

On the Impact of Weather Variability and Climate Change on Agriculture

Evidence from Ethiopia

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Abstract

Weather fluctuations tend to be as important as climate change in farmers' decision making in countries such as Ethiopia that have virtually no weather insurance. This paper assesses the distinct impacts of weather and climate change measures on agricultural productivity of households, measured in terms of crop revenue, in the Amhara region of Ethiopia. Four waves of survey data, which included about 1500 households in each round, combined with interpolated daily temperature and monthly rainfall data from the meteorological stations, are employed in the analysis. The distinction between weather and climate is highlighted by observations in the temperature data, which show that the pattern of temperature for both short-term and long-term values follows a bell-shaped distribution, with the striking feature that the extreme ends of the distribution have fatter tails for the long term values. The analysis employs monthly rainfall and 14 temperature categories related to weather measures and four categories corresponding with the extreme ends of the long-term temperature distribution. The analysis also distinguishes between summer and spring seasons and different crops, in recognition that Ethiopia's agriculture is multi-cropping and multi-season. The major findings show that temperature effects are distinctly non-linear, but only when the weather measures are combined with the extreme ends of the distribution of the climate measures. In addition, rainfall generally has a less important role to play than temperature, contrary to expectations for rainfed agriculture.

Key Words: crop revenue, climate change, weather variability, Mundlak's Fixed Effects method, Ricardian analysis, Ethiopia

JL Codes: D2, Q12, Q15

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Introduction

Developing countries and their economic progress are likely to suffer tremendously from climate change, given their extremely nature-dependent agrarian economies (Mendelsohn and Dinar 2009). As a result, accurate quantification of the impact of climate change on the agricultural sector is of paramount importance in guiding appropriate adaptation measures (Sachs et al. 1999; Stage 2010) and ensuring genuine participation of developing countries in climate change agreements (Cao 2008; Timmins 2006).

One critical issue in assessing the links between agricultural revenue and climate change is the measurement of climate change indicators, and in particular, the distinction between weather and climate-related measures and the handling of extreme values. In line with this, Rosenzweig et al. (2009) argue that due consideration should be given to disproportionately large changes in the frequency of extreme events that are associated with, and not captured by, small changes in long term mean temperatures. Indeed, the effects of such variations and extremes are likely to be captured through measures that account for changes in patterns of temperature in a more detailed manner, as opposed to average climatic parameters (De Salvo et al. 2013). In addition, Maraun et al. (2010) show that extreme events and temporal-spatial variations tend to be poorly represented by average climate change measures. Accordingly, this paper focuses on

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assessing the impacts of weather variability and climate change on agricultural productivity in Ethiopia by incorporating the different features of short term (weather) and long term (climate) measures and emphasizing extreme values corresponding to the measures.¹

The literature on the relationship between agricultural revenues and climate change has so far been dichotomous, in the sense that analysis has focused on either long term average measures or more detailed short term measures. Assessing the potential impacts of climate change on agriculture based on the long term mean values of climatic parameters has been largely done using the so-called Ricardian approach. The approach, pioneered by Mendelsohn et al. (1994), has the attractive feature that it automatically captures adaptation (Masseti and Mendelsohn 2011), and its reliance on long term mean climate measures is based on the implicit assumption that it is these measures (and not short term measures) that farmers respond to, by adjusting inputs and outputs to match local conditions (Lang 2007).

The second variant of studies justifies the use of short term measures (as opposed to long term climate measures) as a mere diagnostic indicator or an imperfect substitute for long term measures. For instance, Schlenker and Roberts (2009) argue that estimating the correct relationship between weather and yields is a critical first step before assessing structural shifts in response to climate change. Massetti and Mendelsohn (2011) argue that measuring the impacts of climate change on agriculture using inter-annual changes in weather is simply wrong, as farmers have only limited opportunities to adapt to weather and the measurements cannot capture any of their longer-term adjustments to climate. Similarly, Deschenes and Greenstone (2007) argue that the quantified impact of climate change using year-to-year weather fluctuation measures is likely to be greater than that of long term measures, as the latter accounts for the possibility of adaptations. Massetti and Mendelsohn (2011) argue that long term climate

¹ The difference between weather and climate is a measure of time. While weather is the day-to-day state of the atmosphere, and its variation over minutes to weeks, climate is defined as statistical weather information that describes the variation of weather at a given place for a specified interval. To determine climate, the weather of a locality is usually averaged over a 30-year period (Gutro 2005). Weather and climate are expected to have different economic implications, as they represent essentially different phenomena (Fischer et al. 2012). It should also be noted that, to the extent that the distributions of weather and climate are identical, the distinction between the two is irrelevant. The essence of the distinction becomes relevant when the two are distributionally different.

measures capture systematic adaptations such as crop variety choice,² while weather-related short term variations only account for limited adaptation efforts. In addition, Schlenker and Robert (2009) argue that the observed limited historical adaptation of seed varieties or management practices to warmer temperatures is associated with the fact that the time-series analysis does not include farmers' adaptations to warmer climates while cross-section analysis does and.

The use of short term measures is also generally accompanied by more detailed distributional measures, as opposed to average measures. As Hodges (1991) and Grierson (2002) show, plant growth depends on the cumulative exposure to heat and precipitation during the growing season. Specifically, as plants cannot absorb heat above or below a specific threshold, the effect of heat accumulation tends to be non-linear. As a result, the standard agronomic approach involves converting daily temperatures into degree days, which represent heating units accounting for such non-linearities. Accordingly, Deschenes and Greenestone (2007) employ temperatures measured in terms of growing degree days in their analysis as a better way of accounting for some of the non-linearity between temperature and plant growth. Similarly, Schlenker and Roberts (2006; 2009) argue that the use of monthly average temperature can hide extreme temperatures that occur even during a fraction of a day and suggest a fine-scale weather measurement to help identify non-linear effects across scale and over time.

In this paper, the approach to assess the links between climate change and agriculture differs in two major ways from the previous approaches discussed above. First, we argue that not just climate change but also weather variability leads to a significant level of adaptation at the farm level, implying that weather-related measures capture adaptation that is possibly different from that captured by long term climate-related measures in Ricardian analyses. Indeed, there is a wealth of evidence, particularly from developing countries, showing that weather variability

² Farmers can do a great deal to adapt to changes in climate. For example, they can adjust which crops to plant (Kurukulasuriya and Mendelsohn 2008; Seo and Mendelsohn 2008a) and which livestock to raise (Seo and Mendelsohn 2008b; Massetti and Mendelshon 2011).

could lead to non-negligible changes in farming practices, as a form of adaptation. In line with this, Burgess et al. (2013) show that weather fluctuations have a profound effect on the health and mortality of India's rural population, through their effect on agricultural production. As adaptation is implicitly an important feature of the Ricardian approach (Maseti and Mendelsohn 2011), omission of the shorter term impacts implies that the approach would fail to account for the full range of farmer adaptations.³

Second, the use of both short and long term measures would benefit from disaggregation across different temperature values. Hence, we use disaggregated measures not only for weather values but also for long term climate-related values. Accordingly, our approach follows Schlenker and Roberts (2006; 2009) in incorporating the distribution of temperature outcomes in a flexible way. Furthermore, unlike many climate change studies that have focused on estimating the impact of either temperature or precipitation in isolation, we combine both measures in our analysis. As argued in Auffhammer et al. (2013), such an approach is crucial in order to obtain unbiased estimates of the effects of changes in precipitation and temperature; because these two variables are historically correlated, both must be included in the regression equation, especially if the correlation is predicted to change in the future.

