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Cropland expansion in Ethiopia

Economic and climatic considerations for highland agriculture

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ABSTRACT

Agricultural GDP in Ethiopia grew at an average 7.3 percent per year between 2001/02 and 2012/13. Most of this dynamism occurred in the highlands, where high population density and land scarcity begs the question of how future agricultural output can be maintained to sustain the previous decade's momentum. This paper uses a spatial regression approach to calculate the maximum crop area potential of each kebele in Ethiopia. We find that although the highlands have a greater potential for cropped area, there is little room to expand. A substantial share of the highlands has limited economic potential to expand the land base devoted to agriculture. In fact, many areas may be reaching an environmental threshold that will require the local agricultural land area to contract to maintain the agricultural productivity outcomes realized in previous years.

1. INTRODUCTION

The agricultural sector is the cornerstone of Ethiopia's economy with approximately three-quarters of the economically active population engaged in agricultural production activities (Schmidt and Bekele 2017). Under the Agriculture Development Led Industrialization (ADLI) strategy, agricultural production in Ethiopia increased substantially with increases in agricultural GDP averaging 7 percent per year between 2004/05 and 2013/14.[1] During the earlier part of this period, land area expansion was the primary contributor to increases in agricultural GDP. However, in more recent years, rising crop yields coupled with continuing agriculture area expansion contributed to agricultural GDP growth (Bachewe et al. 2018). Given Ethiopia's reliance on agriculture as a mainstay of livelihoods as well as the country's rapidly declining area of unexploited cultivable land in the agricultural highlands, a question arises of whether this type of agricultural growth is sustainable for the foreseeable future.

While the highlands have benefitted from impressive growth in agricultural production during the last several decades, recent studies have identified some of the costs of the associated increasing population density and farming intensity. Farmers are cultivating on steeper slopes in the highlands without using proper sustainable land management techniques, i.e., terracing and fallowing (Schmidt and Zemadim 2015; Taddesse 2001; Hamza and Anderson 2005). Production losses approaching 1.1 percent per year have been linked to increasing erosion and topsoil loss in the highlands (Holden and Shiferaw 2002). In addition to unsustainable cultivation practices, increased levels of deforestation are attributed to cropland conversion (Cleaver and Schreiber 1994). Pasturelands are also increasingly being put under crops (Tshopp et al. 2010).

Options for relieving rural agricultural land pressures in Ethiopia are few. Agriculture is the primary source of income for most Ethiopians and non-farm employment remains limited throughout the rural highlands. [2] Moreover, the potential for rural-rural migration to seek out less densely populated agricultural areas is constrained by current land tenure restrictions. Understanding the potential for further agricultural expansion is necessary to inform investment priorities aimed at maintaining agricultural performance. We address this knowledge gap by using a combination of data from country-level databases and from remote sensing satellites to evaluate change in agricultural area over time. We employ a spatial regression approach to identify correlates of crop area expansion at the kebele (sub-district) level considering current

[1] GDP growth occurred throughout the economy over the last decade. Large increases were also seen in the industry and services sectors, which grew at approximately 14 and 13 percent per year, respectively, between 2004/05 and 2013/14. Given the growth in industry and services, agriculture's share of GDP has fallen over the last decade. However, agriculture remains an important driver of economic growth and employment (Schmidt and Bekele 2017).

[2] Schmidt and Bekele (2017) find that a large share of the rural working population (78 percent) is engaged solely in own-farm activities. Only 12 percent report having a secondary job outside of their own farm.

estimates of cropped area within the kebele. Finally, we calculate the maximum potential for cropland expansion, controlling for a collection of bioeconomic factors.

When assessing future potential for agricultural area expansion, our analysis suggests that agricultural area expansion in the highlands is reaching its maximum economic potential, especially in the drought-prone highland agro-ecological zone. Select areas in the lowlands have greater potential to expand the share of their land areas devoted to agriculture. However, this will require investments in transportation and social infrastructure to attract investment and to link the newly expanded agricultural areas to input and output markets.

The remainder of the paper is as follows. Section 2 provides a background to Ethiopia's agricultural production, including a description of the country's diverse agro-ecological zones. Section 3 evaluates Ethiopia's agricultural landscape at the disaggregated kebele level, utilizing satellite landcover data to characterize agricultural area expansion over the last decade. Section 4 details the satellite and other complementary data used to evaluate the determinants of agricultural land expansion, followed by a description of our empirical strategy for evaluating market access correlation with agricultural land expansion. Section 5 provides results and discussion. Finally, section 6 concludes

2. AGRICULTURAL PRODUCTION IN ETHIOPIA

Over the last decade, the agricultural sector in Ethiopia has performed well. The increase in agricultural GDP (approximately 7 percent per year during the period from 2004/05 to 2013/14) was primarily due to crop production, contributing almost 80 percent to agricultural GDP growth (Table 2.1). Rising crop yields were the primary driver of increased agricultural GDP followed by land area expansion. These factors contributed 60 and 28 percent, respectively, to agricultural growth (Table 2.2). Cereals generated more than half of crop GDP growth between 2004/05 and 2015/16 (Table 2.2). The five major cereals (teff, barley, wheat, maize, and sorghum) constitute 73 percent of total cultivated area (CSA 2015/16).

Table 2.1. Sub-sectoral contributions to real agricultural GDP, 2004/05 to 2015/16, percent

	Initial agricultural GDP share 2004/05	Final agricultural GDP share 2015/16	Contribution to increase in agricultural GDP 2004/05 to 2015/16
Agriculture	100.0	100.0	100.0
Crop	63.8	72.0	79.5
Livestock	23.6	19.5	15.8
Forestry	12.5	8.4	4.7

Source: Own calculations using data from national accounts (CSA 2016) and Agricultural Sample Survey reports (CSA various years).
Note: Shares calculated using constant factor cost GDP

