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Research, part of a Special Feature on Land Acquisitions, Well-being, and Environment

Climate change, degradation, and land acquisitions: evaluating inequalities among competing interests for suitable cropland in Ethiopia

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ABSTRACT. Land is the central resource for agriculture. In many parts of Sub-Saharan Africa (SSA), where a large portion of the population relies on agriculture for subsistence and household incomes, future declines in the productive capacity of the land owing to environmental change pose a major threat both to farming and the well-being of smallholders. Smallholders' access to land is concurrently at risk due to large-scale land acquisitions (LSLA), promoted by governments across SSA as a means to secure capital investments for agricultural growth and economic development. These issues are especially widespread in Ethiopia, which has faced both extensive land degradation and been a primary target country for LSLA investments. This study analyzes the relative quality of land under the control of smallholders vs. large investors in western Ethiopia, with particular attention to how future suitability of land is likely to change for growing three major smallholder crops: Maize (*Zea mays*), sorghum (*Sorghum bicolor*), and beans (*Phaseolus vulgaris* L.). Spatial analyses are applied to compare the suitability in areas allocated to LSLAs and the remaining land available to smallholders in the country's western farming systems. Crop-specific suitability datasets are used to approximate the change in land quality between baseline conditions and scenarios of future climate change to assess the effects of climate-induced land degradation. Results indicate large areas of decreasing suitability by the late 21st century for all crops across Ethiopia. Furthermore, this study shows that LSLA occupy land with more stable suitability, suggesting more secure agricultural land is being offered to investors.

Key Words: *climate change; crop suitability; land acquisition; land degradation; Sub-Saharan Africa*

INTRODUCTION

Arable land constitutes one of the most critical resources for smallholder farmers in Sub-Saharan Africa (SSA). More than half of the labor force in countries such as Ethiopia depend on agriculture for their livelihood (OECD-FAO 2016). Even with the emphasis that country governments in the region have placed on structural transformation and economic diversification, land remains of central importance because of its significance for the agricultural sector, employment, and economic growth (Tomšík et al. 2015, Usman and Landry 2021). However, the region now confronts demographic, structural, and adverse environmental changes that jeopardize the productivity of arable land and the subsistence of smallholder farmers.

Land degradation, defined by the United Nations Convention to Combat Desertification (UNCCD) as a reduction in land's biological and economic productivity, has become a pervasive issue in many parts of SSA (Nkonya et al. 2008). Exploitative agricultural practices drive ongoing declines in productivity and are resulting in lower soil fertility and reductions in ecosystem health. The negative effects of unsustainable intensification methods are now compounded by climate change (IPCC 2019). Extreme weather events linked to climate change are expected to cause soil erosion, while shifts in long-term climate trends will alter the agroecological suitability of croplands, threatening to reduce yields and limit the capacity for sustainable intensification in some regions of SSA (Chijioke et al. 2011, Lobell et al. 2011, Lambin et al. 2013). Climate models predict losses in attainable yields of major crops across much of the African continent by mid-century and imply widespread reductions in actual output if current yield gaps are not closed (Pugh et al. 2016). Meanwhile, food insecurity is still a reality for many in SSA and per capita food production has declined as higher demand outpaces the increase in agricultural production (Otsuka and Kijima 2010, Chauvin et al. 2012). Intensification is imperative to support smallholder productivity and meet future food demand, but experts posit that expanded cultivation will be necessary in addition to intensification to achieve needed agricultural growth (Gibbs et al. 2010). The realities of growing demand, extensive land degradation, and climate change underscore the critical need for farmers to retain access to quality land as part of a broader strategy to address food security and poverty reduction. Only then may it be possible to adapt agriculture, secure climate resilience, and foster economic security for some of the most vulnerable populations.

Historically, SSA has been regarded as possessing large amounts of unused land (OECD/FAO 2016). Estimates of available cropland range from 247 to 800 million hectares, although much of the unused land is concentrated in relatively few countries (Fischer and Shah 2010, Alexandratos and Bruinsma 2012, Chamberlin et al. 2014, Jayne et al. 2014). Prior to emerging concerns over land availability, minimal access to inputs was a major issue that drove extensification rather than intensification from farmers seeking to increase their production. Indeed, historical growth in the region's agricultural production has relied more on cropland expansion rather than intensification. But such expansion has come at the cost of more rapid environmental change and use of marginal land that in reality is not as suitable for agriculture as had been assumed in the past. Many estimates of unused land in SSA have largely focused on ecological production potential while failing to consider aspects such as infrastructure and market access. For example, Chamberlin et al. (2014) highlighted the disregard of economic factors in many estimates of suitability of land for agricultural development and Young (2005) questioned assertions about extensive availability of agricultural land even earlier, with the observation that agricultural expansion has led to cultivation in marginal landscapes with infertile soils and steep slopes. Additionally, much of the region's uncultivated land is covered by woodlands, the clearing of which would incur major environmental costs and exacerbate degradation (Chamberlin et al. 2014). As many parts

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of SSA in fact now confront a shortage of agricultural land, average landholding size of smallholder farmers has declined and the potential for continued extensification is limited (Josephson et al. 2014). However, intensification with inadequate soil fertility management is driving ecological and agricultural land degradation (Jayne et al. 2003, Headey et al. 2014). Thus, ensuring access to land resources and promoting sustainable land management practices for smallholder farmers are both essential to bolster agricultural productivity and contribute to equitable transitions in the agricultural sector of SSA.

Beyond land degradation and scarcity, smallholders in SSA face substantial competition for cropland from investors who have leased large parcels for commercial agriculture through what are known as large-scale land acquisitions (LSLA). Although the initial perception of such investments was that governments were distributing marginal and unused land for LSLA, analyses show that investors have largely acquired more fertile land in proximity to water for irrigation and with better access to the infrastructure required to reach markets (Yassin 2010, Keeley et al. 2014, Nalepa et al. 2017). Had assumptions of abundant available cropland been accurate, host governments could grant investors privatization of fertile lands without worsening land exploitation or displacing smallholders from their livelihoods (Balehegn 2015, Chu et al. 2015). But this is clearly not the case. The substantial amounts of arable land that have been allocated to investors compels the need to assess the effects of LSLA on smallholders and the croplands on which they depend. Proponents of LSLA, including host governments, endorse these investments as an opportunity to generate employment, infuse needed capital into the agricultural sector, and improve productivity through technology transfer to local farmers (Moreda 2018, De Maria 2019). But this optimistic narrative is belied by much research on LSLA, which highlights their negative developmental outcomes on smallholder livelihoods, food security, and land availability (Balehegn 2015, Shete et al. 2016, Cochrane and Legault 2020). Indeed, allocation of scarce resources toward private investors flies in the face of evidence that improvements in small-scale agriculture rather than large-scale production have contributed substantially to achieving the development objectives of poverty reduction and food security (Deininger et al. 2011, AGRA 2018, Jayne et al. 2021).

