Advancing human nutrition without degrading land resources through modeling cropping systems in the Ethiopian Highlands

Tilahun Amede, Ann Stroud, and Jens Aune

Abstract

*Food shortage in sub-Saharan Africa is generally considered a function of limited access to food, with little thought to nutritional quality. Analyzing household production of nutrients across farming systems could be valuable in guiding the improvement of those systems. An optimization model was employed to analyze the scenario of human nutrition and cropland allocation in enset (*Enset ventricosum*)/root crop-based and cereal-based systems of the Ethiopian Highlands. The type and amount of nutrients produced in each system were analyzed, and an optimization model was used to analyze which cropping strategies might improve the nutritional quality of the household using existing resources. Both production systems were in food deficit, in terms of quantity and quality of nutrients, except for iron. The energy supply of resource-poor households in the enset/root crop-based system was only 75% of the recommended daily dietary allowance (RDA) of the World Health Organization (WHO), whereas resource-rich farmers were able to meet their energy, protein, zinc, and thiamine demands. Extremely high deficiency was found in zinc, calcium, vitamin A, and vitamin C, which provided only 26.5%, 34%, 1.78%, and 12%, of the RDA, respectively. The RDA could be satisfied if the land area occupied by enset, kale, and beans were expanded by about 20%, 10%, and 40%, respectively, at the expense of maize and sweet potato. The cereal-based system also had critical nutrient deficits in calcium, vitamin A, and vitamin C, which provided 30%, 2.5%, and 2% of the RDA, respectively. In the cereal system, the RDA could be fully satisfied by reducing cropland allocated to barley by about 50% and expanding the land area occupied by faba beans, kale, and enset. A shift from the cereal/root crop-dominated system to a perennial-enset dominated system would decrease soil erosion by improving the crop factor by about 45%. This shift would also have a very strong positive impact on soil fertility management. However, any policy suggestions for change in cropland allocation should be done through negotiations with households, communities, and district stakeholders.*

Key words: C-factor, cropping systems, human nutrition, modeling, land allocation

Introduction

The food situation in sub-Saharan Africa is continuing to deteriorate as a consequence of multiple calamities such as drought, occasional flooding, decline in soil fertility, increasing pests and diseases, land scarcity, and poor market access, coupled with discouraging policy environments. The effect is visible as recurring food shortage, malnutrition, and poverty. Food shortage in sub-Saharan Africa is generally regarded as a function of limited access to food, with little thought given to nutritional quality [1]. Malnutrition in the most vulnerable groups (children and women) could occur even in good crop harvest years because of nonbalanced food intake. Studies in Ethiopia showed that about 45% of the children were stunted and about 42% were underweight, in association with zinc, iron, and vitamin A deficiencies [2]. The most important documented forms of malnutrition countrywide in Ethiopia were protein-energy malnutrition and vitamin A, iodine, and zinc deficiencies [2, 3]. A recent survey showed that 53% of boys and 26% of girls aged between 6 and 72 months had night-blindness or Bitot's spots, with the highest prevalence in those between 36 and 72 months [2].

Tilahun Amede is affiliated with the African Highlands Initiative/Tropical Soils Biology and Fertility Institute of the International Center for Tropical Agriculture (CIAT), Addis Ababa, Ethiopia. Ann Stroud is affiliated with the African Highlands Initiative, Kampala, Uganda. Jens Aune is affiliated with the Agricultural University of Norway, Aas, Norway.

Please direct queries to the corresponding author: Tilahun Amede, P.O. Box 1412, code 1110, Addis Ababa, Ethiopia; e-mail: T.Amede@cgiar.org.

Analyzing household production of nutrients across farming systems may be valuable for guiding the improvement of those systems, particularly in situations where markets are less important than securing subsistence. For instance, in Papua New Guinea, communities farming in flat wetland areas had significantly higher energy and protein intakes than those in the drier hills [4]. In Uganda, both banana-based and cereal-based systems failed to satisfy a range of nutritional needs, with calcium and zinc being the most deficient [5]. However, there is scant information on the interaction of enset/root crop-based and cereal-based systems of the Ethiopian Highlands in relation to household nutrition and human health. Enset (*Enset ventricosum,* known also as false banana) is a carbohydrate-rich perennial crop with a strong pseudostem and edible bulbs and corms [6], which is a staple of millions of households in the Ethiopian Highlands.

The nutritional quality of food may be improved by various practices, such as application of fertilizers and soil fertility improvement, selection of varieties with high micronutrient content, use of indigenous high-nutrient-value crops, and genetic modification of plants to improve micronutrient supplies [1, 7]. However, the application of these methods to address malnutrition depends upon the availability of technological and policy interventions that are commonly not within the reach of small-scale farmers. It may also be possible to supplement the diet with animal products where livestock is an integral part of the system, but animal products are rarely consumed by rural households, because they are scarce sources of cash [3]. Dietary supplements are also rarely available to the rural poor.