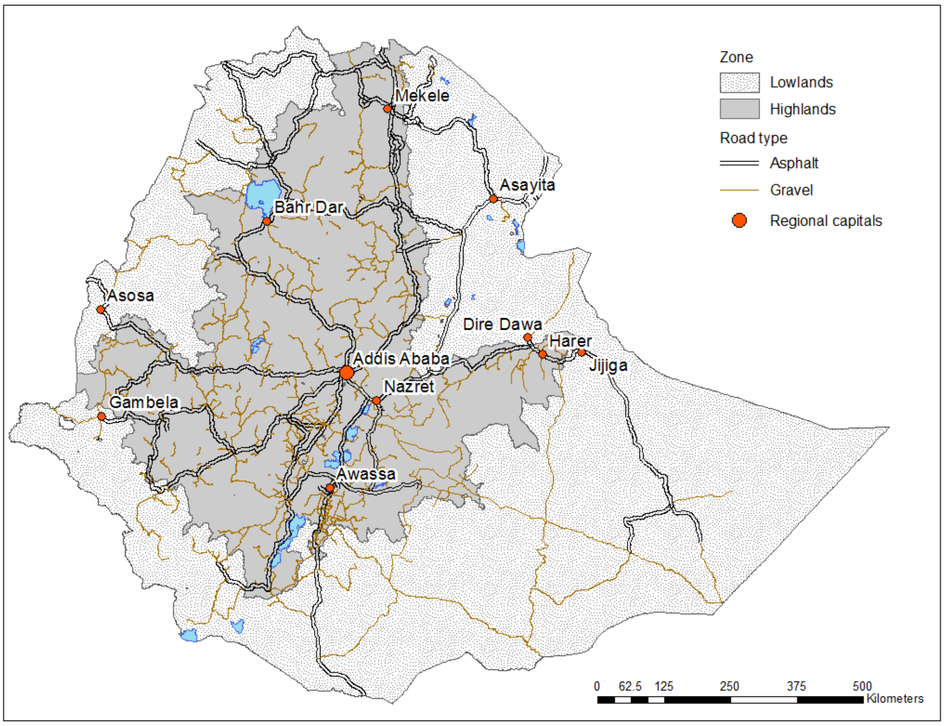
Table 2.2. Contribution of cereals and non-cereals to agricultural GDP change, 2004/05 to 2013/14, percent

	All crops	Cereals	Non-cereals
Share of agricultural GDP in 2004/05	100.0	56.2	43.8
Share of agricultural GDP in 2013/14	100.0	54.9	45.1
Contribution to total agricultural GDP	100.0	53.8	46.2
Increase in crop yields	60.3	40.7	19.7
Cultivated land expansion	27.5	15.4	12.0
Reallocating land to higher value crops	12.2	-2.3	14.5

Source: Own calculations using data from national accounts (CSA 2016) and Agricultural Sample Survey reports (CSA various years).

In a country where rainfed agriculture is the predominant production system, agro-ecological conditions determine production patterns and, in the case of Ethiopia, dictate the location of major economic centers and transportation corridors (Figure 2.1). Ethiopia's topography has influenced demographic and agricultural patterns throughout its history. The highlands of Ethiopia, defined as locations with a minimum elevation of 1,500 meters above sea level[3], are more densely populated and reflect the physical and climatic advantages that led to the country's agricultural development (Figure 2.1). The highlands are endowed with relatively more predictable rainfall and do not house vectors that carry diseases, such as malaria or tsetse fly (Pankhurst and Piguet 2009). In contrast, the lowlands experience more erratic and limited rainfall and have greater risk for disease. These factors have constrained expansive development in lowland agriculture (Josephson et al. 2014; Headey et al. 2014).

Figure 2.1. Highland and lowland areas of Ethiopia



Source: Authors' calculation

Most agricultural production is in the country's highlands, which constitutes the breadbasket of the country where 92 percent of the area planted to cereals is found and 92 percent of total cereal production is obtained (Table 2.3). The majority of teff, the local cereal used to make injera, a principal staple food, is grown in the highlands, accounting for 97 percent of teff production and 96 percent of area dedicated to teff cultivation. In addition, highland cultivation accounts for 99 percent of total wheat production and 90 percent of total maize production.

Urbanization and population density is significantly greater in the highlands compared to the lowlands (Table 2.4). People living in the highland areas have greater market access to urban centers. While the average travel time to a city of at least 20,000 people in the highlands is approximately 3 hours, the average travel time to a city of at least 20,000 people in the lowlands is approximately 6 hours. This is for several reasons. First there are fewer cities in the lowland areas. While there are 96 cities of at least 20,000 people in the highlands, there are only 20 urban centers of this size in the lowlands.[4] The lowland areas of Ethiopia also have a sparser transportation infrastructure compared to the highlands. In the highlands, road

[3] For references on highland and lowland definitions in Ethiopia, see Food and Agriculture Organization – FAO (1986); Constable (1985); Hurni (1998).

[4] When evaluating larger cities of 50,000 population, the highlands have 36 cities of at least 50,000 people, while the lowlands have 16 cities of at least 50,000.

density is approximately 0.17 km of road per square kilometer, while in the western areas of the lowlands (including parts of western Oromiya, Gambella and Benishangul Gumuz regions) the road density is 0.05 km per square kilometer (Table 2.4 and Figure 2.1). There are variations in climatic, demographic and physical infrastructure within the highland and lowland regions as well – see Appendix Table A1.

Table 2.3. Cereal crop production and area by agro-ecological zone, 2014/15

	Highlands	Lowlands	Total
Production ('000 mt)			
Barley	1,859	49	1,908
Maize	5,865	627	6,492
Sorghum	3,088	741	3,829
Teff	4,277	141	4,419
Wheat	3,888	37	3,925
Other	824	179	1,003
Total	19,802	1,774	21,575
Area ('000 ha)			
Barley	988	32	1,019
Maize	1,771	224	1,995
Sorghum	1,380	298	1,677
Teff	2,900	117	3,017
Wheat	1,588	18	1,606
Other	427	97	524
Total	9,053	785	9,838

Note: Other cereals include rice, millet and oats.
Source: Authors' calculations using Agricultural Sample Survey Report 2014/15

Table 2.4. Characteristics of highland and lowland areas of Ethiopia

	Highlands	Lowlands
Rainfall, mean annual, mm	1,221	1,152
Elevation, mean, meters	2,065	1,385
Travel time to a city with population of more than 20,000 persons, mean, hours	2.9	6.1
Population density, persons per sq.km.	321	61
Population 2016, millions		
Total	75.4	16.8
Urban	15.4	2.9
Rural	60.0	13.9
Total land area, sq.km.	421,594	709,890

Source: Authors' calculation using a variety of remote sensing datasets including Jarvis et al. (2008), Bright et al. (2012), Funk et al. (2017), and CSA (2013)

