

Research Article

Nutrient Budget and Economic Assessment of Blended Fertilizer Use in Kenya Tea Industry

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Received 2 May 2018; Revised 1 October 2018; Accepted 22 October 2018; Published 18 November 2018

Academic Editor: Amaresh K. Nayak

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Kenya's tea industry depends predominantly on imported compound NPK fertilizers to replenish nutrients removed through plucking. These fertilizers cannot be easily manipulated for specific soils and tea clones. They also frequently become hazardous within tea-growing environments. In this respect, two fertilizer blends containing NPKS 25 : 5 : 5 : 4 + 9Ca + 2.62Mg and NPKS 23 : 5 : 5 : 4 + 10Ca + 3Mg with trace elements have been produced commercially in the country. However, the extent to which the blended fertilizers may contribute to optimal economic gains without degrading the environment has not been determined. This was the knowledge gap that this study seeks to address. The goal of this study was to evaluate the economic efficacy of fertilizer blends with the aim of identifying optimal levels of application which would maximize tea productivity with minimal negative impacts on the environment. The study hypothesized that blended fertilizers maximize productivity of tea clones with minimal environmental damage. The fertilizer blends were evaluated in two study sites, i.e., Timbilil Estate in Kericho and Kagochi farm in Nyeri. The sites were selected purposefully, one in the eastern and the other in the western tea-growing areas. The trial was laid out in randomized complete block design with two fertilizer blends and the standard NPK 26 : 5 : 5 as control. The treatments were applied at four fertilizer rates (0 (control), 75, 150, and 225 kg-N-ha⁻¹·yr⁻¹), replicated thrice. Leaf samples were collected and analyzed for nutrient uptake as well as associated yields and economic trends. The economic optimum nitrogen rate (EONR) was achieved at 75 kg-N-ha⁻¹·yr⁻¹ at Kagochi with all fertilizers, while at Timbilil, EONR was variable, between 75 and 225 kg-N-ha⁻¹·yr⁻¹ with fertilizer types. This study has shown that, based on the economic point of view, Blend "A" was the most efficient and consistent fertilizer in production and economic returns across the two sites.

1. Introduction

Tea is a major cash crop whose sustained productivity is highly desired by all stakeholders in its value chain. Nutrient requirements for commercial tea production are particularly high because the pluckable portions contain the largest percentage of nutrients in the plant [1]. Minimum concentration of nutrient required for fertilization of crops varies depending on factors such as type of crops, type of nutrients, soil conditions and composition, cropping season, and plant growth stage. However, excessive fertilization would increase soil acidity or salinity leading to plant

toxicity [2], while unbalanced application has negative effects on crop physiology and yields [3]. Overapplication or excessive fertilization is also detrimental to the environment and is not economically sustainable [3]. These challenges require innovative ways of mitigation with minimal costs and environmental damage.

Chemical fertilizers with ability to replenish depleted nutrients in optimum quantities and forms have been recognized as an important component of sustainable soil fertility management [4]. Such fertilizers are available commercially in many physical and chemical forms. Each physical form has its own uses and limitations, which

provide the basis for selecting the best fertilizer for specific crops or location [5]. Sources and rates of fertilizers recommended for tea production vary from region to region depending on soil types and weather conditions. In Kenya, the most popular formulation is the imported compound NPK 25:5:5 or NPK 20:10:10 based on nutrients removed in plucked leaves [6]. The government has identified a need of having locally manufactured fertilizers, which would address their shortage in the market and ensure timeliness in their applications. In response, some companies began the production of blended fertilizers whose possible negative impacts and mitigation measures had not been established. These developments and related fears constituted the basis of this study. The objectives were to assess the apparent nutrient budget of blended fertilizers application at different rates, determine economic optimum levels of blended fertilizers, and develop a soil replenishment model for the blended fertilizers. The study hypothesized that blended fertilizers maximize productivity of tea clones with minimal environmental damage.

Soil nutrients availability, their content, and degree of accessibility are very dynamic because of the various inorganic and biochemical processes in the soils [7] and biotic and abiotic factors including temperature, water content, soil reaction, and nutrient uptake, input, and losses [8]. Nitrogen (N) is the main nutrient [9] and energy input in cropping systems and the critical nutrient for tea production [10]. Response of nitrogen at any level depends on the availability of other nutrients. Although essential for achieving high crop yields, its abundant use makes fertilizer the dominant contributor to global nitrogen pollution, which poses substantial risks to climate, human health, and ecosystems [11].

