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Long-run Spatial and Temporal Yield Variability Analysis of Three Major Crops Affected by Fertilizer Use and Rainfall in Ethiopia over the Past 15 Years (2004/05–2018/19)

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Abstract

Ethiopia is one of the major producers of maize and wheat and the only producer of teff at a larger scale for grain in sub-Saharan Africa (SSA). Various efforts have been made by the government of Ethiopia to increase productivity over the past 15 years. Here we analyze a dataset with more than 1,260 yield observations from 2004/05 to 2018/19 for three crops (teff, maize, and wheat) in the 28 zones of the two major cereal-growing regions of the country. These two regions, Amhara, and Oromia represent around 81% of cropped area, 75% of fertilizer use, and 82% of cereal production of Ethiopia annually. Zonal level crop production data were used to analyze spatial and temporal patterns of teff, wheat, and maize yield. Zones were categorized as wet and dry based on annual rainfall. We dissect the evolution of yield trends over time and space, analyze yield variation, and evaluate whether growth of yields has increased, decreased, or stalled in recent years. We found that productivity of teff, wheat, and maize continued to increase from 0.95 to 1.76 metric tons per hectare (mt ha⁻¹), 1.56 to 2.76 mt ha⁻¹, and 1.72 to 4.0 mt ha⁻¹ respectively, between 2004/05 and 2018/19. There was an average annual increase of 5%–8% during this time. The data also show a strong correlation of yield with rainfall and fertilizer use patterns; therefore, we recommend that the fertilizer advisory service should also make use of the rainfall conditions of the different locations to fine-tune fertilizer recommendations.

Keywords: Ethiopia, fertilizer, teff, trend

1. Introduction

Ethiopia is among the fastest-growing non-oil economies in the world. Its economy has experienced strong and broad-based growth, averaging 9.98% a year from 2008/09 to 2018/19, Ethiopia's real gross domestic product (GDP) growth rebounded to 9% in 2018/19 (World Bank, 2020). Agriculture is the mainstay of the economy, contributing between 31% and 45% of its growth annually for the past 10 years (Statista, 2020).

The Ethiopian government has formulated a series of policies, strategies, and programs to promote agricultural development to achieve food and nutrition security and build resilience. Through its Agricultural Development Led Industrialization (ADLI) economic policy, several five-year strategies have been implemented over the last 15 years: Sustainable Development and Poverty Reduction Program (SDPRP, 2001/01–2004/05), Plan for Accelerated and Sustained Development to End Poverty (PASDEP, 2005/06–2009/10), the first Growth and Transformation Plan (GTP I, 2010/11–2014/15), and the second Growth and Transformation Plan (GTP II 2015/16–2019/20). All of these strategies had a set of clear objectives and targets and recognized agriculture as the heart of the Ethiopian economy. Each set of objectives aimed to boost agricultural production, strengthen agricultural research, and facilitate stronger market linkages.

Several studies indicate that agricultural crop production may need to be increased by 60–110% to meet projected global demand for food by 2050 (FAO, 2009; OECD-FAO, 2012; Tilman, Balzer, Hill, & Befort, 2011). Ethiopia's population is increasing, and its food production will also have to rise significantly to address the food needs of the current 110 million people and the projected increase in population. So, the main challenge is to maintain its strong economic performance and meet that substantial increase in food demand without major damage to the environment.

However, comparatively few studies assess in any comprehensive detail the shifting historical structure of crop production in Ethiopia. Moreover, almost all such studies focus exclusively on the changing production at country level and do not relate this much to production constraints, such as rainfall variability and inputs, and do not acknowledge the variability within the different zones. This paper discusses the production trend of three major cereal crops (teff, wheat and maize) over the past 15 years. Those three crops accounted for more than 56% of total crop area and 62% of total production each year in Ethiopia (Central Statistics Agency of Ethiopia [CSA], 2005 -2019). The increase in area and production of these three crops during the last two decades has greatly contributed to Ethiopia's effort to become food self-sufficient. However, there is substantial variation in yield performance across regions and zones, with some regions reporting yield declines and others continued improvement. However, much needs to be done, especially on production of wheat, to reduce the amount of imports.

The Ethiopian government acknowledges the need for increased use of modern fertilizer and seed technologies to achieve sufficient agricultural productivity growth to meet economic development, poverty reduction, and food security goals. Since the early 1980s, the challenge has been to increase farmers' use of productivity-enhancing inputs in a cost-effective, financially sustainable, and environmentally sound manner. The fertilizer recommendations in Ethiopia are currently 100 kg urea and 100 kg compound fertilizers (DAP, NPS, NPSZn, NPSB, NPSZnB) regardless of the type of crop, soil, or agroecological zone. Even though the amount of fertilizer imported increases every year (Fig.1), Ethiopian farmers still lag far behind other developing countries in fertilizer use, and crop productivity is not increasing at the same rate. This is because the recommended fertilizers and the amounts commonly applied cannot address site-specific needs associated with nutrient-deficient soils and crop nutrient requirements. A soil fertility status map for the agricultural lands in Ethiopia has been developed through the Ethiopian Soil Information System (EthioSIS) project, and the types of fertilizers required for the different areas have been identified (Ethiopian Soil Information System [EthioSIS], 2013, 2016). However, crop- and soil-specific rate recommendations are lacking, and farmers are still applying the blanket rate recommended years ago.

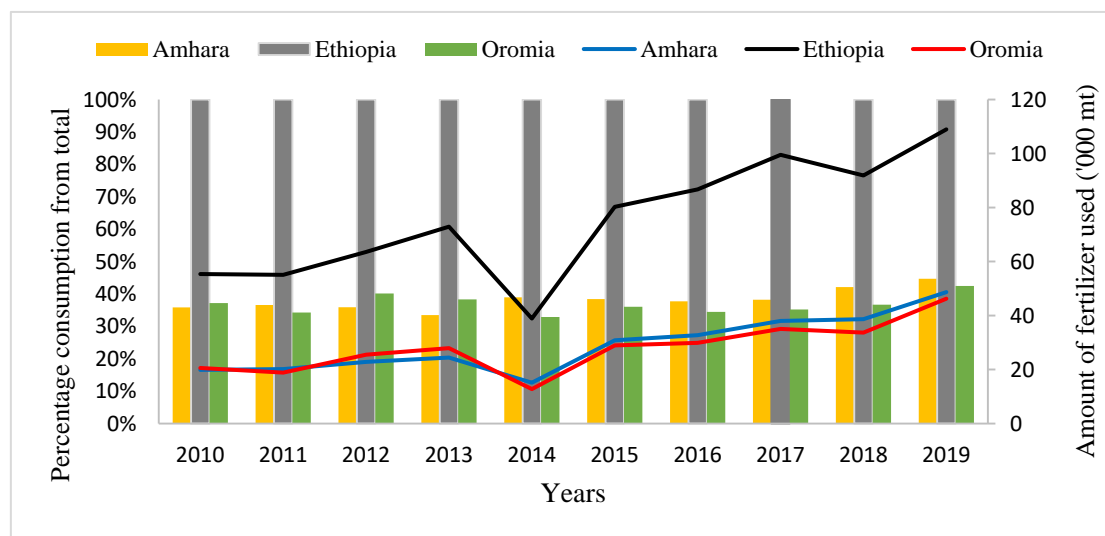


Figure 1. Total fertilizer consumption trends for the two regions and the country from 2010 to 2019 in metric tons. The two regions together consume more than 75% of the country's fertilizer annually

Source: Authors' analysis using data from MoA (2019).