One option to minimize the risk of malnutrition is reallocation of cropland in favor of crops with high contents of the nutrients in deficit. Once the nutrient budget of these systems has been quantified and the type of the nutrient in deficit or excess has been identified, the nutritional balance may be improved by reallocation of cropland and by increasing the land area allocated to crops rich in the requisite nutrients [5]. Modeling the cropping system, by considering the adaptability of the crop to the environment in question, could offer a better and faster method of reversing malnutrition. However, the possible acceptance or rejection of the model depends largely on the compatibility of the new crop adjustment with cultural values, food habits, labor, input demands, and soil fertility management options.

Ethiopia is one of the most severely affected countries in sub-Saharan Africa in terms of land degradation, having lost about 17% of its potential gross domestic product (GDP) because of physical and biological soil degradation [8, 9]. Land degradation may be the major cause of recurrent crop failure, i.e., food insecurity. Hence, any attempt to efficiently exploit the potentials of land resources to produce more food should be integrated with strategies to rehabilitate depleted land resources [10]. Changing the plot size of one crop and reallocating it to another crop may have significant implications on soil erosion [11] because the change in crop type, which may be characterized by different leaf area, root density, and vegetative cover index, would affect the interception of rain by the vegetative cover. This is presented as a “crop factor” (C-factor) in the universal soil loss equation (USLE) [12]. The relationship between relative erosion and crop cover of the soil surface is strongly parabolic: a 25% increase in cover would yield a 50% reduction in erosion [10]. A shift from a cereal-dominated system to a perennial-dominated system may improve the C-factor, whereas the reverse may cause more erosion and land degradation. Therefore, altering crop allotment to improve human nutrition should take soil fertility, conservation, and management into account.

The objective of this study was to estimate the type and amount of nutrients that enset/root crop-based or cereal-based systems furnish, in terms of protein, energy, zinc, calcium, iron, thiamine, vitamin A, and vitamin C, to model cropping strategies that may improve the nutritional quality of the household using the existing resources, and to estimate the effect of reallocation of crops on land management and soil erosion.

Methods

Site description

The research was conducted in two contrasting farming systems of the Ethiopian Highlands: Areka and Ginchi. Areka is characterized by a multiple cropping system, with strong perennial components of enset and coffee, accompanied by sweet potato, taro, maize, wheat, and many others (table 1). The population pressure is high (> 400 inhabitants per square kilometer), with average landholdings of less than 0.5 ha per household. The elevation ranges from 1,880 to 1,960 m above sea level, with a mean annual rainfall of about 1,300 mm and an average temperature of 19.5°C. Rainfall is bimodal, with a short rainy season from March to June and the main rainy season from July to October. The dominant soils are eutric nitisols, which are characterized by high water-holding capacity, moderately acidic pH, low levels of nitrogen, and high phosphorus fixation.

Ginchi is an example of an mountainous Ethiopian plateau with an elevation of 2,700 to 3,000 m. The area has a weak annual bimodal rainfall of 1,200 mm and an average temperature of 15°C. The farming system is dominated by barley-fallow-barley rotation and livestock, which are grazed according to a communal management system. Crop diversity is restricted by low

TABLE 1. Crop yield and nutrient composition of major crops grown in Areka and Ginchi

		Nutrient content/kg edible yield							
Crop	Yield (dry) (qt/ha)	Energy (kcal)	Protein (g)	Zinc (mg)	Iron (mg)	Calcium (mg)	Thiamine (mg)	Vitamin A (μg)	Ascorbic acid (mg)
Enset (*kocho*)[a]	119.08	2,111	6	6	37	320	0.3	0.2	0
Taro	29.66	1,038	13	1.4	20	550	0.4	0	90
Pumpkin	6.78	249	11	1.9	9	400	0.3	0	40
Kale[a]	18.75	401	25	8.6	22	50	0.4	112.5	13.2
Sweet potato	39.35	1,370	0.7	2	7	130	0.2	0	14.2
Irish potato[a]	14.46	840	15	4	36	184	0.1	0.4	2.83
Maize	14.84	2,234	41	13.3	20	80	0.2	0	0
Teff	4.09	1,620	41	11	115	690	0.3	0.03	0
Wheat[a]	8.93	2,220	68	2	27	270	2.1	0.8	0
Barley[a]	5.81	2,020	44	15.8	35	160	2.1	0	0
Pea	6.97	2,071	109	24.6	31	450	2.4	10.5	0
Faba bean[a]	6.77	2,759	164	13.8	43	870	1.9	1	0
Common bean	6.52	1,700	91	3	33	560	2.6	0.6	0
Sorghum	8.31	2,360	50	4.9	49	150	2.2	1.1	0

a. Crops grown both in Ginchi and Areka.

average temperature. Population pressure on the land is exerted by humans (100/km^2) and livestock, with an average farm size of 3 ha. About 24% of the farmers own more than 4 ha. On the upper side of the watershed, the system is predominantly barley-fallow-barley accompanied by wheat, potato, and enset. The soils in the Ginchi plateau are litisols, which are acidic and low in organic matter, nitrogen, and phosphorus. The fertility of the soil is so low that it does not currently support continuous cropping.