Our analysis builds on the growing trend of using panel data to analyse links between climate change and agriculture. This approach addresses concerns with the cross-sectional Ricardian analyses and the significant problems associated with omitted variables bias. In a significant deviation from earlier cross-sectional approaches, Deschenes and Greenstone (2007) assess the link between agricultural profits and climate change using year-to-year weather variations and controlling for county fixed effects and state-year interactions. While the use of panel data analysis is a significant improvement over previous analyses, Fisher et al. (2012) argue that the approach by Deschenes and Greenstone (2007) does not control for time-varying omitted variables which may be quite highly correlated with weather shocks and, therefore, may

³ This distinction between short term and long term climate measures is highly relevant in a setting like Ethiopia, where both seasonal and yearly variations in rainfall are significant, rainfall is hugely erratic and weather insurance mechanisms are virtually nonexistent (Dercon et al. 2009), leaving considerable room for weather-related adaptations.

measure something different from the impact of climate on long-run profit. In line with this, Massetti and Mendelsohn (2011) estimate the Ricardian model by interacting climate variables with year dummies in order to allow the climate coefficients to change over time. These are compared with a two stage estimation in which land value is regressed on the time-varying variables using the covariance method with county fixed effects, followed by a regression of the time-mean residuals on the time invariant variables.

Hence, the major departure of our approach lies in the use of long term climate measures along with short term weather measures, while at the same time controlling for unobserved heterogeneity using data from a four-wave survey conducted in Ethiopia between the years 1999 and 2007. Plot level panel data from Ethiopia combined with 30-year monthly rainfall and temperature data are employed in the analysis. Long term mean measures are used as climate variables, while the weather variables were constructed as averages for the years corresponding to the survey years. We also exploit the multi-plot characteristics of the individual farms in our study, which provides us with the opportunity to assess links between climate change at both crop level and farm level. This enables us to identify differences between crop and farm level adaptation, if any.

The rest of the paper is organized as follows. The next section presents an overview of the importance of climate change and weather uncertainty in Ethiopia. Next, the data employed in the empirical analysis is presented. The econometric methodology employed is discussed in the section that follows. The empirical findings are then discussed, and the last section concludes the paper.

Weather Variability, Climate Change and Agricultural Productivity in Ethiopia: Background

Agriculture remains one of the most important sectors in the Ethiopian economy for the following reasons: (i) it directly supports about 83% of the population in terms of employment and livelihood; (ii) it contributes over 40% of the country's gross domestic product (GDP); (iii) it generates about 85% of export earnings; and (iv) it supplies around 73% of the raw material requirements of agro-based domestic industries, such as biofuels (MEDaC 1999; AfDB 2011). It is also the major source of food for the population and hence the most important sector for food

security. In addition, agriculture is expected to play a key role in generating surplus capital to speed up the country's overall socioeconomic development (MEDaC 1999).

Ethiopia has a population of over 80 million, with a population growth rate of about 2.6% (AfDB 2011). The country has a total land area of about 112.3 million hectares. Of this, about 16.4 million hectares are suitable for producing annual and perennial crops. Of the estimated arable land, about eight million hectares are used annually for rainfed crops. Small-scale farmers who are dependent on rainfed mixed farming dominate the agricultural sector; they use traditional technologies with low inputs and get low output. The present government of Ethiopia has given top priority to this sector and has taken steps to increase its productivity. However, various problems are holding this back. The causes of poor crop production include declining farm size; subsistence farming, partly due to population growth; land degradation due to inappropriate land use such as cultivation of steep slopes; over-cultivation and overgrazing; and inappropriate policies. Other causes are tenure insecurity; weak agricultural research and extension services; lack of appropriate agricultural marketing; an inadequate transport network; low use of fertilizers, improved seeds and pesticides; and the use of traditional farm implements. However, the major causes of low levels of production are drought, which often causes famine, and floods. These climate-related disasters make the nation dependent on food aid.

With agriculture almost completely dependent on rainfall, rain rules the lives and well-being of many rural Ethiopians. It determines whether they will have enough to eat and whether they will be able to provide basic necessities and earn a living. Indeed, the dependence on rainfall and its erratic pattern has contributed greatly to the food shortages and crop crises that farmers constantly face. Even in good years, the one-time harvest or crop may be too little to meet the yearly household needs; as a result, the majority of Ethiopia's rural people remain food insecure (Devereux 2000.)⁴

⁴ Ethiopia has experienced at least five major national droughts since 1980, along with dozens of localized ones (World Bank 2008b). These cycles of drought create poverty traps for many households, constantly consuming any build-up of assets or increase in income. Evidence shows that about half of all rural households in the country experienced at least one major drought during the five years preceding 2004 (Dercon 2009). The evidence also suggests that these shocks are a major cause of transient poverty. That is, had Ethiopian households been able to

Rainfall contributes to poverty both directly, through actual losses from rainfall shocks, and indirectly, through responses to the threat of crisis. The direct impacts most often occur when a drought destroys a smallholder farmer's crops. Under such circumstances, not only will the farmers and their families go hungry, but they also will be forced to sell or consume their plough animals in order to survive. They are then significantly worse off than before, because they can no longer farm effectively when the rains return (Barrett et al. 2007).

Data and Variables

Data used in the analysis were collected through four waves of rural household surveys conducted in the years 2000, 2002, 2005 and 2007 with the same households. The surveys were conducted by the Ethiopian Development Research Institute and Addis Ababa University, in collaboration with Gothenburg University, and through financial support from the Swedish International Development Cooperation Agency (Sida). The survey sites include households in two zones (South Wollo and East Gojjam) of the Amhara National Regional State, a region that encompasses part of the Northern and Central Highlands of Ethiopia. Figure 1 shows the study area.

Monthly rainfall and daily temperature data were obtained from the Ethiopian Meteorology Authority, in eight stations close to the study villages (*kebeles*) for the years 1976 to 2006. In order to impute farm-specific information from station level observations, an inverse distance weighting interpolation method was employed. This method combines latitude, longitude, and station level rainfall and temperature observations. The climate change and weather measures used in the analysis are then constructed from these rainfall and temperature data.⁵

smooth consumption over drought and non-drought periods, then poverty in 2004 would have been at least 14 percent lower, which translates into 11 million fewer people falling below the poverty line.

⁵ There are two instances where the assessment of weather as a separate variable may not be important. First, to the extent that weather variability is stable over time, it may also mimic climate change, making the impact of climate change on agricultural productivity akin to that of weather variability. Second, if mechanisms are in place to insure against weather risks, then farmers are unlikely to incorporate much of the impact of weather variability into their decision making.

Temperature and Rainfall Variables

Following Schlenker and Roberts (2006; 2009), we construct the distribution of temperature by first fitting a sinusoidal curve between predicted minimum and predicted maximum temperatures. This sinusoidal interpolation gives the time spent in each 1°C temperature interval between -5°C and +40°C within each day.⁶ Each of the 1°C intervals in the -5 to 40° Celsius range is then converted into a more aggregate distribution by summing together each three degree temperature interval. The length of time that each three degree Celsius temperature interval occurs each day is then summed across all days of the month, for each farm household.

Given the seasonality of rainfall and cropping patterns in Ethiopian agriculture, further aggregation of the temperature distribution is done for the minor and major rainy seasons, instead of considering an aggregate growing season, as in much of the literature.⁷ The spring (Belg) includes the months between March and May, while the summer (Kiremt) months are between June and September. Accordingly, spring temperature distribution is comprised of the total sum of the monthly values for each three degree interval over the spring months, and the summer temperature distribution will be the summation of the values over the spring months, corresponding to each survey year.

The long term seasonal temperature distribution is obtained by averaging the three degree range distribution over the 30 years, for each season. The seasonal rainfall measure is the sum total of monthly rainfall values for the months in the corresponding season, for each survey year.

Table 1 shows the frequency distribution of temperature variables corresponding to the survey years and over the long term. As expected, the pattern of temperature over the three degree ranges follows a bell-shaped distribution, with many of the days spent in the 10-30° ranges. This holds true for both yearly and long term mean distributions. What is striking, however, is the fact that the extreme ends of the distribution have unequal values for the short and long term mean temperature, highlighting the need to include the extreme long term

⁶ The determination of the maximum and minimum values of the range is based on our observed data.