Different factors can contribute to changes in farming area and production of crops from year to year. Among these are the amount and onset of rainfall, timely availability of the right type and amount of fertilizer and seed inputs, crop rotation patterns and, more importantly, the market price of produce. Suboptimal agronomic practices constrain farmers' ability to improve yields, especially in Ethiopia where over 97% of cultivation is rainfed, making the sector highly vulnerable to challenging weather patterns. High variability of the rainfall pattern across years and regions exists in Ethiopia because of climate change effects (Zerga & Mengesha, 2016). Ethiopian rainfall is characterized by both seasonal and interannual spatial variability (Alhamsry, Fenta, Yasuda, Kimura, & Shimizu, 2020). This variability in rainfall puts significant pressure on crop production in Ethiopia, given that most of its crop production is rainfed (Diro, Grimes, & Black, 2011a). The Ethiopian highlands, where

most cereal production occurs, is described as exhibiting three cycles of seasonal rainfall: spring mid-rainy season (February–May), summer rainy season (June–September), and dry season (October–January), locally known as Belg, Kiremt, and Bega, respectively (Diro et al., 2011b).

The goal of this study is to characterize the nature of the long-term trends in production of maize, teff, and wheat in the regions of Amhara and Oromia and to assess whether they are influenced by the trends in fertilizer use, weather conditions, or interaction of the two. Based on the relationships identified, recommendations will be made for crop production improvements in the Amhara and Oromia regions.

2. Methodology

2.1 Data

Agricultural survey data for 15 years from CSA of Ethiopia were used for this study. CSA covered the entire rural areas of the country to conduct the annual Agricultural Sample Survey (AgSS). In order to select the sample households, CSA used a stratified two-stage cluster sample design. Enumeration areas were the primary sampling units, and the secondary sampling units were agricultural households (CSA, 2005–2019). The data were classified by crop and geographically by region and zone. Areas and totals for crop production and inputs used were calculated as indicated in the AgSS documentation (CSA, 2005–2019).

2.2 Data Analysis

The datasets contain information about production, area cultivated under a given crop, area fertilized and under other inputs, and quantities and types of fertilizers and other inputs used in crop production each year from 2004/05 to 2018/19. The inputs recorded in the datasets are fertilizers, pesticides, improved or local crop varieties, and extension services. The above-mentioned information is presented by crop, region, zone, and year. A segment of the AgSS data containing the information described above for the three most important crops in Ethiopia – maize, teff, and wheat – in the Amhara and Oromia regions from the 2004/05 through 2018/19 growing seasons was selected for this study.

These data were complemented with weather data downloaded from the NASA Prediction of Worldwide Energy Resources (POWER) Agroclimatic System, which provides meteorological parameters from satellite and modeling procedures on a global scale after validation with ground data from meteorological stations (Stackhouse et al., 2018). Daily data for rain, maximum temperature, minimum temperature, and solar radiation for 2004–2019 and from three to five weather stations per zone were downloaded from the NASA POWER site. Seasonal total rainfall and solar radiation and averages of maximum and minimum temperatures per growing season were used in the process of identifying factors affecting crop production. The time period used for calculation of season totals or means of weather parameters was from 10 days before planting to harvest time.

Rainfall data gathered from the NASA POWER Agroclimatic System were validated from rainfall measured at ground weather stations. The modeling procedures used in the estimation have limitations in estimating rainfall from individual events or daily accumulated precipitation; however, the estimation quality improves for rainfall accumulated in time units larger than a day. Appendix 3 shows how the rainfall accuracy improves substantially as the rainfall accumulation is compiled weekly and monthly, because the prediction capability of the regression model (R^2 value) grows and the number of rainfall values outside the confidence interval decreases as the time unit accumulation increases. Therefore, the seasonal total rainfall from the NASA Agroclimatic System was adequate as a predictor of crop production.

2.3 Study Regions

The two major cereal-growing regions of the country, Amhara and Oromia, were used for this study (Appendix 2). Data were disaggregated at the zonal level. Accordingly, 11 zones from Amhara and 17 zones of Oromia were used for this study.

2.4 Classification of Time Series as Wet or Dry

Rainfall, temperature, and solar radiation data from the past 15 years (2004–2018) from 31 and 46 weather stations (Appendix 1) representing Amhara and Oromia, respectively, were collated to determine the effect of weather variables on cereal production. Based on rainfall probability distribution, a rainfall threshold was set for the dry-wet classification. The threshold was based on the median (50% cumulative probability distribution) for each crop and region. The combination of zones and years that presented rainfall lower than the threshold were grouped under the dry condition category; otherwise, the zone-year combinations were grouped in the wet conditions category for the production modeling of each region and crop.

2.5 Modeling

The relationships between crop production and both fertilizer use, and total seasonal rainfall were evaluated with linear polynomial models (Neter, Wasserman & Kunter, 1983). Models containing linear and quadratic forms of the fertilizer use and total seasonal rainfall were tested. The adjusted R^2 was used as a measure of model fitness and prediction capability of the model. Regression coefficients indicate whether the relationship between crop production and either fertilizer used, or total rainfall is significant. Regression coefficients with a P value lower than or equal to 0.05 are significant.

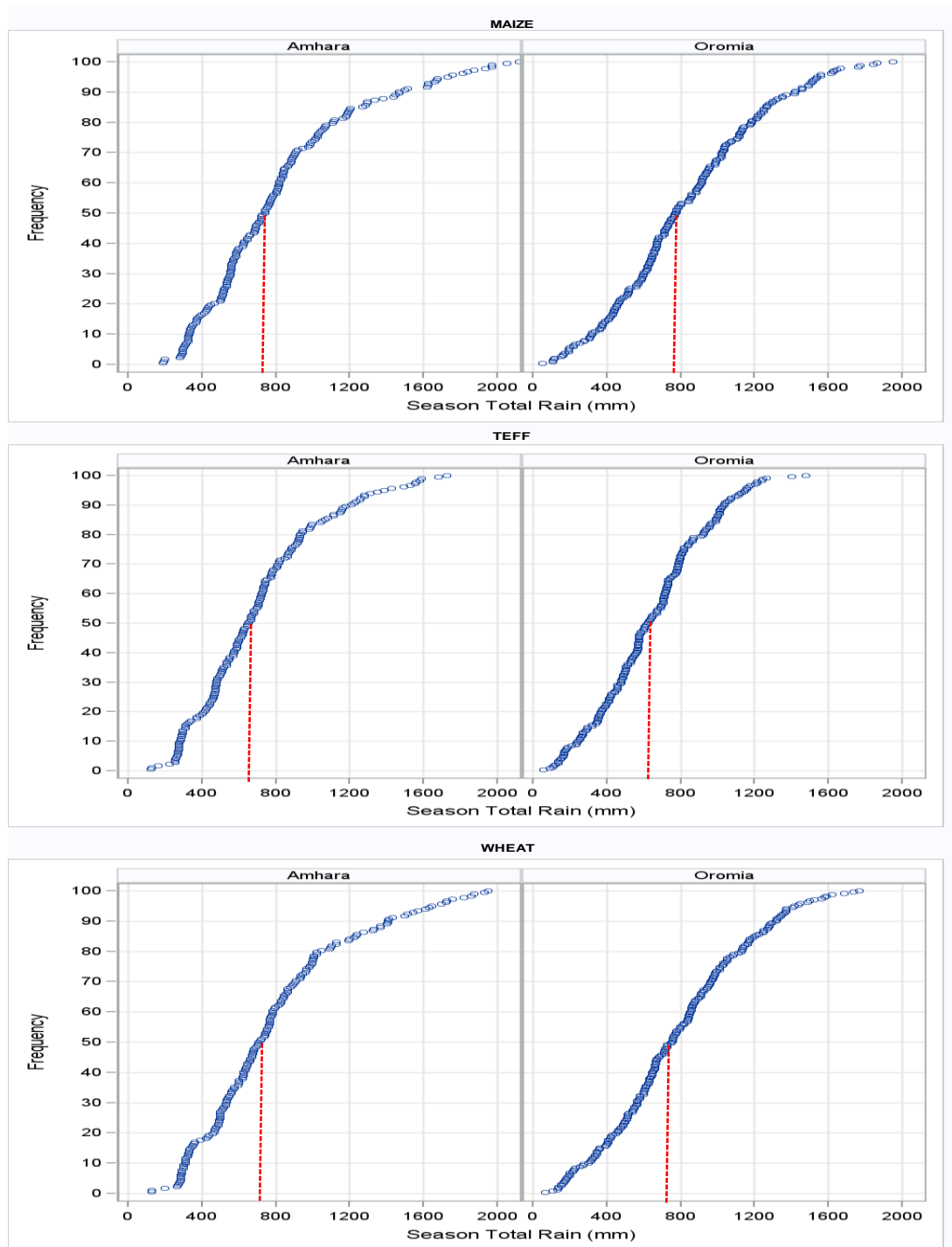


Figure 2. Cumulative frequency distribution of seasonal total rainfall for classification of locations and growing seasons as dry or wet

Source: Authors' construction using data from NASA POWER.

