PART 1

Natural Resources and Production

Chapter 2

CROPLAND EXPANSION

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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 2016). Under the strategy of agriculture development–led industrialization (ADLI), agricultural production in Ethiopia increased substantially, with increases in agricultural GDP averaging 7 percent per year between 2004/2005 and 2013/2014.[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.

Increases in agricultural production via agricultural expansion is not unique to Ethiopia. A variety of analyses have evaluated land use expansion and expansion potential within Africa south of the Sahara (SSA). Brink and Eva (2009) used historical satellite images to evaluate landcover change in SSA and concluded that agricultural area expanded by 57 percent, while natural vegetation decreased by 21 percent in SSA between 1975 and 2000. Deininger et al. (2011) use geospatial data to estimate potential crop area expansion in SSA, and find large potential for expansion of agricultural cropland overall in Africa, but with significant differences between African regions. Chamberlin, Jayne, and Headey (2014) find that SSA land resources are concentrated in a

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[1] GDP growth occurred throughout the economy over the past decade. Large increases were also seen in the industry and services sectors, which grew at approximately 14 percent and 13 percent per year, respectively, between 2004/2005 and 2013/2014. Given the growth in industry and services, agriculture's share of GDP has fallen over the past decade. However, agriculture remains an important driver of economic growth and employment (Schmidt and Bekele 2017).

few countries and currently are comprised of forested areas that would require significant development investments. Van Ittersum et al. (2016) pose the question of whether SSA will be able to achieve cereal self-sufficiency (approximately 80 percent) by 2050 considering current population growth rates. They find sobering evidence suggesting that a major effort to increase crop production via intensification will be necessary to avoid massive cropland expansion (with significant environmental costs) and a heavy dependence on imports of cereals.

While the Ethiopian highlands have benefited from impressive growth in agricultural production during the past several decades, recent studies have identified some of the costs of agricultural extensification. Farmers are cultivating on steeper slopes in the highlands without using proper sustainable land management techniques—that is, 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 (Tschopp et al. 2010).

Agricultural intensification, in particular increased input use, has contributed to important increases in overall production volumes (see Bachewe et al. 2015 and 2018; Chapter 3 of this book); however, microlevel analysis suggests intensification may not be enough to continue the agricultural GDP growth witnessed in previous decades. Although Headey, Dereje, and Taffesse (2014) find evidence to support Boserup's hypothesis of greater agricultural intensification strategies within land-constrained villages, they do not find increases in household income due to greater adoption of agricultural inputs in Ethiopia. Similarly, Josephson, Ricker-Gilbert, and Florax (2014) reported that smaller farm sizes had a positive influence on input demand; however, increased input use did not correspond to an increase in staple crop yields in Ethiopia, suggesting that farmers may be addressing declines in soil fertility with increasing inputs but only managing to maintain a base level of productivity.

Options for relieving rural agricultural land pressures in Ethiopia are few. Agriculture is the primary source of income for most Ethiopians and nonfarm employment remains limited throughout the rural highlands.[2] Moreover, the

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[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.

potential for rural–rural migration to seek out less densely populated agricultural areas is constrained by current land tenure restrictions that permit usufruct land rights; however, these do not guarantee ownership if an individual is not seen to be working on their own land (Diao et al. 2013). Gebregziabher and Holden (2011) reported a need to facilitate land rental markets due to evidence of land rental being used as a last-resort coping mechanism after depleting other household resources (livestock, firewood, reducing household consumption). Recent studies have shown an increase in rural–urban migration of youth (particularly in the highlands) due to agricultural land scarcity; however, tenure security in urban areas remains a challenge for recent migrants as well (Moller 2012; Bezu and Holden 2014).

Understanding the potential for further agricultural expansion within Ethiopia is necessary to inform investment priorities aimed at maintaining agricultural performance. We build upon studies such as Chamberlin, Jayne, and Headey (2014) and Deininger and Byerlee (2011) that employ remote sensing data on land cover and other biophysical and economic data to estimate unused potentially arable cropland across Africa south of the Sahara (SSA). As Chamberlin, Jayne, and Headey (2014) establish, calculation of available cropland is very sensitive to model assumptions of potential availability. These results are illustrative when comparing across the region as a whole; however given the global nature of their studies, they are unable to evaluate more localized, potentially arable cropland within-country.

