Using Linear Programming to Optimize the Use of Biomass Transfer and Improved Fallow Species in Eastern Uganda

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ABSTRACT

Most soils in sub-Saharan Africa (SSA) have declining soil fertility, with low available nitrogen (N) and in many areas deficiencies in Phosphorus (P). Soil fertility measures soil health and is a crucial factor in crop production. Technologies exist that can replenish soil fertility but many are constrained by access to input or the availability and costs of labour therefore contributions of organic and inorganic fertilizers have been advocated by many. On-farm trials with 10 farmers to compare the effectiveness of different sources of N were conducted. This paper uses a linear programming analysis to determine the optimal combination of organic and inorganic soil improvement options. The incorporation of 100% and 50% of above-ground biomass of improved fallow (IF) species (*Mucuna pruriens* and *Canavalia eniformis)* and the use of biomass transfer (BT) species (*Tithionia diversifolia)* in combination with inorganic fertilizer were investigated. The optimal treatments for maize productivity were found to be 100% incorporation of above-ground Mucuna biomass on 0.06 hectares of land and 0.9 t ha^{-1} Tithonia + N on 0.82 hectares of land. This solution would give an optimal net benefit of 276.8 United States Dollars (US $) over three cropping seasons. An investment of US $ 288.4 would be required and a minimum of 299.3 labour days over three cropping seasons. All IF and BT options in this solution are profitable. Adoptable technologies depend on their profitability and practicability.

Key words: Legume cover crop, optimization model, soil fertility

INTRODUCTION

Soil productivity has declined in many areas of sub-Saharan Africa (FAO, 2001a). 494 million hectares of land are affected by soil degradation and of this, 25% is highly degraded with a loss in the productive capacity. An additional 39% is moderately degraded and faces a deforestation threat if there is no replenishment of depleted resources and sustainable use in the future (Ayoub, 1993). This decline has been attributed to many causes, for example, continuous cropping, cultivation of marginal areas, inadequate replenishment of nutrients (Kaizzi *et al.*, 2002). This has led to the decline in soil organic matter, the degradation in the soil structure and loss of other bio-physical soil processes and consequently, low soil fertility (Bekunda *et al.,* 1997).

According to Graene and Casee (1998), the most sustainable method of soil fertility improvement is the integrated nutrient management approach. Mineral fertilizers are an important soil fertility management input, however, organic inputs also serve as compliments in fertility management. Soil organic matter also increases the efficiency of use of mineral fertilizers. In SSA, however, structural adjustment due to budgetary concerns has been responsible for the removal of inorganic fertilizer subsidies (FAO, 2001b). Without these subsidies, resource poor smallholder farmers have been unable to afford inorganic fertilizer purchase and they are thus experiencing increasing negative nutrient imbalances at the farm level (Kaizzi *et al.,* 2002). SSA has the lowest mineral fertilizer utilization level valued at about 10 kg N; P_2O_5; K_2O $ha^{-1}yr^{-1}$ (FAO, 2001b).

Farmers have also, often perceived mineral fertilizers as substitutes to additions of soil organic matter rather than as compliments (FAO, 2001a). This is not surprising because where as the use of inorganic fertilizers is constrained by the lack of financial resources, the use of organic sources of nutrients is associated with bulkiness, low availability of shrubs and tree species; high labour requirements (Rommelse, 2000); reduction in output of staple food crops; delay in economic returns and hindrances to the mono-cropping culture (Nair, 1993). According to Place and Dewees (1999) however, these are not substitutes because inorganic fertilizers are incapable of producing the benefits associated with organic inputs, such as increasing the water holding capacity of soils or buffering low pH soils. Kaizzi *et al.,* (2002) agree that the improvement in the balance of N sources can be achieved through the biological nitrogen fixation (BNF) and the use of inorganic nitrogen. Therefore there is a need to determine the balance in use of both organic and inorganic fertilizers to improve the biological soil component and hence, realise sustainable agricultural production, meet long and short-term food requirements and ensure sustainable resource management.

