Total cost of modern inputs (thousand birr/ha)	Total cost of modern inputs (thousand birr/ha), logs	Share of improved seeds in total seeds used (%)
Area in ha	1.635**	0.068***	10.902***
	(0.703)	(0.025)	(1.193)
Area in ha, squared	−0.085*	−0.004**	−0.458***
	(0.048)	(0.002)	(0.082)
Constant	32.507***	3.247***	13.602***
	(1.065)	(0.038)	(1.806)
R2	0.008	0.009	0.136
Number of observations	805	805	805

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).
Note: ***$p<0.01$, **$p<0.05$ and *$p<0.1$.

TABLE A4 Regression results including input expenditures and the adoption of modern farm technology in the vegetable sector, disaggregated at the vegetable level.

	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)
Area in ha	3.407***	38.248***	16.783***
	(0.654)	(6.899)	(4.872)
Area in ha, squared	−0.161***	−1.986***	−0.934***
	(0.040)	(0.420)	(0.297)
Gender of head of household	1.348	−13.762	9.323
	(2.607)	(27.500)	(19.419)
Age of head of household	−0.161***	−1.269***	−1.215***
	(0.046)	(0.488)	(0.345)
Education of head of household	0.756	10.002**	2.249
	(0.476)	(5.019)	(3.544)
Household size	0.081	−0.166	−0.405
	(0.237)	(2.499)	(1.765)
Total labour use per ha (person/days)	0.001	0.019**	0.006
	(0.001)	(0.009)	(0.006)
Cost of fertiliser per ha (thousand birr)	0.339***	2.527***	1.606***
	(0.079)	(0.836)	(0.590)
Cost of agro-chemicals per ha (thousand birr)	0.146**	1.836***	0.026
	(0.059)	(0.624)	(0.441)
Seed type (=1 if hybrid)	4.213***	67.042***	36.958***
	(1.481)	(15.623)	(11.032)
Variable cost of irrigation per hectare (thousand birr)	0.160***	0.814	0.586
	(0.062)	(0.650)	(0.459)
Soil quality (=1 if fertile)	1.827*	16.727	3.892
	(1.008)	(10.631)	(7.508)
Experience cultivating vegetables (years)	−0.011	0.525	1.137**
	(0.068)	(0.714)	(0.504)
Applied extension information	−0.374	−29.150**	−19.408**
	(1.108)	(11.692)	(8.256)
Plot affected by drought or excess rainfall	−1.536	−20.549	−27.619***
	(1.286)	(13.569)	(9.582)
Plot suffered from diseases	−4.161***	−46.409***	−19.857**
	(1.044)	(11.011)	(7.775)
Distance to nearest coop selling inputs	−0.018	−0.145	−0.141
	(0.016)	(0.170)	(0.120)
Interaction of onion cultivation and area	−0.289	6.450	9.519**
	(0.564)	(5.947)	(4.199)
Interaction of cabbage cultivation and area	8.214**	−35.789	−12.703
	(3.755)	(39.615)	(27.975)

TABLE A4 (Continued)

	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)
Interaction of green pepper cultivation and area	−2.651*	−8.943	−19.948*
	(1.565)	(16.505)	(11.655)
Interaction of Ethiopian kale cultivation and area	−4.168	−25.991	−8.990
	(2.656)	(28.022)	(19.788)
Vegetable_type==Onion cultivation	−17.386***	−135.522***	−69.002***
	(2.001)	(21.103)	(14.902)
Vegetable_type==Cabbage cultivation	−7.134**	−204.435***	−91.518***
	(3.108)	(32.789)	(23.155)
Vegetable_type==Green pepper cultivation	−21.394***	−129.017***	−42.958**
	(2.455)	(25.901)	(18.290)
Vegetable_type==Ethiopian kale cultivation	−1.597	−184.514***	−60.665***
	(2.426)	(25.587)	(18.068)
Constant	32.226***	329.546***	160.470***
	(4.206)	(44.364)	(31.329)
Adjusted R2	0.362	0.358	0.193
Number of observations	1164	1164	1164
Turning point, ha	10.59	9.63	8.99

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).
Note: ***$p<0.01$, **$p<0.05$ and *$p<0.1$.