3. Results

3.1 Production, Fertilizer Use, and Rainfall Trends

Results indicated that production and fertilizer use for these three crops varied across locations and years. Production of the three crops showed an increasing trend over the years in Amhara and Oromia regions (Figure 3). In Amhara and Oromia regions, the average productivity of teff, wheat, and maize increased by 81%, 75%, and 129%, respectively, from 2004/05 to 2018/19, but the annual increments were 5–8%. Though there is such progress, the current productivity of 1.8, 2.8, and 4.1 mt/ha for teff, wheat and maize, respectively, is far less than their potential, and there is a large productivity gap.

While overall fertilizer use showed an increasing trend across the years, it was erratic from year to year and zone to zone for a given crop. The peaks and troughs in fertilizer use coincided with seasonal rainfall amounts. The relationship patterns of crop production with fertilizer use and with total seasonal rainfall for the three crops are shown in Figure 4. In Amhara Region, the zones of Awi, West Gojjam, and Oromia were continuously under wet conditions, while other zones, such as North Shewa and Waghemra, were mostly under dry conditions and few other zones, such as North Gondar and South Gondar, fluctuated between wet conditions and dry conditions over the years. In Oromia Region, East Welega and Horoguduru zones were under wet conditions all of the time, while the zones of Bale, Guji, and Jimma were under dry conditions during the growing period and West Welega, Kelem, and Arsi switched from dry to wet conditions or vice versa (Figure 4).

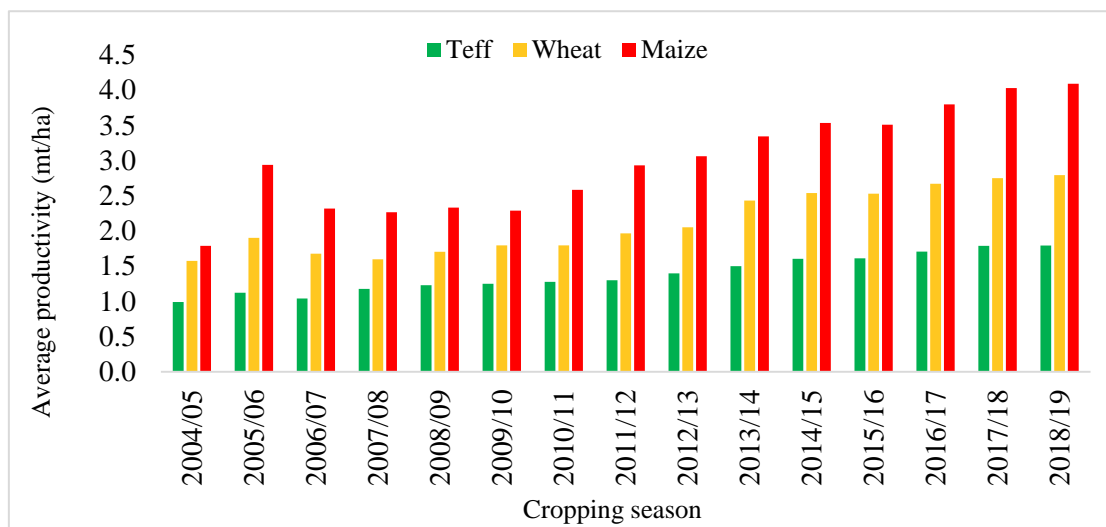


Figure 3. Average productivity (mt/ha) of teff, wheat, and maize over the past 15 years in Amhara and Oromia regions

Source: Authors' analysis using data from CSA.

The similarities of relationships between crop production and fertilizer use and seasonal rainfall are better defined in Oromia. Response surface models of crop production were developed as a function of seasonal fertilizer use and rainfall under dry and wet conditions in the Amhara and Oromia regions of Ethiopia during the 2004–2018 period. The interaction of season rainfall and fertilizer use was not significant; hence, the term interaction was dropped from the regression models. All of the regression models have significant regression coefficients for either seasonal fertilizer use, rainfall, or both (Table 1). This last characteristic made the models useful in identifying the significant effect of seasonal fertilizer use, seasonal rainfall, or the combined factors on crop production. The effect of maximum and minimum temperature, solar radiation, pesticide use, and variety did not correlate well with cereal production.

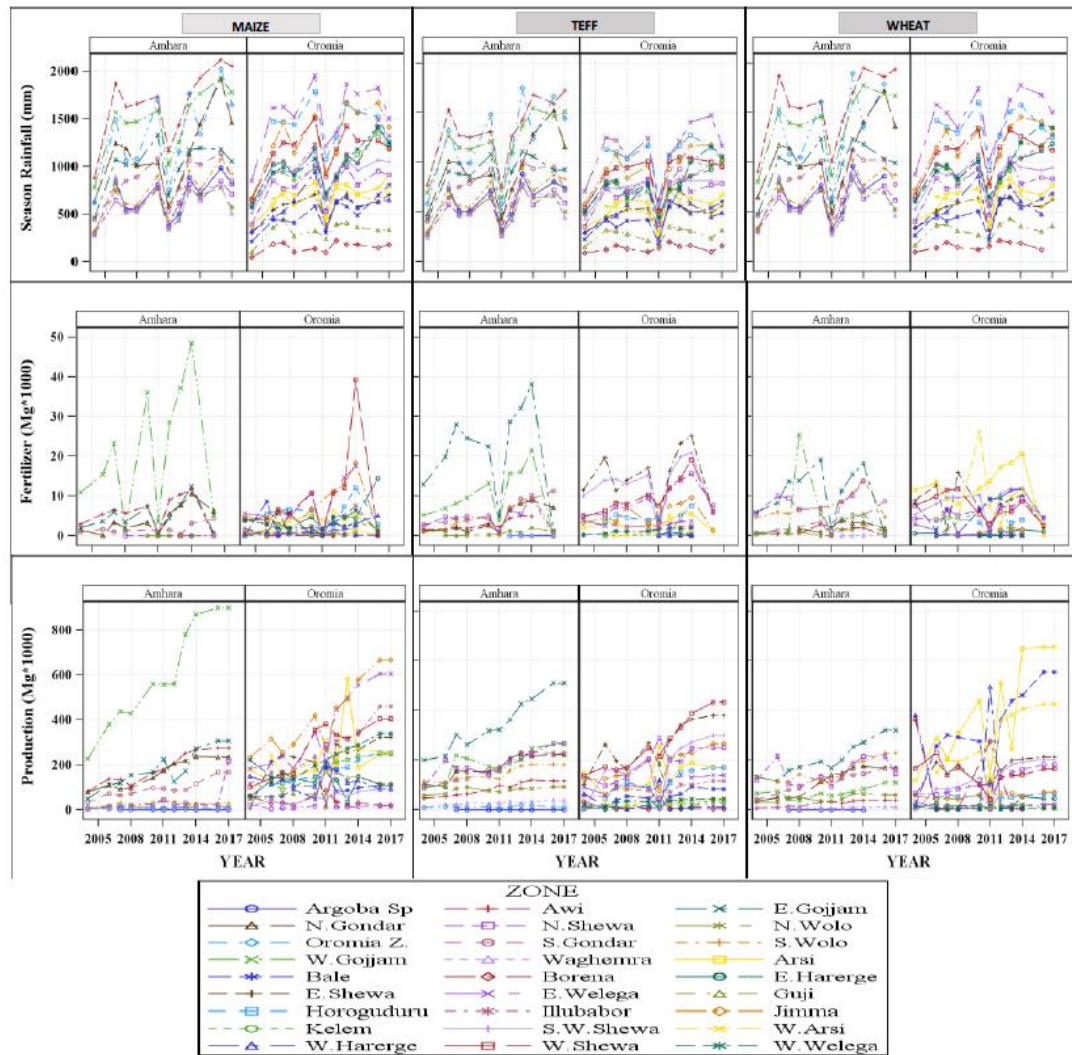


Figure 4. Production, fertilizer use, and rainfall patterns of maize, wheat, and teff across the years in zones of the Amhara and Oromia regions of Ethiopia