In Ethiopia, agriculture and the status of smallholder farmers resemble many of the prevailing patterns described above. The country hosts a large number of LSLA, has experienced substantial environmental degradation, and its rural households are vulnerable to the adverse effects of both these macro-level shifts in addition to climate change threats. Recent estimates highlight an extensive decline in land productivity, with 40% of cropland and perhaps as much as 85% of Ethiopia's total land area exhibiting degradation, rendering it less suitable for cultivation (Gebreselassie et al. 2016, Zerssa et al. 2021). Such environmental conditions expose a high percentage of the population to food insecurity and chronic poverty, impeding prospects for rural economic growth (Berry et al. 2003). Moreover, monitoring the distribution and vulnerability of Ethiopia's arable land is essential to achieve national goals of enhancing the economic role of smallholder farmers, increasing resilience of agriculture to climate and environmental shocks, and reducing malnutrition (ENPC 2016; https://www.feedthefuture.gov/)

Unlike investors who can afford to implement a variety of management practices, smallholders face many barriers that make farming on marginal lands inefficient. Small farm sizes, insecure tenure, and low levels of investible capital are only some of these barriers (Bryan et al. 2009). It is therefore essential to understand where LSLA prevent smallholders from accessing agroecologically suitable land. Additionally, studies that contradict the claims made by government officials regarding the quality of land allocated to LSLA warrant a closer review of the parcels that have been made available to investors in Ethiopia (Lavers 2012, van der Wulp 2013, Mulleta et al. 2014).

In light of the above analysis of the agricultural context and current and future threats to smallholder well-being, the overarching goals of this work are as follow: (1) evaluate the agricultural suitability of Ethiopia's land for three time periods and three of the most important crops, and (2) using Ethiopia's western farming systems for a regional case study, examine climate-induced degradation at LSLA compared to the nearby land that hypothetically can still be used by smallholders, henceforth referred to as "potential smallholder land." Datasets obtained from the Food and Agricultural Organization of the United Nations (FAO) and the International Institute of Applied Systems Analysis (IIASA) are employed to determine the suitability for three of the main smallholder crops (*Zea mays*, *Sorghum bicolor*, and *Phaseolus vulgaris* L.) under intermediate inputs and rainfed conditions. Gridded crop suitability estimates from models with historic and projected climatic conditions are used to assess anticipated changes in the quality of land for agricultural production over time. Additionally, the data are used to assess differences in predicted suitability of land allotted to LSLA and the potential smallholder land, where privatization does not limit access. We use data from the federal land bank established by the Government of Ethiopia (GOE) to delineate the boundaries of LSLA, while potential smallholder land is classified based on various characteristics of land cover, tenure, and farming systems. The quality of land is then evaluated for the selected crops across three time periods at multiple areas of interest (AOI). For the potential smallholder AOI, the focus is specifically placed on the lowland agropastoral and maize-mixed farming systems of western Ethiopia, as classified by the FAO. This region has historically struggled with social inequalities imposed by the country's ruling parties and is now the most affected by LSLA as the current GOE directs investments to the western lowland areas of the country (Lavers 2012, Keeley et al. 2014).

METHODS and MATERIALS

Study area

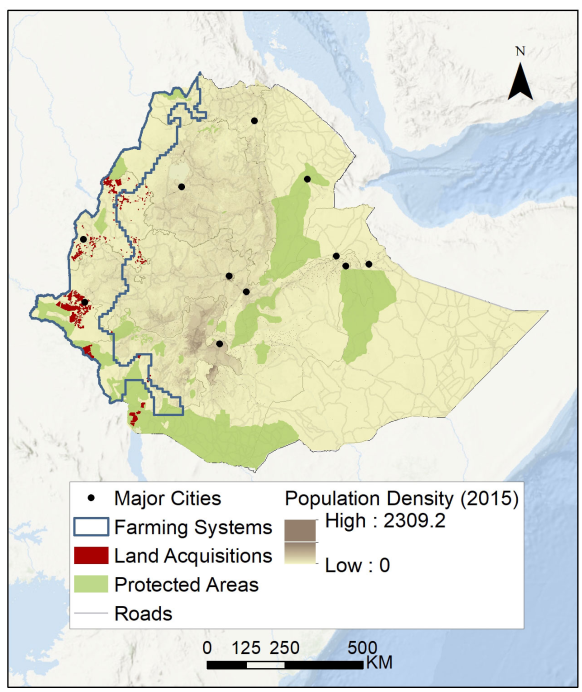
The majority of Ethiopia's total population, approximately 80-85%, relies on rainfed agriculture (Diro et al. 2011, Gebreselassie et al. 2016). Although the contribution of agriculture to the country's GDP has declined (Tomšík et al. 2015), the sector will continue to provide essential jobs for the growing labor market, particularly in rural areas where 79% of the total population resides (OECD 2020; https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS). Ethiopia witnessed remarkable economic progress since the adoption of the Agricultural Development Led Industrialization (ADLI) strategy beginning in the 1990s, despite the current deterioration in the internal security of the country. The GOE focused during much of the last decade of the 20th and the first two decades of the 21st centuries on changing smallholder farming through rural education, infrastructure, agricultural research, and extension, all with the objective of enhancing rural economies (AGRA 2018, Jayne et al. 2021). Evidence suggests this approach was successful, apparent by the large gains in average annual growth of agriculture (6.6%) and GDP (7.4%) during the early part of this century (AGRA 2018). The ADLI approach also contributed to a decline in rural poverty, from 45% to 25% between 2000 and 2016 (OECD 2020). Nonetheless, Ethiopia still ranks as 172 of a total 189 countries in terms of GDP per capita (USAID 2019) and observers stress that agriculture will remain the principal mechanism of continued poverty reduction (Bundervoet et al. 2020). More recent development strategies enacted by the GOE and its partners continue to highlight the role of smallholder farmers in meeting the larger goal of obtaining lower-middle income status by 2025 (ENPC 2016; https://www.feedthefuture.gov/). However, successful implementation of these strategies, such as extension services and improved management strategies, may be hindered if smallholders do not retain access to suitable agricultural land.

Most agriculturalists in Ethiopia are smallholders operating on an average 0.96 hectares, yet they represent the largest contribution to the country's agricultural sector. Approximately 95% of the production comes from small farms, and they manage over 90% of the country's cropland, giving them a central role in combating food insecurity (Taffesse et al. 2012, Headey et al. 2014, CIAT and BFS/USAID 2017). A range of crops are cultivated in regionally specific farming systems that vary considerably due to the diversity in agroecological conditions (Baye 2017), but cereals and legumes are widely grown and remain essential to the food economy and household food security (Taffesse et al. 2012, Abera et al. 2020). Traditional practices include mixed farming through land-intensive shifting cultivation and agropastoralism in the lowlands and more permanent cultivation in the highlands (Getahun 1978, Terefe and Kim 2020). However, increasing rural population density coupled with limited opportunities for cropland expansion have led to a reduction in the size of landholdings (USAID 2018, Zerssa et al. 2021).

Land shortages and insufficient livelihood alternatives have also led to poor management decisions that reduce the overall productivity of land, creating a cycle of poverty and resource degradation. For example, Headey et al. (2014) found increased cropping intensity to be the primary adaptation strategy to land constraints in Ethiopia, but the low use of supplemental inputs indicates high potential for nutrient mining with consequential reductions in soil health. Degradation caused by overgrazing has also become a significant problem caused by land scarcity, with farmers choosing between using crop residues for livestock feed or applying it to fields for soil fertility management (Zerssa et al. 2021). Moreover, low cropland availability has driven farmers to pursue land that is ill-suited to farming, including areas with steep slopes and shallow erodible soils (Taddese 2001). Such agricultural land use is a leading cause of ecosystem degradation, and certainly these practices have led to reductions in soil fertility and productivity in Ethiopia. In fact, Ethiopia has been labeled one of the nations most affected by land degradation, with studies citing a range from 23% to 85% of the country's land being affected to some degree (Gebreselassie et al. 2016, Kirui et al. 2021). The severity of the issue has prompted concerns that absolute poverty reduction will not be possible without addressing land degradation, as much of the population now generates their income from land classified as moderately to severely degraded (von Braun et al. 2013, Wassie 2020).