Fertilizer recommendations are based on field input trials and their effects on crop yield (yield responses) in both agronomic and economic terms [12–15]. Data from the crop responses to nutrients should always be subjected to economic analysis in order to account for differences in input and output and to identify the economic optimum rates (EORs) [16]. Several methods have been developed to internalize environmental issues in economic assessments. The valuation of benefit or loss in money was in terms of the amount saved due to increased nutrient status or amount to be incurred for increasing the nutrient status, respectively [17].

2. Materials and Methods

2.1. Research Design. The trial was established using a factorial randomized completely block design (RCBD) with three fertilizer types (one is control) and four fertilizer application rates (one is control) replicated three times. The randomized complete block design (RCBD) is a standard design for agricultural experiments in which similar experimental units are grouped into blocks or replicates [18]. The defining feature of the RCBD is that each block sees each treatment exactly once.

2.2. Treatment Application. The trial was set using clone BBK 35 in Timbilil planted in 1988 at a spacing of 4×2.5 ft.

and clone TRFK 6/8 in Kagochi planted in 1965 at a spacing of 5×2.5 ft. The plot size in Timbilil measured $(7 \times 12$ M) inclusive of a net plot of 7×10 M (70 plants), while in Kagochi, the plot size measured $(8 \times 8$ M) with a net plot of 7×8 M (56 plants). Variables used were three fertilizer types (one was control) and four fertilizer application rates (one was control).

(a) Fertilizer types:

- (i) Blended NPKS 25:5:5:4 + 9Ca + 2.6Mg + trace elements (TE) as Blend A
- (ii) Blended NPKS 23:5:5:4 + 10Ca + 3Mg + trace elements (TE) as Blend B
- (iii) Standard NPK 26:5:5 as control

(b) Fertilizer application rates (0 (control), 75, 150, and $225 \text{ kg} \cdot \text{N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$)

The fertilizer types were spread in rows as per characteristics and bush calculation based on spacing.

The areas receive the bimodal type of rainfall with peaks in April to May and October to November. Total annual precipitation in Timbilil estate is 2175 mm, while in Kangaita, annual rainfall is about 2040 mm. Temperature ranges from 12 to 20°C in Kangaita and 14 to 19°C in Timbilil.

2.3. Leaf Sampling and Analysis. Leaf samples (approximately 100 g of two leaves and a bud and mature leaf) were plucked in each plot and taken to laboratory. The samples were oven-dried at a temperature of 105°C for 72 hours before milling. Total nitrogen in the leaves was determined by the Kjeldahl method [19]. Phosphorus and potassium concentration in the leaves was determined using inductively coupled plasma emission (ICPE) spectroscopy [19].

2.4. Tea Yield Determination. Yield components of tea are described as the number of plucked shoots per unit land area and the mean weight per shoot [20]. Plucking of tea was done in conformity with the standard procedure. The fresh yield was converted to kilograms (kg) processed yield per hectare per year ($\text{kg} \cdot \text{Mt} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}$) using the following equation [21]:

$$\text{yield} (\text{kg} \cdot \text{Mt} \cdot \text{ha}^{-1} \cdot \text{y}^{-1}) = \frac{n * a * 0.225}{b}, \quad (1)$$

where n is the green leaf yield per plot, a is the plant population per hectare, 0.225 is the factor converting green leaf to made tea, and b is the number of plants per plot.

2.5. Data Analysis. Effect of treatments application on mean yields and leaf nutrients uptake data of mature tea clone BBK 35 in Timbilil and TRFK 6/8 in Kagochi was subjected to the analysis of variance (ANOVA) using the MSTAT C computer software package [1, 22].

2.6. NPK Dynamics and Budgeting. An estimated nutrient balance (inputs and outputs) was calculated by assuming

that (i) soils existing nutritional status was minimal (ii) over the short-term, there were no nutrients recycled as plant prunings, and (iii) the amount of nutrients sequestered in the standing crop was generally small [23]. The mean for the nitrogen, phosphorus, and potassium contents of two leaves and a bud were multiplied by the yield dry matter weight to get N, P, and K removed through harvest [24]. The nutrients removed with the harvest were considered to be lost from the soil. These were then subtracted from the fertilizer applied to get approximate nutrients remnant in the soil. The nutrients residual in the soil could lead to environmental degradation. However, it is an incomplete indicator for sustainability with respect to soil fertility because it does not differentiate between nutrients in soil solution and in different types of organic matter [25]. Any fertilizer type or application rate with minimal residual effect is considered to be environmentally friendly. Although there were some shortcomings on the formula, it served as an effective tool for estimating the magnitude of nutrient loss/gain to the agroecosystems and to appraise their sustainability.

