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NOVEL-RESULT

Analysis of declining trends in sugarcane yield at Wonji-Shoa Sugar Estate, Central Ethiopia

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Abstract

Yield decline has been the hallmark of Ethiopian sugarcane plantations. However, the extent and causes of the decline have not yet been empirically studied, making it difficult to manage the problem. This study aimed at analyzing the long-term yield data (1954–2022) with respect to variety and soil type. Thus, 8,923 records of yield data were summarized and sorted into decades, varieties, and soil types and then analyzed by applying Mann-Kendall and Tukey's tests. The fields were classified and mapped using ArcGIS 10.3. The results revealed that 69% of the plantation fields were classified as "yield declining," and the overall rate of decline has been 8.4 quintals ha^{-1} $year^{-1}$ ($R^2 = 0.76$). The rate of decline was higher for older than newer varieties and for vertisols than cambiols. Therefore, the older varieties should be micropropagated or replaced with improved ones, and the vertisols should be amended through practices such as green manuring, improved fallows, etc.

Keywords: soil type; variety; yield class; yield gap; yield map

Introduction

Increasing crop productivity is a key objective of the United Nations' 2030 Agenda for Sustainable Development (Jhariya et al., 2019; Polivova & Brook, 2021). Previous research has shown that a 0.6–1.0% increase in crop productivity can reduce the proportion of households living in extreme poverty by 0.6–1.2% (Liliane & Charles, 2020; Thirtle et al., 2001). In order to satisfy the food and nutrition requirements of the present and future generations while maintaining the environmental, social, and economic facets, sustainable production is essential (Guiné et al., 2021). As the agricultural sector make up over 85% of all employment in Ethiopia and contributes 46% to the country's GDP (Globaledge, 2022), sustainable crop production is critical for ensuring food security and for lifting people out of poverty. Thus, considering the country's ambition for sustainable development, the Ethiopian House of People's Representatives has approved the "2030 Agenda" as a component of the second five-year Growth and Transformation Plan (GTPII) (National Plan Commission, 2017).

The sugar industry is one of the subsectors that have been given a great emphasis by the Ethiopian government during the GTPII period (Gebeyehu & Abbink, 2022). This is due to the fact that Ethiopia possesses vast potentials and opportunities for developing the sugarcane agro-industry, which can play a significant role in the economic growth of the country. Among other things, the country's suitable agroclimatic conditions, strategic geographic location, availability of potentially arable lands, and ample freshwater resources make it one of the most ideal places in the world to establish sugarcane plantations (Aleme, 2019; Ming et al., 2006). According to Business Info Ethiopia (2022), the country possesses 1.4 million ha of irrigable, fertile, and virgin land for the cultivation of sugarcane.

Considering this potential, the Ethiopian government has made a substantial investment to expand the existing sugar estates and establish new ones (Ethiopian Sugar Corporation [ESC], 2019). Accordingly, 10 modern and high-capacity sugarcane mills that can produce up to 4.6 million tons of sugar are being established along with the ultimate development of 400,000 ha of sugarcane plantations (Abriham et al., 2017). It was suggested that a full implementation of this strategy would increase the contribution of the sugar agro-processing industry to the efforts being made to attain food security, increase foreign exchange earnings, and reduce poverty.

However, one of the major problems affecting the sugar industry in Ethiopia has been the drastically declining sugarcane yields. In this connection, Dinka and Ndambuki (2014) and Tesfaye (2021) reported yield declines of 45% and 48%, respectively, in the Wonji-Shoa Sugarcane Plantation (WSSP) alone. Due to this problem, the profitability of sugarcane plantations has dropped dramatically, imperiling the industry's production capacity and sustainability. As a result, Ethiopia is unable to attain its ambitious strategy to produce enough sugar even to meet the domestic market. Business Info Ethiopia (2022) has stated that the country's local sugar demand was anticipated to be 1.2 million tons during the periods of 2020 and 2021, while local sugar production was only 340,000 tons, leaving an 860,000-ton gap. It was also estimated that by 2029/2030, the demand for sugar in the domestic market is projected to reach 1.7 million tons at a compound annual growth rate of 3%. Due to this circumstance, Ethiopia has been compelled to import sugar from other countries at the expense of draining its foreign currency reserve. For instance, the country has imported sugar worth US$150 million in 2020 (Business Info Ethiopia, 2022).

A comprehensive investigation is required to determine the extent of yield decline and its root causes, which will aid in the design of appropriate mitigation strategies. In this regard, Jones and Singels (2015) have emphasized that analyzing the trends of sugarcane yield is very vital as it can indicate the source of the problem and provide critical information about the constraints. It can also show the potentials of crop production in the future (Kucharik & Ramankutty, 2005). However, in Ethiopia, no empirical studies have been conducted to diagnose the problem of sharp declines in sugarcane yields. A lack of research data obtained from such studies has hampered efforts to solve the problem of declining yields.

In this study, the declining trends of sugarcane yields are analyzed with emphasis on sugarcane variety and soil types. Prior studies have indicated that, in crop production, varietal characteristics and soil quality are the major yield-limiting factors that determine attainable yield (Tittonell & Giller, 2013). Soil type and its properties significantly affect crop performance through influencing soil aeration, water-holding capacity, soil fertility, and N leaching (Chen et al., 2020; Nyiraneza et al., 2012; Wang et al., 2022), and any soil property that impairs soil's water and air circulation can result in poor crop yields (Wallace & Nelson, 1986). On the other hand, varieties account for 50–95% of the global increase in agricultural output (Ming et al., 2006). The objective of this study was, therefore, to analyze the declining trends in sugarcane yield and to assess the role of variety and soil type in the yield decline at WSSP in central Ethiopia.