⁷ In studies from the United States, the convention is to include the months of January, April, July, and October (see, e.g., Deschenes and Greenstone 2007; Schlenker et al. 2006).

temperature values in our analysis along with the short term (weather-based) temperature measures.⁸

Table 2 presents the descriptive statistics of the variables used in the regressions, including the relevant temperature and rainfall measures. As would be expected, the summer season, which is the wettest, receives average precipitation of 551 mm, while the average precipitation in the spring season is 334 mm.

Dependent Variables: Crop and Farm Level Revenues⁹

The crop production system consists of cereals, pulses, legumes, oil seeds and other crops, with a given farm typically growing different crop types, each on a single plot. As will be discussed in the next section, the analysis is conducted for both farm level and plot level revenues. Accordingly, plot level characteristics are used for the plot level analysis, while information aggregated from the plot level is used in the analysis of farm level characteristics. For the plot level analysis, two distinct categories are employed: one is small cereals, and the other is large cereals and pulses. Small cereals include white, red and mixed teff, wheat, barley and oats. Large cereals include maize, sorghum, millet, rice, horse beans, cow peas, soya beans, lentils, chick peas, vetch, haricot beans and fava beans. The reason for such a grouping is that crops in each group have a similar growing temperature range, as well as similar soil quality and land preparation requirements. As shown in Table 2, the overall farm revenue averages around Br.¹⁰ 3634 while revenue from small cereals and large cereals are Br. 340 and 260, respectively.

⁸ In order to highlight the significant differences across villages with respect to temperature, Appendices C and D present a t-test on the distribution of temperature values between a selected *kebele* (village), Amanuel, and all other kebeles. In addition, the presence of significant differences in access to infrastructure across kebeles is presented in Appendix B.

⁹ We follow many Ricardian studies in developing countries by using agricultural profit instead of land values. The use of land values in such analyses requires perfect operation of land markets, so that land prices reflect the present discounted value of land rents into the infinite future (Deschenes and Greenstone 2007). This condition does not hold in Ethiopia, as there is no information on prices for land sales due to full state ownership of the land (Di Falco et al. 2011).

¹⁰ Br. is a short form for the Ethiopian currency Birr, with an exchange rate of about 20 Br. per USD.

Socioeconomic and Physical Farm Characteristics

Around 18% of the surveyed households have a female head. The average age of the household head is 52. The proportion of household heads that are able to read and write is 56%. An average household has 1.98 male and 1.83 female adults of working age, indicating a gender balance between male and female labour availability. Livestock ownership, measured in tropical livestock units,¹¹ is around six per household, while the number of oxen owned by an average household is around two.

The average farm size is 1.60 ha, slightly higher than the national average of 1.1 ha. On average, 69% of the plots are flat, with moderately steep and steep plots making up the rest of the plots. In addition to topographic features, plots are defined by their soil colour, which is also a rough representation of other features such as water retention capacity and texture. An average of 40% of the plots per farm have black soil colour, while an average of 56% have red soil colour. The average proportion of fertile plots per household is 40%, while the average number of plots with moderately fertile and infertile soil types is 40% and 20%, respectively.

Estimation Procedure

This section sets up a framework for analyzing the link between crop specific (or total farm) revenue on the one hand, and weather and climate variables on the other. We frame our analysis following the approach by Schlenker and Roberts (2006; 2009), which maps an entire season of temperature distribution to each year's yield, through the construction of temperature values, each depicting the number of hours/days spent in each three degree range over a growing season. This approach is extended to simultaneously incorporate both weather and climate measures as determinants of crop-specific and farm level revenue, as presented in equation 1.

As Schlenker and Roberts (2006; 2009) argue, the essence of constructing such fine-scale weather data is to facilitate estimation of a flexible model that can detect non-linearities

¹¹ Tropical livestock unit is a common unit to describe livestock numbers of various species as a single figure that expresses the total amount of livestock present – irrespective of the specific composition.

and breakpoints in the effect of temperature on yield. Indeed, a potentially non-linear relationship between yield and temperature could be mis-specified if the temperature measure is averaged over time or space, diluting the true temperature response in the process.

Accordingly, the estimated relationship between a crop revenue and temperature and rainfall is given by:

$$y_{iht} = \delta_{iht} + \beta x_{iht} + \sum_{j=1}^n \gamma_j r_{hjt} + \sum_{k=1}^m \mu_j S_{hk} + \vartheta w_{hit} + \varepsilon_{iht} \quad (1)$$

where iht denotes the i^{th} crop in farm household h in period t .¹² Revenue from the i^{th} crop of farm household h at year t is denoted by y_{iht} . r_{hjt} represents the time spent in each degree range j over a growing season for each household h at year t , while S_{hk} represents the time spent in each of the extreme degree ranges k over a growing season for each household h over a 30 year period. The seasonal rainfall measures are represented by w_{hit} , while x_{iht} are the socioeconomic and physical farm characteristic variables. The coefficients δ , β , γ , μ and ϑ represent the respective vector of parameter estimates, and ε_{ht} represents the error term. The composite error term $\varepsilon_{iht} = \alpha_{ih} + u_{iht}$ is composed of a normally distributed random error term, $u_{iht} \sim N(0, \sigma_u^2)$, and an unobserved household specific effect, α_{ih} .

Under the assumption that α_{ih} is orthogonal to the observable covariates, a random effects estimator can be employed as an effective estimator (Baltagi 2001; Wooldridge 2002). However, allowing arbitrary correlation between α_{ih} and the regressors/observed covariates requires a fixed effect, as it takes α_{ih} to be a group-specific constant term and uses a transformation to remove this effect prior to estimation (Wooldridge 2002).

The alternative approach of the random effects estimator has a specification similar to the fixed effects estimator, with the additional requirement of no correlation between the fixed effect α_{ih} and the regressors/observed covariates (Baltagi 2001). Despite this shortcoming, however, the random effects estimator does not rely on the data transformation in the fixed effects estimator and thus is not affected by the associated shortcoming of removing any time-constant

¹² The same structure applies for farm level analysis, which is an aggregation of the crop-specific analysis at a farm level.

explanatory variables along with α_{ih} (Wooldridge 2001). However, the random effects specification assumes exogeneity of all the regressors and the random individual effects. As long as the assumption of no correlation between the regressors and individual effects is satisfied, the random effects estimator guarantees a consistent and efficient estimator (Baltagi 2001; Mundlak 1978).¹³

To remedy the major drawback of removing the household-specific effects of the fixed effects estimator, we employ Mundlak's pseudo-fixed effects estimation approach (Wooldridge 2002). The approach involves explicitly modeling the relationship between time-varying regressors and the unobservable effect in an auxiliary regression (Mundlak 1978).

In particular, α_{ih} can be approximated by its linear projection onto the observed explanatory variables:

$$\alpha_{ih} = \omega Z_{iht} + v_{iht} \quad (2)$$

where v_{iht} represents the random error term and Z_{iht} is a vector of all the time-varying regressors in equation (2). Averaging over t for a given observational unit h and substituting the resulting expression into equation (1) gives:

$$y_{iht} = \delta_{iht} + \beta x_{iht} + \sum_{j=1}^n \gamma_j r_{hjt} + \sum_{k=1}^m \mu_j S_{hk} + \vartheta w_{hit} + \omega \bar{Z}_{ih} + U_{iht} \quad (3)$$

Discussion of Results

Table 3 presents the estimation results of the determinants of revenue corresponding to small cereals. In the first panel of Table 3, we present the results based on summer temperature measures. In the second panel, the results from the spring temperature measures are presented. In each of the panels, the first column presents the regression results based on short term temperature measures. The succeeding columns gradually add long term temperature measures,

¹³ The standard test for this is the Hausman test with the null hypothesis that there is no significant difference between the coefficients of the fixed and random effects estimators (Wooldridge 2002).

rainfall measures, physical farm characteristics, and finally socioeconomic characteristics. While the results reported in the earlier columns are added as robustness checks, discussion of the results is based on the last column in each panel, where all these variables are controlled for.