TABLE A5 Regression results of the size–productivity relationship among dairy producers in Ethiopia.

	Yield (litre/cow/year)		Value of output (Thousand birr/cow)		Profits (Thousand birr/cow)	
	(1)	(2)	(1)	(2)	(1)	(2)
Total number of cows	44.690***	66.06*	0.028***	0.207***	25.330***	25.810***
	(36.470)	(36.930)	(0.472)	(0.477)	(19.990)	(20.660)
Number of cows. squared	5.048**	2.303***	0.0989***	0.0661**	0.011***	0.022***
	(2.337)	(2.336)	(0.031)	(0.031)	(2.011)	(2.038)
Gender of head of household		1.188		−1.446		−9.937
		(106.100)		(1.521)		(18.440)
Age of head of household		1.454**		0.040**		0.409***
		(2.521)		(0.031)		(0.622)
Education of head of household		284.8***		3.979***		−7.360
		(45.780)		(0.586)		(6.467)
Household size		−70.54***		−0.725***		0.782
		(18.650)		(0.240)		(4.482)
Constant	603.7***	652.8***	8.344***	8.119***	−13.750***	−23.950***
	(80.660)	(173.900)	(1.101)	(2.146)	(32.620)	(48.400)
Household characteristics	No	Yes	No	Yes	No	Yes
Explanatory mechanism variables	No	No	No	No	No	No
Adjusted R2	0.046	0.142	0.051	0.162	0.065	0.068
Number of observations	835	835	802	802	784	784

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (2018).
Note: ***$p<0.01$, **$p<0.05$ and *$p<0.1$.

TABLE A6 Regression results of the relationship between modern inputs and number of cows.

	Cost of modern input/cow/year (Thousands Birr)	Cost of modern input/cow/year (Thousands Birr), logs	Share of cross-bred cows
Total number of cows	0.694***	0.081***	0.039***
	(0.198)	(0.011)	(0.005)
Number of cows, squared	−0.008**	−0.001***	−0.001***
	(0.003)	(0.000)	(0.000)
Constant	1.026	0.793***	0.529***
	(0.734)	(0.116)	(0.056)
R2	0.256	0.500	0.493
Number of observations	801	801	801

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (2018).
Note: ***$p<0.01$, **$p<0.05$ and *$p<0.1$.

TABLE A7 Robustness check regression results of the size–productivity relationship among vegetable producers in Ethiopia.

	2% outliers removed (1% in each tail)			**5% outliers removed (2.5% in each tail)**			**10% outliers removed (5% in each tail)**		
	Yield (MT/ha)	**Value of output (Thousand birr/ha)**	**Profits (Thousand birr/ha)**	**Yield (MT/ha)**	**Value of output (Thousand birr/ha)**	**Profits (Thousand birr/ha)**	**Yield (MT/ha)**	**Value of output (Thousand birr/ha)**	**Profits (Thousand birr/ha)**
Area in ha	4.805***	58.760***	29.272***	4.493***	53.148***	27.092***	3.876***	48.548***	23.715***
	(0.477)	(3.783)	(3.065)	(0.451)	(3.490)	(2.819)	(0.427)	(3.488)	(2.710)
Area in ha, squared	−0.213***	−2.464***	−1.179***	−0.201***	−2.197***	−1.050***	−0.181***	−2.141***	−1.075***
	(0.033)	(0.258)	(0.209)	(0.031)	(0.236)	(0.191)	(0.029)	(0.248)	(0.194)
Constant	19.439***	144.575***	68.747***	19.495***	146.011***	69.146***	19.793***	150.467***	71.603***
	(0.729)	(5.694)	(4.608)	(0.686)	(5.218)	(4.234)	(0.642)	(5.020)	(3.911)
Adjusted R2	0.151	0.314	0.152	0.148	0.311	0.165	0.124	0.273	0.125
Observations	789	788	787	761	761	765	725	722	725

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

Note: *** $p<0.01$, ** $p<0.05$ and * $p<0.1$.

TABLE A8 Robustness check regression results of the size–productivity relationship among vegetable producers in Ethiopia, including household controls.