Studies on the use of organic nutrients in addition to inorganic nutrient sources to enhance soil productivity (Sanchez, 1999) and their profitability (Shepard and Soule, 1998; Jama, *et al.*,1997; Kwesiga *et al.*, 1999) have been widely conducted. These technologies largely included the integrated use of nitrogen-fixing fallow species, biomass transfer species and inorganic fertilizers. According to Sanchez (1999), the large-scale adoption of short term improved fallows has been reported in west, east and southern Africa, whilst Rommelse (2000) and Place *et al.*, (2000) have reported successes of biomass transfer species in western Kenya and Fischler and Wortmann (1999) in Uganda.

In eastern Uganda, integrated soil management technologies were introduced into farming systems (Waata *et al.*, 2003, Nyende and Delve, 2004). *Mucuna pruriens, Canavalia ensiformis, Tithonia diversifolia, Sesbania sesban, Crotalaria ochroleuca, Calliandra calothrysus, Dolichos lablab, and Tephrosia vogelli* species were introduced to this area. The species of interest in this paper are Mucuna, Canavalia and Tithonia and it focuses on the optimal combinations of legume cover crops or biomass transfer species and inorganic fertilizers for managing soil fertility.

The objectives of this study are therefore to:

1. Determine the optimal solution to soil fertility replenishment using cover crops and BT for fertility replenishment
2. Determine the nature of labour utilisation across the cropping season

METHODOLOGY

Site description

Tororo district in eastern Uganda is located 33°45′ - 34°15′ East and 0°30′ - 1°00′ North, with an altitude range of between 1,097 m and 2,336 m a.s.l. It has a land area of 2,336 km^2. The average land holding is 2 ha (DSOER, 1997), where the agricultural production is purely subsistence. The major economic activity is farming dominated by annual crops, such as finger millet, sorghum, maize and beans. Cotton is the major cash crop. The district soils comprise sandy clays and loam soils with low organic carbon and low soil fertility. The area is made up of non-mechanized farms; poor agronomic practices, such as, poor distribution of farm inputs; unavailability of chemicals and lack of farm implements (DSOER, 1997).

Experimental design

Farmer managed on-farm trials were conducted on ten farmers' fields in Kisoko and Osukulu sub-counties. An unfertilised maize crop was grown for one season before starting the experiment. Experimental details of this work has previously been reported for the IF species and the BT species (TSBF, 2002). The next section gives the experimental detail.

IF experiment

Mucuna (0.75m by 0.6m) and Canavalia (0.75m by 0.3m) were planted under farmers' conditions. No amendments were made to the soil at the time of legume planting. The cover crops were cut at the beginning of the next season, allowed to wilt for five days and incorporated into the soil, at the rates of 50% and 100% of the above-ground biomass. The six experimental treatments were i) maize grown where vegetation from a natural fallow was incorporated, ii) a positive control with maize grown where P + K was added and natural fallow vegetation incorporated, iii) 100% Mucuna above-ground biomass incorporated, iv) 100% Canavalia above-ground biomass incorporated v) 50% Mucuna above-ground biomass and vi) 50% Canavalia above-ground biomass incorporated. A randomised complete block design was used with each of the ten farms acting as replicates. Following biomass incorporation maize hybrid Longe 1 was sown at a spacing of 0.75 m by 0.25 m. The maize was harvested at physiological maturity at the end of the season, and another maize crop was planted to determine any residual effects of the IF species.

BT experiment

The treatments for the BT experiments were i) the control (farmers' practice) ii) the control with P + K iii) Tithonia applied at 1.82 t ha^{-1} iv) Tithonia added at 1.82 t ha^{-1} with P + K, v) Tithonia applied at 0.91 t ha^{-1} with 30kg ha^{-1} inorganic nitrogen added, vi) inorganic N+P+K added. Tithonia was collected from local hedges, spread over the plots and incorporated the same day. Treatments iii), iv) v) and vi) were balanced to add 60 kg N $ha^{-1}$from the nitrogen source. Longe 1 maize hybrid variety was planted at a spacing of 0.75m by 0.25m.

The Linear programming problem

A partial budget was computed (CIMMYT, 1988) to derive the gross margins (Table 1). The results of the partial budget were subjected to LP analysis (Chiang 1984) to determine which of the soil management options (SMO's) produced optimal benefits. Linear programming allows the unique optimal solution with the consideration of alternatives (Reklaitis *et al.*, 1983; Bernard and Nix, 1993).

Objective function

The problem was to maximise the discounted net benefits subject to constraints.