Even as smallholders in Ethiopia contend with land degradation and shrinking farm sizes, the GOE has identified 3.31 million hectares of available land for LSLA (MoARD 2009, as cited in Keeley et al. 2014). Land investors, both international and domestic, have targeted Ethiopia land for acquisitions, and nearly 15% of all types of land acquisitions in Africa have occurred in Ethiopia (Land Matrix https://landmatrix.org/). The greatest number of LSLA in the country are in the lowlands comprising the agropastoral and maize-mixed farming systems, stretching north-south along the border with Sudan and South Sudan. For this reason, our analysis of inequalities in cropland suitability between potential smallholder land and LSLA particularly focuses on the vulnerability of the lowland farming systems located to the west of the Ethiopian Highlands, as shown in Figure 1.

Fig. 1. The map depicts major geographic characteristics of Ethiopia that provide important context for this analysis. Boundaries are shown for protected areas, land acquisitions, as well as the agropastoral and maize-mixed farming system. The boundary of the farming systems is used to delineate the potential smallholder land area of interest (AOI), less the pixels included in large-scale land acquisitions (LSLA) or deemed uncultivable due to land cover. The LSLA AOI is depicted by the red parcels that represent land assigned to the Government of Ethiopia (GOE) land bank. The national level AOI represents pixels across the country, except for those masked based on predefined land cover and tenure criteria. Anthropogenic characteristics are also depicted, including roads, major cities, and population density.



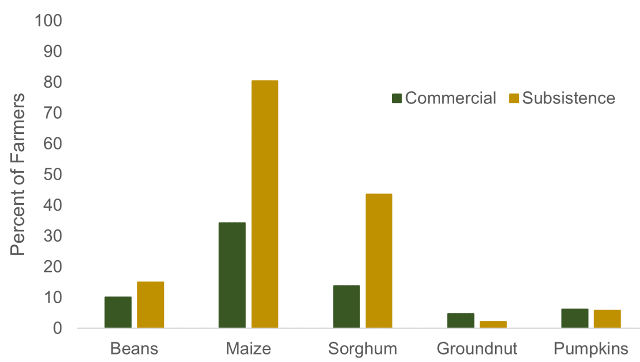
These agropastoral and maize-mixed farming systems constitute land uses that are historically characterized by livestock grazing and swidden farming. In the lowland maize-mixed system, smallholders practice shifting cultivation with maize for both subsistence as well as a cash crop, and this is supplemented by sorghum and beans. The agropastoral system relies on a mix of livestock and cultivation of drought-tolerant crops (Garrity et al. 2012, Amede et al. 2017). Both systems depend on strategies that require abundant land and periodic movement across the landscape. This makes agriculturalists in these systems more vulnerable to LSLA. The barriers LSLA create for migration of pastoralists and shifting cultivation patterns include reduced access to water and grazing (Nalepa et al. 2017). The introduction of intensive commercial agriculture into this landscape has also led to encroachment on forests and grasslands, including in protected areas (Keeley et al. 2014). Such land cover change represents a major threat to land productivity by reducing ecosystem services and increasing degradation. These changes threaten the well-being of rural populations (USAID 2018) and smallholders in western Ethiopia especially acutely because parts of the region already endure chronic food insecurity and pervasive poverty (Wolde et al. 2014, Zeray et al. 2019).

Data

We obtained an estimate of crop suitability from the FAO and IIASA Global Agro-Ecological Zone v. 3.0 (GAEZ). The database provides raster files with a five arc-minute pixel resolution, with pixel values representing agroecological suitability for selected crops with specified management conditions. Values range continuously from 0 to 100, where higher values indicate greater suitability, but can also be classified into categories of suitability. The GAEZ methodology is grounded in fundamental principles of land evaluation (IIASA 2023), and it inventories agricultural potential and resources based on agronomically important climatic and terrestrial conditions at specific geographic locations. This methodology has served as a pillar for numerous applications analyzing the anticipated outcomes of climate change on various aspects of crop production (Skryzhevska et al. 2015, Costinot et al. 2016, Davis et al. 2017a, b, Tuninetti et al. 2017, Schiferl and Heald 2018, Sridharan et al. 2020). To estimate crop suitability, the GAEZ model incorporates an array of variables including land resources, biomass and yield, agroclimatic conditions, and agroedaphic constraints. Suitability value for a given pixel is dependent upon the land utilization type (LUT), which is defined by the water supply, level of inputs, and farming strategies. This analysis uses a LUT characterized by rainfed cultivation with intermediate inputs and partial market orientation and subsistence production, which assumes some use of improved seed varieties, moderate manual labor, and limited application of agrochemicals or conservation measures. We utilize crop specific data for maize, sorghum, and common bean over three time periods, providing a sample of nine unique raster images. The first period is a baseline, estimated with climatic data from 1961 to 1990, while future climate conditions correspond to 2050, and 2080 estimates from the Hadley Centre coupled General Circulation Model version 3 (HadCM3) under the A1FI emission scenario (IIASA 2023). Future suitability for 2050 and 2080 is predicted by integrating rainfall and temperature from the HadCM3 into the baseline GAEZ model. The HadCM3 model has been evaluated by McHugh (2005), who found it to be superior at simulating precipitation over East Africa compared to other global circulation models. Furthermore, it has been widely used, including contributions to the third, fourth, and fifth assessments by the Intergovernmental Panel on Climate Change.