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 define a spatial regression to identify correlates of crop area expansion at the kebele (subdistrict) level considering current estimates of cropped area within the kebele. Finally, we calculate the maximum potential for cropland expansion, controlling for a collection of biological and economic 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 agroecological 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 as well as linking the newly expanded agricultural areas to input and output markets.

The remainder of the chapter provides a background to Ethiopia's agricultural production, including a description of the country's diverse agroecological zones; evaluates Ethiopia's agricultural landscape at the disaggregated kebele level, using satellite landcover data to characterize agricultural area expansion over the past decade; 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; and provides results and discussion. The final part of the chapter concludes.

Agricultural Production in Ethiopia

Since 2004/2005, the agricultural sector in Ethiopia has performed well. The increase in agricultural GDP (approximately 7 percent per year during the period from 2004/2005 to 2013/2014) 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 percent and 28 percent, respectively, to agricultural growth (Table 2.2). Cereals generated more than half of crop GDP growth between 2004/2005 and 2015/2016. The five major cereals (teff, barley, wheat, maize, and sorghum) constitute 73 percent of total cultivated area (Ethiopia, CSA 2015/2016).

In a country where rainfed agriculture is the predominant production system, agroecological 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, are more densely populated and reflect the physical and climatic advantages that led to the country's agricultural development (Figure 2.1).[3] 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, Ricker-Gilbert, and Florax 2014; Headey, Dereje, and Taffesse 2014).

Most agricultural production is in the country's highlands, which constitutes the breadbasket of the country, where 90 percent of the area planted

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

TABLE 2.1 Subsectoral contributions to real agricultural GDP, 2004/2005–2015/2016 (%)

	Initial agricultural GDP share	Final agricultural GDP share	Contribution to increase in agricultural GDP
Indicator	2004/2005	2015/2016	2004/2005–2015/2016
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: Authors' calculations using data from national accounts (Ethiopia, CSA 2016) and Agricultural Sample Survey reports (Ethiopia, CSA various years).

Note: Shares calculated using constant factor cost GDP.

TABLE 2.2 Contribution of cereals and noncereals to agricultural GDP change, 2004/2005–2013/2014 (%)

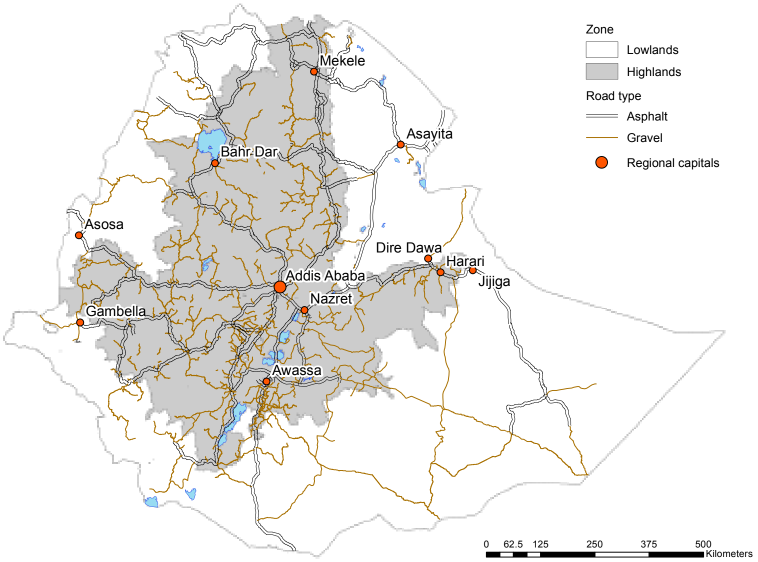
Indicator	All crops	Cereals	Noncereals
Share of agricultural GDP in 2004/2005	100.0	56.2	43.8
Share of agricultural GDP in 2013/2014	100.0	54.9	45.1
Contribution to total agricultural GDP	100.0	53.8	46.2
Increase in crop yields	60.3	40.7	19.7
Cultivated land expansion	27.5	15.4	12.0
Reallocating land to higher value crops	12.2	–2.3	14.5

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

to cereals is found and 89 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 94 percent of teff production and 94 percent of area dedicated to teff cultivation. In addition, highland cultivation accounts for 98 percent of total wheat production and 89 percent of total maize production.