Materials and methods

Description of the study area

Location

The study was conducted in 2022 at WSSP, which is located at a distance of 12 km south of Adama city and 110 km southeast of Addis Ababa in Oromia Region, Ethiopia. The sugarcane plantation occupies an

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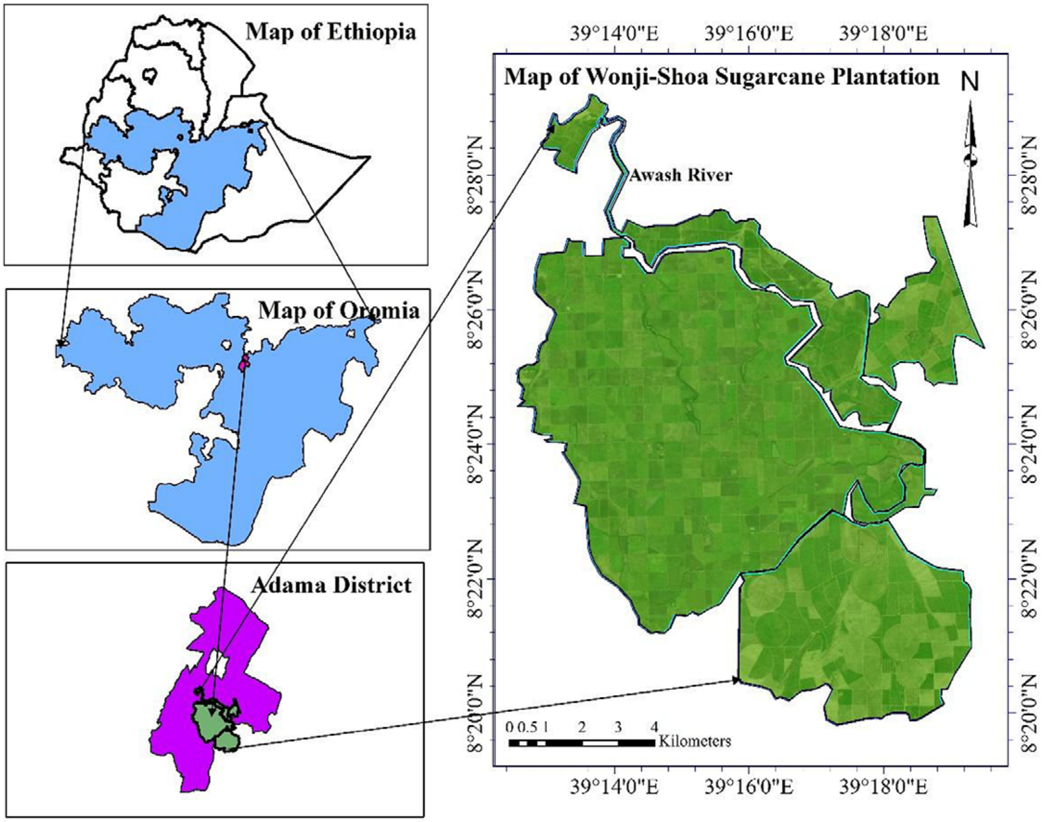

Figure 1. Map of the study area.

alluvial basin of the Awash River, within 8°19′54″–8°29′15″N and 39°13′34″–39°19′21″E at altitudes ranging between 1,540 and 1,650 m.a.s.l (Figure 1).

Climate

The study area belongs to the tropical "wet and dry" climate. A cool dry winter, a hot dry period right before the rainy season, and a hot wet rainy season are the three temperature phases that define the climate of the WSSP. The high altitude of the area significantly moderates the temperature profile and hence favors the use of extended cropping cycles (Mukherji, 2000). The long-term (1984–2020) mean maximum and minimum temperatures as well as the total annual rainfall of the study area are 14.5°C, 27.4°C, and 768 mm, respectively (Figure 2).

Establishment of WSSP

Cane sugar manufacturing in Ethiopia was started in the 1950s by the Dutch company Handles-Vereening, Amsterdam (HVA) at Wonji on 5,000 ha of land (Abriham et al., 2017). The plantation area reached 7,000 ha in 1978 and 8,000 ha in 2009. Monoculture has been the main system of sugarcane production, despite the fact that very few fields undergo fallow cycles or are amended with green manure during the rainy season.

The study area is divided into 430 fields (parcels of land) (Figure 1). A single field covers up to 28 ha of plantation area, which is managed the same way from planting to harvesting. Since the establishment of the sugar estate, the yield of each field has been documented. Cane yields have been recorded during the

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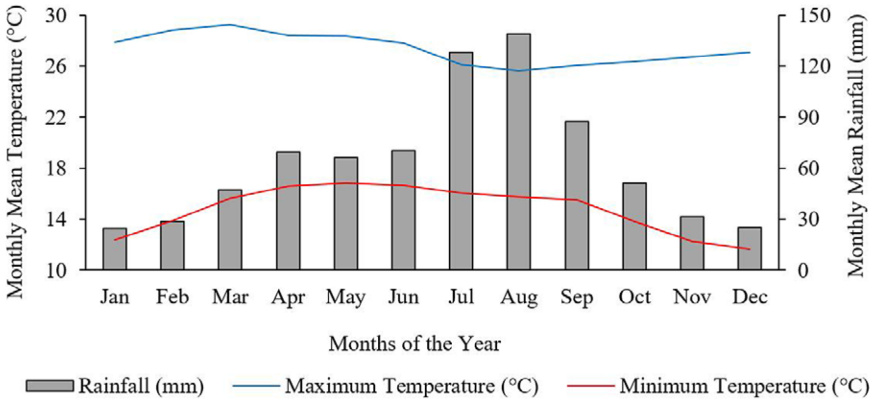

Figure 2. Mean monthly maximum and minimum temperatures and rainfall of the study area.

harvesting of each field using a weighbridge prepared for this purpose. The total weight of cane from each field is divided by the area of the field and then reported as quintals per hectare (cane yield). One quintal weighs 100 kg, or 0.1 ton.