Data collection

A household survey was conducted over two years (2000–01) in the two communities of the enset/root crop-based and cereal-based systems. Farmers from two wealth categories (relatively rich and poor) were considered for the study in Areka ($n = 24$) and Ginchi ($n = 31$). A participatory wealth-ranking exercise, which was undertaken by the African Highlands Initiative Program, grouped households into three wealth categories based on the size of landholdings, number of livestock, perennial crops grown, and sources of income, was used in this study [8]. During the household surveys, the researchers were able to observe and quantify over a period of two years. The major parameters considered for the analysis were farm and household size, household family composition by age and sex, cropland allocation, household food items available over seasons, household food allocation or distribution among family members, crop yield on the farm, and crop purchase or sales over seasons. Household food consumption was monitored in each household on a weekly basis by interviewing the women. The consumption unit (CU) of each household was calculated by adding the CU of each household member using Food and Agriculture Organization (FAO) designations [13]. Secondary data were also collected on average crop yield in the district [14], nutritional composition of each crop [15] (table 1), and other relevant factors. For crops for which reliable data were not available, measurement of yield, moisture content, and estimation of edible components was done on the farm at harvest. The survey was composed of a stratified questionnaire, household group discussion, and direct measurement of crop yields during harvest, and was administered by a technical assistant residing in a nearby village. Continual follow-up was made at all levels.

Since the bimodal rainfall supports at least two crops per year at Areka, land size per household was calculated as the sum of land used for growing crops in both seasons per year. Hence, the farm size presented here is larger than the actual land size. In the process, intercropping and relay cropping practices complicated the establishment of land area and yield per individual crop. However, for the purpose of this exercise, we followed a procedure similar to that used by McIntyre et al. [5], whereby the dominant crop is assumed to occupy the entire area if the populations of the crop mixtures are sparsely grown. The area occupied by the companion crop was calculated from the current plant population density and the optimal plant population density. In situations where none of the crops grown in the crop mixture comprised the highest ratio, crop area was calculated based on the proportional areas they occupied.

The nutrient yields of annuals were determined by measuring the edible yield per area, analyzing the nutrient content of the produce, and converting it to household nutrient supply as the sum of all consumable crop products of the household in the respective systems. Besides annuals, the system comprises perennial crops (e.g., *Enset ventricosum*) of various ages. The nutrient yield of perennial crops *in situ* was determined by estimating crop yield per plant from measurements of corm height and the circumference of plants, as described earlier [16], supplemented by sample weighing, and multiplied by the nutrient content of the product [15] and the number of plants to be harvested per year.

Alterations in crop area and crop species may affect erosion by changing the vegetative cover. Therefore, the relative farm erosivity index (FEI) was calculated by considering the C-factor in terms of cover effect on soil erosion [10] and by considering the cropland size allocated to each crop at present and after optimization of the cropping system for optimum human nutrition, as follows:

$$\mathrm{FEI} = \frac{\sum \mathrm{CF} \times \text{optimized cropland area}}{\sum \mathrm{CF} \times \text{current cropland area}}$$

where

FEI = cumulative farm erosivity index
CF = C-factor of respective crop species

The model

An optimization model was developed using the Solver in Microsoft Excel and employed to analyze the scenario of human nutrition and cropland allocation. After the land size allocated per crop, yield data, percent edible yield, moisture content, and nutrient composition of each crop had been assembled, an annual nutrient budget and household consumption unit was calculated. The recommended dietary nutritional allowance defined by the World Health Organization (WHO) [17] was used to establish optimal nutrient balances.

The objective function used in the model was energy availability per consumption unit and day:

$$\frac{\sum_{i=j}^{N} LS_j \times EY_j \times DM_j \times NC_j}{CU \times 365}$$

where

LS = land allocated to crop *i*
EY = edible yield of crop *i*
DM = dry matter yield of crop *i*
NC = nutrient content of crop *i*
CU = number of consumption units in the household (number of people eating in the house)

Farm land size and daily nutritional requirements for protein, zinc, calcium, iron, thiamine, vitamin A, and vitamin C were used as constraints in the model (see list of constraints below). The constraints differ between the locations because the farming systems were different. The constraints were set to ensure that the households would continue to cultivate, at least partly, their current staple crops. The staple crops in Areka are enset, sweet potato, and maize, whereas those in Ginchi are barley, faba beans, and kale.

Constraints for Areka communities:

Total farm land ≤ 1,659 $\mathrm{m^2}$/CU
Land size of enset ≥ 100 $\mathrm{m^2}$/CU
Land size of sweet potato ≥ 100 $\mathrm{m^2}$/CU
Land size of maize ≥ 100 $\mathrm{m^2}$/CU
Protein ≥ 35 g/day/CU
Vitamin C ≥ 25 mg/day/CU
Zinc ≥ 15 mg/day/CU

Constraints for Ginchi communities:

Total farm land ≤ 4,081 $\mathrm{m^2}$/CU
Land size of barley ≥ 1,000 $\mathrm{m^2}$/Cu
Land size of faba bean ≥ 80 $\mathrm{m^2}$/CU
Land size of kale ≥ 50 $\mathrm{m^2}$/CU
Protein ≥ 35 g/day/CU
Calcium ≥ 500 mg/day/CU
Vitamin A ≥ 25 μg/day/CU
Zinc ≥ 15 mg/day/CU

The decision variables in the model are land allocation for different crops, energy availability per consumption unit, and day, subject to the constraints given above.