Urbanization and population density is significantly greater in the highlands compared with the lowlands; however, a large degree of variation exists within the highland and lowland regions as well (Table 2A.1). People living in the highland areas have greater market access to urban centers (Table 2.4). While the average travel time to a city of at least 20,000 people in the highlands is approximately three hours, the average travel time to a city of at least 20,000 people in the lowlands is approximately six 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

FIGURE 2.1 Highland and lowland areas of Ethiopia



Source: Authors' calculation.

centers of this size in the lowlands.[4] The lowland areas of Ethiopia also have a sparser transportation infrastructure compared with the highlands. In the highlands road density is approximately 0.17 kilometers of road per square kilometer, while in the western areas of the lowlands (including parts of western Oromia, Gambella, and Benishangul-Gumuz regions) the road density is 0.05 kilometers per square kilometer (Figure 2.1). There are variations in climatic, demographic, and physical infrastructure within the highland and lowland regions as well (see Table 2A.1).

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, three-fourths 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

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

TABLE 2.3 Crop production and area in Ethiopia by highland and lowland areas, 2014/2015

Production (thousand metric tons)	Highlands	Lowlands	Total
All	**106,255**	**7,675**	**113,930**
Cereals	21,065	2,526	23,590
Barley	1,898	56	1,953
Maize	6,430	795	7,225
Sorghum	3,315	1,017	4,332
Teff	4,481	270	4,751
Wheat	4,132	100	4,232
Other cereals	809	289	1,098
Pulses	2,477	181	2,658
Oil Seeds	498	262	760
Other crops	54,324	2,589	56,912
Permanent crops	27,892	2,118	30,010
Area (thousand hectares)			
All	**12,537**	**1,618**	**14,155**
Cereals	9,102	1,034	10,136
Barley	961	33	994
Maize	1,840	266	2,106
Sorghum	1,447	381	1,829
Teff	2,835	181	3,016
Wheat	1,622	42	1,664
Other cereals	398	131	529
Pulses	1,441	103	1,544
Oil Seeds	519	336	856
Other crops	301	20	321
Permanent crops	1,173	124	1,297

Source: Authors' calculations using Agricultural Sample Survey 2014/2015 (Ethiopia, CSA 2016).

Note: Other cereals = rice, millet, and oats. Other crops = vegetables, root crops, and other temporary crops.

evaluate the expansion in agricultural land throughout Ethiopia during the past decade and estimate the potential for further expansion using a spatial regression approach.

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

TABLE 2.4 Characteristics of highland and lowland areas of Ethiopia

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

Source: Authors' calculations using a variety of remote sensing datasets including Jarvis et al. (2008), Bright, Rose, and Urban (2013), Funk et al. (2015), and Ethiopia, CSA (2013).

Ethiopia. A total of 17 landcover classes have been identified, including croplands and a cropland/natural vegetation mosaic classification, at a 500-meter resolution for the 2001–2013 period (see Friedl et al. [2010] for more details). The MODIS Land Cover Type product is derived from a year (during the years of 2001 to 2013) of observations collected from the Terra- and Aqua-MODIS sensors, satellites that view the entire Earth's surface every one to two days.

Although the MODIS Land Cover Type product (and similar remotely sensed data products) provides the ability to analyze year-to-year changes in landcover, there are several limitations to this dataset that are important to recognize, which we attempt to overcome with our analysis. 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. Given the multispectral mode of the MODIS sensors, satellite imagery of the Earth cannot be observed through clouds, dust, or other atmospheric factors. This lack of data in certain areas given differences in weekly/monthly/yearly weather conditions introduces noise in the data that may result in perceived landcover changes that do not exist in reality. Another source of data error in landcover analysis is the relatively low spatial resolution of satellite input data (in this case at a 500-meter resolution for the 2001–2013 period). Lower-resolution imagery presents several challenges: (1) in areas of low agricultural intensification, it is difficult to distinguish between croplands and grasslands; (2) in areas with complex landscapes, lower-resolution imagery has difficulty capturing intercropped agricultural systems. Finally, highly divergent results have been reported in published landcover datasets due to differences in classification algorithms, different satellite sensors used to collect primary imagery, and different datasets used to train the landcover identification algorithms.[5] Taking into account these challenges, remote sensing data provides the opportunity for an objective, frequent, and consistent measure of landcover over time; however, ground-truthing is also important to verify satellite interpretations and analysis. Patil and Gumma (2018) provide a comprehensive review of different landcover data products and their advantages and disadvantages.