Table 1. Response surface models of crop production as a function of seasonal fertilizer use and rainfall under dry and wet conditions in the Amhara and Oromia regions of Ethiopia during the 2004–2018 period

Crop	Region	Conditions	n		Intercept	Fertilizer	Rain	Adj. R2
Maize	Amhara	Dry	15	Coefficients	5176.13	18.71	62.69	0.59
				P Values	0.947	0.011	0.618	
		Wet	37	Coefficients	-80847.7	12.45	168.81	0.69
				P Values	0.318	<0.001	0.011	
	Oromia	Dry	47	Coefficients	28647.95	7.21	182.9	0.48
				P Values	0.392	0.134	0.0041	
		Wet	48	Coefficients	-56682.58	5.76	210.38	0.51
				P Values	0.401	0.036	0.0005	
Teff	Amhara	Dry	32	Coefficients	109404.62	12.23	-21.47	0.58
				P Values	0.0043	0.0001	0.768	
		Wet	49	Coefficients	105671.45	8.49	-2.75	0.67
				P Values	0.0107	<.0001	0.944	
	Oromia	Dry	38	Coefficients	63904.71	8.03	109.11	0.50
				P Values	0.347	0.0038	0.454	
		Wet	68	Coefficients	-37443.67	12.7100	112.48	0.64
				P Values	0.3171	<0.0001	0.005	
Wheat	Amhara	Dry	22	Coefficients	47300.43	10.99	10.32	0.66
				P Values	0.153	<0.0001	0.877	
		Wet	52	Coefficients	127635.09	6.33	-44.630	0.56
				P Values	0.0006	0.0004	0.098	
	Oromia	Dry	43	Coefficient	59747.07	8.13	54.97	0.450
				P Values	0.118	0.0035	0.4874	
		Wet	68	Coefficients	221177.33	9.8300	-128.6	0.67
				P Values	<0.0001	0.0003	0.0012	

Models with determination coefficients (R^2) of 0.60 or higher, such as the ones fitted for maize and teff production under wet conditions in Amhara, teff and wheat under wet conditions in Oromia, and wheat under dry conditions in Amhara, are adequate for production prediction. All of the regression models have significant regression coefficients for either seasonal fertilizer use, rainfall, or both. This last characteristic made the models useful in identifying a significant effect of seasonal fertilizer use, seasonal rainfall, or the combined factors on crop production (Table 1).

3.2 Maize Production in Amhara Region

Only total fertilizer use gave a significant response for maize production under dry conditions in Amhara (Figure 5A). Regional maize production increases can be attributed to the amount of fertilizer used during the growing season; the production increment was at the rate of 18.7 mt of maize per metric ton of fertilizer used. The total seasonal rain, ranging from 300 to 800 mm per season, did not have a significant effect on maize production. However, maize production under wet conditions (Figure 5B) was significantly affected by both fertilizer use and total rainfall. Regional maize production in Amhara during the wet conditions increased at a rate of 12.45 mt per metric ton of fertilizer used and at 168.8 mt of maize per millimeter (mm) of rainfall. The fertilizer effect ($p < 0.001$) had a highly significant effect on maize production during wet conditions (Table 1).

The considerably fewer points available to build the maize production response surface under dry conditions and the concentration of most of the points below 4,000 mt per season of fertilizer use indicate that maize growers used less fertilizer because of scarce rainfall. The maize production response under wet conditions had fertilizer use up to 60,000 mt per season, with most points between 1,000 and 20,000 mt per season (Figure 5B). Rainfall amounts during wet season maize production ranged from 800 to 2,200 mm per season. The maize production mean of 201,337 mt per season under wet conditions was significantly higher than the 43,942 mt per season under dry conditions of Amhara. Higher production in wet conditions is attributed to both the higher fertilizer use and rainfall.

3.3 Maize Production in Oromia Region

The maize production surface response under dry conditions in Oromia was significantly affected only by seasonal total rainfall (Figure 5C; Table 1). Regional maize production grew at a rate of 182.9 mt for every millimeter of rainfall during the growing season. The number of points to fit the response surface increased as precipitation became greater than 500 mm per season and with fertilizer use of over 4,000 mt per season. This suggests that fertilizer use is stimulated by higher amounts of precipitation; however, with rainfall of less than 800 mm per season, only a few cases of fertilizer use exceeded 4,000 mt per season. Hence, there was no significant maize production response to fertilizer use under dry conditions.

Maize production under the wet conditions of the Oromia Region was significantly affected by both fertilizer use and total rainfall during the growing season (Figure 5D). Regional maize production increased at a rate of 5.7 mt per metric ton of fertilizer used, and there was an additional maize production increase at a rate of 210.4 mt per millimeter of total rainfall during the season. Fertilizer use and maize production increased with total seasonal rainfall. The combined effect of fertilizer use and rainfall resulted in an upward trend for regional maize production. The average regional maize production under wet conditions in Oromia was 242,838 mt per season, which was significantly higher than the average of 136,293 mt per season produced under dry conditions.