2.7. Economic Assessment. Economic appraisal of the blended fertilizers was determined using two simple approaches: productivity change approach (PCA) and replacement cost approach (RCA) [26].

For the productivity change approach, a function that stipulates a technical relationship between inputs and outputs was used. Market conditions and policy distortions affecting production decisions were taken into account [27]. They include the following:

- (1) One (1) kg made tea is equivalent to 4 kg green leaves (GL)
- (2) Cost of plucking is average of KSh. 9 per kg GL
- (3) Cost of leaf collection and processing per kg made tea is KSh. 100
- (4) Cost of pruning and tipping is estimated at KSh. 4 per bush of a third of the farm per year
- (5) Cost of weeding is one man-day per two months (or six man-days in a year)
- (6) Average price of made tea per kg is KSh. 250
- (7) Cost of fertilizers is KSh. 2,150 and KSh. 2,300 per 50 kg fertilizer bag for compound and blended, respectively

The replacement cost approach (RCA) focuses on the additional input required to compensate for lost soil nutrients. Replenishment models were calculated only for the lost nutrient or the negative net nutrient balance bearing in mind that

- (1) The nutrients can either be a limiting factor for growth or not
- (2) Available nutrients are supposed to replace, in part, nonavailable nutrients
- (3) Fertilizer efficiency is assumed

- (4) Likely side-effects of large fertilizer applications on micronutrient availability and soil acidity

3. Results and Discussion

3.1. NPK Dynamics and Budgeting. Nutrient pools measured in this study were total N, P_2O_5 , and K_2O in harvested tea. Nutrient inputs were mainly from applied fertilizers. Other sources and losses were not determined in this study due to limitations of time and resources. Tables 1–3 show dynamics and apparent nutrient budgeting of NPK in tea arising from application of the Mavuno fertilizer blends versus standard NPK.

Estimation of nutrient budgets showed that fertilizer Blend A when applied at the rate of 0 and $75 \text{ kg-N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ resulted in negative nitrogen balances of 96 and $48 \text{ kg}\cdot\text{ha}^{-1}$, respectively, in Timbilil. In Kagochi, N budgets for 0 rate were $77 \text{ kg}\cdot\text{ha}^{-1}$ and $21 \text{ kg}\cdot\text{ha}^{-1}$ for the $75 \text{ kg-N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ rate. Fertilizer rates of 150 and $225 (\text{kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1})$ showed positive N balances of 17 and $79 \text{ kg}\cdot\text{ha}^{-1}$, respectively, in Timbilil and 60 and $138 \text{ kg}\cdot\text{ha}^{-1}$ in Kagochi as shown in Table 1. The first two N rates for P_2O_5 gave negative values while the last two resulted in positive values. K_2O in all the nitrogen rates were negative in both sites (Table 1).

Fertilizer Blend B showed negative apparent nutrient budgets in N, P_2O_5 , and K_2O at rates of 0 and $75 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in both sites. However, the last N rates of 150 and $225 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ resulted in negative K_2O balances of 45 and $38 \text{ kg}\cdot\text{ha}^{-1}$, respectively, in Timbilil (Table 2). In Kagochi, $225 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ rate resulted in positive K_2O balance of 1 (Table 2).

Apparent nutrient budgets for the standard tea fertilizer resulted in negative P_2O_5 balances of 23, 11, and $1 \text{ kg}\cdot\text{ha}^{-1}$ in Timbilil when applied at rates of 0, 75, and $150 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, respectively (Table 3). N for the first two N rates resulted in negative balances while the last two N rates resulted in positive balances for both sites as shown in Table 3. However, apparent nutrient budgets for K_2O were negative in both sites for all the N rates (Table 3).