We take into account the inadequacies in remote sensing data in this analysis in several ways. First, rather than evaluate each year of landcover output produced by the MODIS Land Cover Type product, we average total landcover area values by kebele (subdistrict) and average values over three periods: early (2001–2004), middle (2005–2009), and late (2010–2013). In doing so, we attempt to reduce noise in the landcover data due to differences in weather patterns, cloud cover, time of day of the satellite pass, and data collection accuracy. Second, it is important to note that 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 to account for the difficulty of distinguishing between croplands and other similar landcover types (scrub, grasslands, and so on). Finally, we report descriptive statistics at an aggregated highlands and lowlands level considering recent analysis that finds improved accuracy of cropland acreage at higher levels of aggregation (Leroux et al. 2014).

Landcover analysis of Ethiopia during the 2010–2013 period suggests that most cropped area is in the highlands. Kebeles in the Amhara region have the greatest share of land under agriculture, with more than 60 percent of total land area dedicated to agricultural uses (Figure 2.2). Kebeles in central Oromia and northeast Southern Nations, Nationalities, and Peoples (SNNP) region have between 50 percent and 70 percent of total land area dedicated to

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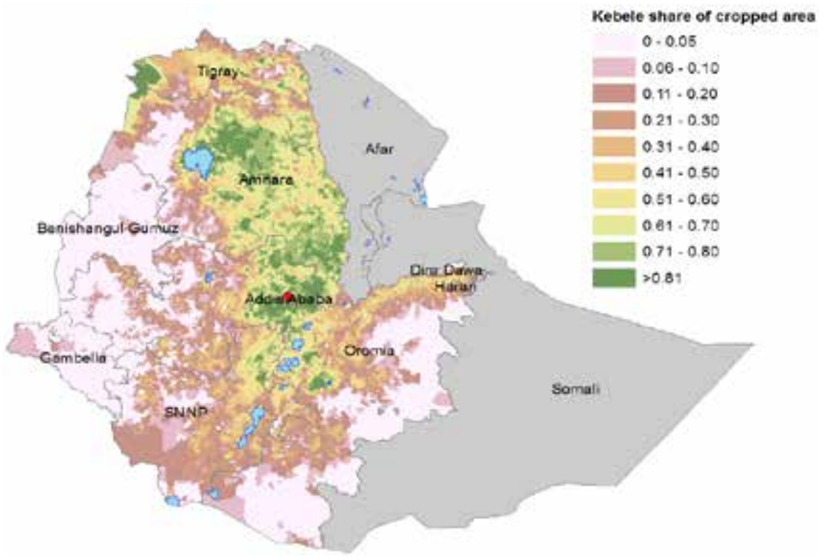
[5] For example, GlobCover cropland distribution estimates are 20 percent higher than MODIS-derived global cropland area estimates (Patil and Gumma 2018).

FIGURE 2.2 Map of average share of area cropped, 2010–2013



Source: Authors' calculations using MODIS Land Cover type product.
Note: SNNP = Southern Nations, Nationalities, and Peoples.

crop cultivation. In contrast, kebeles in the lowlands have very little area dedicated to cultivation.[6]

Changes in cropped area in Ethiopia show varying spatial patterns over time. Looking at changes between the first (2001–2004) and second (2005–2009) 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 (2010–2013) period were greater in the lowlands of northwest Amhara region and in the far western kebeles of Tigray region (Table 2A.2). 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 2001–2004 to 2010–2013 (Table 2.5).[7]

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

[7] Evaluating by region, the greatest growth in crop area occurred in the Amhara and Oromia regions, which increased by 2.1 percent and 2.4 percent, respectively, over the 2001–2013 period (Table 2A.2).

TABLE 2.5 Changes in crop area in Ethiopia, 2001/2004–2010/2013

Indicator	Highlands	Lowlands	Total
Percentage of kebeles with declines in crop area of 5 percentage points or more			
2001–2004 to 2005–2009	21.3	6.9	19.3
2005–2009 to 2010–2013	19.2	23.5	19.8
2001–2004 to 2010–2013	17.3	14.0	16.8
Average annual growth in crop area (%)			
2001–2004 to 2005–2009	2.2	5.6	2.7
2005–2009 to 2010–2013	1.1	0.2	1.0
2001–2004 to 2010–2013	1.6	2.6	1.8
Total percentage point change in cropland area, 2001–2013	4.8	2.4	3.8

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 2001–2004 to 2005–2009, this annual growth decreased to 1.1 percent from 2005–2009 to 2010–2013 (Table 2.5). Similarly, 21 percent 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 2001–2004 and 2005–2009, although average annual growth in crop area there dropped considerably to 0.20 percent between 2005–2009 and 2010–2013. This pattern may be due to droughts in 2009/2010 and 2010/2011 that affected areas of southern Ethiopia and lowland Oromia, Tigray, and Somali regions (Viste, Korecha, and Sorteberg 2012).