The linear programming problem is stated in equation 1.

Maximize:

$$GM = \sum_{k=1}^{6} \sum_{t=1}^{n} GM_i \, T_i \ldots\ldots 1$$

Where:

GM_i = gross margin of the i^{th} SMO in Uganda Shillings hectare^{-1},

$t = 1 \ldots n$, Where t is the season, and n is the second season for BT SIP and third season for the IF SIP; $k = 1 \ldots 6$, where k is the most profitable SMO selected from the MRR

T_i = the i^{th} SMO or i^{th} treatment with different resource levels.

Activity levels

The activity levels used in this study were the inputs used in the experiments for the most profitable IF and BT experiments (Table 2). The profitable experiments were selected from the marginal rate of return analysis. The average prevailing exchange rate (US$ 1 = 1,500 Uganda Shillings), labour and maize output prices for the 2000/2001 seasons were used. The average prices of maize were valued at US$ 0.1 kg^{-1} and the labour wage rate was valued at US$ 1.0. (A wage rate of US$ 0.67 and US$ 0.33 lunch allowance).

In the activity levels, nitrogen contribution to the soil from the organic source was computed from N levels available in this source. The nitrogen levels from the organic source were computed from values reported in TSBF, (2002). The input costs and values for the objective function were also derived from the values in Pali (2003).

Constraints

The constraints in the raw data were US $562.8 depicting the farmers' annual income. Labour was segmented into 114.9 labour days for land preparation, planting, incorporation of organic material, (labour 1) and 200 labour days for the weeding and harvesting of the crop (labour 2). A total of 315 labour days ha^{-1} 2 seasons^{-1} was used. This labour limitation was based on the average prevailing labour utilisation in the area (for associated activities of cereal crops) for the cropping year and these values were derived from a farmer survey conducted following experimental trials. Nitrogen was used as the most limiting macronutrient (Waata *et al.,* 2003). A total of 60kg ha^{-1} was used as the recommended nitrogen level for maize in eastern Uganda.

Equation 2 shows inequalities where labour (workdays), Nitrogen (Kg ha^{-1}) and the farmers gross income p.a. (US $) were used as constraints. In this study, all treatments were experimented on 5m by 5m plots, however, all economic evaluations were computed on a unit hectare basis. A hectare of land in this study may not necessarily be exhausted; therefore the recommended level of nitrogen, income and the labour utilization levels are be based on this land area for each treatment.

Subject to:

$$\sum_{r=1}^{n} \beta_{ij} X_i \leq C_{ij} \qquad \text{.........} 2$$

Where:

β_{ij} are coefficients for labour (Labour 1, Labour 2 and Total Labour), organic nitrogen application and investment costs used for the jth resource respectively for the ith SMO. These coefficients are computed from the partial budgets.

X_i = the vector of variable inputs used for the ith SMO,

C_{ij} = the amount of jth resource available for ith SMO. These resources are labour (workdays) and the recommended level of nitrogen Kilograms hectares^{-1}, and available capital.

The non-negativity constraint is given in equation 3:

$$X_i \geq 0 \qquad \text{.........} 3$$

Where:

X_i = Vector of variable inputs used for the ith each SMO

RESULTS AND DISCUSSION

Given the farmers resource availability, the optimal solution to the linear programme shows that US$ 276.8 would be realised from the combination of 100% mucuna incorporation and 0.9 t ha^{-1} of tithonia + N on 0.062 and 0.824 ha of land respectively (Table 3). The average land size in the study area is 3.90 ha (Pali, 2003), thus the optimal solution allows for the allocation of land to alternative crop production whilst improving the soil nutrient status in other areas.

A higher land area was allocated to the optimal Tithonia treatment, due to the highest net benefit (US $324) got from the gross margin analysis compared to all other treatments (Table 1). The Tithonia optimal treatment also supported the use of INM. Rommelse (2000) argues that the application of large amounts of Tithonia above 1 ton is uneconomical due to collection and application costs. Yields could reach diminishing returns hence the practicability in the addition of smaller quantities. An investment of US $288.4 would be required for this optimal solution.