Soil types

The estate is located in the Wonji plain, downstream of the Koka Dam, in the Awash Valley basin. Most of the plantation area is situated on the flood plains made up of levee and basin deposits. The levee soils found along river courses are classified as Fluvisol/Entisols, but the formations of neighboring basins (the basin proper and back swaps) are classified as vertisols (Mukherji, 2000). According to the soil survey conducted by BRLi and GIRDC (2013), three major soil types, namely, Haplic-vertisols (70%), Cambisols-clayic (26%), and Cambisols-ruptic (4%), were identified in the study site.

Sugarcane variety

Most of the sugarcane cultivars being grown at WSSP were imported, primarily from Barbados, India, South Africa, and Cuba (Table 1). The WSSP currently grows three major sugarcane varieties: N14 (39%), NCo334 (20%), and B52298 (12%). Twenty minor varieties take up the remaining 30% of the plantation (Table 1).

Collection of yield data

The yield data of 1954–2022 were obtained from the Plantation Department of Wonji-Shoa Sugar Estate. The information acquired consisted of comprehensive yield data from 1999 to 2022 as well as summarized yield data (quintal ha^{-1} month^{-1}) for the years spanning from 1954 to 1998. The yield data from 1999 to 2022 included details of each individual field, including its area, yield, soil type, variety, age, and crop type, as well as the dates of planting and harvesting. In total, 8,923 yield data from 430 cane fields were utilized for this study.

Data organization

The sugarcane age (growing period) in the WSSP ranges from 13 to 24 months. Therefore, yields were presented on a monthly (quintal ha^{-1} month^{-1}) basis to enable accurate inter-seasonal comparisons of production at times when the age at harvest varies. Yield per month was obtained by dividing the yield ($\hat{Y}a$, quintal ha^{-1}) by age at harvest (months). Finally, the yield data were sorted from oldest to most recent and then filtered based on variety and soil type. These two parameters were chosen because cane

Table 1. Sugarcane varieties currently under production at the WSSP in central Ethiopia

Variety	Area coverage (%)	Length of cultivation years	Country of origin
N14	38.54	27	South Africa
NCO334	19.9	51	India/South Africa
B52298	11.96	49	Barbados
C86–12	5.54	7	Cuba
C86–56	4.03	7	Cuba
B59/212	4.02	16	Barbados
B41227	3.01	57	Barbados
N52/219	1.52	7	South Africa
N53/216	1.27	7	South Africa
Mex 54/245	0.78	41	Mexico
C132–81	0.39	7	Cuba
Others	9.02	—	—

Source: Cane Composition WSSP (2021).

varieties and soil types are the most important variables that determine yield dynamics (Chen et al., 2020; Glaz, 2000; Ming et al., 2006; Nyiraneza et al., 2012; Barbosa and da Silveira, 2015; Wang et al., 2022). The actual yield for each field was calculated by computing the mean of its recent seven-year (2016–2022) yield data, because the mean yield data of the most recent 5–7 years are expected to best represent the current yield level (Dobermann et al., 2003).

Analyzing yield trends

The declining trend of yield data, which includes yields from the plantation's inception to the present (1954–2022), was analyzed. Afterward, the yield data were further categorized into subsequent decades (1954–1963, 1964–1973, 1974–1983, 1984–1993, 1994–2003, 2004–2013, and 2014–2022), and then a trend analysis was conducted for each period. Additionally, a trend analysis was conducted for each of the three soil types and for each of the 11 sugarcane varieties.

To analyze both the significance of trends and the rate of change in cane yield, the Mann-Kendall test and Sen's slopes were applied, respectively, using Real Statistics Resource Pack software (release 7.6) (Zaiontz, 2020). Furthermore, Genstat 2018 (VSN International, 2015) was used to compare the mean cane yields of the seven decades. To that end, mean separation was analyzed using Tukey's test at 95% confidence intervals.

Relative yield gap

Yield gap (ΔY, quintal ha^{-1}) can be calculated as the difference between the actual yield ($\hat{Y}a$, quintal ha^{-1}) and benchmark yield ($\hat{Y}p$, quintal ha^{-1}) (FAO & DWFI, 2015). The benchmark yield represented the yield of the best-performing fields from the historical yield data. To that end, the yields (quintals ha^{-1} $month^{-1}$) of three top-performing fields were selected from each soil type, and the weighted mean was computed (FAO & DWFI, 2015). Then ΔY was expressed as a percentage of $\hat{Y}b$, which is termed as the relative yield gap (RYG) (Equation 1).

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$$RYG = 100\frac{\Delta Y}{\hat{Y}b} = 100\frac{\hat{Y}b - \hat{Y}a}{\hat{Y}b} \quad (1)$$

where $\hat{Y}_b$ and $\hat{Y}_a$ are benchmark and actual yields, respectively.

For the WSSP, the exploitable increase in cane production (ΔQCANE, quintal annum^{-1}) was calculated as a product of the exploitable yield gap (expressed as a percentage) in the current year (2021/2022) and the average cane production (QCANE, quintal annum^{-1}) in the most recent seven years (2016–2022). Exploitable yield gap (ΔYe, quintal ha^{-1}) is defined as the difference between $\hat{Y}b$ and $\hat{Y}a$ in the current year (2021/2022) and was expressed as a percentage of $\hat{Y}a$.

$$\Delta QCANE = QCANE\frac{YGe}{100} \quad (2)$$

where

$$YGe = 100\frac{0.85\left(\hat{Y}b - \hat{Y}a\right)}{\hat{Y}a} \quad (3)$$

The commercial value of the exploitable yield gap was calculated as a product of ΔQCANE and price of sugarcane. The price of sugarcane during the study period at field level was 97 birr per quintal (Wonji-Shoa Sugar Estate [WSSE], 2020).