	2% outliers removed (1% in each tail)			5% outliers removed (2.5% in each tail)			10% outliers removed (5% in each tail)		
	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)
Area in ha	4.414***	56.571***	27.940***	4.134***	51.293***	26.009***	3.585***	47.354***	22.760***
	(0.480)	(3.824)	(3.107)	(0.455)	(3.518)	(2.851)	(0.432)	(3.520)	(2.751)
Area in ha, squared	−0.195***	−2.369***	−1.121***	−0.185***	−2.120***	−1.003***	−0.168***	−2.096***	−1.040***
	(0.032)	(0.257)	(0.209)	(0.030)	(0.235)	(0.191)	(0.029)	(0.248)	(0.194)
Gender of head of household	−0.806	−2.626	−5.925	−0.892	−1.581	−5.763	0.622	−12.715	−5.094
	(2.621)	(20.947)	(16.983)	(2.419)	(18.814)	(15.404)	(2.253)	(18.362)	(13.863)
Age of household head	−0.110**	−0.855**	−0.775**	−0.114***	−0.776**	−0.790***	−0.087**	−0.762**	−0.729***
	(0.047)	(0.370)	(0.302)	(0.044)	(0.338)	(0.277)	(0.041)	(0.324)	(0.255)
Education of head of household	1.670***	9.043**	5.200*	1.442***	7.615**	4.162	1.204***	6.163*	3.790
	(0.494)	(3.870)	(3.152)	(0.464)	(3.551)	(2.896)	(0.436)	(3.409)	(2.684)
Household size	0.080	−0.575	−0.592	0.211	−2.272	−0.900	0.286	−1.787	−0.083
	(0.245)	(1.927)	(1.570)	(0.233)	(1.751)	(1.454)	(0.219)	(1.681)	(1.352)
Constant	21.757***	171.781***	101.624***	21.714***	180.426***	105.693***	19.402***	194.112***	101.098***
	(3.383)	(26.820)	(21.794)	(3.149)	(24.245)	(19.831)	(2.944)	(23.422)	(18.046)
Adjusted R2	0.176	0.328	0.167	0.173	0.329	0.183	0.143	0.290	0.142
Observations	789	788	787	761	761	765	725	722	725

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

Note: $^{***}p<0.01$, $^{**}p<0.05$, and $^{*}p<0.1$.

TABLE A9 Robustness check regression results of the size–productivity relationship among vegetable producers in Ethiopia, full regressions.

	2% outliers removed (1% in each tail)			5% outliers removed (2.5% in each tail)			10% outliers removed (5% in each tail)		
	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)
Area in ha	3.116***	45.533***	22.542***	3.123***	43.390***	21.363***	2.751***	41.052***	19.178***
	(0.467)	(3.621)	(3.142)	(0.451)	(3.397)	(2.932)	(0.431)	(3.408)	(2.829)
Area in ha, squared	−0.138***	−1.844***	−0.857***	−0.141***	−1.731***	−0.780***	−0.129***	−1.797***	−0.841***
	(0.031)	(0.235)	(0.204)	(0.029)	(0.219)	(0.189)	(0.028)	(0.232)	(0.193)
Gender head of household	0.253	10.611	1.750	0.013	8.288	1.216	1.161	−3.732	0.440
	(2.393)	(18.549)	(16.062)	(2.258)	(17.056)	(14.804)	(2.127)	(16.849)	(13.380)
Age head of household	−0.118**	−0.855**	−0.905***	−0.126***	−0.882***	−0.908***	−0.107***	−0.984***	−0.910***
	(0.046)	(0.347)	(0.302)	(0.044)	(0.324)	(0.282)	(0.041)	(0.315)	(0.260)
Education of head of household	0.740	1.872	0.959	0.670	1.153	0.253	0.540	−0.079	−0.022
	(0.467)	(3.552)	(3.094)	(0.449)	(3.327)	(2.887)	(0.427)	(3.234)	(2.690)
Household size	0.045	−0.973	−0.560	0.200	−2.482	−1.199	0.263	−2.106	−0.515
	(0.227)	(1.727)	(1.501)	(0.221)	(1.607)	(1.414)	(0.210)	(1.561)	(1.324)
Total labour use per ha (person/days)	0.000	0.006	0.003	0.000	0.005	0.002	0.000	0.003	0.001
	(0.001)	(0.005)	(0.005)	(0.001)	(0.005)	(0.004)	(0.001)	(0.005)	(0.004)
Cost of fertiliser per ha (thousand birr)	0.262***	4.494***	2.564***	0.198***	3.394***	1.970***	0.178**	2.935***	1.851***
	(0.076)	(0.584)	(0.508)	(0.073)	(0.556)	(0.476)	(0.070)	(0.545)	(0.448)
Cost of agro-chemicals per ha (thousand birr)	0.052	1.534***	0.786**	0.038	1.559***	0.696**	0.031	1.297***	0.569*
	(0.045)	(0.405)	(0.334)	(0.043)	(0.377)	(0.326)	(0.040)	(0.373)	(0.302)
Share of improved seeds	10.237***	60.932***	23.660***	8.601***	43.861***	22.600***	7.725***	39.730***	12.227
	(1.322)	(10.089)	(8.779)	(1.274)	(9.469)	(8.364)	(1.217)	(9.230)	(7.777)
Variable cost of irrigation per ha (thousand birr)	0.233***	0.946**	0.591	0.200***	0.997**	0.513	0.156***	1.082***	0.458
	(0.061)	(0.463)	(0.401)	(0.059)	(0.434)	(0.372)	(0.057)	(0.417)	(0.343)
Soil quality (=1 if fertile), weighted	3.352***	4.313	5.393	2.613***	4.517	5.160	2.217**	3.009	6.394
	(1.009)	(7.698)	(6.679)	(0.966)	(7.204)	(6.212)	(0.919)	(6.989)	(5.786)