Results

Although the average family size is equal in the two regions, the land size per consumption unit is much higher in the cereal-based system (Ginchi) than in the enset/root crop-based system (Areka) (table 2). The difference in land size would be even higher if the fallow land in Ginchi were considered as a potential area for expansion of current crop fields. Both systems are considered nutrient deficient, especially in drought years; the Ginchi farmers have a better ability to cope with drought by selling small ruminants, whereas the Areka system includes very few animals.

Enset/root crop-based systems

The population density in Areka is relatively high (> 400/$\mathrm{km^2}$), and the landholdings are relatively small, about 816.8 $\mathrm{m^2}$/CU. More than 50% of the land is allocated to root/corm crops, in particular sweet

TABLE 2. Characteristics of an average household in enset/root crop-based (Areka) and cereal-based (Ginchi) systems in Ethiopia

Characteristic	Areka	Ginchi
Household size		
Males	3.2	3.1
Females	3.1	3.3
Total	6.3	6.4
Mean CU	4.59	4.65
Actual cropland/ household (m^2)	3,749.7 (± 511)[a]	17,499.7 (± 1,149)
Cropland used/ household (m^2)	5,218.7 (± 679)	10,402 (± 709)
Actual cropland/ CU (m^2)	817	3,764
Cropland used/ CU (m^2)	1,137	2,237
Land used for cash crops (%)	6	0

CU, Consumption unit. Numbers in parentheses indicate standard deviation.

[a] mean (± SD)

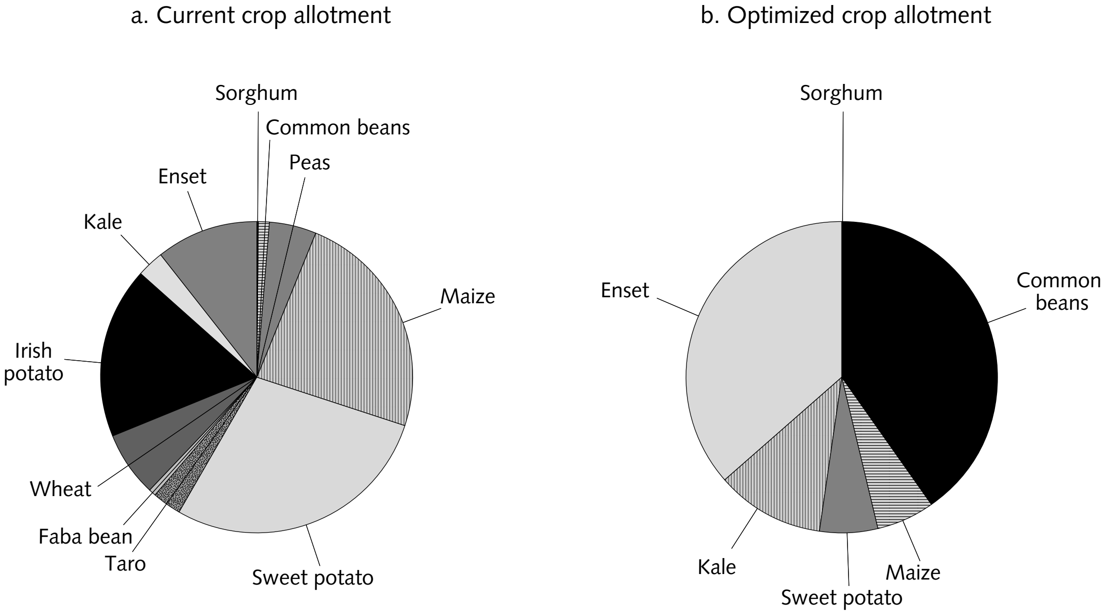
potato, Irish potato, enset, and taro, with land areas of 25.8%, 16.2%, 10.1%, and 2.75%, respectively (figs. 1 and 2). Most of these crops are grown in the homestead or the mid-field, which is halfway between their home and the end of their farm. Another 45% of the land is allocated to cereals, with maize as the dominant grain crop in the system. The total land allocated to legumes and vegetable crops is less than 5%.

The current enset/root crop-based system was found to be in deficit for most of the nutritional components, regardless of household wealth status. Except for iron, the system failed to cover the needs for macro- and micronutrients (table 3). The daily energy supply of resource-poor households was only 75% of that recommended by WHO [17]. Extremely high deficits were found of zinc, calcium, vitamin A, and vitamin C, at 26.5%, 34%, 1.78%, and 12% of the required levels, respectively (table 3). The situation was similar even for relatively resource-rich farmers, except for energy, which was higher.