From these findings, it was observed that, within the margin of error, the third rate for all the fertilizer types in Timbilil was almost in equilibrium. The same equilibrium was observed by Sitienei and Kamau [28] while working on fertilizer import versus processed tea export. The difference in potassium was negative in all the fertilizer types and rates except for the highest rate of Blend B in Kagochi. If NPK use agronomic and apparent recovery efficiencies were taken into consideration, the difference would be much higher. The negative nutrient balance is due to inadequate external inputs exacerbated by the loss of nutrients in harvested products, hence depletion and degradation of soils [29, 30]. This is the problem at lower rates of fertilizer application in tea-growing areas. The total net global flows of nitrogen (N), phosphorus (P), and potassium (K) in the form of commodities, estimated in the study of Sitienei and Kamau [28], will be 8.8 million tonnes in 2020. The nutrient balance approach allowed quantification and valuation of nutrient depletion and modelling [31].

TABLE 1: Apparent nutrient budget of Blend A (NPKS 25:5:5:4 + 9Ca + 2.6Mg + trace elements) in Timbilil and Kagochi.

Site	NPK input as fertilizer (kg·ha ⁻¹)			Yield (kg·Mt·ha ⁻¹ ·yr ⁻¹)	Mean NPK content in 2L + B (%)			Gross NPK removed through harvest (kg·ha ⁻¹)			Nutrient budget (input as fertilizer and output as harvest) (kg·ha ⁻¹)		
	N	P ₂ O ₅	K ₂ O		N	P	K	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
Timbilil	0	0	0	2052	4.67	0.466	2.15	96	23	53	-96	-23	-53
	75	15	15	2532	4.84	0.478	2.29	123	27	70	-48	-12	-55
	150	30	30	2683	4.97	0.48	2.31	133	30	75	17	0	-45
	225	45	45	2995	4.86	0.509	2.41	146	34	87	79	11	-42
Kagochi	0	0	0	1654	4.53	0.497	2.32	77	18	46	-77	-18	-46
	75	15	15	1975	4.44	0.482	2.36	96	23	57	-21	-8	-42
	150	30	30	1808	4.54	0.454	2.26	90	18	49	60	12	-19
	225	45	45	1795	4.61	0.457	2.27	87	18	49	138	27	-4

“–” denotes a negative value.

TABLE 2: Apparent nutrient budget of Blend B (NPKS 23:5:5:4 + 10Ca + 3Mg + trace elements) in Timbilil and Kagochi.

Site	NPK input as fertilizer (kg·ha ⁻¹)			Yield (kg·MT·ha ⁻¹ ·yr ⁻¹)	Mean NPK content in 2L + B (%)			Gross NPK removed through harvest (kg·ha ⁻¹)			Nutrient budget (input as fertilizer and output as harvest) (kg·ha ⁻¹)		
	N	P ₂ O ₅	K ₂ O		N	P	K	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
Timbilil	0	0	0	2140	4.67	0.466	2.15	100	23	55	-100	-23	-55
	75	15	15	2336	4.84	0.478	2.29	113	25	64	-38	-9	-48
	150	30	30	2816	4.97	0.48	2.31	140	32	78	10	1	-45
	225	45	45	2854	4.86	0.509	2.41	139	34	83	86	15	-34
Kagochi	0	0	0	1420	4.53	0.497	2.32	66	16	40	-66	-16	-40
	75	15	15	1870	4.44	0.482	2.36	91	21	53	-16	-5	-37
	150	30	30	1859	4.54	0.454	2.26	92	18	51	58	15	-18
	225	45	45	1742	4.61	0.457	2.27	85	18	48	140	31	1

“–” denotes a negative value.

TABLE 3: Apparent nutrient budget of standard NPK in Timbilil and Kagochi.

Site	NPK input as fertilizer (kg·ha ⁻¹)			Yield (kg·Mt·ha ⁻¹ ·yr ⁻¹)	Mean NPK content in 2L + B (%)			Gross NPK removed through harvest (kg·ha ⁻¹)			Nutrient budget (input as fertilizer and output as harvest) (kg·ha ⁻¹)		
	N	P ₂ O ₅	K ₂ O		N	P	K	N	P ₂ O ₅	K ₂ O	N	P ₂ O ₅	K ₂ O
Timbilil	0	0	0	2132	4.67	0.466	2.15	100	23	55	-100	-23	-55
	75	15	15	2329	4.84	0.478	2.29	113	25	64	-38	-11	-50
	150	30	30	2679	4.97	0.48	2.31	133	30	75	17	-1	-46
	225	45	45	3099	4.86	0.509	2.41	151	37	90	74	6	-47
Kagochi	0	0	0	1683	4.53	0.497	2.32	79	18	47	-79	-18	-47
	75	15	15	1781	4.44	0.482	2.36	86	21	51	-11	-7	-37
	150	30	30	1810	4.54	0.454	2.26	90	18	49	60	11	-20
	225	45	45	1800	4.61	0.457	2.27	87	18	49	138	25	-6

“–” denotes a negative value.