Analysis of the impact of the short term summer temperature on revenue from cereal crops shows statistically significant and positive impacts of almost all the categories of temperature. However, for long term temperature measures, both the lower ($<3^{\circ}$ Celsius) and upper ($>37^{\circ}$ Celsius) coefficients show strongly significant and negative impacts on the small cereal revenue. This result is in line with Schlenker and Roberts (2006; 2009), who find similar non-linear impacts of temperature on yield.¹⁴ These results generally hold when using or dropping other controls, such as physical farm characteristics, socioeconomic characteristics and rainfall, indicating the robustness the temperature results, which is the main focus of our analysis.

Summer rainfall is found to have no significant effect on the average small cereal revenue. Of the soil characteristics, plot size appears to be the most significant determinant of cereal revenue, while other characteristics such as plot slope, soil color and fertility are insignificant. This could be due to the possible correlation of plot size and other desirable physical farm characteristics. Number of oxen has a positive and significant impact on small cereal revenue, indicating the importance of the lack of oxen ownership as a major constraint to productivity. Education has a reasonably significant impact on agricultural revenues of cereal crops. The effect of the number of male adults and female adults is positive and significant, with the female adult labor availability having a smaller impact in terms of magnitude. This indicates that male labor availability is a binding constraint to agricultural productivity, at least for small cereals. Land size has a negative and significant impact on crop revenues, conforming to the inverse farm size-productivity relationships found in other studies.

The second panel of Table 3 presents an analysis of the determinants of cereal crop revenues based on spring season temperature. The results show that the impacts of short term

¹⁴ Burgess et al. (2013) also find similar patterns of temperature on mortality in India.

spring temperature, while generally significant, are not consistently positive. Values corresponding to the extreme ends in the distribution of long term temperature values for the spring season are insignificant. In comparison with the impacts of short term summer temperature (discussed above), this indicates that short term spring temperature has a less consistent impact on revenue from small cereals. Average spring rainfall (short term) has a positive and significant impact. While surprising given the insignificance of the major (summer) season rainfall, this result is in line with the agronomic characteristics of many small cereals. Such crops are susceptible to waterlogging and drought in the early stages of their growth (spring season), and are water-intensive in the later stages of their growth (summer season), when moisture is generally relatively abundant. The impacts of the physical and socioeconomic characteristics are similar in the alternative (summer and spring temperature) analyses.

Table 4 presents the analysis of the impact of temperature on the revenues of large cereals and pulses. The effects of the different ranges of short term summer temperature measures during the summer season are shown to be minimal. However, the extreme temperature values are found to have a significantly negative and large impact. The short term spring temperatures are shown to have a consistently positive and significant impact for all the temperature ranges. The long term temperature measures corresponding to the extreme ends of the spring temperature distribution also show significant and negative impacts. In line with Schlenker and Roberts (2009), the results show that the extreme ends of the temperature distribution are always harmful for crop growth, irrespective of the type of crop. The results corresponding to precipitation show insignificant impacts both in the summer and spring seasons. While the patterns of the impact of physical farm characteristics and socioeconomic characteristics are largely identical across the two crop categories, the impact of adult female labour is not significant in the large cereal and pulses category. This could be due to the fact that the small cereals are susceptible to weeds; because pulling weeds is largely a female labour task, the availability of female labour is more critical in the case of small cereal crops.

The results from the farm level analysis are presented in Table 5. The results indicate that short term summer temperature is a much less important determinant of farm level revenue compared to spring temperature, which has a consistently positive and significant impact. The extreme values of long term temperature, both in the summer and spring seasons, have strongly

negative effects. It should be noted that these effects of extreme temperature are replicated for the different crop categories too. The average of summer precipitation has no effect, while the average of spring rainfall has a significant and positive effect, indicating that spring rainfall has an important and positive effect on overall farm level revenue, while the crop-specific effects of rainfall are generally much weaker across crops or seasons. The effects of the physical farm characteristics and socioeconomic characteristics remain similar to those of the crop-specific analyses.

Conclusions

A large body of literature demonstrates negative impacts of climate change on the agricultural sector. In particular, as climate change is likely to intensify high temperature and low precipitation, its most dramatic impacts will be felt by smallholder and subsistence farmers suffering the brunt of the effects (Mendelsohn et al. 2004). In this study, we examine the possible impacts of climate change based on data from Ethiopia, a rain-fed agrarian economy with notorious fluctuations in weather and frequent drought. This paper emphasizes the importance of simultaneously considering the impacts of weather and climate in such settings, because focusing on either measure may leave out the distinct effects of each of the measures.

Accordingly, we assessed the importance of weather and climate variables on agricultural revenues using plot level panel data from the Amhara Region of Ethiopia. This is combined with 30-year meteorological data corresponding to survey villages, interpolated at an individual farm level. The analysis employs 14 temperature categories related to short term (weather) measures and four categories corresponding with the extreme ends of the long term temperature distribution (climate measures). The analysis distinguishes between summer and spring seasons and different crops in recognition of Ethiopia's multi-cropping and multi-season agriculture.

The major findings of the analysis can be summarized in three ways. First, temperature effects are distinctly non-linear, with extreme temperature values having consistently negative effects across seasons and crop types. In this respect, our finding is similar to previous studies that registered as significant the non-linear impacts of temperature, using weather variables. However, the fact that non-linearity is consistently detected in the extreme ends of the distribution of long term temperature values points to the importance of simultaneously

analysing the impacts of weather and climate measures to detect such distinctions. Second, the impact of temperature varies drastically across crops and across seasons for a single crop. This result highlights the potentially heterogeneous impacts of climate change even within a farm and a given year, indicating the need for understanding such complexities in the design of crop insurance and climate change policies. Third, rainfall generally has a less important role to play than temperature, contrary to expectations for rainfed agriculture.

In sum, given the general tendency of previous related studies to focus on either long term or short term measures of temperature and rainfall, this study takes an important stride in simultaneously incorporating short term and long term temperature patterns. Indeed, our analysis shows significant responsiveness of agricultural productivity to both weather variability and climate change. Given the multi-cropping nature of our farming system, however, a number of crop types are lumped into one category. Future studies that look into the simultaneous impacts of weather and climate change on individual crops would more accurately illuminate our understanding of the underlying relationships. We may note, however, that, to the extent that the pattern of climate change mimics weather uncertainty, policy measures aimed at mitigating the impacts of climate change could serve the same purpose for weather uncertainty. From a policy perspective, the results highlight the need to factor in the distinction between crops and seasons in designing yield insurance measures. In addition, insurance schemes also need to look into specific measures that target extreme values.