Cereal-based systems

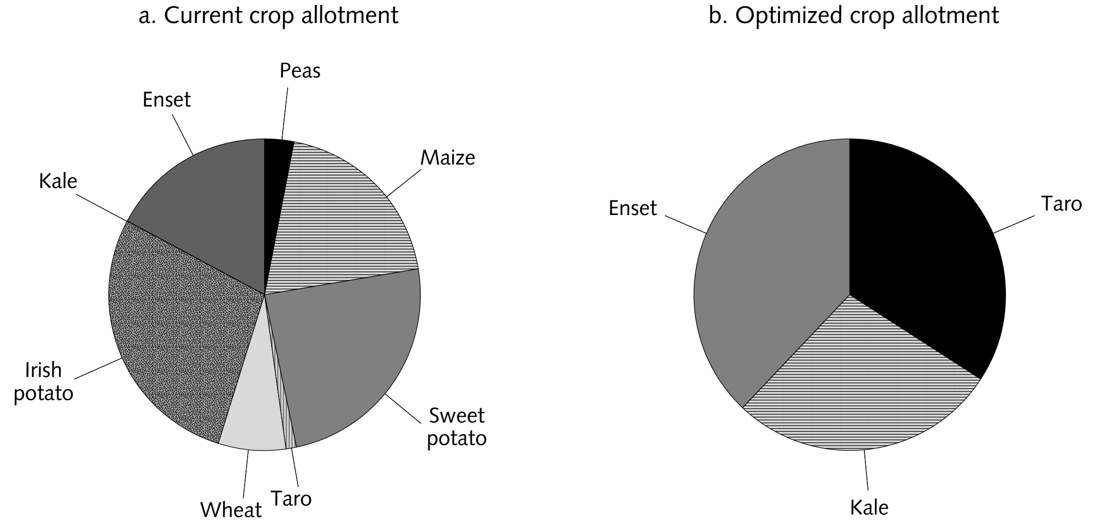
The average landholdings are much larger in the cereal-based system (4 ha per household) than in the enset/root crop-based system. However, in the cereal-based system the farmers leave about 40% of their land fallow, due to declines in soil fertility and lack of grazing land for keeping livestock. Crop diversification at Ginchi is very low, with only six crop species. The greatest proportion of land is allocated to barley (63.5%), followed by wheat and Irish potato (fig. 3). Similar to the situation in Areka, the amount of land allocated to legumes and vegetables in Ginchi is relatively small. Hence, it is predominantly a barley-fallow-barley system.

The current production system is unable to satisfy the human requirements for most nutrients. The system is able to deliver relatively high amounts of iron and thiamine. The resource-rich farmers can satisfy their energy, protein, zinc, iron, and thiamine


a. Current crop allotment

b. Optimized crop allotment

FIG. 1. Land allocation by resource-rich farmers in the enset/root crop-based systems for various food crops, currently (a) and after optimization for improved human nutrition (b)



a. Current crop allotment

b. Optimized crop allotment

FIG. 2. Land allocation by resource-poor farmers in the enset/root crop-based systems for various food crops, currently (a) and after optimization for improved human nutrition (b)

requirements. However, they can provide only 30%, 2.5%, and 2% of the RDA for calcium, vitamin A, and vitamin C, respectively [17] (table 3).

Modeling results

The modeling was run by taking system constraints into account, including household food habits, the adaptability of crops, and the effects of pests and diseases. In Areka enset and sweet potato are the major components of household nutrition, whereas in Ginchi barley is currently the major staple crop. Thus, we ran a simulation model that included barley in Ginchi and enset and sweet potato in Areka.

In Areka, the major constraint affecting the model was the extremely low landholdings of the majority of community members, who were regarded as resource-poor in the analysis. When the whole system was considered in modeling, it was not possible to improve the system with regard to most nutrients, except in terms of energy. However, when the simulation was run separately for the relatively resource-rich households, the energy supply became much higher than the recommended levels, while the demand for all other nutrients was fully covered (table 3). This finding recommends a significant shift from cereals and root crops to an enset-bean dominant system. There needs to be a shift in land allocation, from about 10% to 36% and from 0.1% to 40% for enset and the common bean, respectively (figs. 1 and 2).

At Ginchi, there was a better possibility for the model to improve the nutritional quality of the household by increasing the amount of cropland per consumer unit, if the land was not compromised by a decline in soil fertility and a shortage of livestock feed. The existing cropland, at 2,237 m^2/CU, is enough to provide bal-

TABLE 3. Nutrient budget of households in enset/root crop-based and cereal-based systems of Areka and Ginchi, at current cropping systems and after the system was optimized for improved human nutrition.