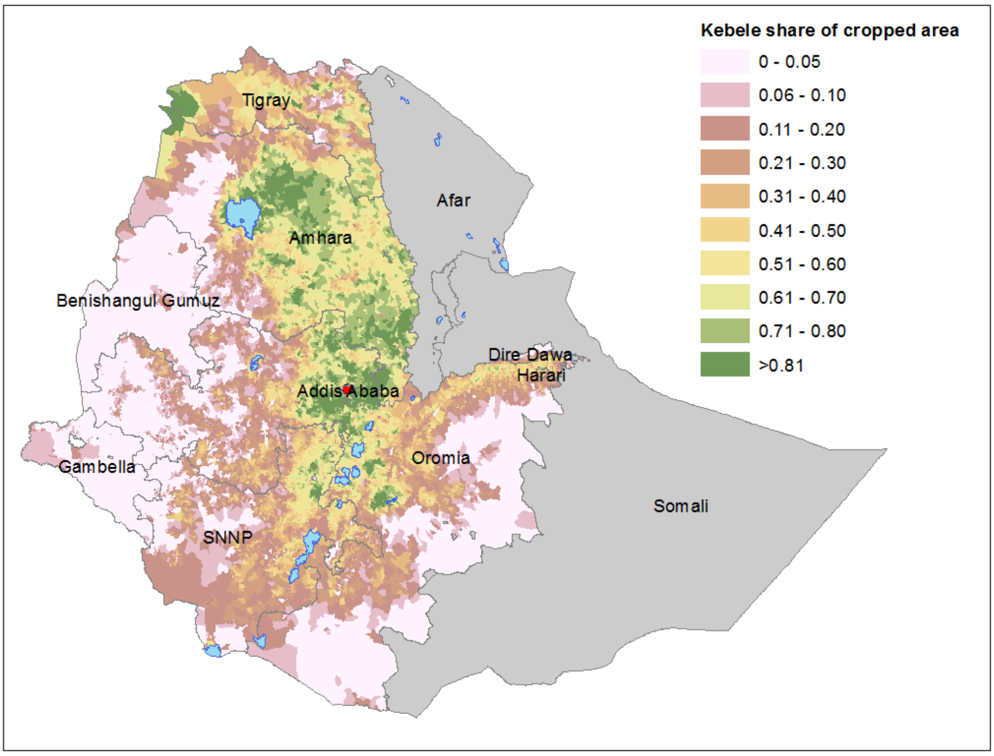
Rainfed agricultural production systems are vulnerable to variations in rainfall and climate. Over time, cultivated land in Ethiopia has expanded within the geographic area that permits relatively less risky agrarian livelihoods. Although the highlands make up only 37 percent of the total landmass of Ethiopia, more than 80 percent of the total population live in the highlands (Table 2.4). Looking forward, understanding the future potential for agricultural area expansion will be critical for future investment and establishing policy priorities to ensure continued economic growth. The following sections evaluate the expansion in agricultural land throughout Ethiopia during the last decade and estimate the potential for further expansion using a spatial regression approach.

3. AGRICULTURAL AREA EXPANSION

To analyze changes in agricultural crop area across the Ethiopian landscape, we use the MODIS Land Cover Type product to classify agricultural areas of Ethiopia. The remote sensing product is derived from a year of observations collected from the Terra- and Aqua-MODIS sensors, satellites which view the entire Earth's surface every one to two days. Seventeen landcover classes have been identified, including croplands and a cropland/natural vegetation mosaic classification, at a 500-meter resolution for the period from 2001 to 2013 (see Friedl et al. (2010) for more details). Production practices in Ethiopia are spatially and temporally heterogeneous with production occurring on smallholder farms characterized by diverse farming practices, intercropping, and mixed livestock-crop production systems. Given these complex agricultural production characteristics, we calculate total agricultural area as the cropland area extent plus half of the cropland/natural vegetation mosaic area extent.

Landcover analysis of Ethiopia during the 2010-13 period suggests that most cropped area is in the highlands. Kebeles in Amhara region have the greatest share of land under agriculture with more than 60 percent of total land area dedicated to agricultural uses (Figure 3.1). Kebeles in central Oromiya and northeast Southern Nations, Nationalities and Peoples' (SNNP) regions have between 50 and 70 percent of total land area dedicated to crop cultivation. In contrast, kebeles in the lowlands have very little area dedicated to cultivation.[5]

Figure 3.1. Map of average share of area cropped, 2010-2013



Source: Authors' calculations using MODIS Land Cover type product

Comparing landcover change over time presents a challenge because of the variation in the reflectance data collected by the satellite sensors due to differing environmental conditions, i.e., time of day of the satellite pass, weather conditions, etc. To smooth variations in overall landcover values from year to year, we average total landcover area values by kebele (sub-district) and average values over three periods: early (2001-04), middle (2005-09), and late (2010-13).

[5] We do not include Afar and Somali regions in this analysis given their limited agricultural cultivation activities.

Changes in cropped area in Ethiopia show varying spatial patterns depending on these periods. Looking at changes between the first (2001-04) and second (2005-09) periods, most of the agricultural area expansion occurred in the highland areas of Amhara region east of Lake Tana. However, changes between the second and third (2010-13) period were greater in the lowlands of northwest Amhara region and in the far western kebeles of Tigray region (Appendix Table A2). Over the entire period, the greatest growth in cropped area as a share of total area occurred in the lowlands, averaging 2.6 percent growth per year from 2001-04 to 2010-13 (Table 3.1).[6]

Table 3.1. Changes in crop area, 2001-2004 to 2009-2013

	Highlands	Lowlands	Total
Kebeles with declines in crop area of 5 percent or more			
2001-04 to 2005-09	7.3	21.3	19.3
2005-09 to 2010-13	23.6	19.2	21.5
2001-04 to 2010-13	14.1	17.3	16.8
Average annual growth in crop area, percent			
2001-04 to 2005-09	5.6	2.2	2.7
2005-09 to 2010-13	0.2	1.4	1.2
2001-04 to 2010-13	2.6	1.6	1.8
Total percentage point change in cropland area, 2001-13	25.5	15.3	17.0

Source: Authors' calculations using MODIS Land Cover type product

Although expansion occurred in several areas throughout the analysis period, these data suggest that cropland expansion is slowing down. Whereas the agricultural area in the highlands expanded at 2.2 percent per year from 2001-04 to 2005-09, this annual growth decreased to 1.4 percent from 2005-09 to 2010-13 (Table 3.1). Similarly, 21 and 19 percent of kebeles in the highlands experienced a contraction in their share of total land under crops during the first period and second period, respectively. In comparison, the lowlands experienced an average annual growth in crop area of 5.6 percent between 2001-04 and 2005-09, although average annual growth in crop area there dropped considerably to 0.25 percent between 2005-09 and 2010-13. This pattern may be due to droughts in 2009/10 and 2010/11 which affected areas of southern Ethiopia and lowland Oromiya, Tigray, and Somali regions (Viste et al. 2012).