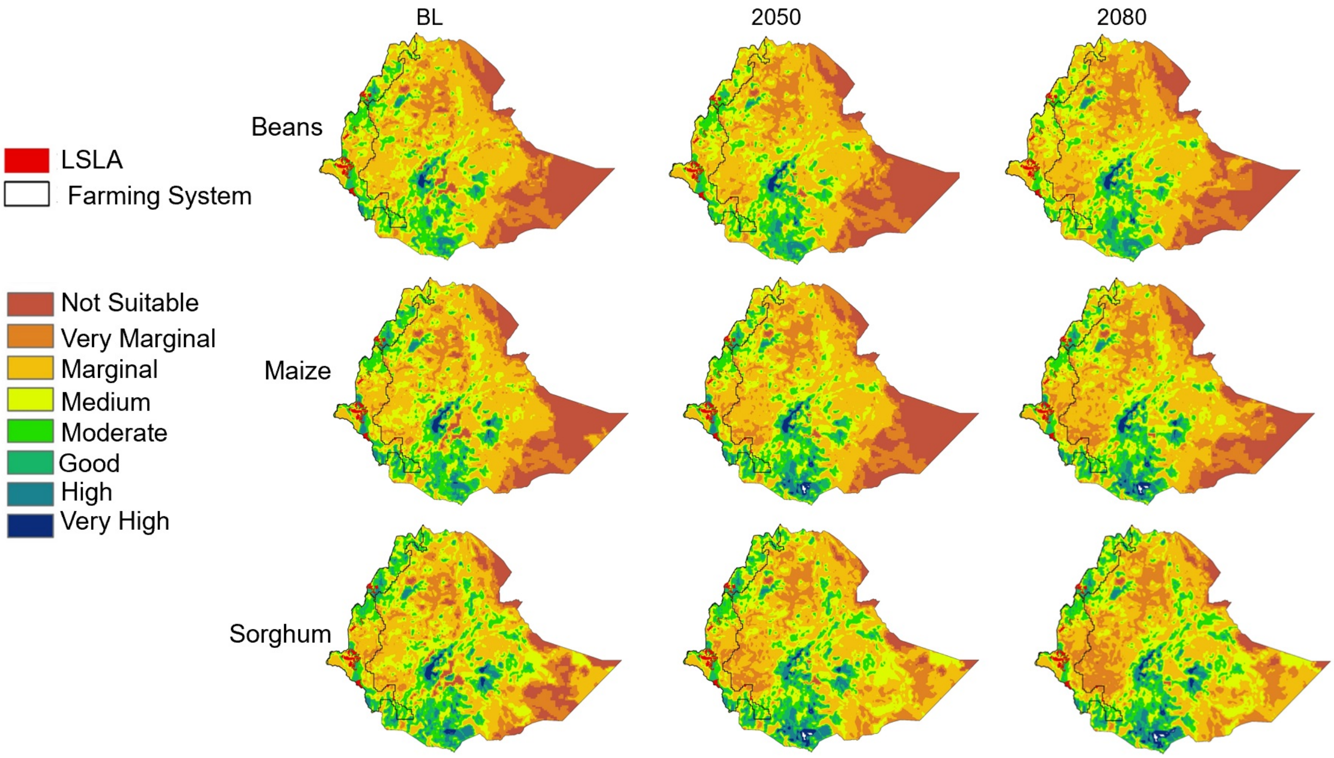
The crops selected for this analysis were chosen for their extensive use by smallholders. Maize and sorghum are staple crops and essential for the country's food security, with maize constituting the most important crop for calorie intake among rural Ethiopians followed by sorghum (Abate et al. 2015). These crops make up 32% of the area planted with grain crops and 43% of grain production (Yang et al. 2020) and have experienced the highest rates of expansion during the early part of the 21st century (Demeke and Marcantonio 2013). Pulses, including beans, comprise the second most common crop type in both planted area and percent of total crop production (Taffesse et al. 2012). Of these, the common bean is important due to its high nutrient content and value as an export commodity (Demelash 2018). Field surveys conducted with rural communities in Gambella and Benishangul-Gumuz between 2017 and 2019 support the selection of these crops because they were reported to be the principal species grown for both subsistence and commercial purposes (Fig. 2).

Fig. 2. The graph depicts the importance of crop species according to rural communities near land acquisitions in Gambella and Benishangul-Gumuz, which was obtained through household surveys collected in 2017-2019.



To address the second objective of this study, we use data from the GOE landbank to delineate bounds of parcels intended for foreign investment, enabling valuation of the effect LSLA have on smallholder farmers' access to suitable cropland. The GOE dataset contains a total of 737 LSLA, occupying a cumulative land area of 6774 km² and with parcel sizes ranging from 9 to more than 30,000 hectares. However, we use a subsetted sample to capture only those LSLA located within the lowland maize-mixed and agropastoral farming systems, falling within the potential smallholder AOI. The subset constitutes a final sample of 589 plots with a combined total area of 5529 km². Our focus on the two most western farming systems serves to reduce the areal extent of the study and enable a more selective analysis of land-use suitability for prominent crop types of interest to smallholders in the region most affected by LSLA. The farming systems are defined by characteristic agroecological and socioeconomic factors. They are a geographic representation of

Fig. 3. Crop suitability raster data from the Food and Agriculture Organization (FAO) GAEZ database for three crops and time periods, which were used to extract measures for the three areas of interest (AOI). These maps show classified suitability, values for which are shown in Table 1. The AOI can be seen in red large-scale land acquisitions (LSLA), demarcated with a black line (potential smallholder land), and the national level. Note: BL = baseline.



areas with populations that share similar agricultural practices, livelihood strategies, and development pathways (IFPRI 2014).

Spatial analysis

Prior to conducting the spatial analysis, data from the GAEZ database was preprocessed to achieve better alignment when demarcating the geographic extents of LSLA boundaries and the potential smallholder areas. Pixels containing continuous values of crop suitability were resampled for all of Ethiopia using a bilinear interpolation with weighted distance average of the four nearest pixel centroids. Suitability values were then extracted for three time periods and three crops, as shown in Figure 3. This was used to quantify several measures of suitability for the various AOI: (1) Ethiopia at the national level, (2) land allotted to LSLA, and (3) potential smallholder land in Ethiopia's western lowlands. To better identify available land for agricultural production in Ethiopia, including that which can still potentially be used by smallholders, it was necessary to mask pixels that have been privatized or would otherwise not be acceptable for agricultural production. This includes the approximately 5529 KM^2 of LSLA from the land bank dataset, as well as pixels where land cover is classified as built or permanently covered by water, and protected areas categorized as level II, IV, or VI by the International Union for the Conservation of Nature (Dudley 2008).

The percentage of land within each suitability class is quantified for each of the three AOI. This process was carried out for the baseline period and projections of 2050 and 2080 to obtain an output that indicates how the proportion of pixels within each class is expected to change under future climate conditions within each AOI. Suitability classes as defined by the GAEZ are provided in Table 1. However, we reclassify values into four groups with larger intervals to more readily discern shifts into lower or higher suitability over time, similar to the approach taken by van Velthuizen et al. (2013).

Table 1. Classification scheme for grouping continuous suitability values. Note: FAO = the Food and Agriculture Organization of the United Nations.

Reclassified Suitability	FAO Designated Suitability Class	Reclassified Suitability Raster Value
Not suitable	Not suitable	0
Marginal	Very marginal	1-10
	Marginal	10.1-25
Moderate	Moderate	25.1-40
	Medium	40.1-55
High	Good	55.1-70
	High	70.1-85
	Very high	85.1-100

This assessment summarizes the crop-specific suitability of land and provides an empirical approach to examine the quality of land that has been privatized by LSLA compared to the remaining

Table 2. The percent of pixels within each suitability class for the three areas of interest (AOI), based on climatic conditions during the baseline period (1961-1990), 2050, and 2080. The first column represents values for the national level. Estimates for the potential smallholder AOI are shown in the second column and values for the large-scale land acquisitions (LSLA) AOI are listed in the last column.

		Percent of Area by Suitability Class for Areas of Interest								
		Ethiopia			Potential smallholder land			Large scale land acquisitions		
		BL	2050	2080	BL	2050	2080	BL	2050	2080
Maize										
	Not suitable	15.6	15.9	11.8	-	-	-	-	-	-
	Marginal	50.7	51.8	56.5	34.5	37.0	42.7	31.1	30.8	34.7
	Moderate	27.4	25.9	25.0	52.6	51.9	48.0	46.6	48.6	50.3
	High	6.3	6.4	6.7	12.9	11.1	9.3	22.4	20.5	15.0
Sorghum										
	Not suitable	7.8	2.2	2.4	-	-	-	-	-	-
	Marginal	49.6	56.4	57.7	32.5	34.3	40.4	33.9	30.1	36.1
	Moderate	34.7	33.4	32.0	53.7	52.9	49.0	42.4	47.0	49.3
	High	7.9	8.0	7.9	13.9	12.8	10.5	23.7	22.9	14.6
Beans										
	Not suitable	16.8	17.3	14.3	-	-	-	-	-	-
	Marginal	51.3	52.1	55.5	29.9	34.6	42.1	34.9	36.2	40.5
	Moderate	27.3	26.2	25.7	61.5	59.9	56.3	48.2	52.2	59.5
	High	4.6	4.5	4.4	8.6	5.5	1.6	16.9	11.6	-