		Areka				Ginchi			
		Resource-poor		Resource-rich		Resource-poor		Resource-rich	
Nutrients	RDA	Current	Optimized	Current	Optimized	Current	Optimized	Current	Optimized
Energy (kcal)	2,000.00	1,293.66	2,000.00	2,284.18	4,758.4	1,397.5	3,329.00	2,081.50	3,695.60
Protein (g/kg)	37.53	7.82	9.31	17.39	35.98	32.39	40.00	42.40	42.75
Zinc (mg/kg)	15.00	3.98	6.09	7.38	15.00	7.39	15.33	19.75	20.80
Iron (mg/kg)	7.61	21.48	36.63	35.68	81.664	26.41	78.00	33.55	68.56
Calcium (mg/kg)	528.00	178.76	362.42	310.00	758.70	163.25	694.00	194.50	547.04
Thiamine (mg/kg)	0.92	0.21	0.35	0.41	0.89	1.17	1.08	1.52	1.30
Vitamin A (μg/kg)	10.00	0.18	10.00	2.54	10.00	0.25	12.51	1.45	20.80
Vitamin C (mg/kg)	25.42	2.98	14.95	9.08	2.41	0.54	1.62	0.01	2.61

RDA, Recommended dietary allowance [17].

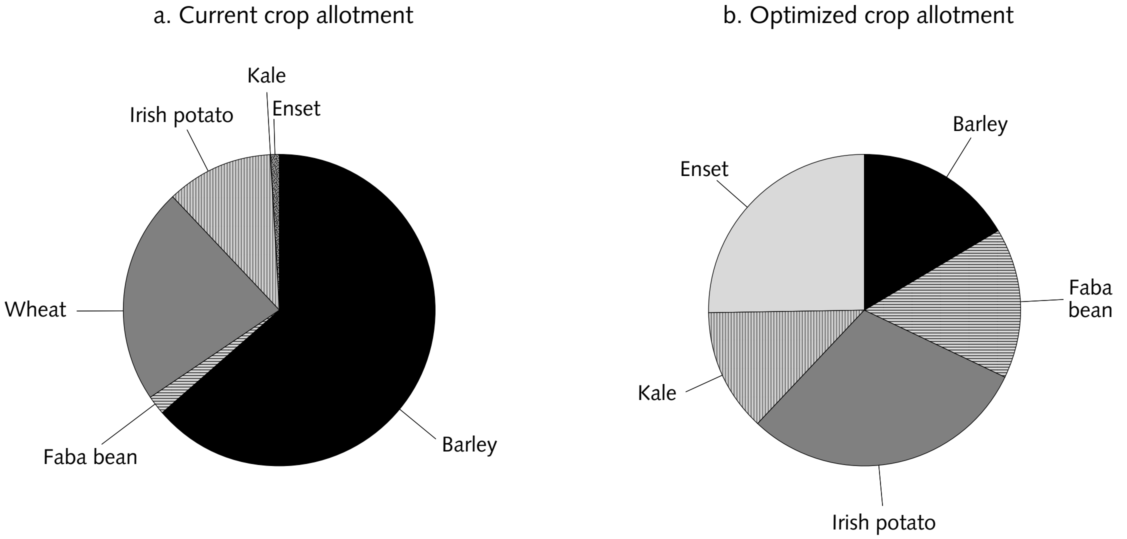


FIG. 3. Land allocation in the cereal-based systems for various food crops, currently (a) and after optimization for improved human nutrition (b)

anced nutrition with a moderate change in the cropping system. The suggested shift was intended to reduce the area occupied by barley by about 50% and expand the land area available for enset, kale, and faba bean to 25.3%, 17.7%, and 15.6%, respectively (fig. 3). By doing so, the requirements for the nutrients of interest were fully satisfied, except for vitamin C. In this case, vitamin C supplements could be used, or a new vegetable crop could be introduced into the system.

Implications of crop reallocation for soil erosion

A shift from one cropping system to another may have a considerable effect on soil loss and nutrient management [10]. In the enset/root crop-based system, a shift from the enset-root crop mix to an enset-bean system improved the C-factor at the farm level by 42%, indicating that soil erosion could be significantly minimized. The same applies to the cereal-based system, in which FEI was improved by 45% (table 4). This has a very strong implication for soil-fertility management, since the enset system traditionally attracts more organic matter into the system [6, 8, 18] because it does not grow in soils with low organic matter content.

Discussion

Integrating human nutrition with sustainable land management

An attempt to address food security cannot be complete without a thorough consideration of the relationship between land degradation and nutritional availability. Initiatives and policies directed toward food security should integrate strategies to turn the negative chain reactions between productivity and land use into positive balances.

Crop reallocation with human nutrition as the sole criterion could affect land management in at least two ways. First, the system may demand intensified soil fertility management because of the expansion of perennials. Traditionally, farmers have divided their farms into three categories, homestead, mid-field, and outfield, based on fertility status, type of soil management, and type of crops grown. About 80% of a farm's available organic fertilizer is applied to the homestead area, where enset is traditionally grown [6, 8]. Hence, it is the most fertile corner of the farm because of the addition of manure, crop residues, and household wastes [6, 8]. Farmers even export crop residues from the outfield to the enset field because the local wisdom considers enset a mulch-loving crop. The expansion of enset at the expense of cereals may, therefore, improve the nutrient budget of the system by encouraging farmers to intensify soil fertility management options, such as composting, better manure management, and fair distribution of resources across soil fertility gradients. Fertilizing the expanding enset fields may have a strong effect on labor and the availability of organic resources. In this case, farmers would be encouraged to practice better organic resource production and management. Second, a shift from a cereal-dominant system to an enset-dominant system may minimize erosion effects by improving vegetative cover, thus reducing the erosivity power by about 45%.