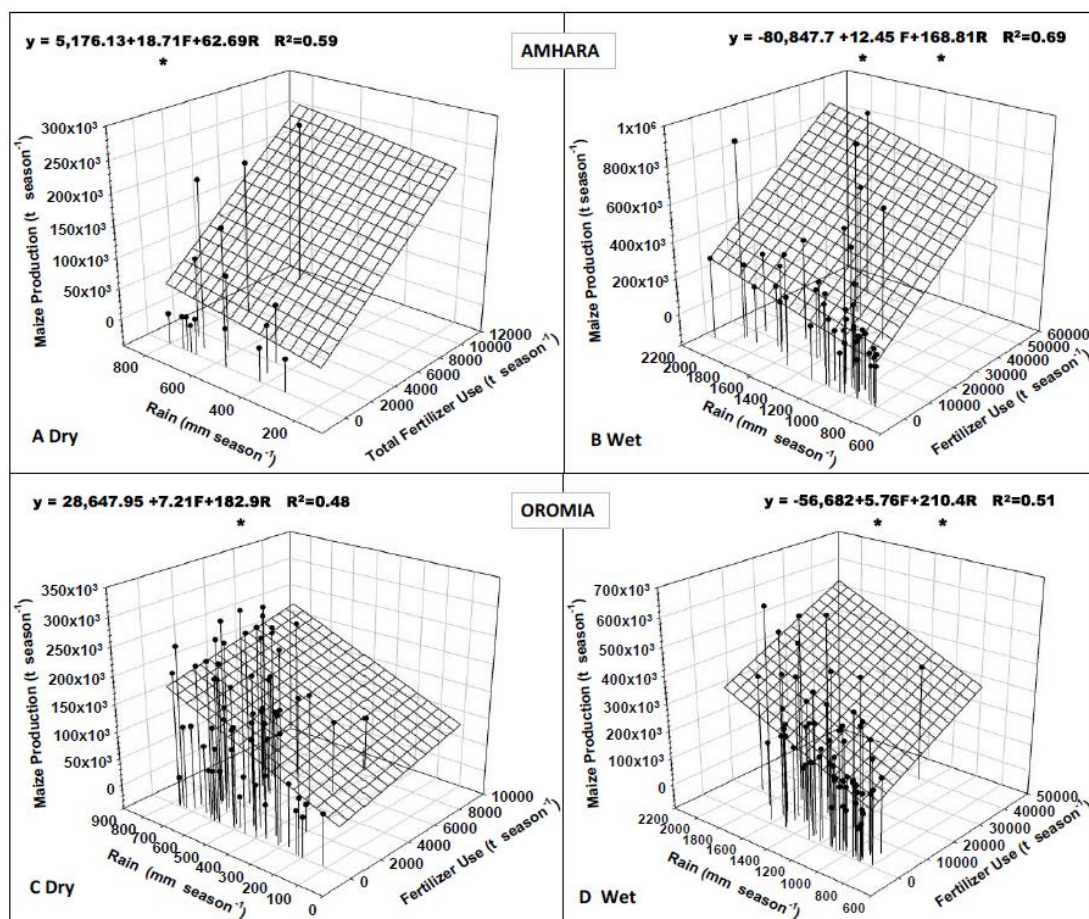


Figure 5. Maize production as affected by seasonal fertilizer use and rainfall under dry and wet climatic conditions in the Amhara and Oromia regions of Ethiopia during the 2004–2018 period. Significant coefficients are marked with an asterisk

3.4 Teff Production in Amhara Region

The teff production surface response during dry conditions was significantly affected only by fertilizer (Figure 6A; Table 1). Regional teff production under dry conditions increased at a rate of 12.23 mt per mt of fertilizer used during the season. The cases of fertilizer use above 4,000 mt per season increased when total seasonal rainfall was higher than 400 mm. The substantially fewer points to fit the response surface for teff production

under dry conditions relative to wet conditions (Figure 6B) can be taken as evidence of lower fertilizer use when rainfall is a production-limiting factor.

Teff production under wet conditions was significantly affected only by fertilizer use (Figure 6B). Regional teff production under wet conditions increased at rate of 8.49 mt per metric ton of fertilizer use during the growing season. Most of the cases were associated with fertilizer use under 20,000 mt, but the production response to fertilizer use is explained mainly by fertilizer use of more than 20,000 mt when seasonal rainfall was over 800 mm. The average regional teff production under wet conditions in Amhara was 156,332 mts per season, which was significantly higher than the average of 104,243 mt per season produced in the same region under dry conditions (Figure 8).

3.5 Teff Production in Oromia Region

The teff production response surface in dry conditions (Figure 6C) was significantly affected only by fertilizer used during the growing season within 0 to 30,000 mt. Seasonal total rainfall of 180 to 600 mm per season did not have a significant effect on teff production. Regional teff production under dry conditions increased at a rate of 8.03 mt per metric ton of fertilizer used. Most of the data used to build the response surface model came from fertilizer use of less than 10,000 mt per season and total seasonal rainfall of 180–600 mm.

The teff production response surface in wet conditions was significantly affected by seasonal fertilizer use and total rainfall (Figure 6D; Table 1). Regional teff production grew at a rate of 12.7 mt per metric ton of fertilizer use during the growing season and teff production grew at a rate of 112.5 mt per millimeter of rainfall during the season. Fertilizer use from a few metric tons per season to near 25,000 mt per season was associated with the full range of precipitation from 600 to 1,500 mm per season. The numerous points available for building the teff production response surface under wet conditions were the result of higher fertilizer use adoption under no rain restrictions (Figure 6D), compared with the few points to produce the surface response under dry conditions, when the rain scarcity evidently discouraged fertilizer use by farmers (Figure 6C). Higher fertilizer use and rainfall in wet conditions in Oromia produced an average of 140,000 mt of teff per season, which was significantly higher than the average of 80,000 mt of teff per season in dry conditions in the region.

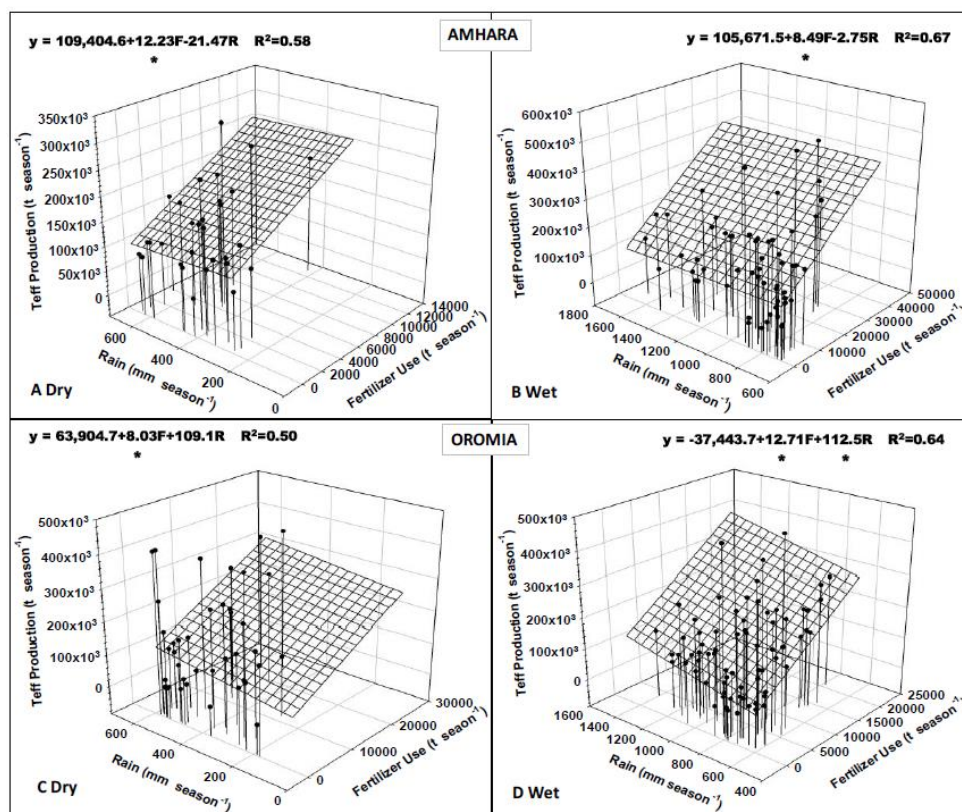


Figure 6. Teff production as affected by seasonal fertilizer use and rainfall under dry and wet climatic conditions in the Amhara and Oromia regions of Ethiopia during the 2004–2018 period. Significant coefficients are marked with an asterisk

3.6 Wheat Production in Amhara Region

The wheat production surface response during dry conditions was significantly affected only by fertilizer use of 0–16,000 mt per season (Figure 7A). Regional wheat production in Amhara increased at a rate of 10.9 mt per season per metric ton of fertilizer used. Rainfall of 250–700 mm per season had no significant effect on wheat production, and the few points available for fitting the response surface suggest that rainfall shortages discouraged both fertilizer use and use of higher fertilizer quantities by many farmers.

Wheat production under wet conditions in Amhara was significantly affected by the amount of fertilizer used per season. Total rainfall during the season had a weak effect ($p = 0.098$) on wheat production (Figure 7B; Table 1). Fertilizer use in wet conditions in Amhara ranged from 0 to 30,000 mt per season, while total rainfall ranged from 600 to 2,200 mm per season. Regional wheat production under wet conditions increased at a rate of 6.3 mt per metric ton of fertilizer used during the growing season, and wheat production decreased at a rate of 44.6 mt per season per millimeter of rainfall during the season. The cluster of points associated with greater than 1,400 mm rainfall per season and fertilizer use of less than 5,000 mt per season contributed to the negative effect of rainfall on wheat. There was no significant difference in wheat production in wet and dry conditions in Amhara, with a mean production of 85,000 and 100,000 mt per season, respectively.