Overall, between 2001-04 and 2010-13, average annual growth in crop area was 2.6 percent in the lowlands and 1.6 percent in the highlands (Table 3.1). This suggests that, although highland agriculture is the preferred location for production, there may be limited area in which to expand further in the highlands. This descriptive analysis of agricultural land area expansion and contraction in Ethiopia suggests that significant spatial and temporal patterns exist, which may be associated with inherent biophysical endowments, as well as climate and infrastructure characteristics. Given these trends and Ethiopia's dependence on highland agriculture, we evaluate the potential for future agricultural land expansion, taking into account bioeconomic factors and the current share of land area that is cropped in each kebele.

4. UNDERSTANDING ETHIOPIA'S POTENTIAL TO EXPAND CULTIVATED AREA: DATA AND EMPIRICAL SPECIFICATION

Data description

The objective of this analysis is to evaluate the factors associated with changes in agricultural area over time. Utilizing the MODIS landcover data, which identifies cultivated area, as well as a variety of other landcover types, including grasslands, savanna, forest, etc. (see Friedl (2010) for details), from 2001 through 2013 at a 500-meter resolution, we evaluate the change observed in cultivated area between the

[6] Evaluating by region, the greatest growth in crop area occurred in Amhara and Oromia regions which increased by 20 and 23 percent, respectively, over the 2001-2013 period and approximately 2 percent per year (Table A2).

period of 2001-04 and 2010-13 at the kebele (sub-district) level. In doing so, we calculate by year the share of 500-meter grid cells within a kebele that are classified as cropland or cropland/natural vegetation mosaic, assuming 50 percent of the mosaic cells are dedicated to agricultural production. We then average this share over the analysis periods, 2001-04 and 2010-13, to reduce noise in the satellite reflectance values and to aid data interpretation. Finally, we subtract the share of cropland area calculated for the 2001-04 period from the share of cropland area calculated for the 2010-13 period by kebele to determine the change in the share of total area under crops in each kebele between the two periods time. This change represents our dependent variable in the following analysis.

A variety of factors are related to the attractiveness of expanding the area under agricultural production. An important factor that needs careful consideration is the share of the total area that is already under cultivation. As cultivated land area expands across a kebele, the propensity to continue expanding becomes less attractive as the more productive land areas are adopted into agricultural use. We hypothesize that the change in cropland area will be smaller for kebeles that have a greater share of their total land area already cultivated. To test (and to control for this in regard to other variables), we include the share of area under cultivation in the initial period (2001-04) as well as its squared term as explanatory variables (median and 10^{th} and 90^{th} percentile values of regression covariates are reported in Appendix Table A3).

As mentioned, Ethiopia's topographic and climatic variability influence the location of productive activities. Climate conditions such as the level and variations in rainfall, temperature and elevation affect agricultural patterns within the country. We account for variations in climate by controlling for average precipitation, variation in precipitation, and average annual maximum temperature for the main growing season between June and September over the last 30 years. We include a square term for precipitation and elevation based on the assumption that, while area expansion initially increases with greater rainfall and higher elevation, eventually flood and frost would affect cultivable area in some of Ethiopia's more extreme climates. In addition, Ethiopia's topography varies dramatically from flat lowlands at 500 meters above sea level to rugged highlands reaching elevations above 3,500 meters. We control for topographic variation by including a terrain roughness indicator. This indicator is computed first for every one-kilometer square, and then averaged for all such squares within each kebele.

Related with climate factors, we assume that the cropping system available to smallholder farmers would also affect cropland expansion. The majority of kebeles in Ethiopia are dependent on one primary *meher* harvest, derived from the main *meher* rainy season that occurs from June through September. However, in some areas of the country a second *belg* season harvest is obtained. We include a dummy variable calculated using the Agricultural Sample Survey (AgSS) data collected by the Central Statistical Agency (CSA) to account for areas that benefit from two harvests.

Finally, the potential for profitable cropland expansion is highly dependent on the ability to access input and output markets. We measure market access potential by taking the difference in a measure of travel time between, 2001 and 2013, from each location in Ethiopia to the nearest secondary market of at least 20,000 people. Given that we are evaluating change in agricultural area between 2001-04 to 2010-13, we include the base travel time in 2001 to account for the initial market access of the kebele. As travel time to a market decreases, we assume the cost of transporting goods to markets and the cost of purchased inputs decreases, making agricultural production and, hence, agricultural land expansion more attractive.

Empirical specification

While we are interested in seeing how each of the variables influences the change in the proportion of the total land area of a kebele that is under crops, ΔC, we also intend to find the steady state maximum proportion of cropland, C^{max}, for each kebele. To make this clear in mathematical terms, we will make explicit both C (the proportion of cropland in each kebele) and ΔC in our specification:

$$\Delta C = \alpha_1 C + \alpha_2 C^2 + X\beta + \epsilon$$

where X is a matrix of bioeconomic variables as described above, β is the vector of parameters to be estimated, and ϵ is the error vector. The steady state maximum is found when $\Delta C = 0$.

We control for potential spatial dependence that may be present in ordinary least square model estimates by utilizing a spatial regression framework that controls for both spatial error and spatial lag. Allowing for spatial error recognizes that data observations associated with spatial units may reflect measurement error (i.e. administrative boundary misalignment or road placement inconsistencies within the GIS road database) or that there are unmeasured variables that by definition are not part of the regression but are spatially correlated. Allowing for the possibility of a spatial lag takes into account that cropland expansion in one kebele might also influence expansion in neighboring kebeles.

For the full spatial case, which controls for spatial errors as well as spatial lags, we have

$$\Delta C = \rho W_1 \Delta C + \alpha_1 C + \alpha_2 C^2 + X\beta + \epsilon$$

where W_1 is a spatial weights matrix indicating the strength of influence that each neighbor has, and where

$$\epsilon = \lambda W_2 \epsilon + u$$

with u being independent and identically distributed (i.i.d.) normal with a mean of 0 and a variance of σ^2. W_2 is also a spatial weights matrix which may possibly be and in our case is equal to W_1.

Rearranging and substituting in the equation for the full spatial case gives us

$$\Delta C = (I - \rho W_1)^{-1} \alpha_1 C + (I - \rho W_1)^{-1} \alpha_2 C^2 + (I - \rho W_1)^{-1} X\beta + (I - \rho W_1)^{-1} (I - \lambda W_2)^{-1} u$$

where I is the identity matrix. From this we note that

$$E(\Delta C) = (I - \rho W_1)^{-1} \alpha_1 C + (I - \rho W_1)^{-1} \alpha_2 C^2 + (I - \rho W_1)^{-1} X\beta$$

since the expected value of the residual is 0.