Nitrogen is the most dynamic nutrient and after transformation, can move in the atmosphere, as well as in aquatic systems. The amounts of nitrogen (N) involved in transfers through trade are ecologically significant especially when the 2020 projections are considered. Potassium and phosphorus transfers are also significant and may provide opportunities for the eventual recycling of the important nutrients, especially given the high cost of potassium mining and transportation

[32, 33]. It is therefore important for each country to consider the effects of nutrient flows in food trade on its own ecosystem.

3.2. Economics of Blended Fertilizers. The valuation of benefit or loss in money was in terms of the amount saved due to increased nutrient status or amount to be incurred for increasing the nutrient status, respectively [17].

3.3. Productivity Change Approach (PCA). The method involves a two-step procedure. Firstly, the physical effects of changes in the environment on productive activity are determined, i.e., the value of productivity change is equal to the difference in crop yields with and without that nutrient change. The second step consists of valuing the resulting changes in production, usually using market prices. In this case, the PCA takes the reduction in the capitalized net annual income stream gained through agricultural production (i.e., loss of income through crop yields) as a substitute for the costs of nutrient depletion.

3.4. Gross Profit Analysis. The profitability of the three fertilizers under study was analyzed in Tables 4–6 by obtaining the gross profit $\text{ha}^{-1}\cdot\text{yr}^{-1}$ for a particular rate. In order to determine the highest profit ratio or economic optimum ratio to use, the output was multiplied by the market price (long-term average annual price) of processed tea in Kenya minus the cost of input. The nutrient value is equal to the change in revenue or profit caused by nutrient change (changes in nutrient contents as a proxy for the value of the nutrients) [34].

Profitable rates fluctuated among the rates of the three fertilizers in the two sites. In Timbilil, profitable rates were $225 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ for Blend A at KSh. 281,550 per hectare per year (Table 4) and standard NPK (KSh. 297,611 per hectare per year) (Table 6) while fertilizer Blend B was more profitable when applied at $150 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ (KSh. 274,944 per hectare per year) (Table 5). The reduction in gross profit for Blend A and standard NPK with the lower rates of fertilizer application was compensation for nutrients depletion. This is because tea is rarely adapted to growing under low nutrient conditions and fails to yield economically without the addition of fertilizers. However, the same rate for Blend B might have been excessive leading to negative effect. The application of high rates of N, P, and K allows for increased production. However, N and P application in excess of crop demands can lead to profound environmental consequences [35].

In Kagochi, the fertilizer rate of $75 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ was the most profitable for all the three fertilizers (192,870, 180,900, 172,084 KSh. $\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ for Blend A, Blend B, and NPK standard (Tables 4–6), respectively). The reduction in gross profit with fertilizer rates higher than $75 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}$ means that the higher rate might have brought negative effects on various nutrients in the soil. This study attempted to quantify the economic value of soil productivity conservation and its economic cost by productivity losses.

These findings are consistent with those by Njogu et al. [16] that different clones have different nutritional needs and differ in their abilities to absorb nutrients even when the agronomic practices are similar, which is depicted in their yield response to varying fertilizer application rates and the fertilizer types applied. Different clones with different yield potentials require different fertilizer rates. For a high yielding clone like AHP S15/10, the most profitable production has been achieved by applying $200 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in Kericho [6].

3.5. Economic Optimum Nitrogen Application Rate. In the economic analysis studies, the economic optimum rate and the most profitable rate for each fertilizer in each site were determined. The economic optimum nitrogen rate (EONR) is realized when the cost of the last increment of additional N equals the value of tea yield increase. Tables 4–6 show the economic analysis of the different fertilizers in the two sites. From the data tabulation, the following were deduced:

- (1) For Blend A, the EONR was achieved at 6 bags of fertilizer per hectare per year at both Timbilil and Kagochi
- (2) For Blend B, the EONR was achieved at 13 and 6.5 bags of fertilizer per hectare per year in Timbilil and Kagochi, respectively
- (3) For the standard NPK, the EONR was achieved at 19.6 and 5.8 bags of fertilizer per hectare per year in Timbilil and Kagochi, respectively
- (4) Kagochi had the least fertilizer requirement across all the fertilizer types

The magnitude of the increase in yield tended to diminish as the total level of nitrogen rate increased. As successive units of fertilizer were added to other costs, it reached a point where the value of the marginal product was less than the unit cost of N used to produce it. The economic implication of this trend is that the value of the additional crop at first exceeded the cost of applying fertilizer but eventually only marginal additional crop was obtained for each unit of additional fertilizer resulting in no achievement of monetary gain. A fertilizer type may do well agronomically but poorly in economic terms as a result of low commodity prices or high production costs.