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Figure 1. A map of the study zones in the Amhara Region



Table 1. Descriptive statistics of variables used in the regression

year	1999.000	2001.000	2004.000	2006.000	long term average
temperature (<1°C)	0.000	0.000	0.000	0.000	0.001
temperature (1°C-3°C)	7.164	7.322	6.228	7.651	7.829
temperature (4°C-6°C)	1.462	0.728	0.672	3.440	1.660
temperature (7°C-9°C)	7.044	6.276	6.207	8.850	6.831
temperature (10°C-12°C)	26.954	24.991	23.183	26.581	25.555
temperature (13°C-15°C)	66.334	69.827	63.783	66.728	66.941
temperature (16°C-18°C)	60.564	60.020	60.115	61.337	60.035
temperature (19°C-21°C)	53.995	54.514	50.707	52.866	53.346
temperature (22°C-24°C)	58.734	61.040	58.674	58.710	59.584
temperature (25°C-27°C)	51.842	54.347	55.288	50.888	53.567
temperature (28°C-30°C)	23.397	19.909	31.076	21.957	22.083
temperature (31°C-33°C)	2.817	1.269	4.276	1.637	3.174
temperature (34°C-36°C)	0.054	0.000	0.018	0.001	0.108
temperature (>=37°C)	0.000	0.000	0.000	0.000	0.007

Table 2. Descriptive statistics of variables used in the regression

Variable name	Variable Description	Mean	Std. Dev.
<i>Rainfall and Temperature* Variables</i>			
average summer rainfall	the mean summer rainfall corresponding to the survey year (mm)	551.402	226.3119
average spring rainfall	the mean spring rainfall corresponding to the survey year	390.4621	216.9102
temperature (<1°C)	the number of hours spent in the <1°C range in a given season	0.000	0.000
temperature (1°C-3°C)	the number of hours spent in the 1°C-3°C range in a given season	25.043	10.040
temperature (4°C-6°C)	the number of hours spent in the <1°C range in a given season	1.864	15.334
temperature (7°C-9°C)	the number of hours spent in the 7°C-9°C range in a given season	17.481	58.099
temperature (10°C-12°C)	the number of hours spent in the 10°C-12°C range in a given season	67.792	106.927
temperature (13°C-15°C)	the number of hours spent in the 13°C-15°C range in a given season	418.991	223.938
temperature (16°C-18°C)	the number of hours spent in the 16°C-18°C range in a given season	463.192	83.662
temperature (19°C-21°C)	the number of hours spent in the 19°C-21°C range in a given season	423.698	142.825
temperature (22°C-24°C)	the number of hours spent in the 22°C-24°C range in a given season	346.042	112.055
temperature (25°C-27°C)	the number of hours spent in the 25°C-27°C range in a given season	230.138	213.730
temperature (28°C-30°C)	the number of hours spent in the 28°C-30°C range in a given season	111.072	139.199
temperature (31°C-33°C)	the number of hours spent in the 31°C-33°C range in a given season	22.737	41.205

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temperature (34°C-36°C)	the number of hours spent in the 34°C-36°C range in a given season	0.257	1.414
temperature (>=37°C)	the number of hours spent in the >=37°C range in a given season	0.000	0.000
long term temperature (<1°C)	the number of hours spent in the <1°C range in a given season over a 30 year period	0.000	0.000
long term temperature (1°C-3°C)	the number of hours spent in the 1°C-3°C range in a given season over a 30 year period	25.373	3.957
long term temperature (34°C-36°C)	the number of hours spent in the 34°C-36°C range in a given season over a 30 year period	0.253	0.534
long term temperature (>=37°C)	the number of hours spent in the >=37°C range in a given season over a 30 year period	0.098	0.113

Physical farm characteristics

temperature (31°C-33°C)	plot size	0.271529	0.244013
temperature (34°C-36°C)	plot flat slope (1=yes ; 0=otherwise)	0.696406	0.459821
temperature (>=37°C)	plot steep slope (1=yes ; 0=otherwise)	0.037267	0.189421
soil slope:medium	plot medium slope (1=yes ; 0=otherwise)	2.58E-01	4.38E-01
soil quality of parcel:lem	plot highly fertile (1=yes ; 0=otherwise)	0.419801	0.493539
soil quality of parcel: lem-tef	plot moderately fertile (1=yes ; 0=otherwise)	0.393605	0.488561
soil quality of parcel: tef	plot highly infertile (1=yes ; 0=otherwise)	0.18373	0.387274
soil type (color) of parcel:black	plot black (1=yes ; 0=otherwise)	0.399212	0.489749
soil type (color) of parcel:red	plot red (1=yes ; 0=otherwise)	0.533937	0.49886
soil type (color) of parcel:white	plot white (1=yes ; 0=otherwise)	0.016828	0.128629

Socioeconomic characteristics

number of oxen	The number of oxen	2.128773	1.376499
sex of household head	Sex of the household head	0.183228	0.386863

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age of household head	Age of household head	52.2738	16.39595
household head literate	Head's formal education (1=read and write ; 0=otherwise)	0.562399	0.496104
number of male adults in household	The number of male working-age family member of the household	1.97723	1.184656
number of female adults in household	The number of female working-age family member of the household	1.825399	1.013283
Total land area by hh	Total farm size of the household in hectares	1.59883	1.08573
<i>Dependent variables</i>			
Crop revenue (small cereals)	Revenue from small cereal crops grown by the household	340.5678	9176.328
Crop revenue (large cereals and pulses)	Revenue from large cereal and pulse crops grown by the household	260.4774	289.3356
Farm revenue	The sum of all revenues from the different crops grown by the household	3634.352	3006.27

* Temperature variables given in the table correspond to summer season measures.

Table 3. Pseudo-fixed effects estimation of the impacts of climate change and weather on crop level revenue (teff crop)**

	Analysis based on summer temperature					Analysis based on spring temperature				
	teff1	teff2	teff3	teff4	teff5	teff1	teff2	teff3	teff4	teff5
temperature (1°C-3°C)	0.478 (0.920)	0.451 (0.972)	2.606** (1.241)	2.220* (1.189)	3.034*** (1.169)	9.911*** (3.474)	9.482*** (3.543)	9.324*** (3.537)	10.235*** (3.376)	6.789** (3.277)
temperature (4°C-6°C)	-0.125 (0.556)	0.436 (0.589)	5.374*** (1.852)	3.586** (1.797)	3.331* (1.755)	-7.410*** (2.287)	-7.837*** (2.302)	.	.	-4.887** (2.305)
temperature (7°C-9°C)	0.307*** (0.085)	0.293*** (0.086)	6.449*** (2.197)	4.544** (2.124)	4.644** (2.081)	2.230*** (0.196)	0.785*** (0.280)	8.356*** (2.303)	9.325*** (2.199)	2.509*** (0.940)
temperature (10°C-12°C)	-0.138** (0.065)	0.023 (0.073)	6.121*** (2.178)	4.174** (2.106)	4.367** (2.061)	-2.407*** (0.135)	-1.413*** (0.193)	6.189*** (2.288)	6.764*** (2.184)	-0.308 (1.087)
temperature (13°C-15°C)	0.386*** (0.067)	0.453*** (0.074)	6.603*** (2.191)	4.508** (2.118)	4.697** (2.074)	1.131*** (0.107)	1.108*** (0.109)	8.697*** (2.244)	9.070*** (2.142)	2.138** (1.049)
temperature (16°C-18°C)	0.359** (0.145)	0.364** (0.152)	6.649*** (2.245)	4.270** (2.170)	4.466** (2.127)	-1.592*** (0.287)	-0.934*** (0.301)	6.728*** (2.210)	7.844*** (2.111)	0.925 (1.125)
temperature (19°C-21°C)	-0.591*** (0.101)	-0.345*** (0.105)	5.616*** (2.136)	3.749* (2.067)	3.969** (2.023)	5.055*** (0.283)	4.014*** (0.322)	11.368*** (2.309)	10.876*** (2.205)	4.210*** (0.973)
temperature (22°C-24°C)	0.049 (0.066)	0.073 (0.066)	6.157*** (2.169)	4.241** (2.098)	4.535** (2.054)	-3.448*** (0.252)	-3.567*** (0.258)	4.007* (2.289)	4.788** (2.185)	-1.960* (1.016)
temperature (25°C-27°C)	-0.253*** (0.074)	0.204** (0.097)	6.218*** (2.149)	4.291** (2.079)	4.390** (2.035)	0.18 (0.147)	0.299* (0.153)	7.848*** (2.304)	7.923*** (2.199)	0.998 (1.045)
temperature (28°C-30°C)	-0.884*** (0.124)	-0.383** (0.155)	5.638*** (2.155)	3.705* (2.085)	4.082** (2.041)	-0.244** (0.097)	-0.387*** (0.106)	7.136*** (2.276)	7.428*** (2.172)	0.602 (1.003)
temperature (31°C-33°C)	1.686*** (0.271)	1.410*** (0.333)	7.514*** (2.198)	5.819*** (2.123)	5.851*** (2.081)	-1.689*** (0.103)	-1.527*** (0.105)	6.095*** (2.262)	6.784*** (2.160)	-0.066 (1.066)
temperature (34°C-36°C)	-9.151*** (2.625)	-13.106*** (2.924)	-8.257** (3.389)	-0.488 (3.273)	-3.615 (3.191)	-0.208 (0.928)	-2.100* (1.090)	5.111** (2.472)	8.446*** (2.365)	.
long term temperature (1°C-3°C)		-8.383***	-8.489***	-7.634***	-8.567***		-2.249	-1.653	-2.48	2.659