To solve for $E(\Delta C) = 0$, we can multiply the right of the previous equation by $I - \rho W_1$ to give us

$$0 = \alpha_1 C + \alpha_2 C^2 + X\beta$$

The terms involving the weights matrix drop out because all spatial units are assumed to have ΔC approaching 0. This is the key difference when compared to the non-spatial case, for which the solution did not depend on neighbors. In the spatial case, if the neighbors are not approaching 0, the computation is much more complicated.

We can use the quadratic formula to solve for the C at which each woreda converges. Note that the value of $X\beta$ will be different for each woreda, and therefore the value of C that it converges to will also be different for each woreda.

$$C_{max} = \frac{-\alpha_1 \pm \sqrt{\alpha_1{}^2 - 4\alpha_2 X\beta}}{2\alpha_2}$$

The following section describes the results and discusses the potential consequences of Ethiopia's cultivable land scarcity in the highlands.

5. RESULTS

Table 5.1 presents the results of running the regression with spatial parameters restricted to non-negative values.[7] The parameters for the linear and quadratic terms for the proportion of cropland are highly significant and quantitatively large. The maximum change in cropland occurred in kebeles that in the initial period of 2001-04 had only approximately 5 percent of land under crops. A kebele with 5 percent of its land dedicated to cropland is likely to expand by 6 percentage points more than a kebele with approximately two-thirds of its land under crops. Compared to kebeles with 30 percent of initial land under crops, a kebele with 5 percent of its land dedicated to cropland increases the share of area cropped by 1 percent more over the study period. Although both population density parameters are highly statistically significant in the regression results, there is little quantitative difference in cropped area expansion between low and moderate population densities, with slightly higher expansion rates at low population densities.

Table 5.1. Factors associated with change in proportion of kebele area in cropland

Variable	Parameter	Standard error	
Initial cropland proportion	0.0173	0.0108	
- squared	-0.1594	0.0140	***
Population density in 2000, persons per sq.km.	-5.05E-06	1.01E-06	***
- squared	6.64E-11	1.82E-11	***
Precipitation (June to September), meters	2.08E-04	1.32E-05	***
- squared	-1.27E-07	7.99E-09	***
Coefficient of variation for precipitation	0.2171	0.0215	***
Maximum temperature (June to September), °C	1.16E-03	2.85E-04	***
Belg cropping (two growing seasons), 0/1	-0.0096	0.0016	***
Elevation, kilometers	2.14E-05	7.10E-06	***
- squared	5.64E-11	1.70E-09	
Terrain roughness measure	-1.13E-04	1.20E-05	***
Travel time to town with population of more than 20,000, hours	-8.79E-04	2.90E-04	***
Reduction in travel time to town	-1.61E-04	3.67E-04	
National park, 0/1	-0.0323	0.0077	***
Intercept	-0.1210	0.0140	***
Rho (spatial lag parameter)	0.7417	0.0292	***

Source: Authors' calculations
Note: Standard errors are in parentheses. *** indicates p<0.01; ** indicates p<0.05; and * indicates p<0.10.
Missing values for standard errors were due to negative elements on the diagonal of the inverted Hessian.

Precipitation is also an important influencer of the likelihood of increasing cropped area. Cropped area expansion increases with greater rainfall until reaching approximately 820 mm of rain during the main growing season from June to September, then falls thereafter. The difference between the driest kebele and a kebele with the optimal rainfall (820 mm) between the two periods is 8.5 percent greater cropland conversion. Similarly, the difference between the optimal and the wettest kebele is 7.8 percent of cropland expansion within a kebele. The optimal rainfall for conversion is very close to the median rainfall of kebeles in our study area of 713 mm over the four-month period.

It is not clear why higher coefficients of variation in rainfall lead to higher rates of conversion. This variable is highly negatively correlated with total rainfall, so perhaps it is in part reacting to how rainfall influences conversion of land to agriculture. Overall, however, the difference in cropland conversion levels

[7] We ran this in Stata with the *spregress* command, using the generalized spatial two-stage least-squares estimator, treating errors as heteroskedastic. Before running the full spatial model, we ran it with spatial error only and spatial lag only. Both times the spatial parameters were positive and significantly different from 0 and also significantly less than 1. Running it as a full unrestricted model, we found the spatial lag parameter to be positive, but the spatial error parameter to be negative, but not significantly different from 0. Therefore, we opted to report the results of the model with only a spatial lag.

between kebeles at the 10th percentile and the 90th percentile levels of rainfall variance is 3 percent of total kebele area. The quantitative significance of this variable is modest for explaining differences in conversion rates, except in kebeles with extremely high measures for this variable.

High temperature, although significant within the regression output, does not constrain cultivated areas in a large manner. Many crops are sensitive to high temperatures and generally hotter areas are less likely to be cultivated. However, in Ethiopia the hottest month of the year does not occur during the growing season. Therefore, it is not surprising that the temperature parameter had little quantitative effect on cropland conversion rates.

Although our regression results suggest cropland expansion in *belg* areas with two potential growing seasons is significant, this parameter has a very small effect on overall cropland expansion, amounting to a land conversion rate of 0.9 percent of total kebele area slower than non-*belg* areas. One possible reason might be that converting new land takes labor, and *belg* areas are likely to have less labor availability than other areas due to the need for agricultural labor in two seasons instead of just one.

As expected, elevation and terrain are important factors in cropland area conversion. In general, higher elevations are associated with greater area converted to cropland. The difference from a kebele with an elevation at the 10th percentile to a kebele at the 90th percentile (a difference of 1,300 meters in elevation), is associated with a change of 3 percentage points in cropped area within the kebele. This variable is an important indicator of differences in cropland conversion rates between the highlands and lowlands (see Table A3 for 10th and 90th percentile and median values of the covariates). As average terrain roughness increases (measured first as the range of elevation within a 1 km grid cell, then averaged over all grid cells in the kebele), crop area expansion decreases. This makes intuitive sense, because it is more difficult to cultivate on hilly terrain, making the land less desirable for conversion. Comparing the flattest to the hilliest kebele leads to a 6 percent difference of total kebele area converted to cropland during the study period that is, rougher terrain areas, such as hilly areas, have 6 percent less land converted to cropland. Comparing the 10th percentile to the 90th in terrain roughness shows a 2.5 percent difference in the share of total land in a kebele converted to cropland.