Yield classification

To classify each plantation field based on its yield trend, the methods demonstrated by Madhukar et al. (2020) and Ray et al. (2012) were adopted. They stated that the type of model that best fits the yield data indicates the type of yield trend (Table 2). Accordingly, the models that can be of use include the intercept-only model (Y = a), linear model (Y = a + bt), quadratic model ($Y = a + bt + ct_2$), and cubic model ($Y = a + bt + ct_2 + dt_3$), where Y stands for the yield and *t* the year. Hence, a polynomial regression model with a maximum degree of 3 was employed when using Real Statistics Resource Pack software (Zaiontz, 2020). Finally, the significance of the selected model was confirmed using the ANOVA

Table 2. Descriptions of the criteria for the classification of yield trends of plantation fields at the WSSP in central Ethiopia

SN	Yield class	Criteria for the determination of yield class
1	*Yields still increasing*	• A linear model with a positive slope • A quadratic model with a positive quadratic term • A cubic model with the peak of yield in recent years
2	*Yields stagnated.* Yields historically increased but now are stagnating	• A quadratic model with a negative quadratic term or a cubic model with stagnation in the recent years. Additionally, the yield in the recent years should not be as low as the years with the lowest yield.
3	*Yields declined.* Yields are collapsed to the lowest level	• A linear model with a negative slope • A quadratic model with a negative quadratic term, but a recent year yield that is equal to the lowest yield years • A cubic model with a yield of recent years equivalent to the year of lowest yield
4	*Yields never improved.* Fields that have witnessed no significant yield improvements to date	• An intercept-only model

Source: Madhukar et al. (2020).

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provided by the software. In the case where no significant ($p > 0.05$) differences were observed, the model would be taken as intercept-only (Y = a).

After the identification of the best-fit model for the yield trend of each field and for the WSSP as a whole, the yield trend classification was performed as presented in Table 2.

Since the majority of cane fields were classified under the "yield declining" category, they were further divided into three classes, namely, the top 25% yield-declining fields, or "yields declining rapidly," the bottom 25% yield-declining fields, or "yields declining slowly," and the intermediate 50% yield-declining fields, or "yields increasing moderately."

Finally, the yield class was mapped based on the yield of each of the 430 plantation fields of WSSP. The coordinates of the center of each field were collected from Google Earth Pro and entered into an Excel spreadsheet along with the associated yield class. For the purpose of mapping, a GIS platform named ArcGIS10.3 was used. The interpolation was done using the command "Spatial Analyst tools–Interpolation–IDW."

Results and discussion

Overall yield trend

The best-fit model for the long-term (1954–2021) yield data of WSSP was found to be quadratic, which was significant at $p < .05$. The model had a negative term, and the current yield was less than the lowest yields of the other years (Figure 3). Therefore, as shown in Table 2, the yield trend was classified under the "yield declining" category. The Mann-Kendall test, too, revealed a significantly decreasing yield ($p < .05$) at 8.4 quintals ha^{-1} year^{-1} and an R^2 value of 0.76 (Figure 3).

Analysis of the overall yield trends suggested that the sugarcane plantation has been losing significant amounts of yields every year. The causes for such a drastic decline might be related to the production system adopted by the plantation. An intensive farming system is at work in the WSSP, which mainly comprises mono-cropping, pre-harvest cane burning, excessive tillage, and uncontrolled traffic of heavy machinery. Such farming systems are frequently blamed for the primary causes of soil degradation (Kopittke et al., 2019) and hence might be responsible for the observed yield decline at the WSSP.

Unless such declining trends of yield are reversed, the survival of the WSSP could be under existential threat, and its future viability is at stake. Similar problems were also reported from Cuba, which was once the dominant sugarcane-producing country in the world. Due to the substantive yield decline (33.3 tons in 2001–2002, down from an average of some 54 tons during the 1980s), most of the sugar estates in Cuba became unprofitable, and the role of sugarcane in the country's economy declined from 70% in 1989 to 10% in 2007 (Pollitt, 2009).

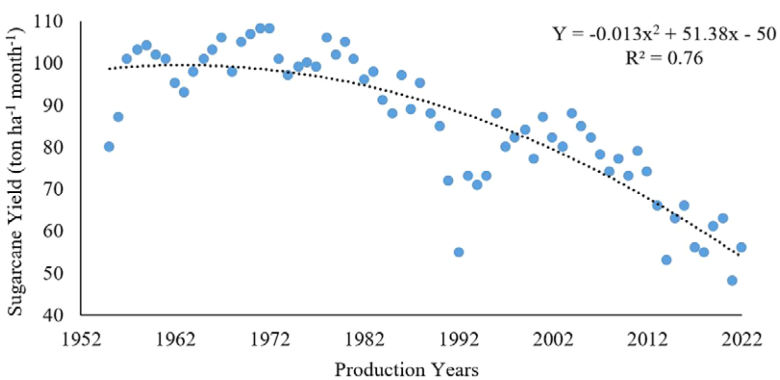

Figure 3. Overall yield trends (1954–2022) of the WSSP. The best-fit and significant ($p < .05$) model was found to be quadratic.