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	(1.792)	(1.792)	(1.753)	(1.721)	(1.820)	(1.831)	-(1.799)	(1.746)	
long term temperature (34°C-36°C)	53.039***	67.474***	20.797	18.708	24.074***	20.357***	20.081***	24.197***	
	(17.639)	(18.314)	(17.689)	(17.208)	(4.893)	(4.996)	(4.797)	(4.752)	
long term temperature (>=37°C)	-1033.7***	-947.9***	-862.76***	-899.754***	-90.588	-22.825	-27.735	-56.803	
	(181.076)	(184.653)	(178.154)	(175.909)	(117.285)	(118.468)	(113.492)	(111.273)	
average summer rainfall		-0.028	-0.009	-0.005		0.075***	0.071***	0.044*	
		(0.021)	(0.020)	(0.020)		(0.026)	(0.025)	(0.025)	
Plot size in hectares: calculated			439.07***	461.939***			453.264***	468.2***	
			(13.871)	(15.035)			(13.952)	(15.108)	
number of oxen				23.416***				25.693***	
				(2.915)				(2.918)	
sex of household head				-10.682				-16.186*	
				(9.432)				(9.460)	
age of household head				-0.199				-0.279	
				(0.242)				(0.243)	
household head illiterate				-12.198*				-15.473**	
				(7.226)				(7.265)	
number of male adults in household				24.677***				26.693***	
				(6.879)				(6.914)	
number of female adults in household				10.698***				14.32***	
				(3.635)				(3.637)	
Total land area by hh				-46.175***				-41.88***	
				(4.668)				(4.759)	
Constant	346.3***	352.8***	-12700***	-8241.7*	-8715.2**	407.3***	400.6***	-15800***	-16500***
	(23.726)	(23.768)	(4674.814)	(4521.533)	(4427.999)	(23.725)	(23.846)	(4908.254)	(4685.665)
Year Dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES
Mundlak's fixed effects	NO	NO	NO	NO	YES	NO	NO	NO	NO
Adjusted R-sq	0.1446	0.15	0.153	0.2342	0.2642	0.135	0.1394	0.1425	0.2281
N	10620	10620	10405	10402	9953	10620	10620	10405	10258

Table 4. Pseudo-fixed effects estimation of the impacts of climate change and weather on farm level revenue (all crops)

	Analysis based on summer temperature					Analysis based on spring temperature				
	pulses1	pulses2	pulses3	pulses4	pulses5	pulses1	pulses2	pulses3	pulses4	pulses5
temperature (1°C-3°C)	-2.222** (1.009)	-0.433 (1.054)	0.908 (1.296)	-0.103 (1.233)	0.604 (1.187)	16.956*** (3.291)	13.123*** (3.401)	13.148*** (3.404)	12.359*** (3.224)	6.656** (3.186)
temperature (4°C-6°C)	1.390** (0.605)	0.313 (0.638)	4.888** (2.426)	1.194 (2.410)	3.072 (2.366)	-10.983*** (2.147)	-9.556*** (2.170)	.	-9.385*** (2.368)	.
temperature (7°C-9°C)	0.328*** (0.099)	0.135 (0.101)	5.440** (2.767)	1.254 (2.730)	3.318 (2.674)	0.017 (0.202)	-0.577* (0.323)	8.979*** (2.186)	-0.624 (1.232)	4.625** (2.056)
temperature (10°C-12°C)	0.083 (0.062)	0.027 (0.074)	5.229* (2.725)	0.979 (2.689)	3.139 (2.632)	-0.946*** (0.131)	-0.091 (0.220)	9.552*** (2.169)	-0.342 (1.408)	5.617*** (2.033)
temperature (13°C-15°C)	0.324*** (0.077)	0.161* (0.085)	5.422** (2.738)	1.04 (2.700)	3.118 (2.643)	0.815*** (0.113)	0.645*** (0.118)	10.227*** (2.124)	0.213 (1.357)	6.073*** (1.990)
temperature (16°C-18°C)	-0.534*** (0.179)	-0.877*** (0.186)	4.477 (2.796)	0.269 (2.752)	2.281 (2.697)	1.237*** (0.313)	1.214*** (0.343)	10.877*** (2.078)	0.996 (1.444)	7.302*** (1.936)
temperature (19°C-21°C)	0.368*** (0.123)	0.676*** (0.131)	5.788** (2.710)	1.507 (2.679)	3.734 (2.620)	0.03 (0.304)	-0.342 (0.381)	9.176*** (2.208)	-0.998 (1.254)	4.500** (2.079)
temperature (22°C-24°C)	-0.279*** (0.075)	-0.284*** (0.075)	4.908* (2.719)	0.725 (2.684)	2.949 (2.627)	-1.534*** (0.233)	-1.068*** (0.263)	8.547*** (2.148)	-1.351 (1.312)	4.483** (2.014)
temperature (25°C-27°C)	0.841*** (0.088)	1.236*** (0.103)	6.414** (2.716)	1.947 (2.684)	3.972 (2.624)	-0.891*** (0.150)	-0.559*** (0.169)	9.043*** (2.198)	-0.921 (1.371)	4.748** (2.065)
temperature (28°C-30°C)	-1.072*** (0.132)	-0.208 (0.166)	4.870* (2.696)	0.679 (2.659)	2.705 (2.596)	-1.103*** (0.108)	-0.852*** (0.122)	8.723*** (2.152)	-1.159 (1.319)	4.542** (2.020)
temperature (31°C-33°C)	1.169*** (0.291)	0.867** (0.350)	6.214** (2.764)	1.89 (2.726)	3.576 (2.660)	-0.533*** (0.117)	-0.279** (0.126)	9.340*** (2.141)	-0.602 (1.384)	5.287*** (2.005)
temperature (34°C-36°C)	0.573 (3.000)	2.911 (3.324)	6.719* (3.824)	7.964** (3.698)	6.672* (3.558)	-1.766 (1.196)	-1.059 (1.410)	8.404*** (2.496)	.	3.941* (2.352)
long term temperature (1°C-3°C)		2.02	1.71	1.226	-0.655		-6.870**	-6.831**	-4.676	-6.454**