Access to markets is important for the profitability of engaging in agricultural work. The farther a kebele is from town, the lower the probability that land will be converted into cropland. For each hour increase in travel time to a city of at least 20,000 people, the probability of expanding cropland decreases by 0.09 percent. The median kebele is 4.4 hours away. The median kebele will convert at a rate of 0.4 percent of total kebele area more slowly than a kebele just outside of an urban center. This is a relatively small effect, and generally tells us that, contrary to expectations, change in cropland is not highly influenced by proximity to markets.

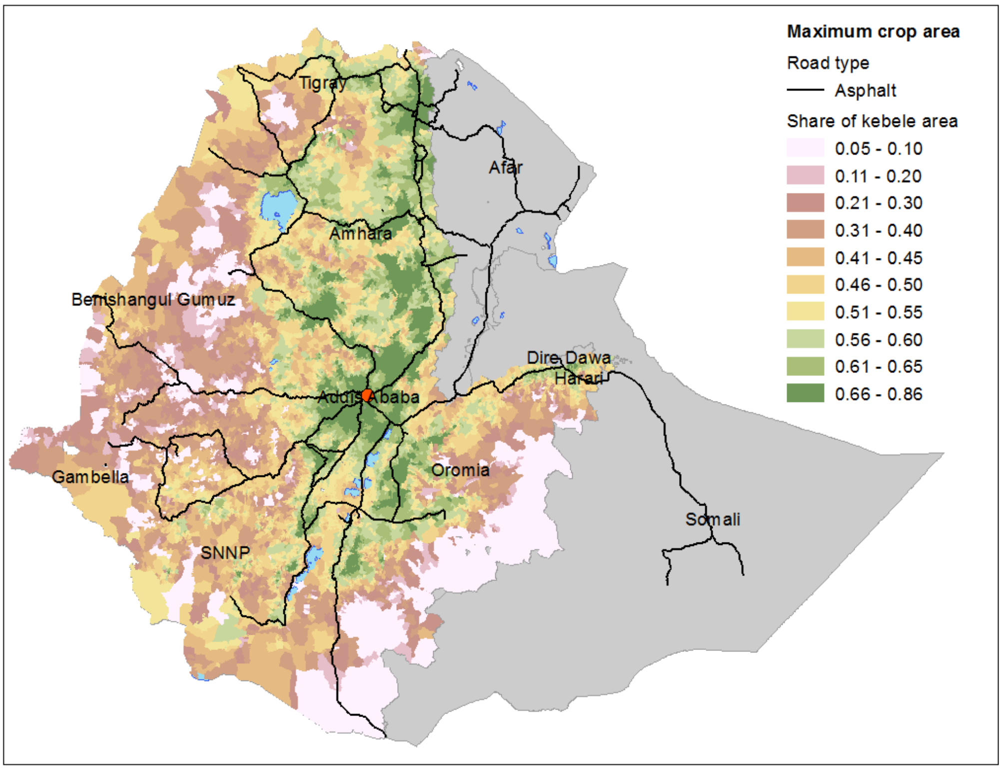
The parameter for the change in travel time to the nearest urban center due to improved roads between the two periods was not statistically significant. This was surprising, because reducing travel time should increase farmgate prices and reduce farmgate costs, giving farmers incentives to increase production. Even if we treated the parameter as being statistically significant, the difference in places with no change in travel time and 34 hours improvement in travel time appears to be only a half of a percent difference in conversion rates. It may be that the two different roads datasets that we used to produce this value had too much noise in them (i.e., inaccuracies) that the change in travel time did not reflect the true change in travel over time.

Finally, all other things being equal, national parks appear to lower the percentage of conversion to cropped land by 3 percentage points. The national parks variable is a binary indicator created using spatial data of protected park areas within the country. As expected, under effective national park management, protected areas would represent 'islands' of limited land conversion as seen in the regression output.

We recognize that conversion of land to cropland is a dynamic process, but it is a process that can reach a steady state value that is dependent on the characteristics that we included in the regression. We note that a steady state would be reached in each kebele when the dependent variable – the change in cropland – would become 0. Thus, we consider at what level of cropland percentage in each kebele – given the relatively fixed characteristics such as elevation, hilliness, and climate -- would the change in cropland be 0. We use the regression parameters in Table 5.1 with the quadratic formula presented earlier. The only changes we make in the variables is that we allow C, the percent under cropland, to reach its steady state level – that is, we solve for C^{max}. We also assume that at a steady state, the change in travel time to the nearest urban center between periods is zero.[8]

Figure 5.1 demonstrates the solution from the application of the quadratic formula to determine C^{max}. Notably, the highlands, particularly near Addis Ababa and along roads leading to Addis Ababa, have the highest projected steady state values – the highest maximum cropland percentages in the country. These levels extend to the northern border of Ethiopia but follow a relatively narrow band centered on the primary north-south highway. Several areas have little or no potential for conversion of land into cropland. Most of these are on the western border of Gambella region and selected kebeles of Benishangul Gumuz, as well as kebeles in eastern Oromiya bordering Somali region.[9]

Figure 5.1. Map of calculated maximum cropland area



Source: Authors' calculations using MODIS Land Cover type product

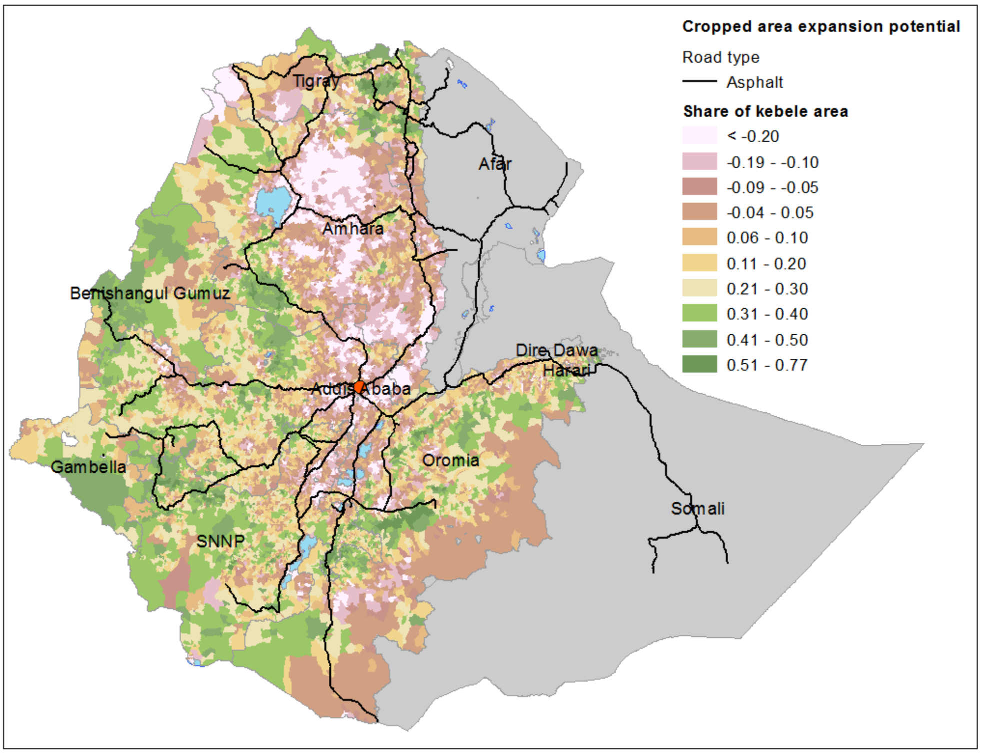
We compare the current reality with the calculated steady state solution. In Figure 5.2, we subtract the data in Figure 3.1 from the data in Figure 5.1 to do so. Given the considerable number of kebeles that had reduced cropland areas over the nine years between the two study periods (Table 3.1), it is not unexpected that there are places that appear to have converted land to cropland above our calculated