Overall, between 2001–2004 and 2010–2013, average annual growth in crop area was 2.6 percent in the lowlands and 1.6 percent in the highlands. This suggests that, although highland agriculture is the preferred location for production, there may be limited area in which to expand farther 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.

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, and the like (see Friedl [2010] for details), from 2001 through 2013 at a 500-meter resolution, we evaluate the change observed in cultivated area between the period of 2001–2004 and 2010–2013 at the kebele (subdistrict) 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, 2001–2004 and 2010–2013, to reduce noise in the satellite reflectance values and to aid data interpretation. Finally, we subtract the share of cropland area calculated for the 2001–2004 period from the share of cropland area calculated for the 2010–2013 period by kebele to determine the change in the share of total area under crops in each kebele between the two time periods. 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 (2001–2004) as well as its squared term as explanatory variables (median and 10th and 90th percentile values of regression covariates are reported in Table 2A.3).

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 past 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 1-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 Ethiopia's 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. A more in-depth discussion of the market access variable construction used in this chapter is provided in Chapter 12 of this volume.[8] Given that we are evaluating change in agricultural area between 2001–2004 and 2010–2013, 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,

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[8] We construct three separate market access measures. The 2001 market access grid was built from a roads database constructed for the 1997 census and updated to reflect city size targets from 2001. The second market access measure is constructed from the 2007 roads database and uses the same methodology as that of 2001; however, newly constructed and improved roads are included to reflect the road network of 2007 and city population of 2007. Finally, a 2013 roads database is constructed from the 2007 roads data by updating road infrastructure to the 2013 level using Google Earth satellite imagery and 2013 city population.

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 biological and economic variables as described above, β is the vector of parameters to be estimated, and ϵ is the error vector.[9] The steady state maximum is found when $\Delta C = 0$.

We control for potential spatial dependence that may be present in ordinary least squares model estimates by using 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 (that is, 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 that 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

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

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[9] This particular specification derives from a dynamic model of a representative farm in which there is an increasing cost in clearing land and which has a production function with decreasing marginal returns in land, except that by allowing for a quadratic specification, we acknowledge the possibility that for very low levels of cropland, the function might have increasing returns.

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 in comparison with the full spatial case where, if ΔC for the neighboring spatial units are not approaching zero, 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.

Results

Table 2.6 presents the results of running the regression with spatial parameters restricted to non-negative values.[10] Table 2A.3 gives the median, 10th percentile, and 90th percentile values of the regression covariates. 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 2001–2004 period 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

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[10] 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.

TABLE 2.6 **Factors associated with change in proportion of kebele area in cropland in Ethiopia**

Variable	Parameter	Standard error	
Initial cropland proportion	0.0173	0.0108	
(squared)	–0.1594	0.0140	***
Population density in 2000, persons per square kilometer	–5.05E-06	1.01E-06	***
(squared)	6.64E-11	1.82E-11	***
Precipitation (June–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–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.

kebele with approximately two-thirds of its land under crops. Compared with 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.

Precipitation is also an important influencer of the likelihood of increasing cropped area. Cropped area expansion increases with greater rainfall until reaching approximately 820 millimeters 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 millimeters) 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 millimeters 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 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 2A.3 for 10th percentile, 90th percentile, and median values of the covariates). As average terrain roughness increases (measured first as the range of elevation within a 1 kilometer 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 those with 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 (that is, 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 included in the regression. A steady state would be reached in each kebele when the dependent variable—the change in cropland—would become zero. 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 zero. We use the regression parameters in Table 2.6 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.[11]

Figure 2.3 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 Oromia bordering Somali region.[12]