land for potential use by smallholders. This elucidates initial inequities that exist among investors and small-scale farmers in the distribution of productive cropland. However, it is of broader interest to understand which lands are vulnerable to degradation, or a decline in crop suitability between the baseline and future climate conditions. Although smallholders may maintain relatively large areas of suitable land for their crop production at present, it is possible that those regions could experience a greater amount of decreasing suitability and are therefore less resilient to long-term climate change, putting them at a greater risk of adverse effects. Spatial analyst tools are applied to address this question by computing the fraction of land that observes increased, decreased, or no change (stable) in suitability class between the baseline and two future periods. This process is carried out based on the eight original suitability classes designated by the FAO GAEZ at the national level, but our interest is primarily in the difference between the LSLA and potential smallholder land AOI. Estimates of the area expected to undergo shifts in suitability class are estimated for each AOI and provide a useful summary for understanding potential susceptibility to climate-induced degradation, but it is limited by the spatial aggregation of pixel-level data. Additional calculations were therefore performed based on the continuous suitability values to spatially visualize the magnitude of change and more precisely measure the anticipated severity of degradation. This was quantified as the percent change between the baseline and future periods, at pixels that shift into a different suitability class over time. The resulting maps more robustly signal the anticipated changes to cropland productivity and facilitate a spatial assessment of vulnerability between areas managed by LSLA and those left to smallholders in Ethiopia's western lowlands.

RESULTS

National-level change in crop suitability

With baseline climate conditions under the predefined LUT, the majority of Ethiopia's land is classified as being of marginal suitability for maize, sorghum, and beans, as shown in the first column of Table 2. This trend is persistent with climate change as the percentage of pixels classified with marginal suitability increases by 2050 and 2080, while the portion of Ethiopia's higher quality land in the moderate suitability class decreases. However, in the case of maize and sorghum, some of the persistent increase in the percentage of marginal land is from an improvement in pixels considered not suitable during the baseline, implying better conditions for those crops at some locations as the climate changes. The crops show differing trends in the percentage of highly suitable land over the three time periods. Though, it is worth noting the slight increase in the fraction of land with high suitability for maize, as opposed to the inconsistent and subtle decline displayed in this class for sorghum and beans.

Table 3 presents the proportion of land within each AOI that exhibits an increase, decrease, or no change (stable) in suitability based on the FAO classification scheme. Compared to the baseline, the most impacted crop at the national level is sorghum, with approximately 14.8% and 18.4% of land degrading to a lower suitability class by 2050 and 2080, respectively. This is followed by maize at 14.2% and 16% and beans with 12.8% and 15.8% of land exhibiting reduced suitability for these crops by 2050 and 2080. These declines in suitability are countered by land that is agroecologically enhanced with future changes in climate. Accounting for Ethiopia's land that displays improved conditions for crop production reveals that sorghum demonstrates the smallest net loss in suitable land by the mid-century, with a net gain between the baseline and 2050, though this trend is reversed resulting in a net loss by 2080. Findings show less volatility in the results of maize and bean production, as seen in the "no change" column of Table 3. Nonetheless, estimates indicate small gains in land of higher suitability that do not fully compensate for losses, creating an overall decline in suitable cropland by the middle and end of the century across Ethiopia.

At locations that exhibit a change in suitability class between the time periods, computations were done to observe the magnitude of change. Suitability values ranging from 0 to 100 were used to

Table 3. The percent of pixels exhibiting stable conditions and changes in suitability class between the baseline (1961-1990) and two future time periods representing new agroclimatic conditions by 2050 and 2080. The "decline" categorization is used to denote the percentage of pixels in each area of interest (AOI) where suitability is expected to diminish into a lower class, while "increase" represents the proportion of pixels in which suitability improves for a given crop. "No change" represents the percentage of pixels in which the suitability class remained unchanged between the baseline and future periods.

		Percent of Area Exhibiting Change in Suitability Class for Areas of Interest								
		Ethiopia			Potential smallholder land			Large scale land acquisitions		
		Decline	No change	Increase	Decline	No change	Increase	Decline	No change	Increase
Maize										
	2050	14.2	76.8	9.0	16.1	78.3	5.6	6.7	89.2	4.9
	2080	16.0	70.2	13.8	29.5	67.2	3.3	23.3	75.7	1.0
Sorghum										
	2050	14.8	69.4	15.8	14.4	78.1	7.5	7.7	85.4	6.9
	2080	18.4	66.2	15.4	28.1	69.3	2.6	19.7	80.1	0.2
Beans										
	2050	12.8	79.4	7.8	19.9	77.1	3.1	9.0	91.0	0.02
	2080	15.8	72.9	11.3	40.8	57.6	1.6	34.0	66.0	-

quantify the pixel-level percent change between the baseline future periods. Figure 4 shows the pixel-level percent change at the national level and within the farming system, where blue pixels signify an increase in suitability and decreases are shown in red, while beige pixels represent pixels that did not exhibit a shift into a new suitability class. Mapping the data in this way allows for a more spatially explicit approach, highlighting the regions in which the selected crops are most impacted by degradation from climate change. All three crops show modest quantities of land with increasing suitability, specifically in the highlands and to the east of the Great Rift Valley. This includes some locations where suitability values doubled, indicated with darker shades of blue. Alternatively, maize and sorghum exhibit extensive and relatively severe declines in suitability in the southwest and localized regions in the north.