3.7 Wheat Production in Oromia Region

Wheat production under dry conditions in Oromia was significantly affected only by the amount of fertilizer used per season (Figure 7C). Regional wheat production under dry conditions grew at a rate of 8.13 mt per metric ton of fertilizer used per season. Most of the points available to fit the production response surface were associated with fertilizer use of less than 15,000 mt per season, indicating that the low rainfall associated with dry conditions in Oromia discouraged higher fertilizer use per season.

Wheat production in Oromia during wet conditions was significantly ($p < 0.01$) affected by both seasonal fertilizer use and rainfall (Figure 7D; Table 1). Regional wheat production increased at a rate of 9.83 mt per metric ton of fertilizer used per season, and wheat production decreased at a rate of 128.6 mt per season per millimeter of rainfall during the season. Major production reductions took place with rainfall of higher than 1,400 mm per season. The figure also suggests a decrease in fertilizer use as the total seasonal rainfall increases. Although not significantly different, the mean wheat production of 120,000 mt and 97,000 mt during the dry and wet conditions, respectively, suggests a detrimental effect of high rainfall on wheat production.

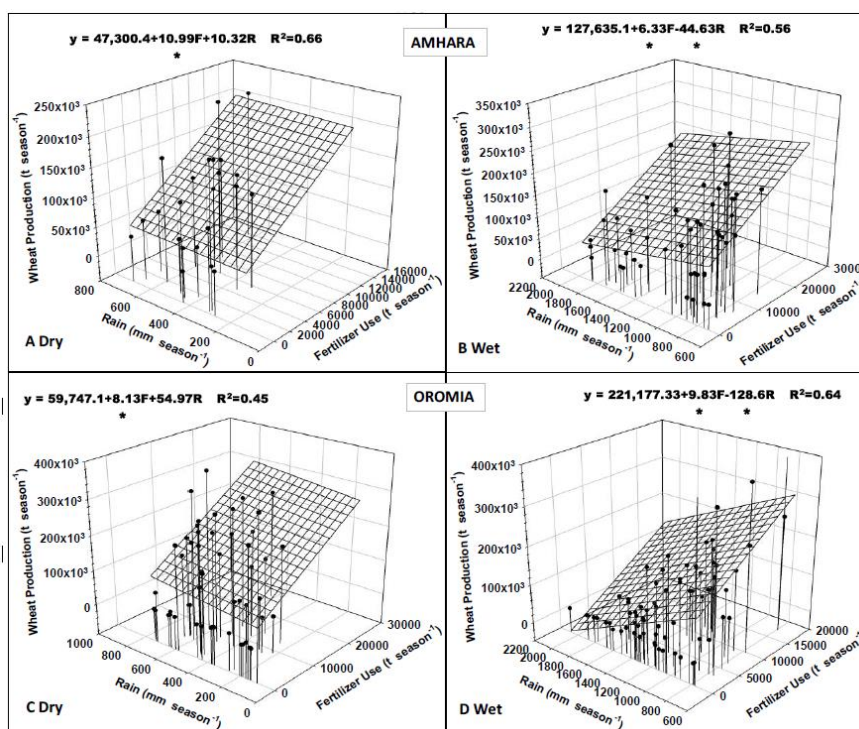


Figure 7. Wheat production as affected by seasonal fertilizer use and rainfall under dry and wet climatic conditions in the Amhara and Oromia regions of Ethiopia during the 2004–2018 period. Significant coefficients are marked with an asterisk

3.8 Effect of Wet and Dry Conditions on Fertilizer Use and Yield Trend

Figure 8 summarizes the joint effects of rainfall and fertilizer use shown in greater detail in Figures 5, 6, and 7. Maize production was significantly higher in wet conditions than in dry conditions, and significantly more maize was produced in Oromia than in Amhara during both dry and wet conditions. Higher maize production in Oromia during both wet and dry conditions relative to Amhara can be explained by the steeper maize production increase resulting from rainfall increments, while the fertilizer use range was about the same in the two regions (Figure 5). Variations in soil fertility and variety used could explain the variations in yield between the two regions.

Teff production differences were significant only between dry and wet conditions, but the differences across regions were not significant. Higher teff production in wet conditions is mainly explained by the higher use of fertilizers and the higher nutrition efficiency occurring in moist soils during the crop cycle. The larger number of farmers growing teff in wet conditions also can explain higher production during the wet conditions in both regions (Figure 6).

No significant differences in wheat production between either dry and wet seasons or across regions could be explained by the detrimental effect of excessive rain on wheat production during the years studied in both regions. Adaptation measures such as growing a crop other than wheat may be needed during wet conditions (Figure 7).

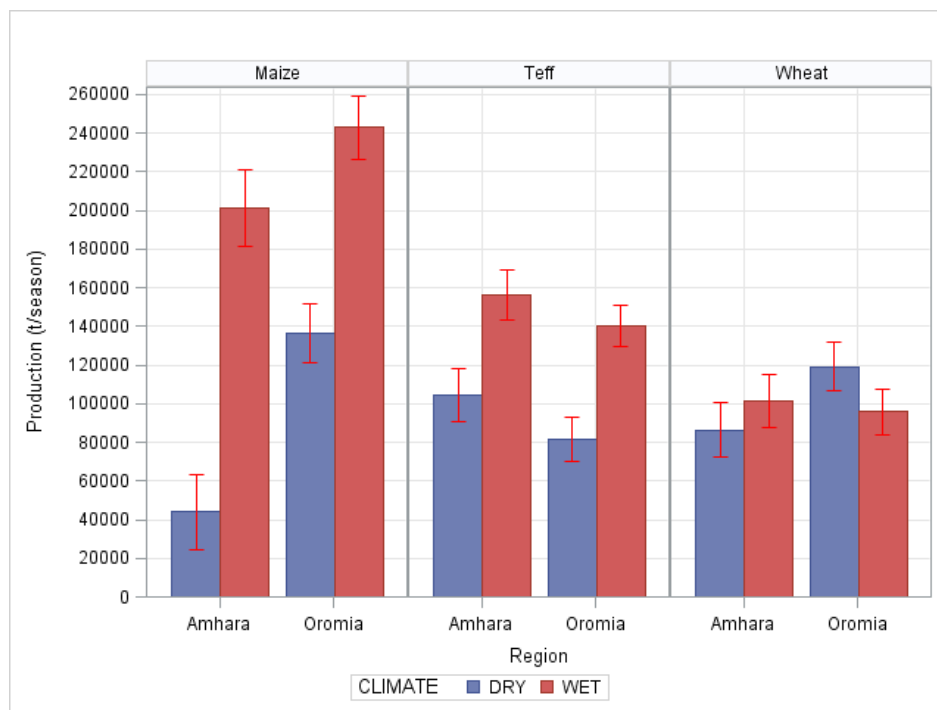


Figure 8. Comparison of crop production under dry and wet climatic conditions in the Amhara and Oromia regions of Ethiopia during the 2004–2018 period

4. Discussion

Rainfall variability and declining rainfall trends had a significant effect on cereal production both directly and indirectly as a result of lower fertilizer use in Amhara and Oromia regions. The variability within each region was associated with differences in rainfall quantities and distribution among zones and differences across years. Similar rainfall variability and declining trends were identified in Bale zone (Fitsum, Negash & Dejene, 2017). Large seasonal and spatial variability of rainfall in Ethiopia is the result of the macro-scale pressure system changes and moisture flows (Beltrando & Camberlin, 1993; Hagosa, Makombe, Namara, & Awulachew, 2009) interacting with topography (Brazel & Balling, 1986).