We compare the current reality with the calculated steady state solution. In Figure 2.4 we subtract the data in Figure 2.2 from the data in Figure 2.3 to do so. In our landcover dataset we observed many kebeles reducing the amount of cropland over time (Table 2.5). Therefore it is not surprising that Figure 2.4 shows a number of kebeles that have exceeded what we calculated as their maximum cropped area potential. Such kebeles are in both the highlands and along the borders with the Somali region. Kebeles might exceed the maximum cropped area because of the errors inherent in the statistical estimates but could also be because of several viable explanations on the ground. First, the profitability of the land could be lower than what farmers assessed it to be due to prices or soil fertility changing over time—or even a miscalculation by the farmers themselves when clearing the land. Second, the labor force size could have decreased in the kebele, reducing the optimal quantity of land required. Third, there could be shifting of optimal crops, which may cause a reduction in land needed. Fourth, forests or agroforests could have become more attractive due to prices for their products or value of their services to the households.

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

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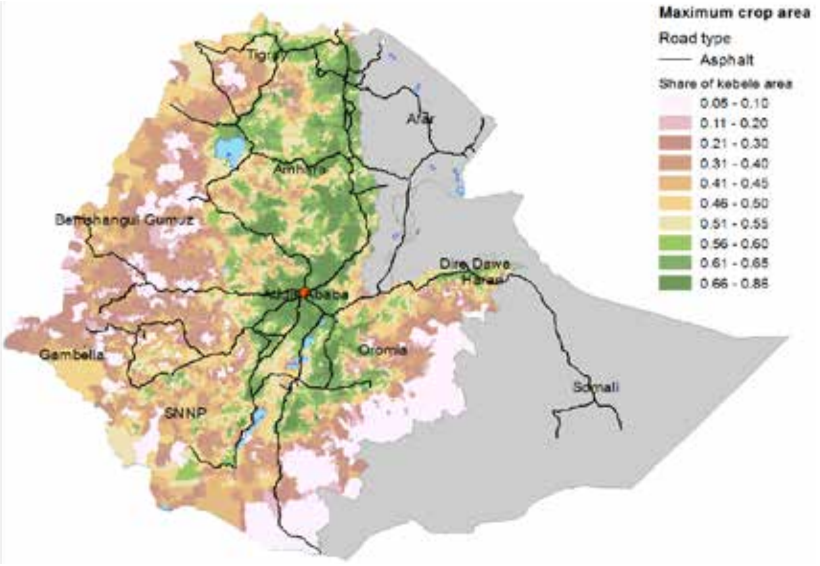
[11] Some woredas had negative values for the term inside the square root of the quadratic formula. For those, we adjusted the estimate of $X\beta$ so that the square root equaled zero and therefore were assigned a maximum cropland area of 5.4 percent.

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

FIGURE 2.3 Map of calculated maximum cropland area in Ethiopia



Source: Authors' calculations using MODIS Land Cover type product.
Note: SNNP = Southern Nations, Nationalities, and Peoples.

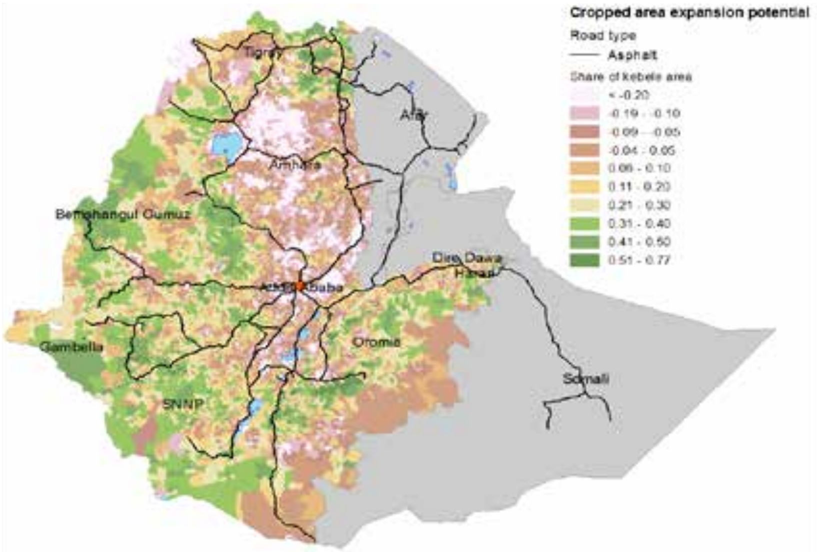
implemented to facilitate cropland expansion in these kebeles, such as improving connectivity and investment in rural towns.