The total labour utilisation would be 299.3 workdays. Labour utilisation for land preparation, planting and organic fertilizer application (labour 1) with the technology was less than the available labour (Slack) of 114.9 labour days. On the other hand, labour for harvesting and weeding (labour 2) was a binding constraint, suggesting that this resource was completely depleted in this solution, however the sensitivity analysis (Table 4) shows that an additional 11.5 days may be utilised, whilst maintaining the optimality of this solution. This labour depletion could be attributed to the yield dependent nature of labour during the harvesting activity. Higher yields compared to the farmers' practice were recorded for all treatments with soil amendments (Table 1), hence higher harvesting labour requirements. In Tororo, harvesting of maize occurs in July, December and January (Table 5.), whilst weeding occurs in May, September and October.

Harvesting of maize in July coincides with harvesting of other crops such as groundnuts, beans and millet hence the high opportunity cost of labour. On the contrary, however, Rommelse (2000) reported that peak labour demands are highest during the long rains when weeding and planting activities are on-going and the opportunity cost of the off peak activities is overstated if valued at the full wage rate. The nature of the harvesting labour also suggests that the opportunity cost of labour during the harvesting season in comparison to the labour for planting and ploughing season was higher.

The shadow price of labour 2 was found to be US $1.66 (Table 6). This was higher than the returns to labour for all treatments (Table 1). This suggests the seasonal differences of labour costs during the harvesting season and that the value of labour is not an average value product as suggested by the returns to labour. White *et al.,* (2003) reports that market wages are reflective of labour input scarcity, however, these may not tally with the smallholder farmers' perception of the prevalent labour values.

The sensitivity analysis (Table 4) shows the optimality ranges between US $-27.5 – 267.2 and from US $286.9 for 100% mucuna and 1.8 t ha^{-1} tithonia + N respectively. A unit increase in nitrogen fertiliser in form of organic or inorganic sources of fertiliser would be worth a reduction of US$ 0.91 in the net benefits (Table 6.). The reduction in the optimal net benefit caused by an additional N increase would be higher than the unit cost of nitrogen (US $0.72), implying that N application was costly.

CONCLUSIONS

The use of all soil improvement practices in this study were profitable, suggesting the possibility of adoption by farmers, however, not all practices are optimal. The practicability of Tithonia use however, would imply that farmer's plant these shrubs around field boundaries to ease on labour required for transportation. Labour seasonality is an issue and labour should not be uniformly costed across the season. The labour during harvesting and weeding has a higher opportunity cost than labour valued at the onset of the season. The use of such soil improvement practices is associated with additional labour costs, however, these occur at the onset of the season when peak labour demands occur and can be easily incorporated into the farming system of these farmers. There is a need to understand the labour dynamics of these technologies in order to assess how to enhance adoption.

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Table 1. Partial budget for the fallow and biomass soil improvement practices

Soil Management Option	Average Yield (kg ha^{-1})	Present value of TVC (US $)	Labour utilization (Workdays)	Net Benefits (US $)	Returns to labour (US $)	Benefit-cost ratio
			Fallow soil improvement practice			
100% Canavalia	3400	419	324.6	118	1.08	1.28
100% Mucuna	3700	426	334.2	157	1.19	1.37
50% Canavalia	3150	399	299.95	97	1.03	1.24
50% Mucuna	3400	405	307.95	132	1.14	1.33
NF	1950	244	269.4	46	0.91	1.19
NF (P+K)	2550	342	288.6	59	0.90	1.17
			Biomass soil improvement practice			
1.8 t Ha^{-1} Tithonia	3210	295	336.86	267	0.79	1.90
1.8 t ha^{-1} Tithonia (P+K)	3420	399	349.74	199	0.277	1.49
0.9 t ha^{-1} Tithonia+N	3640	318	338.13	324	0.89	2.00
N+P+K	4100	430	338.04	283	0.4	1.65
FP	2800	254	290.44	238	0.82	1.94
FP (P+K)	2940	356	300.92	161	0.20	1.45

Source: (Adapted from Pali. 2003)

Table 2. The Linear program in detached coefficient form (Raw data)