Production of maize, teff, and wheat was significantly affected by fertilizer use under wet conditions in both Amhara and Oromia regions. With adequate rainfall, cereal production was not limited by water stress, and nutrients from fertilizer application and soil supply were available for plant uptake. In addition, the expectation

of adequate rainfall also encouraged farmers to use fertilizers. A study by Fufa & Hassan (2006) showed that farmers' expectation of a good rainfall season was positively and significantly associated with fertilizer use, with a 21% higher probability than when they perceived a bad season. Alem, Bezabih, Kassie, & Zikhali (2010), using panel data from the central highlands of Ethiopia matched with corresponding village-level rainfall data, also found that the intensity of current year's fertilizer use is positively associated with higher rainfall levels in the previous year. Rainfall variability, on the other hand, impacts fertilizer use decisions negatively, implying that variability raises the risk and uncertainty associated with fertilizer use (Alem et al., 2010).

However, despite the importance of these crops to economic and food security, the data show that yield and production gaps still exist in Ethiopia (Schneider & Anderson, 2010), indicating that cereal production can likely be further increased with targeted recommendations of best management practices, including fertilizers (Mueller et al., 2012; Pradhan, Fischer, Velthuisen, Reusser, & Kropp, 2015). Gaps in knowledge, information, and skills (e.g., appropriate use, combination, and timing of inputs, including crop protection measures) that prevent farmers from reaching best practice are some of the main factors in yield gap (van Dijk et al., 2020). In Ethiopia, the yield gap of staple crops has been directly implicated in food shortages and the country's dependence on food imports and aid (Abate et al., 2015; Mann & Warner, 2017). Fertilizer use, albeit lower during dry conditions, also had significant effect on teff and wheat production in Amhara and Oromia regions and on maize production in Amhara. Site-specific recommendations based on the regression models presented here and decision support tools can help farmers reduce the risks associated with fertilizer use in dry conditions. The impact of rainfall may be lower on teff yield because of the adaptive nature of the crop. Teff is a highly versatile crop that adapts to different agroecologies, with reasonable resilience to both drought and waterlogging (Assefa et al., 2011; Roseberg et al., 2005). Teff performs well on various soils (Mamo, Teklu, & Balesh, 2000). The crop is unique in its ability to grow and yield on poorly drained Vertisols, which most cereals cannot tolerate (Assefa et al., 2015).

Abiotic factors, such as low amounts and poor distribution of rainfall in lowland areas, plant lodging in half of the highlands, soil erosion, disease, and weeds, also contribute to significant wheat yield losses in the country. For instance, Zewdie, Tanner, Elias, Gofu, & Tarekegne, (1990) suggest that plant lodging causes yield losses of 10–30%. Estimated yield gains with proper weed control through row planting and reduced seeding rates range from 35% to 85% (Tessema & Tanner, 1996, 1997; Desta, 2000; Bogale, Nefo, & Seboka, 2011).

Wheat production was negatively impacted by wet conditions, particularly when rainfall exceeded 1,400 mm, in both regions. However, the effect was more significant ($p < 0.001$) and drastic (a decrease of 128.6 mt per mm rainfall) for Oromia. Increased pest and disease incidences have been reported for wheat grown under wet conditions in tropical and subtropical environments. Disease may persist longer in high production situations, such as high rainfall or humid coastal areas, in which high seed rates or heavy application of nitrogen fertilizers has promoted dense crops that stay moist over extended periods of time. As rainfall increases, diseases become more of a problem. During high rainfall conditions, a combination of excessive rainfall (flooding) and virulent pests and diseases makes wheat productivity less predictable (Tadesse, Bishaw, & Assefa, 2019). A study by Megersa, Tesfaye, Getnet, & Tana, (2019) also showed that the seasonal rainfall amount explained 44%, 21%, 51%, and 41% of the wheat yield variability on average at Debere Berhan, Fitcha, Ambo, and Holeta, respectively, all of which are under the wet category in this study. While pesticide use has increased in Ethiopia, data from CSA (not shown here) indicates that it is not widely practiced on wheat. Studies also indicate that, although wheat stripe control by fungicide application is one of the most popular means of maximizing grain yield globally, farmers in Ethiopia did not use fungicides in wheat production until recently due to a lack of awareness about the yield advantage gained and the availability and cost of fungicides (Gianessi, 2014). Pest and disease outbreaks are also promoted by imbalanced fertilizer use. Balanced fertilization with secondary and micronutrients, such as magnesium, zinc, and copper, can improve crop resilience to abiotic and biotic stresses and improve yields (Cakmak, 2006; Magen, 2008; Uppal, Wani, Garg, & Alagarswamy, 2015). A high amount of rainfall on wheat can also contribute to the loss of nutrients through erosion and leaching (Adimassu, Langan, Johnston, Mekuria, & Amede, 2017; Ma et al., 2016) and to soil acidity (Agegnehu, vanBeek & Bird, 2014; Agegnehu, Yirga, & Erkossa, 2019). Soils of Amhara and Oromia are commonly Cambisols, Vertisols, Ferralsols, and Fluvisols (Appendix 2). Rainfall amounts exceeding 1,400 mm in the presence of coarse soils and soils with poor drainage can contribute to nitrate leaching and denitrification losses, respectively.

As suggested by researchers studying the impact of temporal and spatial rainfall variability and the decline of seasonal precipitation in many agricultural areas of Ethiopia, government and private sector programs of adaptation should be developed (Fitsum et al., 2017). Such adaptation measures must include irrigation, development of crop genotypes resistant to water stress, and higher fertilizer use efficiency under rainfall limitations to improve crop production during years of rainfall scarcity. Crop productivity decreases can be

exacerbated by the rainfall variability in Ethiopia with serious consequences to food insecurity. The productivity reduction of 20% and the poverty increase of 25%, estimated by Osman & Sauerborn (2002) and Hagosa et al. (2009), can likely become worse without climate change mitigation.

5. Conclusion

Both wet and dry conditions have a significant influence on crop performance and fertilizer and water use efficiencies. Crop productivity decreases under the rainfall variability in Ethiopia will have serious consequences on food security, particularly without adaptive measures to mitigate the effects of climatic changes. The use of meteorological information to improve decision-making practices, such as the amount and type of fertilizer to be applied, is recommended. The current national effort of developing nationwide programs of site-specific fertilizer recommendations in Ethiopia should integrate weather data in deciding management options under the changing climate.

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Declaration of Conflicting Interests

The author(s) declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Appendix A

Meteorological stations used to analyze the rainfall pattern in this study in Amhara and Oromia regions, Ethiopia.