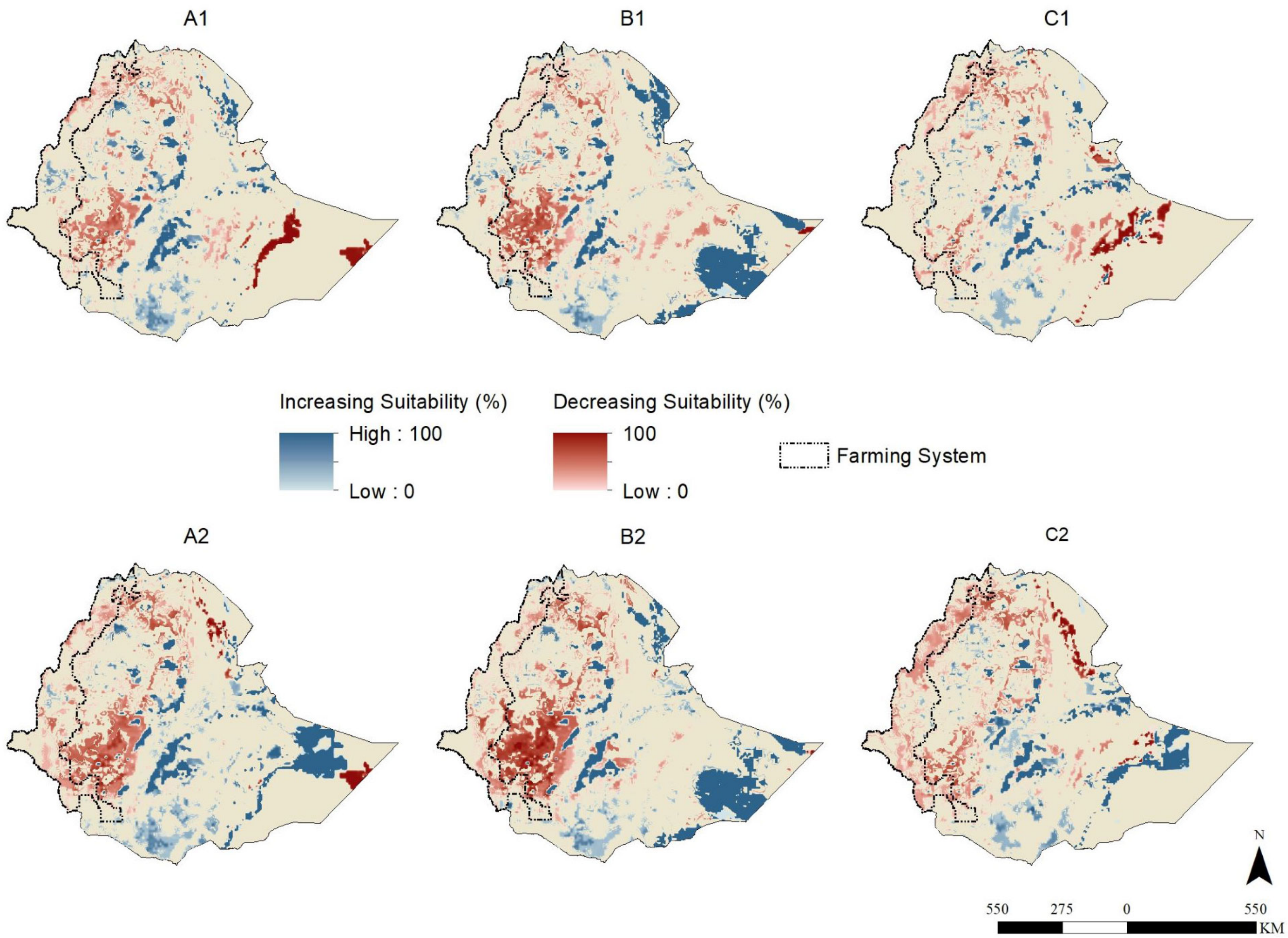
Additional analysis was carried out to examine the suitability of potential cropland adjacent to urbanized areas. This was done by evaluating the crop suitability of pixels located within a 1 km buffer of urban areas, as indicated by a 30 m land cover classification of Ethiopia (Khatami et al. 2020). The land surrounding urban settlements is at greater risk of being converted to built land cover, thereby reducing the possibility for agricultural production. This trend has been exhibited in Ethiopia, with implications for regional food security and poverty reduction (Waldearegay et al. 2021). Most of the land surrounding urbanized areas is classified as marginal suitability for all three crops during the baseline and future time periods. There is a gradual decline in pixels with moderate suitability and a corresponding increase in pixels classified as very marginal. Although this is beyond the scope of this study, analyzing the suitability of pixels near urban land cover offers additional information that can inform impact pathways concerning land use policy.

Change in suitability at land acquisitions and potential smallholder land

To understand inequalities in the distribution of suitable cropland, the same measures as described above were assessed for the privatized land in LSLA and the potential smallholder land in western Ethiopia. For both of these AOI, most pixels are classified as moderate suitability followed by marginal and high. However, key differences in the AOI become apparent by comparing the percentage of land within each suitability class. A greater proportion of the land in LSLA is considered highly suitable for production of the selected crops and in some cases this amount is nearly double the ratio of highly suitable pixels within the smallholder AOI, as shown in the second and third columns of Table 2. The potential smallholder lands retain a larger proportion of moderately suitable land during the baseline and 2050, but this changes by 2080 when LSLA exhibit a greater percentage of land with moderate suitability. A comparison between the baseline crop suitability and values predicted in 2050 and 2080 reveals the shift toward marginal land occurs more rapidly in the potential smallholder land than what is exhibited in LSLA. This suggests that the land left for smallholders is at greater risk of reaching low productive capacity due to climate-induced degradation, thereby intensifying vulnerability of the agricultural communities that inhabit this region. The values in Table 3 reinforce this bias, showing consistently higher proportions of potential smallholder land diminishing to a lower suitability class, while LSLA exhibit more stable conditions for all crops across the study periods. Even when accounting for the offset from land that is expected to shift into higher suitability, the smallholder AOI consistently displays greater proportions of land with declining suitability compared to the LSLA. For the three crops, the average area exhibiting a net decline is approximately 11% and 30% in the smallholder AOI by 2050 and 2080, respectively. This is opposed to the proportion of LSLA land showing net loss in suitability, which is approximately 4% and 25% in 2050 and 2080. These results indicate a more geographically expansive change toward lower quality cropland in the smallholder AOI compared to what is predicted at LSLA.

Figure 5 shows the percent change at pixels that underwent a change in suitability class, as described above for Figure 4, but with a cartographic extent that encapsulates the LSLA AOI. As expected based on the results shown in Table 3, the LSLA show a lower frequency of pixels with increasing or decreasing

Fig. 4. The percent change in suitability at each pixel compared to the baseline value. Maps A, B, and C represent the change in land suitability for maize, sorghum, and beans by 2050 (1) and 2080 (2), respectively. The dashed line delineates the potential smallholder areas of interest (AOI), characterized as agropastoral and maize-mixed lowland farming system, and beige pixels were not analyzed due to no change in suitability class.



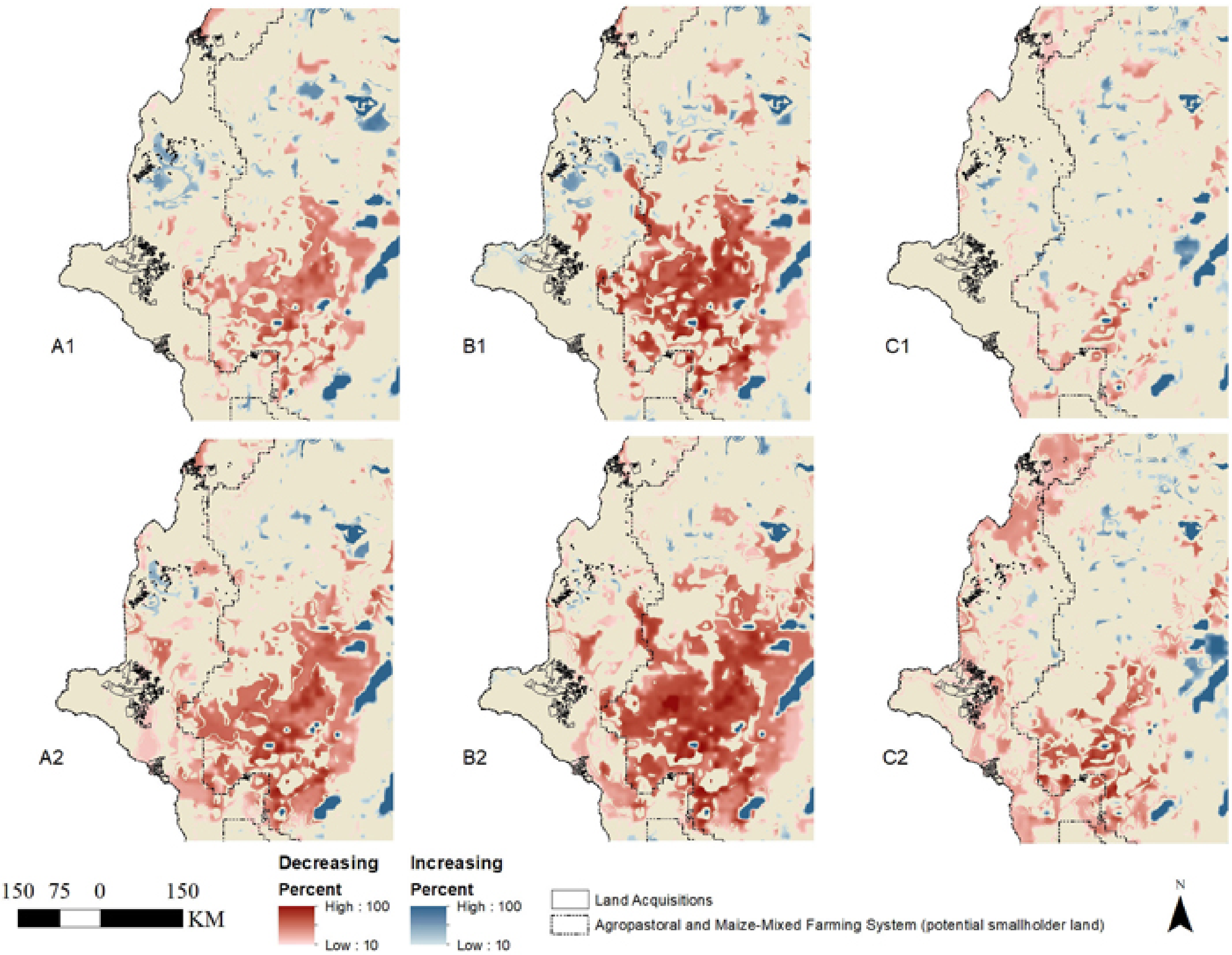
suitability compared to the adjacent land for potential smallholder use. Maize displays consistent increases over time in suitability within the smallholder AOI, though great amounts of land with declining suitability are more frequent by 2080. Sorghum displays a similar trend to maize, but with more severe changes in localized areas. Interestingly, although bean cultivation constitutes the smallest area of anticipated change in suitability at the national scale, as seen in Table 3, by 2080 it is the most impacted crop within the farming systems.