				Land Use system			
Variable	Soil Management Option	**Objective function (US $)**	**Nitrogen Application (Kg ha^{-1})**	**Investment costs (US $)**	**Labour 1 (Labour days)**	**Labour 2 (Labour days)**	**Total Labour (Labour days)**
A	Fertilized Fallow (P + K)	59	0	342	95	193.6	288.6
B	100 % Mucuna	157	170.5	426	145.8	188.4	334.2
C	50 % Canavalia	97	104.5	399	129.15	170.8	299.95
D	50% Mucuna	132	85.25	405	129.15	178.8	307.95
E	1.8 t ha^{-1} sole Tithonia	267	60	295	122.3	214.56	336.87
F	0.9 t ha^{-1} Tithonia + N	324	60	318	109.65	228.48	338.13
Resource Availability (Farmers Resource Constraints)			**60**	**562.8**	**114.9**	**200**	**315**

Source: (Adapted from Pali. 2003)

Table 3. The optimal solution to the fallow and biomass linear programme

Variable	Soil Management Option	Nitrogen (Kg ha^{-1})	Land (Ha)	Investment Costs (US $)	Labour 1 (labourdays)	Labour 2 (labourdays)	Total Labour (labourdays)
A	Fertilized (P + K) Natural fallow	0.0	0.0	0.0	0.0	0.0	0.0
B	100 % mucuna	10.6	0.062	26.4	9.04	11.7	20.7
C	50 % canavalia	0.0	0.0	0.0	0.0	0.0	0.0
D	50 % mucuna	0.0	0.0	0.0	0.0	0.0	0.0
E	1.8 t ha^{-1} sole tithonia	0.0	0.0	0.0	0.0	0.0	0.0
F	0.9 t ha^{-1} tithonia + N	49.44	0.824	262.0	90.4	188.27	278.6
Total resource utilization under optimal solution		**60**	**0.886**	**288.4**	**99.44**	**200**	**299.3**
Constraints		**>60**	**None**	**562.8**	**114.9**	**200**	**315**
Optimal net benefits		**276.8**					

Table 4. The sensitivity analysis of the optimal solution

Variable	Soil Improvement Practice	Objective Function Coefficient (US$)	Objective Function Ranges (US$)
A	Fertilized Natural fallow (P + K)	59	Unlimited – 320.8
B	100 % mucuna	157	-27.5 – 267.2
C	50 % canavalia	97	Unlimited – 187.91
D	50 % mucuna	132	Unlimited – 218.7
E	1.8 t ha^{-1} sole tithonia	267	Unlimited – 300.9
F	0.9 t ha^{-1} tithonia + N	324	286.9 – unlimited
Resource Constraints		**Constraint Coefficient**	**Constraint Ranges**
Nitrogen (Kg ha^{-1})		60	52.52 – 93.79
Investment costs (US$)		562.8	288.5 – unlimited
Labour I (labour days)		114.9	99.45 – unlimited
Labour II (labour days)		200	66.3 – 211.5
Total Labour (labour days)		315	299.4 – unlimited

Table 5. Seasonal labour calendar for Osukuru And Kisoko sub-counties-Tororo district

Month	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
MAIZE												
Activity												
Land preparation	■							■				
Planting	■	■							■	■		
Weeding		■	■	■						■	■	■
Harvesting	■				■	■	■					
Selling					■	■	■					
BEANS												
Activity												
Land preparation	■							■				
Planting	■								■	■		
Weeding		■							■	■	■	
Harvesting	■		■	■							■	■
Selling					■	■	■					
MILLET												
Activity												
Land preparation					■	■	■					
Planting						■	■	■	■			
Weeding								■	■			
Harvesting	■									■	■	■
Selling		■			■							

Source: Participatory diagnosis report for the Katamata group.

Table 6. Linear programming output

Variable	Treatment	Value	Reduced cost
A	Fertilized (P + K) Natural fallow	0.000000	261.808746
B	100 % mucuna	0.061797	0.000000
C	50 % canavalia	0.000000	90.740730
D	50 % mucuna	0.000000	86.713326
E	1.8 t ha^{-1} sole tithonia	0.000000	33.962357
F	0.9 t ha^{-1} tithonia + N	0.824394	0.000000
Row	**Constraint**	**Slack/ Surplus**	**Dual prices/shadow prices**
2	Nitrogen (Kg ha^{-1})	0.000000	-0.910255
3	Investment costs (US$)	274.317322	0.000000
4	Labour I (labour days)	15.495243	0.000000
5	Labour II (labour days)	0.000000	1.657105
6	Total Labour (labour days)	15.595243	0.000000