Table 2.7 summarizes the results presented in Figure 2.3 and Figure 2.4 by highlands and lowlands. The highly cultivated highlands could convert an extra 9.8 percent of their total kebele areas to cropland. Currently, just more than 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.

Seen from another perspective, the percentage 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 60 percent. However, given the current state of cropland area in Ethiopia, the percentage of potential expansion is near 60 percent higher in the lowlands than in the highlands.

We wanted to see how sensitive the results were to assuming that maximum cropland area was 5.4 percent for those with very low values for *XB*

FIGURE 2.4 Map of cropped area expansion potential in Ethiopia



Source: Authors' calculations using MODIS Land Cover type product.
Note: SNNP = Southern Nations, Nationalities, and Peoples.

TABLE 2.7 Cropland, current area and potential area, by highlands and lowlands in Ethiopia

	Percentage of total area		
Region	Current cropland	Potential cropland	Potential expansion
Lowlands	11.6	29.3	17.7
Highlands	35.9	47.1	11.1
Ethiopia	26.4	40.1	13.7

Source: Authors' calculations using MODIS Land Cover type product.

(a measure of profitability). As an alternative, we assumed the maximum cropland area was zero (a lower bound to the upper bound assumption of 5.4 percent). We found small reductions in the aggregate, with potential cropland at 27.7 percent for the lowlands, 46.8 percent for the highlands, and 39.3 percent for the whole country.

We also experimented with different functional forms. First, we endeavored to keep the contribution of the profitability measure in the positive realm by exponentiating *XB* and linearizing the effect of cropland and rate of change in cropland. We did this with the *nl* command in Stata, so we were no longer able to control for any spatial autocorrelation. While the absolute level of predicted conversion was greater with this specification than with the original quadratic, the general results held that there was greater expansion potential in the lowlands than in the highlands and that there are kebeles that have exceeded the predicted maximum cropland.[13]

Potential to Increase the Steady State Cropland Maximum

It is not possible for policymakers 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 2.6, 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 three hours to be equivalent to three hours. We use three hours' travel time as a threshold for peri-urban areas assuming return travel to a market from this time distance would require a day of travel and a maximum for frequent commuters (Kedir, Schmidt, and Waqas 2016). 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 three hours travel time to a city of at least 20,000 from the current steady state of cropped area presented in Figure 2.3. The result of this simulation is presented in Figure 2.5.

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.

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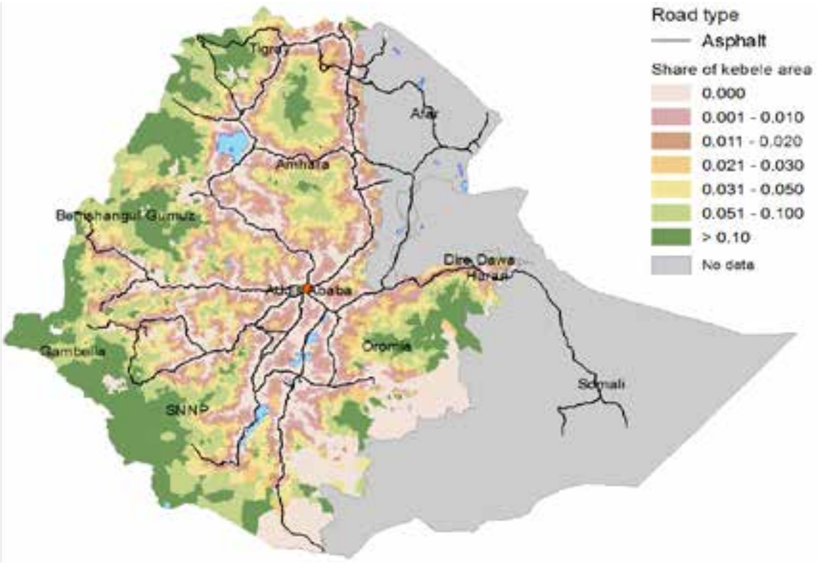
[13] Two other variations were also tried. They involved logitizing XB and keeping linear slopes, and logitizing both XB and slope. The qualitative results were the same even though the predicted quantities of maximum cropland varied.