This is further illustrated by Figure 6, which shows the quantiles of pixel values from raster data containing measurements of percent change between the baseline and future periods. In all cases, the median change for pixels with declining suitability was lower in the LSLA, suggesting that the predicted degradation will be more acute in land external to the LSLA, where smallholders can hypothetically still produce crops. However, it is important to note that in all cases, except change in suitability for sorghum production by 2050, the median change for land exhibiting improved suitability is also higher in the potential smallholder AOI. This creates a more dynamic process for evaluating the impacts of degradation and greater complexity in comparing smallholder land to LSLA.

DISCUSSION

As LSLA continue into the 21st century, concern that their expansion negatively affects the accessibility of suitable farmland for smallholders is an essential element to sustainable development. As stated by Garrity et al. (2012), future outcomes from declining farm size cannot be discussed without considering foreign investment. Host governments may describe land designated for agribusiness investment as marginal or wasteland, implying it is of limited value to local farmers (Lavers 2012, van der Wulp 2013, Mulleta et al. 2014). However, these official assessments are at variance with evidence. Large-scale land acquisitions are often located in regions with high agricultural productivity and more secure access to resources (MoARD et al. 2009). There may be some potential synergies for ecosystem

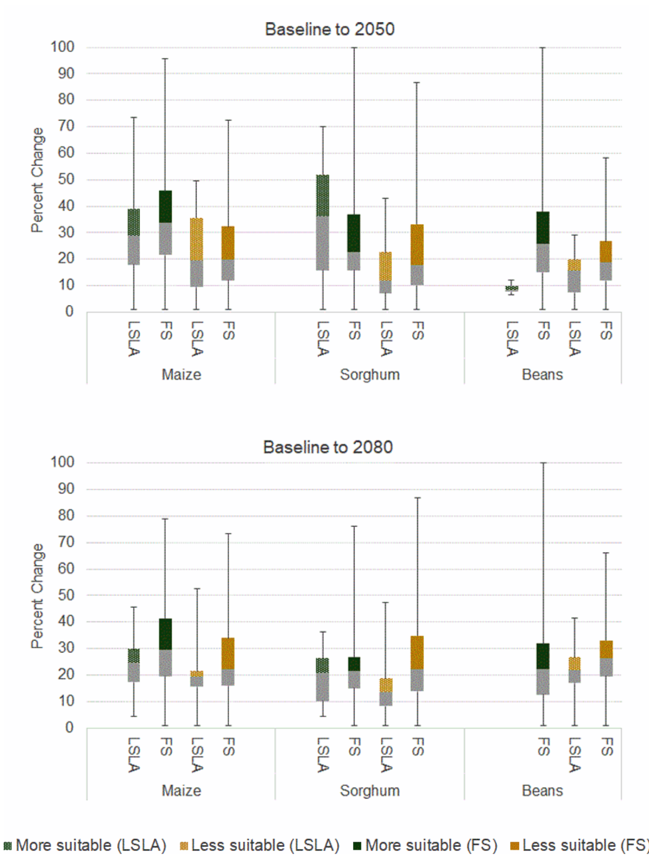
Fig. 5. The percent change in suitability compared to the baseline value at locations of large-scale land transactions and adjacent areas of potential smallholder land. Maps A, B, and C represent the change in cropland suitability for maize, sorghum, and beans by 2050 (1) and 2080 (2), respectively. The dashed line represents the farming system, and beige pixels indicate no change in suitability class.



restoration from LSLA implementation in marginal lands (Nalepa and Bauer 2012), but they are rarely realized and are of little interest to smallholders who lose access to farmland. Despite the potential for economic opportunity governments claim is generated by the investment, case studies suggest that the change in land tenure has resulted in displacement of rural people into less suitable farmland (HRW 2012), worsening their prospects for economic development unless alternative livelihoods are established. In this study, we evaluate disparities in the land quality between potential smallholder cropland within Ethiopia's western farming systems and parcels designated for foreign investment. This is accomplished by comparing the risk of climate-induced land degradation, measured as suitability, over the coming decades.

The results of our analysis demonstrate that private investors gained access to higher quality land for cultivation based on the proportion of each AOI that is classified as not suitable, marginal, moderate, and high suitability. The inequality in the initial distribution of cropland persists into the future in light of an upward trend in the fraction of the LSLA AOI classified as moderate suitability by 2080, while the potential smallholder AOI witnesses a shift from moderate to marginal suitability. Furthermore, LSLA appear to be less vulnerable to climate change-induced degradation expected to occur by the mid and late 21st century, as seen by the higher ratio of stable land and lower proportion of pixels expected to undergo a decline in suitability. Even when considering the greater potential smallholder cropland with improved suitability, the net change toward degradation is more extensive in the potential smallholder land. These results show that smallholders in Ethiopia's western lowlands, specifically within the agropastoral and maize-mixed farming system, have been left with lower quality cropland as a

Fig. 6. Quantiles from raster files measuring the percent change in suitability value at large-scale land acquisitions (LSLA) and potential smallholder land in the farming system (FS).



result of LSLA. Thus, smallholders cultivating maize, sorghum, or beans with intermediate inputs in rainfed systems will be more severely affected by land degradation linked to climate change in comparison to conditions for the same crops in land now occupied by LSLA. Smallholders could address such declines in land quality by securing and using additional agricultural inputs such as fertilizers and other improved farming strategies. But unlike investors with substantial capital, smallholders often lack the means to secure the relevant resources and inputs.