Implications for human nutrition

Malnutrition is common in the farming communities

TABLE 4. Effect of crop reallocation on soil erosion at Areka and Ginchi[a]

		Cumulative C-factor			
		Areka		Ginchi	
Crop	C-factor	Current	Optimized	Current	Optimized
Enset	0.04	6.48	24.20	0.88	24.56
Taro	0.35	16.17	np	np	np
Kale	0.26	11.17	48.47	0.73	80.32
Sweet potato	0.23	99.45	23.00	np	np
Potato	0.22	59.73	np	59.21	159.98
Maize	0.35	127.67	35.00	np	np
Sorghum	0.40	0.94	np	np	np
Teff	0.40	58.84	np	np	np
Wheat	0.42	43.39	np	228.89	np
Barley	0.42	np	np	648.48	167.96
Faba beans	0.24	4.16	np	11.61	91.00
Common beans	0.19	2.132	126.83	np	np
Pea	0.15	11.21	np	np	np
∑C-factor	0.28	441.35	257.51	949.82	523.81
FEI (%)		100	58.3	100	55.1

np, Not planted; FEI, farm erosivity index.

a. Data show the effects of current and suggested (optimized) cropping on C-factor as a component of the universal salt loss equation (USLE).

of the Ethiopian Highlands [2, 3]. This study suggests that one affordable remedy may be reallocation of cropland in favor of perennial crops with a high content of the nutrients that are in deficit. This could be done by considering community food habits, the adaptability of crops to the environment under consideration, and the potential effect of reallocation on the health of the agro-ecosystem.

The conventional wisdom was that enset/root crop-based systems may produce sufficient amounts of carbohydrates and vitamins to cover the household's nutrient requirements, but may be deficient in protein and micronutrients. Our results, however, showed that the system was deficient in most of the required micronutrients, especially vitamin A, vitamin C, zinc, and calcium (table 3). Even the available energy and protein for the resource-poor families was only 75% of the recommended amounts. This was confirmed by the fact that the system has relied heavily on food aid for at least three months a year for the last decade. This was partly the consequence of small landholdings (817 m^2/CU cropland) and very low crop yield caused by low soil fertility, use of low-yield varieties, and occasional drought. Malnutrition was severe in the resource-poor households (table 3), because resource-poor farmers concentrate on annual crops whereas resource-rich farmers allocate large plots to enset [6, 8], in agreement with our findings. Resource-poor farmers would have to allocate about 38% of their land to enset, an increase of 20% from the current system, to increase crop yield by about 20% and thus be able to partially cover the nutritional demands of the household (table 3). As it stands now, unless external supplementation is considered, the resource-poor households will remain deficient in most of the micronutrients.

The constraints on the cereal-based systems were similar to those on the enset/root crop systems except for the severe deficiency of vitamins. Malnutrition in Ginchi could be even more severe in the resource-poor families, because the crop yield is much lower there than in Areka, mainly because of the low temperatures in the mountains. Yet, there is more opportunity to expand cropland and increase productivity by improving the existing fallow-barley system through integration of soil fertility management options and high-yield varieties. Malnutrition was aggravated by limited diversification of crops, and even reallocation of the existing crops would not be enough to fulfill the requirement for vitamin C. Introduction of frost-resistant vegetable crops to be grown under a layer of expanded enset fields may satisfy the vitamin requirements (fig. 3). Households occasionally buy green peppers and citrus fruits (crops high in vitamin C) from the nearby markets in the valley bottoms. Earlier reports also showed that the lowest rates of vitamin A deficiency in Ethiopia were found in predominantly enset/root crop-based systems [3].

Nutrient deficiencies (e.g., protein and calcium) in the two systems could have been alleviated by livestock products. However, 93% of the interviewed households in both systems sold livestock to cover household cash needs. Hence, livestock contributes little to household nutrition.

Our results indicate that if food security and environmental health are to be achieved in the Ethiopian Highlands in the short term, there is an urgent need to shift from a cereal-dominant to an enset-bean-dominant system. Expansion of the land area allocated to beans in Areka and to faba beans in Ginchi is vital to alleviate protein malnutrition. Enset is already supporting 7 to 10 million people as a staple or costaple with cereals and root crops [8, 18], and increasing its land allocation is expected to be an attractive option. The shift would have a positive impact on food security, not only because of the high energy yield of enset, but also because of its protective functions for the land, its greater ability to provide food at any time of the year, and its potential for being drought-resistant.

This approach differs from biofortification in that it does not require the introduction of nutrient-extracting crops or varieties with higher nutrient concentrations. Farmers may adopt the recommendations to reallocate their existing crop fields without the problems in adopting a new crop, i.e., one with a different color and/or different cooking quality. Biofortified varieties could also aggressively consume soil nutrients and might lead to unsustainable production unless the system is continuously supplemented by external inputs.