(Continues)

TABLE A9 (Continued)

	2% outliers removed (1% in each tail)			5% outliers removed (2.5% in each tail)			10% outliers removed (5% in each tail)		
	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)	Yield (MT/ha)	Value of output (Thousand birr/ha)	Profits (Thousand birr/ha)
Experience cultivating vegetables (years)	−0.011	0.348	0.575	−0.004	0.583	0.541	0.020	0.934**	0.634*
	(0.063)	(0.487)	(0.417)	(0.061)	(0.458)	(0.386)	(0.060)	(0.452)	(0.356)
Applied extension information	−0.733	−10.171	−5.739	−0.724	−8.105	−2.862	−0.584	−6.331	2.738
	(1.095)	(8.316)	(7.226)	(1.051)	(7.719)	(6.767)	(0.994)	(7.442)	(6.261)
Affected by weather shock, weighted	−3.763***	−27.733***	−28.093***	−3.872***	−26.298***	−22.621***	−3.577***	−22.109**	−19.823***
	(1.282)	(9.754)	(8.440)	(1.227)	(9.151)	(7.962)	(1.164)	(8.831)	(7.404)
Suffered from diseases, weighted	−3.148***	−12.618	−14.295**	−2.505**	−15.184**	−12.486*	−1.820*	−12.989*	−9.155
	(1.050)	(7.992)	(6.946)	(1.009)	(7.454)	(6.505)	(0.958)	(7.238)	(6.024)
Distance to nearest coop selling inputs	−0.018	−0.014	−0.025	−0.017	−0.145	−0.060	−0.010	−0.181	−0.134
	(0.016)	(0.120)	(0.105)	(0.015)	(0.116)	(0.098)	(0.015)	(0.111)	(0.091)
Constant	17.267***	112.424***	74.209***	18.511***	138.552***	85.676***	16.921***	160.152***	86.964***
	(3.386)	(26.007)	(22.573)	(3.221)	(24.131)	(20.936)	(3.046)	(23.712)	(19.110)
Adjusted R2	0.320	0.479	0.264	0.287	0.456	0.256	0.243	0.410	0.212
Observations	789	788	787	761	761	765	725	722	725

Source: Authors' analyses of data from the Vegetable Value Chain Survey in Ethiopia (IFPRI, 2020).

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE A10 Robustness check regression results of the size-productivity relationship among dairy producers in Ethiopia.