With higher N prices, it becomes more important to fertilize at the most economic rate, which may differ from the agronomic rate. Kiprono et al. [36] found that the EONR changes as market costs and returns change.

The most economic fertilizer rate for fertilizer Blend A was $75 \text{ kg}\cdot\text{N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ for both sites. However, economic rates were different for Blend B and standard NPK in Timbilil and Kagochi. This shows that fertilizer recommendations vary widely for different tea-growing regions depending on the age of the bushes, pruning cycle, yield, and soil fertility as was found by Tshivhandekano et al. [10] and Namu et al. [37]. Several studies have revealed that lack of plant nutrients is one of the principal causes for low agricultural productivity in Africa [12, 15].

The findings here are in agreement with earlier findings that farming should be economically sustainable so that it can contribute to the economic security of key factors in the farm and in the food system as a whole [38]. Economic sustainability can be achieved through increased efficiencies in the use of farm inputs to lower the cost of production for farmers and thus providing savings which can be used to improve on other aspects of livelihood [38]. Such savings available for expenditure on other aspects of life beside food would create new industries in the community and new employment opportunities and hence better living standards for the society.

TABLE 4: Economic evaluation of fertilizer Blend A application in Timbilil and Kagochi.

Site	N rates in kg-ha ⁻¹	Bags of NPK(S) ha ⁻¹ required	Total cost of fertilizer at KSh. 2,300/bag of 50 kg	kg-Mt-ha ⁻¹ -yr ⁻¹ (TPP)	Production in kg of GL-ha ⁻¹ -yr ⁻¹	Cost of plucking (KSh)	Cost of pruning (KSh)	Cost of weeding (KSh)	Cost of collection and processing (KSh)	Gross earnings from made tea ha ⁻¹ -yr ⁻¹ (KSh)	Total cost of production (KSh)	Gross profit ha ⁻¹ -yr ⁻¹ (KSh)	Average physical product (APP)	Marginal physical product (MPP)
Timbilil	0	0	0	2052	8,208	73,872	14355	4125	205,200	513,000	297,552	215,448	0	0
	75	6	13,800	2532	10,128	91,152	14355	4125	253,200	633,000	376,632	256,368	422	80
	150	12	27,600	2683	10,732	96,588	14355	4125	268,300	670,750	410,968	259,782	224	25
	225	18	41,400	2995	11,980	107,820	14355	4125	299,500	748,750	467,200	281,550	166	52
Kagochi	0	0	0	1654	6,616	59,544	14355	4125	165,400	413,500	243,424	170,076	0	0
	75	6	13,800	1975	7,900	71,100	14355	4125	197,500	493,750	300,880	192,870	329	54
	150	12	27,600	1808	7,232	65,088	14355	4125	180,800	452,000	291,968	160,032	151	-28
	225	18	41,400	1795	7,180	64,620	14355	4125	179,500	448,750	304,000	144,750	100	-2

TPP: total physical product, GL: green leaf, MPP: marginal physical product, and APP: average physical product.

TABLE 5: Economic evaluation of fertilizer Blend B application Timbilil and Kagochi sites.