Implications for policy

The current policy of the Ethiopian Government gives great attention to food security, with limited emphasis on natural resource management. On the other hand, the continual quest for food, pasture land, and fuel for mere survival and to meet basic community needs has forced the increased cultivation of marginal lands, regardless of ecological soundness. The current model favors the expansion of perennial crops to address household food security and environmental degradation, while the current system of land tenure, in a situation where the government owns the land, may not encourage farmers to expand their perennial crops and practice sustainable land use.

Integration of the suggested cropping system will need strong policy support in many ways. First, an expansion of enset fields would have a strong impact on labor, mainly that of women, who are commonly responsible for managing enset fields. The most labor-intense operation is the processing of enset into *kocho* (the bulk of the fermented starch obtained from the mixtures of the decorticated leaf sheath and grated corm) and *bulla* (a white powder produced from squeezing the liquid containing starch from the corm), which is currently estimated to take about seven hours to process one single enset plant. Hence, integration of more enset into the system should be accompanied by the integration of processing implements at affordable prices to minimize pressure on household labor. Second, the expansion of perennials calls for an immediate policy decision on land tenure and guarantees. Third, initial policy support, in terms of credit, would be needed, because the expansion of enset may demand more input of organic and mineral fertilizer into the system to establish and grow the crop in the less fertile outfields. However, the farmers' choices of livelihood strategies substantially influence cropping choice decisions and welfare and resource outcomes. Hence, any policy suggestion for change in cropland allocation should be done through bottom-up negotiations at the levels of the individual farmer, the community, and the district. Increasing awareness of nutritional deficiencies inherent to the current system and their implications for health, and of the benefits that could accrue from modification of the current production system, may lead to an early adoption.

Acknowledgments

We would like to thank Dr. B. McIntyre for her initial support, Mr. Wondimu Wallelu for collecting the field data, and the anonymous reviewers for their valuable comments. Dr. Roger Kirkby strongly supported this research work.

References

1. Graham RD, Welch RM. Plant food micronutrient composition and human nutrition. Commun Soil Sci Plant Anal 2000;31:1627–40.
2. Yimer G. Malnutrition among children in southern Ethiopia: levels and risk factors. Ethiop J Health Dev 2000;14:283–92.
3. Kaluski DN, Ophir E, Amede T. Food security and nutrition—the Ethiopian case for action. Public Health Nutr 2002;5:373–81.
4. Yamauchi T. Impact of microenvironment on food security and nutritional adaptation in the Tari basin. ACIAR Proceeding No. 99. In: Bourke RM, Allen MG, Salisburg JG, eds. Food security for Papua New Guinea. Canberra: Australian Centre for International Agricultural Research, 2000.
5. McIntyre BD, Bouldin DR, Urey GH, Kizito F. Modelling cropping strategies to improve human nutrition in Uganda. Agric Syst 2001;67:105–20.
6. Tsegaye A. On indigenous production, genetic diversity and crop ecology of enset (*Enset ventricosum*). PhD thesis, Wageningen University, Netherlands, 2002.
7. Welch RM. Micronutrients, agriculture and nutrition: linkages for improved health and well being. In: Singh K, Mori S, Welch RM, eds. Perspectives on the micronutrient nutrition of crops. Jodhpur, India: Scientific Publishers, 2001:247–89.

8. Amede T, Belachew T, Geta E. Reversing the degradation of arable land in the Ethiopian Highlands. Managing African Soils 2001, No. 23. London: International Institute for Environment and Development, 2001.
9. The Federal Democratic Republic of Ethiopia Environmental Policy, 1997. Addis Ababa: Environmental Protection Authority, 1997.
10. Bergsma E. Terminology for soil erosion and conservation. Wageningen, Netherlands: International Soil Science Society, Grafisch Service Centrum, 1996.
11. Roggero PP, Toderi M. Impact of cropping systems on soil erosion in the clay hills of central Italy. Advances in Geoecology 2002;35:471–80.
12. Wischmeier WH, Smith DD. Predicting rainfall erosion losses. USDA Handbook 537. Washington, DC: US Department of Agriculture, 1978.
13. FAO. Conducting small scale nutrition surveys: a field manual. Rome: Food and Agriculture Organization, 1990.
14. Ethiopian Statistics Authority, Synthesis Report, 1992–2002. Addis Ababa: ESA, 2003.
15. EHNRI/FAO. Food composition table for use in Ethiopia. Part IV. Addis Ababa: Ethiopian Health and Nutrition Research Institute, 1998.
16. Shack R, Ertiro C. A linear model for predicting enset plant yield and assessment of kocho production in Ethiopia. Addis Ababa: United Nations Development Programme, 1995.
17. WHO. WHO/FAO Expert Consultations. Handbook on human nutrient requirements. Geneva: World Health Organization, 1999.
18. Elias E, Morse S, Belchaw DGR. Nitrogen and phosphorus balances of some Kindo Koisha farms in southern Ethiopia. Agric Ecosyst Environ 1998;71:93–114.