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		(2.129)	(2.130)	(2.067)	(2.051)		(3.019)	(3.043)	(3.055)	(2.980)
long term	temperature (34°C-36°C)	-34.270**	-23.254	-47.411***	-17.84		37.547***	38.150***	33.473***	42.606***
		(14.399)	(15.478)	(14.919)	(15.974)		(5.475)	(5.654)	(5.387)	(5.337)
long term	temperature (>=37°C)	-1469.385***	-1372.403***	-1176.376***	-834.142***		-702.116***	-703.094***	-601.433***	-618.454***
		(174.656)	(179.025)	(172.458)	(175.712)		(122.400)	(123.846)	(117.806)	(114.702)
average	rainfall		-0.056**	-0.036	-0.036*			0.001	0.023	0.007
			(0.023)	(0.022)	(0.022)			(0.027)	(0.026)	(0.026)
Plot size in hectares: calculated				365.487***	398.762***				384.751***	419.050***
				(13.119)	(14.321)				(13.203)	(14.447)
number of oxen					19.469***					20.053***
					(3.008)					(3.054)
sex of household head					-26.080***					-29.605***
					(9.014)					(9.125)
age of household head					-0.178					-0.272
					(0.240)					(0.243)
household head illiterate					-6.861					-10.972
					(7.236)					(7.337)
number of male adults in household					13.579**					14.587**
					(6.834)					(6.927)
number of female adults in household					2.558					3.254
					(3.475)					(3.513)
Total land area by hh					-41.852***					-43.552***
					(4.544)					(4.667)
Constant	103.546***	150.813***	-0.000018*	-1807.087	-6407.055	246.699***	220.234***	0.00002	934.801	-1.14e+04***
	(30.151)	(30.570)	(5863.083)	(5785.979)	(5662.435)	(31.277)	(31.675)	(4637.465)	(2877.447)	(4345.801)
Year Dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Mundlak's fixed effects	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
Chi-squared	0.1183	0.1276	0.1306	0.2172	0.2667	0.1353	0.1498	0.1536	0.2244	0.2252
N	7247	7247	7153	7093	6294	7247	7247	7153	7093	6294

Appendices

Appendix A. Pseudo-fixed effects estimation of the impacts of climate change and weather variability for all crops

	all_crops1	all_crops2	all_crops3	all_crops4	all_crops5	all_crops1	all_crops2	all_crops3	all_crops4	all_crops5
temperature (1°C-3°C)	-17.729*	-7.799	-0.736	-3.37	0.561	117.167***	108.439***	68.883*	65.34	36.616
	(9.873)	(10.311)	(15.007)	(14.893)	(13.194)	(38.891)	(40.091)	(41.703)	(41.253)	(37.041)
temperature (4°C-6°C)	9.444	1.89	17.593	8.488	22.11	-86.487***	-100.156***	-19.738	.	6.128
	(6.404)	(6.677)	(21.787)	(21.656)	(19.362)	(25.298)	(25.724)	(28.565)	.	(25.492)
temperature (7°C-9°C)	5.934***	4.871***	18.48	8.366	20.486	20.639***	1.324	53.922***	72.118***	55.824***
	(0.947)	(0.945)	(26.030)	(25.877)	(23.138)	(2.200)	(2.793)	(11.659)	(26.586)	(10.186)
temperature (10°C-12°C)	0.613	-0.164	16.102	5.41	16.086	-27.082***	-12.737***	52.149***	69.352***	50.025***
	(0.644)	(0.734)	(25.731)	(25.580)	(22.849)	(1.276)	(1.782)	(13.895)	(26.374)	(12.180)
temperature (13°C-15°C)	0.226	-0.95	15.024	3.61	15.785	16.325***	13.515***	72.830***	88.448***	72.276***
	(0.687)	(0.729)	(25.898)	(25.748)	(23.007)	(1.113)	(1.151)	(13.187)	(25.894)	(11.585)
temperature (16°C-18°C)	6.005***	2.279	17.902	6.623	19.085	-13.007***	-11.904***	53.355***	70.858***	55.867***
	(1.552)	(1.611)	(26.513)	(26.365)	(23.599)	(2.398)	(2.376)	(14.277)	(25.272)	(12.587)
temperature (19°C-21°C)	1.749*	3.843***	20.192	9.743	18.615	51.123***	38.456***	92.092***	104.857***	82.791***
	(1.031)	(1.055)	(25.338)	(25.187)	(22.478)	(2.620)	(2.834)	(11.918)	(26.814)	(10.493)
temperature (22°C-24°C)	0.34	0.351	14.257	4.012	16.232	-32.582***	-31.019***	33.077***	50.620*	30.449***
	(0.685)	(0.688)	(25.642)	(25.495)	(22.770)	(2.553)	(2.611)	(12.723)	(26.184)	(11.149)
temperature (25°C-27°C)	-1.675**	4.054***	20.211	8.913	18.095	-1.295	4.341***	63.081***	78.352***	58.164***
	(0.768)	(0.956)	(25.490)	(25.344)	(22.616)	(1.385)	(1.459)	(13.213)	(26.723)	(11.582)
temperature (28°C-30°C)	-7.810***	1.048	19.104	8.618	16.42	-2.675***	-1.776*	56.902***	73.319***	55.209***
	(1.294)	(1.522)	(25.517)	(25.376)	(22.621)	(0.915)	(0.979)	(12.644)	(26.227)	(11.070)
temperature (31°C-33°C)	4.751*	0.224	17.595	7.202	27.01	-15.665***	-12.743***	47.972***	65.225**	49.160***
	(2.860)	(3.335)	(26.051)	(25.894)	(23.103)	(1.069)	(1.101)	(13.471)	(26.041)	(11.805)
temperature (34°C-36°C)	-55.164*	-52.648*	-51.18	-28.918	-23.254	-27.824***	-51.012***	.	26.164	.
	(28.762)	(31.632)	(38.974)	(38.683)	(33.982)	(9.753)	(10.971)	.	(28.282)	.
long term temperature (1°C-3°C)		37.479**	-53.715**	-58.807***	-126.308***		-20.479	-59.069**	-60.606**	-56.230***

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		(18.832)	(21.920)	(21.899)	(19.507)		(18.778)	(24.015)	(23.753)	(20.943)
long term temperature (34°C-36°C)		85.987	-22.727	-137.659	-342.181**		479.480***	648.119***	622.014***	559.240***
		(151.860)	(170.110)	(169.371)	(161.394)		(48.165)	(59.720)	(59.434)	(53.449)
long term temperature (>=37°C)		-187000***	-234000***	-224000***	-171000***		-4212.74***	-5681.535***	-4894.469***	-3327.423***
		(1725.170)	(1919.935)	(1922.036)	(1773.336)		(1173.669)	(1344.184)	(1335.140)	(1184.810)
average rainfall			-0.519**	-0.412*	-0.29			0.931***	0.900***	0.804***
			(0.235)	(0.234)	(0.209)			(0.294)	(0.291)	(0.270)
Plot size in hectares: calculated				1543.583**	-1234.7***				1832.354***	-906.934***
				(187.580)	(202.849)				(189.606)	(206.317)
number of oxen					207.616***					215.851***
					(30.776)					(31.596)
sex of household head					-158.709*					-194.940**
					(92.631)					(94.990)
age of household head					-0.337					-2.189
					(2.444)					(2.506)
household head illiterate					-473.590***					-523.363***
					(76.001)					(78.014)
number of male adults in household					-6.242					6.651
					(68.935)					(70.790)
number of female adults in household					1.088					41.415
					(36.593)					(37.449)
Total land area by hh					546.221***					501.991***
					(52.235)					(54.001)
Constant	919.01***	1171.360***	-2.88E+04	-3676.047	-2.84E+04	1819.589***	1653.717***	-1.25e+05***	-1.58e+05***	-1.21e+05***
	(278.416)	(277.313)	(55324.632)	(55024.216)	(49162.744)	(280.590)	(279.841)	(27774.790)	(56562.157)	(24365.361)
Year Dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Mundlak's fixed effects	NO	NO	NO	NO	YES	NO	NO	NO	NO	YES
Adjusted R-sq	0.2044	0.2173	0.2706	0.2855	0.4997	0.1777	0.1964	0.2379	0.2568	0.4727
N	7107	7107	5569	5551	4845	7107	7107	5569	5551	4845

**It should be noted that the results corresponding to physical farm characteristics, year dummy and the average time-variant variables are not reported in the tables.