Site	N rates in $\text{kg}\cdot\text{ha}^{-1}$	Bags of NPK(S) ha^{-1} required	Total cost of fertilizer at KSh 2,300/bag of 50 kg	$\text{kg}\cdot\text{Mt}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (TPP)	Production in $\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ GL	Cost of plucking (KSh)	Cost of pruning (KSh)	Cost of weeding (KSh)	Cost of collection and processing (KSh)	Gross earnings from made tea $\text{ha}^{-1}\cdot\text{yr}^{-1}$ (KSh)	Total cost of production (KSh)	Gross profit $\text{ha}^{-1}\cdot\text{yr}^{-1}$ (KSh)	Average physical product (APP)	Marginal physical product (MPP)
Timbilil	0	0	0	2140	8,560	77,040	14355	4125	214,000	535,000	309,520	225,480	0	0
	75	6	13,800	2336	9,344	84,096	14355	4125	233,600	584,000	349,976	234,024	389	33
	150	12	27,600	2816	11,264	101,376	14355	4125	281,600	704,000	429,056	274,944	235	80
	225	18	41,400	2854	11,416	102,744	14355	4125	285,400	713,500	448,024	265,476	159	6
Kagochi	0	0	0	1420	5,680	51,120	14355	4125	142,000	355,000	211,600	143,400	0	0
	75	6	13,800	1870	7,480	67,320	14355	4125	187,000	467,500	286,600	180,900	312	75
	150	12	27,600	1859	7,436	66,924	14355	4125	185,900	464,750	298,904	165,846	155	-2
	225	18	41,400	1742	6,968	62,712	14355	4125	174,200	435,500	296,792	138,708	97	-20

“-” denotes a negative value.

TABLE 6: Economic evaluation of standard NPK applied to tea in Timbilil and Kagochi.

Site	N rates in $\text{kg}\cdot\text{ha}^{-1}$	Bags of NPK(S) ha^{-1} required	Total cost of fertilizer at KSh 2,300/bag of 50 kg	$\text{kg}\cdot\text{Mt}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (TPP)	Production in $\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ GL	Cost of plucking (KSh)	Cost of pruning (KSh)	Cost of weeding (KSh)	Cost of collection and processing (KSh)	Gross earnings from made tea $\text{ha}^{-1}\cdot\text{yr}^{-1}$ (KSh)	Total cost of production (KSh)	Gross profit $\text{ha}^{-1}\cdot\text{yr}^{-1}$ (KSh)	Average physical product (APP)	Marginal physical product (MPP)
Timbilil	0	0	0	2132	8,528	76,752	14355	4125	213,200	533,000	308,432	224,568	0	0
	75	5.8	12,470	2329	9,316	83,844	14355	4125	232,900	582,250	347,694	234,556	402	34
	150	11.5	24,725	2679	10,716	96,444	14355	4125	267,900	669,750	407,549	262,201	233	61
	225	17.3	37,195	3099	12,396	111,564	14355	4125	309,900	774,750	477,139	297,611	179	72
Kagochi	0	0	0	1683	6,732	60,588	14355	4125	168,300	420,750	247,368	173,382	0	0
	75	5.8	12,470	1781	7,124	64,116	14355	4125	178,100	445,250	273,166	172,084	307	17
	150	11.5	24,725	1810	7,240	65,160	14355	4125	181,000	452,500	289,365	163,135	157	5
	225	17.3	37,195	1800	7,200	64,800	14355	4125	180,000	450,000	300,475	149,525	104	-2

“_” denotes a negative value.

3.6. Replacement Cost Approach (RCA). Figures 1 and 2 show soil replenishment models for mean of the three fertilizer types in Timbilil and Kagochi, respectively. The dependent variable represents the amount of input required to return the soil to optimum conditions. As an independent variable, the fertilizer rate indicated that the more the rate, the more the replenishment required later. Other variables were assumed to have no discernible effects in these models.

According to the results, it was confirmed that the replenishment model for Timbilil was linear while that of Kagochi was polynomial. In Timbilil, the mean soil replenishment model for the different fertilizer types was given by the following equation:

$$Y = N(0.212x + 100.07) + P_2O_5(0.1391x + 54.767) + K_2O(0.0511x + 22.5) \quad (2)$$

This shows that the amount of NPK fertilizer required to restock the soil was higher than applied N and it increased linearly with the N rates.

In Kagochi, the mean replenishment model was given by the following equation:

$$Y = N(-0.0009x^2 + 0.2622x + 74.667) + P_2O_5(-0.0005x^2 + 0.1304x + 45.117) + K_2O(-0.0002x^2 + 0.0562x + 17.883) \quad (3)$$

The model showed that the amount of input required increased initially up to 75 kg·N·ha⁻¹·yr⁻¹ then decreased with the N rates.