	2% outliers removed (1% in each tail)			5% outliers removed (2.5% in each tail)			10% outliers removed (5% in each tail)		
	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)
Total number of cows	85.330***	0.278***	25.230***	115.600***	0.141***	55.59***	142.500***	0.284***	40.21**
	(59.520)	(0.777)	(35.970)	(75.410)	(0.998)	(15.770)	(105.700)	(1.376)	(15.770)
Number of cows, squared	−0.466***	0.062***	−0.079***	−6.192***	0.070***	−4.283*	−11.100***	0.045***	−1.675***
	(7.208)	(0.094)	(5.368)	(10.840)	(0.141)	(2.493)	(18.660)	(0.233)	(3.373)
Constant	549.0***	8.027***	−12.710***	518.1***	8.279***	−53.19***	489.1***	8.115***	−35.55**
	(98.180)	(1.358)	(45.470)	(107.400)	(1.521)	(19.070)	(125.200)	(1.775)	(15.540)
Adjusted R2	0.017	0.012	0.044	0.010	0.005	0.065	0.009	0.003	0.066
Observations	827	794	776	814	781	763	792	760	743

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (2018).

Note: ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.

TABLE A11 Robustness check regression results of the size–productivity relationship among dairy producers in Ethiopia, including household controls.

	2% outliers removed (1% in each tail)			5% outliers removed (2.5% in each tail)			10% outliers removed (5% in each tail)		
	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)
Total number of cows	94.31*	0.320***	28.680***	147.3**	0.515***	58.93***	176.0*	0.629***	43.35***
	(52.580)	(0.674)	(35.700)	(70.810)	(0.918)	(16.300)	(101.200)	(1.293)	(15.000)
Number of cows, squared	−1.333***	0.051***	−0.287***	−10.320***	0.011***	−4.539*	−16.230***	−0.018***	−1.929***
	(5.950)	(0.075)	(5.351)	(10.140)	(0.129)	(2.525)	(17.980)	(0.222)	(3.284)
Gender of head of household	1.771	−1.403	−1.223	−12.420	−1.566	−6.453	32.810	−1.012	−6.095
	(106.400)	(1.525)	(17.910)	(107.200)	(1.525)	(17.340)	(98.690)	(1.440)	(17.180)
Age of household head	1.204**	0.036**	0.287**	1.714***	0.042**	−0.159***	1.581**	0.041**	−0.290**
	(2.547)	(0.032)	(0.606)	(2.543)	(0.032)	(0.533)	(2.550)	(0.032)	(0.523)
Education of head of household	284.3***	3.975***	−7.828*	280.1***	3.907***	2.653	283.0***	3.938***	5.636*
	(46.370)	(0.594)	(6.437)	(47.270)	(0.606)	(3.556)	(48.210)	(−0.618)	(3.480)
Household size	−72.13***	−0.755***	−3.752	−64.58***	−0.648***	−4.950	−63.40***	−0.623**	−5.354*
	(19.000)	(0.244)	(3.573)	(19.180)	(0.247)	(3.066)	(19.640)	(0.253)	(3.075)
Constant	635.2***	8.335***	−2.823***	522.0***	7.409***	−18.530***	450.6**	6.729**	5.350***
	(188.200)	(2.314)	(61.880)	(196.700)	(2.463)	(35.360)	(208.800)	(2.670)	(46.060)
Observations	827	794	776	814	781	763	792	760	743
R-squared	0.114	0.128	0.048	0.101	0.115	0.069	0.101	0.113	0.073

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (2018).

Note: $^{***}p<0.01$, $^{**}p<0.05$, and $^{*}p<0.1$.

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TABLE A12 Robustness check regression results of the size–productivity relationship among dairy producers in Ethiopia, full regressions.