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In fact, most of the countries that produce sugarcane around the world would encounter the problem of yield decline. For instance, a significant decline in cane productivity (up to 15%) has been observed in Brazil since 2008, when the crop's mechanization was advanced (Franco et al., 2018), and the average cane yields have recently dropped from 89 to 69 tons ha^{-1}. Dubb (2013) also emphasized the issue of decreased sugarcane production South Africa. Likewise, Australia's plateau in sugarcane yield was identified in the early 1990s (Garside et al., 2005). These facts show that declines in sugarcane yields have become a common problem facing the world. However, the aforementioned countries are found to be using modern and scientific agricultural technologies to address the problem and exploit ways to fully utilize the potential of the crop. For instance, Australian scientists researched for over 13 years with the aim of preventing stagnation in sugarcane yields (Garside et al., 2005). The researchers have concluded that intensive production practices and monoculture are the main contributors to soil quality deterioration and declining cane yields. They suggested fundamental management techniques that they referred to as "the sustainable pillars for the growth of sugarcane." These strategies include residue retention (ceasing pre-harvest cane burning), control of traffic in sugarcane fields during cultivation, crop rotation, and minimum tillage (Franco et al., 2018). Results from the studies conducted in Papua New Guinea and Brazil also suggested somewhat similar approaches (Bangita et al., 2011; Franco et al., 2018).

A similar strategy could be adopted by Ethiopian sugarcane plantations to address the issue of yield decline caused by intensive production systems. In addition, cutting-edge and contemporary technologies like satellite-based crop monitoring should be used. These tools will allow plantation workers to effectively monitor cane fields and identify potential problems before they get worse (Bhargava, 2019; Jindo et al., 2021; Khanal et al., 2020).

Yield trends in decades of production

In the WSSP, the most significant ($p < .009$) fall in cane yield was observed in the fourth (1984–1993) and sixth (2004–2013) decades, whereas the first two decades of cane production showed increasing trends (though not significant) (Table 3). Furthermore, the mean yields revealed significant ($p < .05$) differences across decades, with the highest yield being recorded in the second and third decades, while the seventh decade showed the lowest yield (Table 3).

The fact that the yield in the second decade was higher than that of the first might be due to the reason that the fields were initially virgin land (grassland) (Kassie, 2022) and hence fertile. Since sugarcane can utilize a considerable amount of nutrients present in the soil (Da Silva Calheiros et al., 2018), soil fertility might eventually deplete, contributing to a decline in yields in the subsequent decades.

Table 3. Annual rate of change in yield (yield trends) and decadal mean yields of sugarcane at the WSSP in central Ethiopia

Decades of production	Rate of change in yield (quintal ha^{-1} $month^{-1}$)	*p* value	Mean yield (quintal ha^{-1} $month^{-1}$)
1D (1954–1963)	0.333	.928	96.56 b
2D (1964–1973)	0.400	.718	103.56 a
3D (1974–1983)	−0.600	.243	99.86 ab
4D (1984–1993)	−3.250	.009	81.46 c
5D (1994–2003)	0.800	.415	82.26 c
6D (2004–2013)	−2.333	.005	74.26 d
7D (2014–2022)	−1.333	.258	58.50 e

Note. 1D–7D denote one up to seven decades. The comparison of mean yields was made using Tukey's test at 95% confidence intervals, and figures followed by the same letters are not significantly different.

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The most significant ($p < .05$) and highest fall in cane yield was observed in the fourth decade (1984–1993) (Table 3). Besides the intensive production system in place, the sharp decline in cane yield in this decade might have been exacerbated by a political transition that witnessed the fall of the former government (Dergue) and the ascent of the Ethiopian Peoples' Republic Democratic Front (EPRDF) government to power in 1991. The lack of proper cane management and the scarcity of agricultural inputs during pre- and post-transitional periods might have also contributed to the decline.

The inadequate research support accorded to the sugar estates is another possible reason for productivity decline over the past few decades. According to Ambachew and Firehun (2013), all plantation operations during the pre-nationalization era (1974) were directed based on the findings of onsite-developed research, and different cultural practices were continually updated based on annual and intermediate research findings. However, due to organizational instability and a lack of skilled personnel, the research units' contribution to the sugar sector has been very low in the later decades. Furthermore, the sugar estate has been too much focused on addressing the minor flaws in the production system, leaving out opportunities for high-level innovations. Consequently, the majority of Wonji-Shoa's current production systems/practices are as ancient as the sugar estate itself (Ambachew and Firehun, 2013).

Yield trends in sugarcane varieties

Those varieties under cultivation for relatively longer periods of time (B52298—49 years, NCo334—51 years, B41227—57 years, N14—27 years, and B59/212—16 years) presented significant ($p < .05$) diminishing trends, except for Mex 54/245 (Table 4). Contrarily, recent cultivars or varieties did not exhibit a declining yield trend, except for variety C86/56.

The analysis suggests that the more the number of years a variety is under cultivation, the greater the possibility of declining trends of yields. From the time that large-scale sugarcane production began almost a century ago, deteriorating tendency in yield performance of varieties has been a frequent occurrence in sugarcane farms (Viswanathan, 2016). Consistent with this postulation, Barbosa and da Silveira (2015) claimed that it is common practice to replace long-cultivated sugarcane cultivars with newer ones that can be more productive and are adaptable to the actual conditions of the cane-growing area (Bernardo et al., 2019).