FIGURE 2.5 Map of potential increase in steady state of cropped area by improving connectivity to markets



Source: Authors' calculations.
Note: SNNP = Southern Nations, Nationalities, and Peoples.

We also note in Figure 2.5 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 2.8 shows the differences such a scenario would make between the highlands and lowlands. Column A provides the maximum share of total area that could be expanded (considering current biological and economic conditions) under the analysis presented in the regression results explained in Table 2.6 and Table 2.7. Assuming improved connectivity, the lowland areas could expand an extra 6.9 percent of the total (maximum) potential for cropland reported in Table 2.7 by improving travel time for all rural inhabitants to reach a market within three hours (Table 2.8).[14] The highlands would only

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[14] Taking into account that the lowlands could expand from the current 11.6 percent of land area under crops (Table 2.7) to the maximum potential area at current state (current road

TABLE 2.8 Change in cropland potential with improved connectivity in Ethiopia

	Percentage of total area		
Region	A Potential cropland	B Potential with better connectivity	C Potential expansion
Lowlands	29.3	37.9	8.6
Highlands	47.1	50.3	3.2
Ethiopia	40.1	45.4	5.4

Source: Authors' calculations.

Note: Potential with better connectivity is maximum cropland potential if distance to market is no longer a major constraint. Potential expansion percent is the difference of columns B and A.

increase total cropland area by 3.2 percent based on our model of improved road connectivity. Given that the highlands cropland area is already used and connected to a market of at least 20,000 people (within three hours), improvements in road infrastructure do not have as great an effect on highland areas compared to lowland areas.

Conclusion

Agricultural production in Ethiopia has increased at an impressive rate over the past 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. 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

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infrastructure) of 29.3, we find the highlands could expand cropland a further 8.6 percent assuming improved road infrastructure. Total expansion possibility under this scenario compared to current state would amount to 17.7 + 8.6 = 26.3 percent greater area under crop agriculture.

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 underused 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 toward agricultural intensification coupled with sustainable land management campaigns will be necessary to maintain the recent agricultural performance experienced by smallholders in the moisture reliable agroecological zones of the highlands.

Appendix 2A: Agroecological Zones, Crop Area Changes, and Regression Covariates

TABLE 2A.1 Characteristics of agroecological zones of Ethiopia

	Highlands			Lowlands	
Characteristic	Drought prone	Rainfall sufficient, cereal	Rainfall sufficient, enset	Drought prone, pastoralist	Humid rainfall sufficient
Rainfall, mean annual (millimeters)	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 square kilometer)	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 (square kilometers)	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, Rose, and Urban (2013), Funk et al. (2015), and Ethiopia, CSA (2013).

TABLE 2A.2 Changes in crop area in Ethiopia, 2001–2004 to 2009–2013 (%)

	Percentage of kebeles with declines more than 6%					
Time Period	**Tigray**	**SNNP**	**Amhara**	**Oromia**	**Other**	**Total**
2001–2004 to 2005–2009	37.8	20.3	13.3	20.8	10.1	19.3
2005–2009 to 2009–2013	19.6	28.4	26.5	13.5	4.2	19.8
2001–2004 to 2009–2013	26.7	25.1	12.6	14.1	9.4	16.8
Average annual growth in crop area (%)						
2001–2004 to 2005–2009	2.7	1.2	3.9	2.2	–1.7	2.7
2005–2009 to 2009–2013	0.1	–0.9	0.6	2.5	3.6	1.0
2001–2004 to 2009–2013	1.2	0.0	2.1	2.4	1.2	1.8
Total 2001–2013	**4.2**	**0.1**	**8.2**	**3.9**	**0.2**	**3.8**

Source: Authors' calculations.

Note: SNNP = Southern Nations, Nationalities, and Peoples.

TABLE 2A.3 Regression covariates, 10th percentile, median, and 90th percentile values

Indicator	10th percentile	median	90th percentile
Initial cropland proportion	0.020	0.303	0.669
Population density in 2000 (persons per square kilometer)	17.875	94.581	348.71
Precipitation (June–September) (meters)	395.71	712.607	1,101.2
Coefficient of variation for precipitation	0.086	0.150	0.225
Belg cropping (two growing seasons), 0/1	0	0	1
Maximum temperature (June–September), °C	21.963	25.419	30.988
Terrain roughness measure	34.839	115.514	257.100
Elevation (kilometers)	1,344	1,936	2,654
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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