	2% outliers removed (1% in each tail)			5% outliers removed (2.5% in each tail)			10% outliers removed (5% in each tail)		
	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)
Total number of cows	10.690	−0.737***	29.800**	20.580	−1.120***	54.36***	24.810	−1.244***	34.10**
	(41.960)	(0.548)	(38.540)	(55.340)	(0.729)	(16.690)	(82.680)	(1.042)	(15.990)
Number of cows squared	1.165	0.083***	−0.432	0.160	0.147***	−4.225*	−1.099	0.164***	−0.986**
	(4.813)	(0.061)	(5.516)	(7.949)	(0.103)	(2.542)	(14.620)	(0.179)	(3.489)
Gender of head of household	29.870	−0.931	−4.178	17.660	−1.054	−8.829	50.930	−0.661	−7.584
	(82.090)	(1.129)	(18.390)	(81.700)	(1.117)	(17.400)	(75.180)	(1.052)	(17.150)
Age of household head	2.003***	0.0438*	0.384***	2.674***	0.0522**	−0.087***	2.311***	0.0480*	−0.246***
	(1.983)	(0.025)	(0.603)	(1.970)	(0.025)	(0.511)	(1.981)	(0.025)	(0.502)
Education of head of household	155.3***	2.316***	−6.993	155.8***	2.299***	2.631	162.9***	2.396***	4.798
	(36.310)	(0.463)	(6.110)	(37.030)	(0.472)	(3.712)	(37.740)	(0.481)	(3.680)
Household size	−38.16**	−0.329*	−2.576	−32.20**	−0.241	−3.814	−32.82**	−0.239	−4.206
	(15.190)	(0.192)	(3.267)	(15.340)	(0.193)	(2.685)	(15.730)	(0.198)	(2.647)
Labour use (person-days/cow/year). Logs	−24.800**	−0.476**	1.975*	−6.871**	−0.270**	−7.045*	−4.730*	−0.231	−10.58**
	(29.880)	(0.392)	(10.760)	(29.140)	(0.382)	(5.674)	(29.920)	(0.391)	(5.182)
Total cost of modern inputs (birr/cow/year). Logs	52.15***	0.642***	1.487***	51.85***	0.646***	1.414***	51.41***	0.648***	0.648***
	(9.198)	(0.123)	(1.577)	(9.123)	(0.123)	(1.425)	(9.298)	(0.125)	(1.225)
Share of cross-bred cows	1.035***	11.81***	39.700	1.033***	11.78***	41.140	1.022***	11.70***	40.520
	(87.870)	(1.111)	(30.840)	(87.910)	(1.109)	(28.940)	(89.420)	(1.123)	(29.730)
Used Artificial Insemination (yes=1)	253.1***	3.898***	−33.290**	247.5***	3.843***	−34.360**	250.7***	3.815***	−26.410**
	(77.690)	(0.976)	(27.170)	(77.790)	(0.974)	(24.050)	(79.100)	(0.985)	(24.460)
Use of extension services	50.910	0.345**	−2.857*	44.310	0.261**	4.033	41.230	0.232*	5.218
	(71.650)	(1.038)	(13.760)	(71.720)	(1.039)	(12.750)	(72.170)	(1.045)	(13.600)
Number of calvings	22.72*	0.241*	4.972***	21.90*	0.237*	4.735***	20.100***	0.213***	4.402***
	(12.370)	(0.138)	(3.030)	(12.630)	(0.139)	(2.997)	(12.680)	(0.138)	(2.952)

(Continues)

TABLE A12 (Continued)

	2% outliers removed (1% in each tail)			5% outliers removed (2.5% in each tail)			10% outliers removed (5% in each tail)		
	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)	Yield (Lt/cow)	Values of outputs ('000 birr/cow)	Profits ('000 birr/cow)
Suffered from diseases	146.400**	1.775	−50.750	141.600	1.747	−13.630	144.800	1.781	−11.540
	(126.700)	(1.570)	(38.500)	(125.900)	(1.552)	(11.570)	(127.700)	(1.573)	(11.280)
Distance to nearest coop selling inputs	−0.206	−0.007	0.034	−0.212	−0.007*	0.070	−0.234	−0.007**	0.044*
	(0.371)	(0.005)	(0.099)	(0.366)	(0.005)	(0.092)	(0.366)	(0.005)	(0.089)
Constant	−14.280***	1.786**	−42.210*	−149.60***	0.631***	−20.170***	−162.40***	0.514***	29.570***
	(239.000)	(2.969)	(91.920)	(244.900)	(3.042)	(40.340)	(265.800)	(3.330)	(41.430)
Observations	827	794	776	814	781	763	792	760	743
R-squared	0.414	0.427	0.062	0.407	0.421	0.086	0.403	0.417	0.089

Source: Authors' analyses of data from the Dairy Value Chain Survey in Ethiopia (2018).
Note: ***$p < 0.01$, **$p < 0.05$ and *$p < 0.1$.