[8] Some woredas had negative values for the term inside the square root of the quadratic formula. For those, we adjusted the estimate of Xβ so that the square root equaled 0.

[9] Although the maximum cropland area appears to be near to zero in kebeles in the border area between Oromiya and Somali regions, it is important to note that this is a reflection of a lower bound constraint on the regression parameter.

maximum cropland area. Figure 5.2 shows that selected kebeles have land being converted to other uses than cropping. These kebeles that are saturated or over saturated in terms of land under crops are in both the highlands and along the borders with the Somali region.

Figure 5.2. Map of cropped area expansion potential



Source: Authors' calculations using MODIS Land Cover type product

Despite the number of kebeles that are at or past their calculated maximum cropland area, there are also a lot of areas that are substantially below this cropland saturation point. These areas, without any intervention, could easily expand cropland in coming years. Appropriate policies could be implemented to facilitate cropland expansion in these kebeles, such as improving connectivity and investment in rural towns.

Table 5.2 summarizes the results presented in Figures 5.1 and 5.2 by highlands and lowlands. The highly cultivated highlands could convert an extra 9.8 percent of their total kebele areas to cropland. Currently, just over 40 percent of the total land area is in cropland, so this would involve increasing cropland by approximately one fourth. However, the lowlands could expand by almost 20 percent of their total area. Since in the lowlands currently only 16 percent of the land is under crops, this would represent an increase of cropland area in the lowlands by 117 percent.

Table 5.2. Cropland, current area and potential area, by highlands and lowlands

	% of total area		
	Current cropland	Potential cropland	Potential expansion %
Lowlands	15.9	35.7	19.7
Highlands	40.5	50.4	9.8
Ethiopia	37.0	48.3	11.2

Source: Authors' calculations using MODIS Land Cover type product

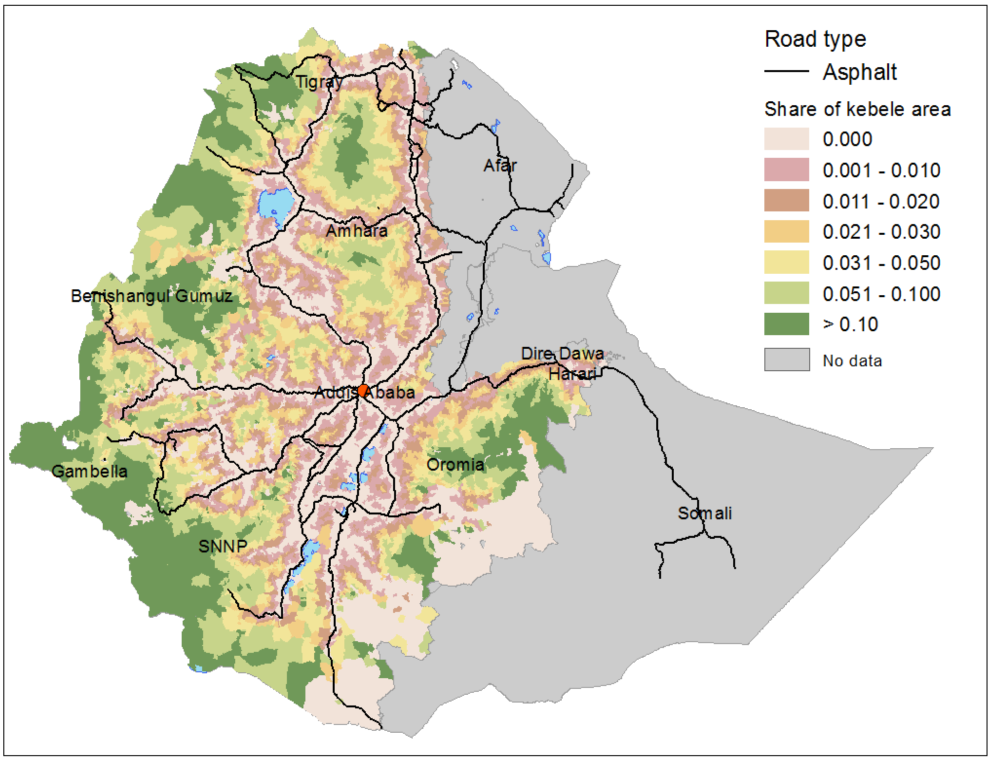
Seen from another perspective, the percent of land area in cropland is more than 150 percent higher in the highlands than in the lowlands. Moreover, the potential for putting land under crops is also higher in the highlands than in the lowlands, but by a lesser factor of just over 40 percent. However, given the current state of cropland area in Ethiopia, the percent potential expansion is 50 percent higher in the lowlands than in the highlands.

Potential to increase the steady state cropland maximum

It is not possible for policy makers to change the climate or terrain sufficiently to change the maximum steady state value of cropland potential for each kebele. However, it is possible to implement policies that better connect rural areas to markets. In the regression results presented in Table 5.1, this idea is proxied in the travel time to cities of 20,000 or more people. The idea is not to force the establishment of towns of this size, per se, but rather to increase the access of farmers to places where they can buy inputs and household items and sell their farm produce and other items. Access to information and other amenities that urban areas bring to nearby rural areas also influences productive farmland potential.