Appendix B. The distribution of Educational and Physical Infrastructure, by Kebele***

	Primary school		Secondary school		Piped water		Community forest
Kebele	Availability	Sufficiency	Availability	Sufficiency	Availability	Sufficiency	Availability
Amanuel	Yes	Yes	Yes	Yes	Yes	No	Yes
Debre Elias	Yes	No	No	No	No	No	No
Kebi	Yes	Yes	No	No	No	No	No
Wolekie	Yes	Yes	No	No	No	No	No
Telima	Yes	No	No	No	Yes	No	Yes
Sekela Debir	Yes	No	No	No	Yes	No	Yes
Kete	Yes	No	Yes	Yes	Yes	No	No
Gudguadit	Yes	No	Yes	No	Yes	No	Yes
Amba Mariam	Yes	No	No	No	Yes	No	Yes
Yamed	Yes	Yes	Yes	No	Yes	Yes	Yes
Addis Mender	Yes	Yes	No	No	Yes	Yes	Yes
Chorisa	Yes	No	No	No	Yes	No	Yes

*** This information is based on the community level survey questionnaire.

Appendix C. T-test for mean differences in the distribution of short term temperature values between Amanuel kebele and the rest of the kebeles****

temperature	D. Elias	Kebi	Wolekie	Telima	Sekela Debir	Kete	Gudguadit	Amba Mariam	Yamed	Addis Mender	Chorisa
short term temperature (1°C-3°C)	-0.321 (1.000)	-5.324 (0.000)	-3.401 (0.016)	-1.568 (1.000)	-3.189 (0.036)	-11.752 (0.000)	-8.850 (0.000)	3.155 (0.040)	-1.324 (1.000)	0.449 (1.000)	-5.528 (0.000)
short term temperature (4°C-6°C)	-3.187 (0.035)	. (0.000)	. (0.000)	-9.945 (0.000)	-5.057 (0.000)	-27.698 (0.000)	-23.361 (0.000)	-17.133 (0.000)	-17.563 (0.000)	-5.634 (0.000)	-12.032 (0.000)
short term temperature (7°C-9°C)	0.413 (1.000)	-7.889 (0.000)	12.464 (0.000)	-30.574 (0.000)	-28.744 (0.000)	-21.993 (0.000)	-17.246 (0.000)	-18.436 (0.000)	-15.653 (0.000)	-33.474 (0.000)	-10.648 (0.000)
short term temperature (10°C-12°C)	3.929 (0.002)	-11.398 (0.000)	6.916 (0.000)	3.451 (0.014)	3.318 (0.023)	18.372 (0.000)	14.640 (0.000)	16.243 (0.000)	18.864 (0.000)	13.061 (0.000)	15.756 (0.000)
short term temperature (13°C-15°C)	-2.211 (0.651)	2.924 (0.080)	-3.441 (0.013)	40.795 (0.000)	26.848 (0.000)	129.028 (0.000)	80.278 (0.000)	77.729 (0.000)	81.365 (0.000)	71.136 (0.000)	46.240 (0.000)
short term temperature (16°C-18°C)	-1.733 (1.000)	-1.561 (1.000)	-9.551 (0.000)	0.373 (1.000)	9.300 (0.000)	-13.798 (0.000)	-19.917 (0.000)	-16.720 (0.000)	-28.966 (0.000)	-19.094 (0.000)	-15.641 (0.000)
short term temperature (19°C-21°C)	-3.046 (0.056)	-1.364 (1.000)	-5.780 (0.000)	29.797 (0.000)	23.449 (0.000)	64.888 (0.000)	65.022 (0.000)	65.713 (0.000)	80.775 (0.000)	64.522 (0.000)	46.021 (0.000)
short term temperature (22°C-24°C)	1.780 (1.000)	9.405 (0.000)	-0.086 (1.000)	-8.987 (0.000)	0.891 (1.000)	30.887 (0.000)	14.989 (0.000)	8.904 (0.000)	5.630 (0.000)	2.113 (0.833)	2.408 (0.402)
short term temperature (25°C-27°C)	-3.843 (0.003)	5.067 (0.000)	-11.336 (0.000)	-1.770 (1.000)	8.963 (0.000)	-69.651 (0.000)	-73.368 (0.000)	-63.033 (0.000)	-88.180 (0.000)	-82.007 (0.000)	-50.938 (0.000)
short term temperature (28°C-30°C)	-2.014 (1.000)	2.709 (0.156)	-3.227 (0.029)	-42.714 2.91e-317	-26.734 (0.000)	-90.447 (0.000)	-72.524 (0.000)	-57.857 (0.000)	-70.370 (0.000)	-49.247 (0.000)	-43.063 2.38e-311
short term temperature (31°C-33°C)	-1.809 (1.000)	-1.881 (1.000)	-1.399 (1.000)	-24.068 (0.000)	-23.822 (0.000)	-79.049 (0.000)	-52.054 (0.000)	-35.775 (0.000)	-37.239 (0.000)	-40.112 (0.000)	-32.595 (0.000)
short term temperature (34°C-36°C)	. (0.000)	. (0.000)	. (0.000)	-2.538 (0.280)	-3.279 (0.026)	-21.341 (0.000)	-16.712 (0.000)	-17.539 (0.000)	-20.398 (0.000)	. (0.000)	-10.656 (0.000)

**** Figures in parentheses are p-values.

**Appendix D: T-test for mean differences in the distribution of long term temperature values between Amanuel kebele
and the rest of the kebeles******

temperature	Debre Elias	Kebi	Wolekie	Telima	Sekela Debir	Kete	Gudguadit	Amba Mariam	Yamed	Addis Mender	Chorisa
long term temperature (1°C-3°C)	4.184	-6.084	-3.945	16.257	11.689	6.736	8.078	13.776	14.556	11.999	11.481
	(0.001)	(0.000)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (4°C-6°C)	0.519	-5.138	-30.826	122.402	28.531	139.418	126.693	76.906	160.542	122.361	83.642
	(1.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (7°C-9°C)	14.641	7.441	17.638	-24.525	-32.815	116.195	107.172	91.477	110.489	114.637	58.204
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (10°C-12°C)	8.586	-7.037	15.529	23.376	19.588	34.272	29.363	30.002	36.924	26.965	27.560
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (13°C-15°C)	-1.696	3.277	-1.264	34.912	20.710	133.155	91.891	84.042	94.484	88.709	50.058
	(1.000)	(0.024)	(1.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (16°C-18°C)	-1.518	-1.940	-11.132	-7.419	4.727	-20.561	-29.142	-21.112	-39.586	-28.854	-21.917
	(1.000)	(1.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (19°C-21°C)	0.339	1.914	-3.181	37.686	24.372	60.038	63.101	64.726	83.239	66.500	44.822
	(1.000)	(1.000)	(0.034)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (22°C-24°C)	-3.290	-1.335	-3.240	-30.087	-8.738	29.493	13.928	8.503	4.363	1.443	3.023
	(0.024)	(1.000)	(0.028)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(1.000)	(0.063)
long term temperature (25°C-27°C)	-7.262	-0.524	-15.512	-19.939	-3.113	-80.224	-99.136	-72.474	-114.281	-117.106	-58.125
	(0.000)	(1.000)	(0.000)	(0.000)	(0.047)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (28°C-30°C)	-7.977	0.820	-15.901	-98.456	-41.719	-110.666	-114.694	-83.553	-133.487	-120.618	-58.615
	(0.000)	(1.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (31°C-33°C)	-5.422	-4.042	-7.681	-108.516	-72.692	-141.849	-67.397	-103.731	-142.638	-123.182	-39.591
	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (34°C-36°C)	2.254	5.262	-0.691	-41.510	-35.407	-23.726	9.287	85.430	102.263	147.284	39.083
	(0.582)	(0.000)	(1.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
long term temperature (>=37°C)	2.628	4.523	-6.331	-52.227	-59.935	-133.043	-67.885	-82.325	-85.675	-93.442	-33.984
	(0.207)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)