The models showed that replenishment is vital if tea productivity is to be sustained. The nutrient balance model proved to be a useful indicator of nutrient depletion and offers a biophysical base for its economic assessment via the replacement cost approach (RCA). Nutrients export from land with no capacity to replenish those nutrients represents long-term stripping of soil stocks, exposing developing countries to significant long-term risk of soil productive failure [35]. From the tea industry, models have been used to bring better understanding on how productivity and resource use of tea agroecosystem is influenced by associated agronomic factors [39, 40], hence exploring the most promising interventions for tea productivity improvement. Different authors have elaborated on nutrient balance calculations into decision support models that allow monitoring of the effects of changing land use and suggestions of interventions to improve the nutrient balance [31].

Researchers have shown that nutrient losses due to uptake by crops, erosion, leaching, and N volatilization are only partially compensated by crop residues left on the field, manure and fertilizer application, and atmospheric inputs; thus, the annual NPK balances for sub-Saharan Africa are negative with minus 22–26 kg·N, 6–7 kg P₂O₅, and 18–23 kg·K₂O·ha⁻¹ [41]. For the whole of SSA, nutrient mining accounts for about 7% of the subcontinental agricultural gross domestic product (AGDP). This amount (US \$4 billion year⁻¹) exceeds the annual external assistance to the development of African agriculture in the past decade by

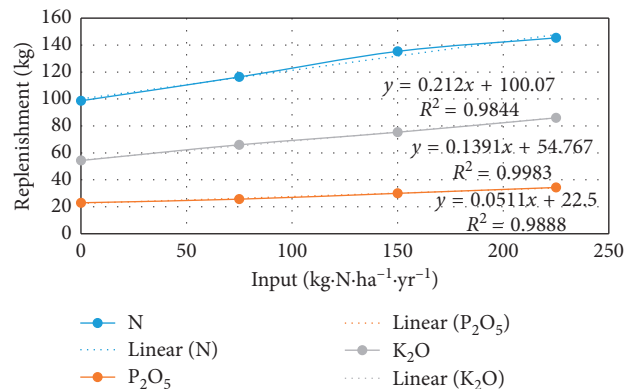


FIGURE 1: Soil nutrient replenishment model for Timbilil.

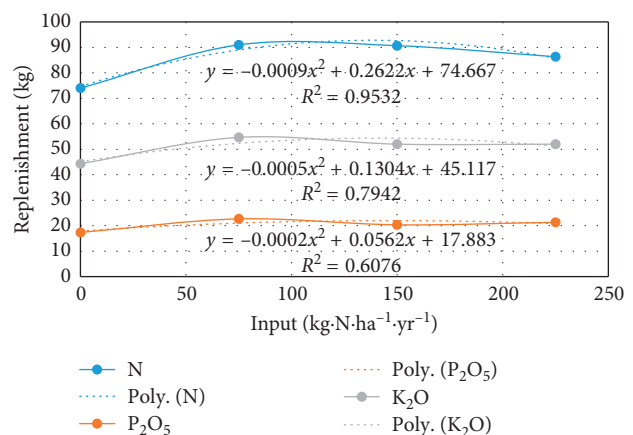


FIGURE 2: Soil nutrient replenishment model for Kagochi.

about 30–50%, which gives an indication of the financial dimension [42].

The models like the NUTMON approach have been developed completely at the farm level. This means that they can also serve as tools for monitoring nutrient flows on farms [43]. To estimate it on a global level, a set of methodologies is usually employed as summarized by Van Ittersum et al. [44]. They are broadly categorized into statistical and crop-modelling approaches. Statistical approaches rely on yield census data of varying size, which are then combined with global data (e.g., climate, fertilizer inputs, and irrigation area). Based on climate binning techniques [45], they divide the world into contingent areas of similar growth environment, looking at main drivers of yield variation within.

As hypothesized, blended fertilizers were found to be capable of increasing productivity while conserving the environment. The positive findings lead to sustainable farming where productivity is raised with minimum negative impacts on the environment and also help in recovering already degraded soil [38].

4. Conclusion

The ultimate aim of this study was to optimize tea production, maximize positive interactions, maximize net

returns, minimize the depletion of soil nutrients, and minimize nutrient losses or negative impact on the environment.

- (1) As hypothesized, blended fertilizers were found to be capable of increasing productivity while conserving the environment. The positive findings could lead to sustainable farming where productivity is raised with minimum negative impacts on the environment and also help in recovering already degraded soil.
- (2) From an economic point of view, Blend A was the most efficient and consistent fertilizer in production, economic returns, and its environmental effects across the two sites.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are very grateful to Athi River Mining Ltd., KALRO Tea Research Institute, and KTDA for funding the research and Karatina University for providing technical support during the process of data collection.

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