Our spatial analysis and maps, showing over-time changes in crop suitability, highlight several interesting patterns. At the national level, selected crops show improvements in suitability at higher elevations, particularly for maize (see also Thornton et al. 2009). Climate change is expected to benefit agricultural production in regions of higher altitude that were previously less agroecologically fit for cultivation. However, a temporal lag appears for some regions between 2050 and 2080 in terms of when suitability begins to decline and then improves in nearby pixels of higher elevation. This lag period reveals important dynamics in the rate of change in temperature and rainfall that can alter the water budget in a manner that negatively influences crop production in the medium term but becomes more favorable by 2080. Such changes will need to be better understood to adequately strategize land management and crop production, with implications for livelihoods and food security.

Much of this study focused on western Ethiopia, where there is a high prevalence of LSLA. There is little improvement expected in cropland suitability of this region for all crops analyzed in this study. Agriculturalists in the western farming systems who have been displaced by LSLA can expect to face greater difficulties in improving yields of staple crops without improved management strategies. These anticipated shifts reinforce the need for farmers affected by LSLA to obtain adequate assistance in adapting to climate change or transitions to alternative livelihoods. It is possible, as some governments would like, that LSLA may offer displaced smallholders new opportunities and that technological spillovers would balance the trade-offs of displacement. However, Yassin (2010) elucidates several major obstacles to these development linkages. Flagrant disregard by investors and the disinterest of the GOE will also likely prevent smallholders from overcoming the obstacles they face. Interviews with local community leaders and LSLA managers showed inadequate efforts on the part of investors to construct infrastructure, a failure to generate valuable employment, and insufficient technology transfer. Furthermore, GOE policies that incentivize exports of commercial agricultural goods promote enclave development, resource extraction and production with little local processing, and limited economic benefits to locally resident households. The inability of LSLA to fulfill the proposed benefits underscores the need for smallholders to retain viable cropland with concurrent improvements in farmland management, in addition to federal action from the GOE to reduce poverty and enhance food security.

CONCLUSION

Many smallholders across SSA are coping concurrently with a reduction in the productive capacity of land and constraints on the potential for cropland expansion. Land degradation worsens the agricultural suitability of affected regions and diminishes crop production, preventing farmers from increasing yields and improving their well-being. Climate change will exacerbate the magnitude and rate of land degradation as it worsens the agroecological conditions through heat stress and erosion caused by extreme weather events, including heavy precipitation (Webb et al. 2017, IPCC 2019). In addition to climate change, increasing rural population density and subsequent declines in farm-size intensify the human pressure on land, all while the demand for agricultural goods continues to rise (Chauvin et al. 2012). These processes reduce the resilience of ecosystems to environmental stressors and amplify the vulnerability of subsistence production. Such circumstances are especially critical in Ethiopia, where as much as 85% of the land has been affected and the majority of the population now relies on degraded land for making a living (Gebreselassie et al. 2016, Wassie 2020). Degradation of cropland is of particular concern to smallholder farmers and indeed for Ethiopia's national economic growth because small-scale farmers are vital to the country's economic and development goals (ENPC 2016).

The burden of rising demand and competition for use of Ethiopia's land is compounded as a result of land acquisitions by private investors who control more than one million hectares, with additional LSLA intended for the future (Cochrane and Legault 2020). Not only do LSLA produce negative environmental impacts, they also displace local peoples. Investors have privatized land previously used by smallholders for farming and grazing and obstructed access to water for irrigation (Nalepa et al. 2017). Government officials justify the allocation of land to LSLA by classifying the areas as marginal or wasteland. However, studies show it is primarily productive land being seized from rural communities for investment opportunities in the federal land bank, estimated at 3.1 million hectares in Ethiopia (Cotula et al. 2009, Keeley et al. 2014, Nalepa et al. 2017). Meanwhile, small-scale farmers are confined to a reduced area with less arable land (Yassin 2010, HRW 2012).

Maintaining the extraordinary economic growth Ethiopia has experienced in recent decades will depend on the ability of smallholders to continue their agricultural production because they represent a critical pillar for economic development, food security, and poverty reduction (Di Falco and Veronesi 2013). This makes it necessary for small-scale rural farmers to maintain access to viable cropland, particularly because their exposure to climate change is at a greater risk than that for investors who can more easily acquire the capital and inputs needed to maintain production under changing agroclimatic conditions. Accordingly, this study analyzed the relative quality of land accessible to smallholders in the western lowlands compared to what is now privatized by investors in the same area, with emphasis on how suitability of land for growing three major smallholder crops is likely to change under future climatic conditions.

We used data acquired from the GAEZ database to analyze the crop suitability of maize, sorghum, and beans with historic climate observation represented as the baseline and future conditions projected with the A1FI scenario for 2050 and 2080. We conducted this analysis at the national level, but then focused our attention on comparing the quality of land occupied by LSLA to the potential smallholder land remaining within the agropastoral and maize-mixed western lowland farming systems, where much of the investment has taken place. Results show that most land is classified as moderate suitability. However, the greater percentage of highly suitable land in LSLA during the baseline period results in better land quality for investors by the mid and late 21st century, as opposed to what is exhibited in the area still accessible to smallholders. This is further supported by spatial analysis to determine the proportion of pixels within the LSLA and potential smallholder land that shift to a lower suitability class between the baseline and future periods. This reveals a more extensive decline in the quality of land in smallholder areas outside of the LSLA, while the acquired land exhibits more stable conditions. The magnitude of change is assessed by quantifying the percent change at pixels where suitability class is altered due to climate change, showing more severe change in the smallholders AOI than what is seen in the LSLA.

The findings of this study broadly contextualize the nexus of threats facing smallholder farmers in western Ethiopia. A spatially explicit analysis indicates where smallholder production of staple crops is at risk from degradation as the climate changes, which can aid decisions regarding regional implementation of support to farmers through extension and provisions of agricultural inputs. Furthermore, it supports the accounts of previous work that has contradicted the common narrative espoused by governments that land being offered to investors is of lower quality (Keeley et al. 2014). Though broad regional conclusions may be drawn from this study, it is limited by the spatial resolution of data from the GAEZ, specifically as the coarse-scale of the crop suitability raster images that restrict the ability to more accurately assess individual smallholder farms due to the average plot size of less than one hectare. Future studies would benefit from localized data regarding small-scale agricultural production to allow for a more comprehensive understanding of farming communities and the trade-offs imposed by allocating suitable cropland to LSLA as climate-induced degradation devalues the remaining land in the region. Similarly, sufficient documentation of crops grown at individual LSLA would enable a more detailed examination of the synergies and trade-offs between intensive production at these sites and alternative uses of the land. Additional analysis using high input LUT would also enhance our understanding of how improved management strategies can mitigate expected declines in cropland suitability.

Author Contributions:

This study was conceptualized and analysis was carried out by Carly Muir. Audrey Culver Smith and Arun Agrawal contributed to the editing and writing of the manuscript.

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Data Availability:

The data for crop suitability and farming systems that support the findings of this study are available in the FAO Global Agro-Ecological Database at https://www.gaez.iiasa.ac.at/ and FAO Farming Systems and Poverty at https://www.fao.org/farmingsystems/maps_SSA_en.htm" target. Data for the location of land acquisitions are not publicly available because of restrictions from the Government of Ethiopia.

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