Since sugarcane is propagated by planting axillary buds, which are clones and cannot contain genetic mutations, genetic deterioration is not to blame for the decline (Srinivasan & Jalaya, 1995). The major

Table 4. Annual rate of change in yield (yield trends) of commercial sugarcane varieties cultivated at the WSSP in central Ethiopia

Variety	Rate of change in yield (quintal ha^{-1} $month^{-1}$)	*p* value	Duration of cultivation (years)
B41227	−1.216	.000	57
NCO334	−1.705	.000	51
B52298	−1.778	.000	49
Mex 54/245	−4.122	.133	41
N14	−1.947	.000	27
B59/212	−2.367	.001	16
N53/216	−5.505	.230	7
N52/219	−4.122	.133	7
C132–81	−1.750	.764	7
C86–56	−3.554	.016	7
C86–12	−5.084	.230	7

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causes of varietal decline have been elucidated by Srtvastava et al. (2006). The authors have emphasized that the gradual deterioration of soil properties, the accumulation of insect pests on the most widely grown variety, the occurrence of new disease strains, etc., play a part in yield decline of particular varieties grown on the same sugarcane farm. In addition, it is possible that sugarcane clones may suffer viral degeneration after a long time of use, as suggested by Viswanathan (2016). Therefore, at the WSSP, the declining yields of older varieties may also be attributed to varietal degeneration of the clonal material. In this regard, meristem tip culture may be used to remove viruses. Consistent with this proposition, Lal et al. (2015) and Bello-Bello et al. (2018) have stated that micropropagation (meristem tip culture) enables the renewal of aged and deteriorated varieties as well as the sanitation of diseased varieties.

It is evident that the introduction and diversification of new varieties, as well as higher varietal update rates and varietal concentration indices, are alternatives to improve sugarcane yields (Santos, 2016). However, these parameters have been hardly maintained at the WSSP because Ethiopia does not have a sugarcane breeding station. The dominant varieties in the WSSP were, therefore, in production for longer than the typical 20 years (Table 4), a time frame when a sugarcane variety is expected to reach its pinnacle of yield (Bernardo et al., 2019). It is clear from this argument that using old cultivars may have contributed to the reported yield decline at the WSSP.

Generally, the results of this study suggest that it is necessary to urgently replace the old cultivars. This is because without high-yielding varieties, sugarcane yields could never be increased (Glaz, 2000), since such varieties can account for 50–95% of the global increase in agricultural outputs (Ming et al., 2006). Consistent with this proposition, Barbosa and da Silveira (2015) also noted that the development and widespread production of high-yielding and stress-tolerant sugarcane cultivars have been primarily responsible for the competitiveness of the Brazilian sugar industry, which is the world's leading producer of the commodity.

Yield trends in soil types

For all the three soil types at the WSSP, the sugarcane yield showed significantly ($p < .01$) declining trends, with the highest rates of decline observed for Haplic-vertisolss (Table 5), followed by Cambisols-ruptic and Cambisols-clayic.

The results of this study reveal that the soil type and its properties can significantly affect crop performance. This is because soil type and its properties significantly affect crop performance through influencing soil aeration, water-holding capacity, soil fertility, and N leaching (Chen et al., 2020; Nyiraneza et al., 2012; Wang et al., 2022), and any soil property that could impair soil's water and air circulation can result in poor crop yields (Wallace & Nelson, 1986). The Haplic-vertisols type at the WSSP is known to frequently experience such problems. Studies elsewhere and in Ethiopia also indicated that the average sugarcane yields obtained from vertisols are very low (Wubie, 2015).

Although vertisols are known to have better fertility than others (Silver et al., 2000), its water-logging problem, susceptibility to soil compaction (Georges et al., 1985), unsuitable soil tilth, and poor aeration make it less productive. The particles of vertisols are fine and can hold water more tightly than others and thus remain wetter for a longer period of time (Gill et al., 2004). Such soil types can restrict root growth through reductions in water and nutrient availability.

In view of the fact that the largest proportion of soil type in the WSSP is Haplic-vertisols (70%), the yield decline could be enormous. The problem might be made worse by the uncontrolled irrigation

Table 5. Rate of change in yield (yield trends) of sugarcane grown on different soil types of the WSSP in central Ethiopia

Soil type	Rate of change in yield (quintal ha^{-1} month^{-1})	*p* value	Area coverage (%)
Cambisols-ruptic	−1.643	<.01	10
Cambisols-clayic	−1.611	<.01	20
Haplic-vertisols	−1.727	<.01	70

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application, poor drainage system, and very flat (slope of 0.02–0.05%) topography of the area (Dinka & Ndambuki, 2014). As Habib and Girma (2006) noted, during each irrigation schedule in the WSSP, an average amount of 45 mm more water was applied than the soil could handle. As a result, about 90% of the WSSP area, particularly in fields with Haplic-vertisols soil types, suffers a critical water-logging problem (Dinka & Ndambuki, 2014). Therefore, this situation might significantly contribute to the overall yield decline of the WSSP. According to Gomathi et al. (2015), water-logging could cause as much as 15–45% reduction in cane yield.

Yield classification

The majority of cane fields (69%) at the WSSP were categorized under "yield declining" class, while 27% of the fields showed no significant yield improvements to date and were hence grouped under the "yields never improved" class (Table 6). Only 2.5% of the fields showed increasing yield trends, which were categorized under the "yields increasing" class. Similarly, fields with previously improved yields but now stagnating yields and thus classified as "yield stagnating" constituted only 0.43% (Table 6).

About 76%, 72%, and 31% of Haplic-vertisols, Cambisols-clayic, and Cambisols-ruptic soil types, respectively, were categorized under the "yield declining" class (Table 6). The Cambisols-ruptic soil type dominated in fields categorized under the "yield never improved" class (63%). Though very few, the proportion of fields grouped under the "yield still increasing" class was the highest for Cambisols-ruptic soil (6%) followed by Cambisols-clayic (3%) and Haplic-vertisols (2%) soil types.