To assess the potential for agricultural expansion given improvements in accessibility, we simulate the effect of improved access to markets by equating any kebele that had a travel time to the nearest urban area of more than 3 hours to be equivalent to 3 hours. This is the definition used in Ethiopian analyses to define "peri-urban" areas. We then re-evaluated, C, the proportion of total land in a kebele under crops, using the equation for steady state. We subtract the cropland expansion potential under a simulated environment of all kebeles being within 3 hours travel time to a city of at least 20,000 from the current steady state of cropped area presented in Figure 5.1. The result of this simulation is presented in Figure 5.3.

Figure 5.3. Map of potential increase in steady state of cropped area by improving connectivity to markets



Source: Authors' calculations

Our simulation results suggest a potential for huge increases in cropped area in the western border areas of Ethiopia that previously had no potential. This simply points to the importance of connectivity to establishing the potential for putting land under crops, in addition to important biophysical features that play a key role in defining the upper bound of cropland potential. We also note in Figure 5.3 that there would be very little change in the area of land that potentially could be put under crops in much of the highlands and particularly along major highways, as these areas already are reasonably well connected.

Table 5.3 shows the differences such a scenario would make between the highlands and lowlands. Clearly the lowlands would benefit the most, with an additional 7 percent of its total area that could be used for cropland. The highlands would only increase total cropland area by less than 2 percent through better connectivity.

Table 5.3. Change in cropland potential with improved connectivity

	% of total area		
	Potential cropland	**Potential with better connectivity**	**Potential expansion %**
Lowlands	35.7	42.6	6.9
Highlands	50.4	52.1	1.7
Ethiopia	48.3	50.8	2.5

Source: Source: Authors' calculations

6. CONCLUSION

Agricultural production in Ethiopia has increased at an impressive rate over the last several decades due to yield increases through improved technology adoption and agricultural area expansion. Most growth occurred in the highlands of Ethiopia, which accounts for 92 percent of total cultivated cereal area. According to satellite data analysis, agricultural area expansion in the highlands is reaching its maximum potential, especially in the drought-prone highland areas. In order to maintain current agricultural growth rates, it will be important for Ethiopia to think strategically and spatially about future agricultural productivity.

Previous research has highlighted the risk of ongoing population pressure in the agricultural highlands, causing a shrinking of farm sizes with smallholder farmers responding by decreasing fallow periods and using unsustainable cultivation practices. An extensive literature has evaluated soil degradation outcomes due to unsustainable cultivation practices in Africa that leads to decreases in overall productivity (Schmidt et al. 2017; Drechsel et al. 2001; Tittonell and Giller 2013).

Although Ethiopia's crop cultivation potential is largely constrained to the highland plateaus due to reliance on rainfed agriculture processes, specific areas in Ethiopia's lowlands have potential for agricultural area expansion, along with some underutilized highland areas. In coming years, connecting lowland areas to vital infrastructure will be necessary to create the conditions necessary to hasten agricultural development in such areas. The potential for smallholder expansion in the more remote locations of Ethiopia could be more attractive given a concerted effort in developing transportation or irrigation infrastructure. Meanwhile, in the densely populated highlands, a focus towards agricultural intensification coupled with sustainable land management campaigns will be necessary to maintain the recent agricultural performance experienced by smallholders in the moisture reliable agro-ecological zones of the highlands.

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APPENDICES

Appendix Table A1. Characteristics of agro-ecological zones of Ethiopia

	Highlands			Lowlands	
	Drought prone	Rainfall sufficient, cereal	Rainfall sufficient, enset	Drought prone, pastoralist	Humid rainfall sufficient
Rainfall, mean annual, mm	861	1,326	1,320	632	1,144
Elevation, mean, meters	2,014	2,051	1,919	1,013	997
Travel time to a city with population of more than 20,000 persons, mean, hours	3.2	3.3	2.5	8.6	7.1
Population density, persons per sq.km.	423	324	448	82	224
Population 2016, millions					
Total	19.3	34.3	16.7	12.6	3.7
Urban	3.1	5.1	2.5	1.8	0.8
Rural	16.2	29.3	14.3	10.8	2.9
Total land area, sq.km.	128,115	226,929	65,192	574,305	133,980
Woredas, number	146	264	126	139	52

Source: Authors' calculation using a variety of remote sensing datasets including Jarvis et al. (2008), Bright et al. (2012), Funk et al. (2017), and CSA (2013)

Appendix Table A2. Changes in crop area 2001-04 to 2009-13

	Percentage of kebeles with declines more than 6 percent					
	Tigray	SNNP	Amhara	Oromiya	Other	Total
2001-04 to 2005-09	34.2	17.2	11.4	18.0	9.2	16.7
2005-09 to 2009-13	17.3	24.7	23.1	11.6	3.9	17.1
2001-04 to 2009-13	24.3	22.5	11.3	12.0	7.7	14.7
Average annual growth in crop area, percent						
2001-04 to 2005-09	2.7	1.2	3.9	2.1	-1.5	2.7
2005-09 to 2009-13	0.1	-1.1	0.8	3.2	4.0	1.2
2001-04 to 2009-13	1.2	0.0	2.1	2.3	1.1	1.8
Total 2001 to 2013	11.6	0.3	20.3	23.2	10.3	17.0

Source: Authors' calculations

Appendix Table A3. Regression covariates, 10th percentile, median, and 90th percentile values

	10th percentile	median	90th percentile
Initial cropland proportion	0.020	0.303	0.669
Population density in 2000, persons per sq.km.	17.875	94.581	348.71
Precipitation (June to September), meters	395.71	712.607	1101.2
Coefficient of variation for precipitation	0.086	0.150	0.225
Belg cropping (two growing seasons), 0/1	0	0	1
Maximum temperature (June to September), °C	21.963	25.419	30.988
Terrain roughness measure	34.839	115.514	257.100
Elevation, kilometers	1344	1936	2654
Reduction in travel time to town	0.017	1.25	7.1
Hours to town of 20,000+	1.183	4.4	13.083
National park, 0/1	0	0	0

Source: Authors' calculations

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The Ethiopia Strategy Support Program is an initiative to strengthen evidence-based policymaking in Ethiopia in the areas of rural and agricultural development. Facilitated by the International Food Policy Research Institute (IFPRI), ESSP works closely with the government of Ethiopia, the Ethiopian Development Research Institute (EDRI), and other development partners to provide information relevant for the design and implementation of Ethiopia's agricultural and rural development strategies. For more information, see http://www.ifpri.org/book-757/ourwork/program/ethiopia-strategy-support-program; http://essp.ifpri.info/; or http://www.edri-eth.org/.

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