Region	Zone	Station	Lat	Long	Region	Zone	Station	Lat	Long
Amhara	Argoba Sp	Gewana	10.17	40.63	Oromia	Arsi	Assela	7.95	39.12
Amhara	Awi	Chagni	10.95	36.50	Oromia	Arsi	Bekoji	7.58	39.33
Amhara	Awi	Dangila	11.27	36.83	Oromia	Arsi	Iteya	8.13	39.23
Amhara	Awi	Injibara	10.95	36.93	Oromia	Bale	Goba	7.00	39.98
Amhara	E.Gojjam	D/ Markos	10.33	37.72	Oromia	Bale	Jimala	6.98	40.10
Amhara	E.Gojjam	Dejen	10.17	38.13	Oromia	Bale	Robe	7.12	40.00
Amhara	E.Gojjam	M/Mariam	10.87	38.27	Oromia	Borena	Negele	5.33	39.58
Amhara	N.Gondar	Chilga	12.75	36.67	Oromia	E.Hararge	Haramaya	9.40	42.02
Amhara	N.Gondar	Debark	13.13	37.90	Oromia	E.Hararge	Babile	9.22	42.33
Amhara	N.Gondar	Gondar	12.60	37.47	Oromia	E.Hararge	Harar	9.32	42.12
Amhara	N.Shewa	Debre Birhan	9.68	39.53	Oromia	E.Shoa	Adama	8.53	39.27
Amhara	N.Shewa	Enewari	9.89	39.15	Oromia	E.Shoa	Gimbichu	8.83	39.17
Amhara	N.Shewa	Shoa Robit	10.00	39.90	Oromia	E.Shoa	Meki	8.15	38.82
Amhara	N.Wolo	Kobo	12.15	39.63	Oromia	E.Welega	Anno	9.07	36.97
Amhara	N.Wolo	Mersa	11.67	39.65	Oromia	E.Welega	Arjo	8.82	36.47
Amhara	N.Wolo	Woldiya	11.83	39.60	Oromia	E.Welega	Nekemte	9.08	36.55
Amhara	Oromia	Artuma	10.50	39.83	Oromia	Guji	Shakiso	5.75	38.92
Amhara	Oromia	Kemisie	10.72	39.87	Oromia	Horogudu	Fincha	9.90	37.45
Amhara	Oromia	Senbete	10.30	40.00	Oromia	Horogudu	Gembo	9.17	35.83
Amhara	S.Gondar	Debre Tabor	11.85	38.02	Oromia	Horogudu	Shambu	9.57	37.10
Amhara	S.Gondar	Dera	8.33	39.32	Oromia	Illubabo	Bedele	8.45	36.35
Amhara	S.Gondar	Gasay	11.75	38.17	Oromia	Illubabo	Gore	8.15	35.52
Amhara	S.Wolo	Chefa	10.98	39.75	Oromia	Illubabo	Metu	8.30	35.58
Amhara	S.Wolo	Dessie	11.13	39.63	Oromia	Jimma	Agaro	7.85	36.58
Amhara	S.Wolo	Were Illu	10.60	39.43	Oromia	Jimma	Jimma	7.67	36.83
Amhara	W.Gojjam	Adet	11.27	37.48	Oromia	Jimma	Sekoru	7.92	37.43
Amhara	W.Gojjam	Dembecha	10.55	37.48	Oromia	Kelem	Aleku	8.63	34.78
Amhara	W.Gojjam	Womberema	10.67	36.75	Oromia	Kelem	Chell	8.68	32.60
Amhara	Waghemra	Degosa	12.10	39.05	Oromia	Kelem	Dembidolo	8.53	34.80
Amhara	Waghemra	Lalibela	12.02	39.03	Oromia	N.Shoa	Chanco	9.33	38.73
Amhara	Waghemra	Sekota	12.63	39.03	Oromia	N.Shoa	Fiche	9.80	38.73
					Oromia	N.Shoa	Tarcha	10.00	39.50
					Oromia	S.W.Shoa	Kersa	9.22	41.65
					Oromia	S.W.Shoa	Sebeta	8.90	38.62

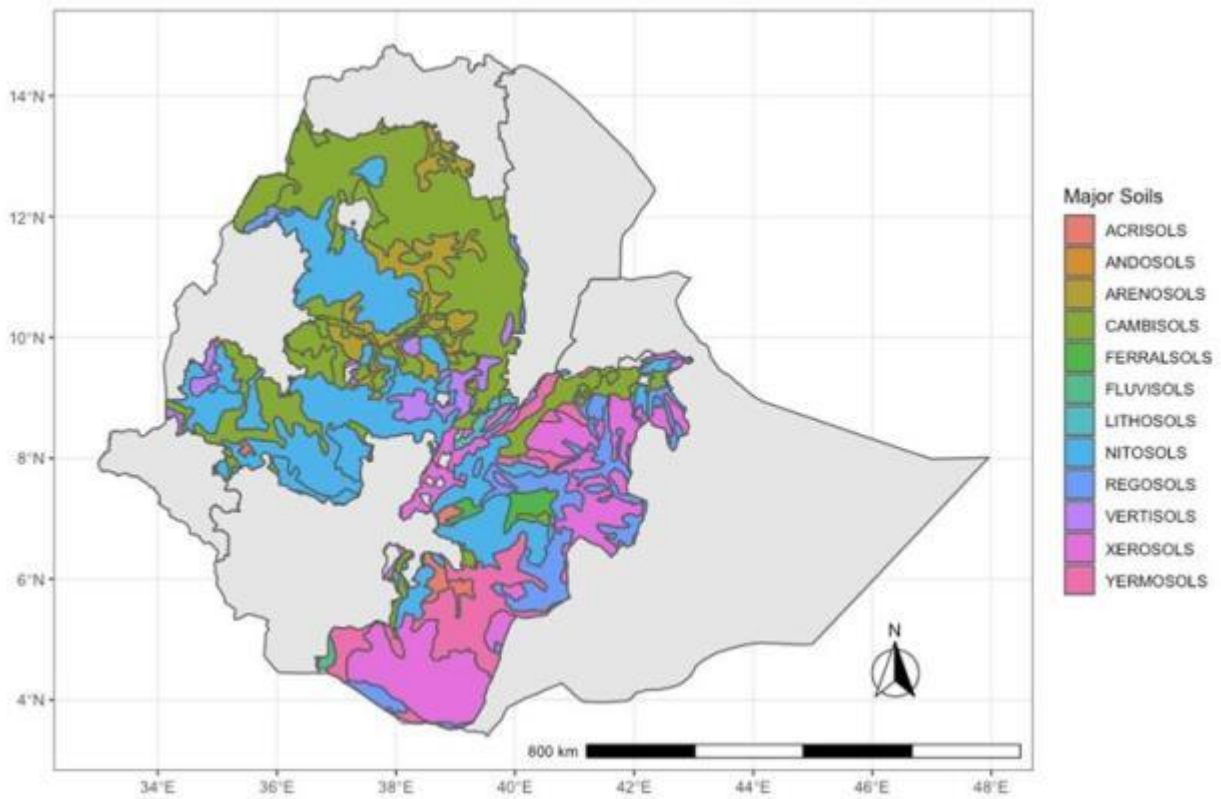
					Oromia	S.W.Shoa	Woliso	8.53	37.97
					Oromia	W.Arsi	Kofele	7.10	38.75
					Oromia	W.Arsi	Negele	5.33	39.58
					Oromia	W.Arsi	Shashemene	7.20	38.60
					Oromia	W.Hare	Asebeteferi_	9.08	40.87
					Oromia	W.Hare	Gelemso	8.82	40.52
					Oromia	W.Shew	Ambo	8.98	37.85
					Oromia	W.Shew	Bako	9.13	37.05
					Oromia	W.Shew	Dendi	8.83	38.00
					Oromia	W.Wele	Gembo	9.17	35.83
					Oromia	W.Wele	Mendi	9.60	35.60
					Oromia	W.Wele	Nejjo	9.50	35.50

Appendix B

Study areas and dominant soils.

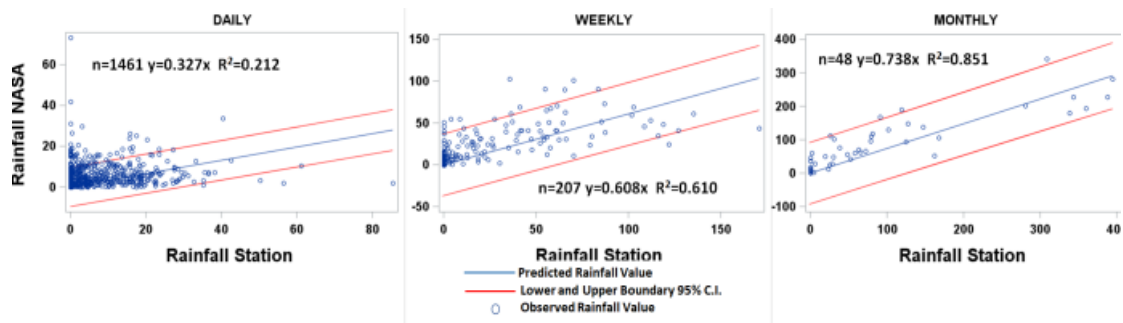
Source: Extracted from

<http://www.fao.org/geonetwork/srv/en/main.home?uuid=446ed430-8383-11db-b9b2-000d939bc5d8>



Appendix C

Validation of the NASA POWER rainfall validation using data from meteorological stations.



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