The finding that most cane fields were classified under the "yield declining" class agrees with the significant decline observed in the overall yield trend of the WSSP (Figure 3). Similarly, Table 5 also confirms the fact that most of the "yield declining" fields were Haplic-vertisols soil types. As previously mentioned, productivity is restricted in such types of soil due to the slow internal drainage and limited workability of the soil caused by its hydro-physical characteristics (Wubie, 2015).

The mapping of yield classes indicates that fields that were categorized under "yield increasing," "yield never improving," and "yield stagnating" classes are mainly located in the eastern and southeastern parts of the plantation, while the central and southern parts are largely dominated by fields categorized under the "yield declining" class (Figure 4). The difference in yield class in relation to location might be related to the length of cultivation years, soil types, and the slope of the field. In the fields located in the eastern part of the plantation, sugarcane production was started in 2009 (Alemayehu et al., 2020), and depletion in soil fertility might not be as high as that of the remaining parts of the plantation where sugarcane

Table 6. Yield class of WSSP fields based on productivity trends (1999–2022) of each soil type

	Soil types											
	Haplic-vertisolss			Cambisols-clayic			Cambisols-ruptic			Total		
Yield class	Area	*N*	%	Area	*N*	%	Area	*N*	%	Area	*N*	%
YSI	132	5	2	25	3	3	30	4	6	187	12	3
YS	0	0	0	32	2	2	0	0	0	32	2	0.43
YNI	1,331	62	23	311	19	21	414	40	63	2056	121	28
L25YDF	836	54	20	238	20	22	0	0	0	1,074	74	14
I50YDF	2045	107	39	505	30	33	203	11	17	2,753	148	37
T25YDF	898	47	17	377	17	19	68	9	14	1,343	73	18
Total	5,242	275	100	1,488	91	100	715	64	100	7,445	430	100

Abbreviations: I50YDF, the intermediate 50% yield-declining fields; L25YDF, the least 25% yield-declining fields; T25YDF, the top 25% yield-declining fields; YS, yields stagnated; YNI, yields never improved; YSI, yields still increasing.

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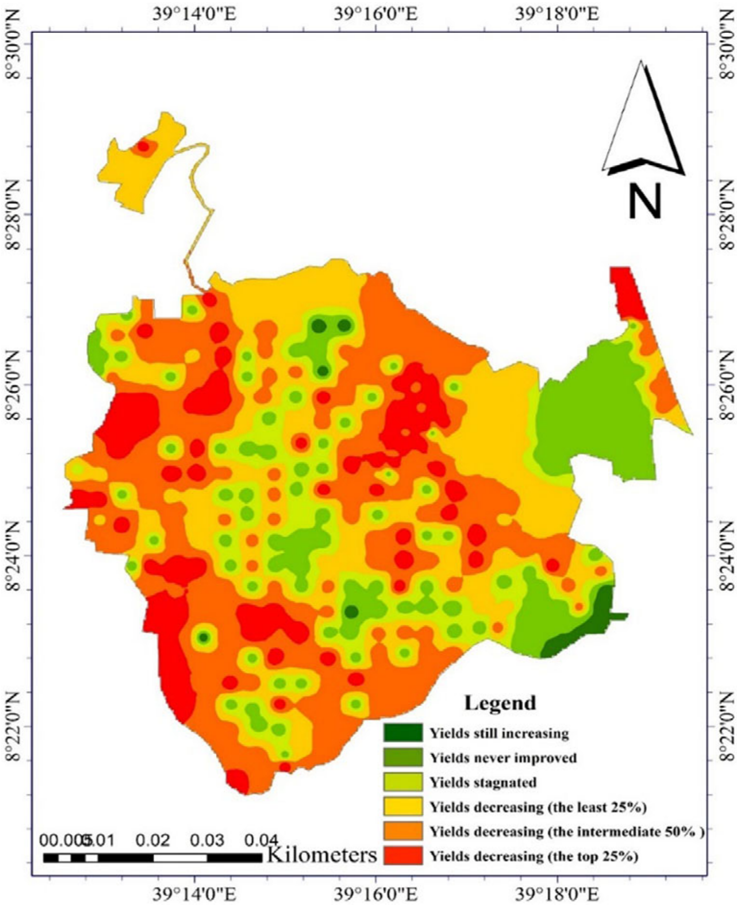

Figure 4. Spatial distribution of yield classes of fields in the WSSP as mapped by IDW interpolation using ArcGIS 10.3 platform.

production was started in 1951 (Abriham et al., 2017). Furthermore, these sites of the plantation have low clay contents (Booker Tate and MCE, 2003) and have relatively steep slope gradients, which facilitate fast internal drainage and surface runoff. However, the remaining parts of the plantations were dominated by vertisols and very flat slopes (BRLi and GIRDC, 2013; Dinka & Ndambuki, 2014), which hamper drainage of excess water.

Exploitable yield gap

Exploitable yield gap of the WSSP was calculated to be 130% of the actual cane yield. This translates into an attainable production increase (ΔQCANE) of 4,371,709 quintals of sugarcane per annum, which is worth about 439,864,989 birr (US$ 8,228,558) at a field-level price. This highlights that the drastic yield declines and yield gaps have resulted in a considerable financial loss to the sugar estate.

The WSSP may no longer be profitable if such conditions persist along the production trends of the sugar estate. This has also a negative effect on the economy of the nation as well as on the livelihoods of thousands of people who depend, directly or indirectly, on the sugar agro-industry. It has been widely noted that the economic development of tropical and subtropical countries has been greatly supported by a well-managed sugar production sector (Selman-Housein et al., 2000). Solomon et al. (2019) also reported that sugarcane contributes significantly to the socioeconomic transformation of poor countries through the production and use of biomaterials, renewable energy, food, and feed. Similarly, if production problems are resolved and declining yield trends are arrested, such a benefit is also feasible in Ethiopia in general, and in the WSSP in particular.

Analysis of the yield trends in this study reveal the temporal and spatial patterns of sugarcane production, which would enable the identification of key mitigation activities. The present analysis also indicated the severity of the problem and its negative implications on the sugarcane industry in the country. However, this study was limited only to variety and soil factors, and there is a need to investigate additional factors both temporally and spatially. Furthermore, future studies should also address other long-established major sugar estates in the country, namely Metehara and Fincha. Additionally, since issues pertaining to soil quality deterioration in a sugarcane plantation are complicated, an in-depth study is required.

Conclusions

This study has demonstrated that sugarcane yields have been declining drastically at the WSSP, where 69% of the fields were categorized under "yield declining" class, which is distributed in all the plantation areas except the eastern part. The Mann-Kendall test revealed that the overall crop yields have been decreasing significantly ($p < .05$) by 8.4 quintals ha^{-1} year^{-1} ($R^2 = 0.76$). The results also showed that the highest yield decline was observed in the fourth (1984–1993) decade of production. Both variety and soil type significantly influenced sugarcane yield trends, where the rate of yield decline was the highest for varieties that had been in production for more than 20 years and in a soil classified as vertisols type. The central and southern parts of the plantation were the areas most affected by the yield decline. The exploitable yield gap of the sugarcane plantation was calculated to be 130% of the actual cane yield, which represents an estimated production increase of 4,371,709 quintals of sugarcane per year, which is worth about 439,864,989 birr (US$ 8,228,558). This implies that, in light of the long-term intensive and monoculture production systems and the vertisols soil type in the WSSP, soil fertility management should be prioritized. Therefore, future research should focus on mitigation options such as green manuring, improved fallows, residue retentions, minimum tillage, and so forth. Developing high-yielding and adaptable sugarcane varieties or rejuvenating the old ones through micropropagation should also be given attention.

Open peer review. To view the open peer review materials for this article, please visit http://doi.org/10.1017/exp.2023.13.

Data availability statement. Data supporting the findings of this study are available from the corresponding author on request.

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Author contribution. Conceptualization: A.D.; Data curation: A.D.; Funding acquisition: A.D.; Investigation: A.D.; Methodology: A.D.; Project administration: A.D.; Software: A.D.; Supervision: A.D.; Validation: A.D.; Visualization: A.D.; Writing – original draft: A.D.; Writing – review & editing: A.D., N.D., L.W., B.A.

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Competing interest. The authors declare none.

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Peer Reviews

Reviewing editor: Dr. Bodil Jørgensen
University of Copenhagen, Department of Plant and Environmental Sciences, Thorvaldsensvej 40, Frederiksberg C, Denmark, 1871

Minor revisions requested.

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Review 1: Analysis of Declining Trends in Sugarcane Yield at Wonji-Shoa Sugar Estate, Central Ethiopia

Reviewer: A. Q. Khan

Date of review: 23 May 2023

Conflict of interest statement. Reviewer declares none.

Comment

Comments to the Author: It is a good work investigating the causes of yield decline at Wonji-Shoa Sugar Estate Ethiopia. The manuscript may be revisited to make its language more coherent and meaningful smooth reading. My comments are to correct, reword or remodel the sentences in the following lines of the manuscript. Appropriate sequence of conclusion for example in lines 14-15 may be reworded as variety and soil management measures. The corrections in the sentences in the following lines of the manuscript may be made: Lines 57-58, 59, 63, 65, 70, 89-91, 95-97, 109-111, 117 may be changed to Collection of Yield Data, line129 and lines 136-137. As far as possible reference in Conclusion should be avoided.

Score Card

Presentation

4.7 /5

Is the article written in clear and proper English? (30%)	5/5
Is the data presented in the most useful manner? (40%)	5/5
Does the paper cite relevant and related articles appropriately? (30%)	4/5

Context

5.0 /5

Does the title suitably represent the article? (25%)	5/5
Does the abstract correctly embody the content of the article? (25%)	5/5
Does the introduction give appropriate context? (25%)	5/5
Is the objective of the experiment clearly defined? (25%)	5/5

Analysis

5.0 /5

Does the discussion adequately interpret the results presented? (40%)	5/5
Is the conclusion consistent with the results and discussion? (40%)	5/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	5/5

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Review 2: Analysis of Declining Trends in Sugarcane Yield at Wonji-Shoa Sugar Estate, Central Ethiopia

Reviewer: Mengistu Sime

Date of review: 27 May 2023

Conflict of interest statement. I declare that should this article be accepted my review will be published online with the article, and that my name will be associated with my review.

Comment

Comments to the Author: The abstract is not comprehensive. It should include justification/rationale of the study as a landing statement, which leads to the objective of the study. Methods of data analysis (statistical tools) need to be included. Recommendation should be clearly stated. What are the possible appropriate management practices you recommend? Specify it!

Besides, minor typographical errors (like grammatical error, misspellings, commas, etc.) observed via the manuscript, and need to be checked & revised. Check thoroughly whether all in-text citations are properly listed in the references.

Score Card

Presentation

4.7 /5

Is the article written in clear and proper English? (30%)	4/5
Is the data presented in the most useful manner? (40%)	5/5
Does the paper cite relevant and related articles appropriately? (30%)	5/5

Context

4.5 /5

Does the title suitably represent the article? (25%)	5/5
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Does the introduction give appropriate context? (25%)	5/5
Is the objective of the experiment clearly defined? (25%)	5/5

Analysis

5.0 /5

Does the discussion adequately interpret the results presented? (40%)	5/5
Is the conclusion consistent with the results and discussion? (40%)	5/5
Are the limitations of the experiment as well as the contributions of the experiment clearly outlined? (20%)	5/5