Ethiop. J. Agric. Sci. 30(4) 147-168 (2020)

Exploring Optimized Synergetic Solutions for Major Constraints of Sustainable Agricultural Production in Chencha, Southern Ethiopia

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የጨንቻ ወረዳ የግብርና ዘይቤ ምርታማነት በተለያዩ ማነቆዎች ተጽዕኖ ስር ያለ መሆኑ አሁን ያለው የግብርና ዘይቤ መሻሻል እንዳለበት ያመለክታል፡፡ ከዚህ ጋር ተያይዞ ቁልፍ የሆኑ የአፈር ለምነት፣ የሰው ጉልበትና የገቢ እጥረት ችግሮችን በአንድ ላይ አዳብሎ ለመፍታት እንዲቻል አማራጭ ለመሻት ይህ ጥናት ተካሂዷል፡፡ በዚህ ጥናት ወረዳውን ሊወክሉ ከሚችሉ አስራ ሁለት አባ/እማወራ ማሳዎች እና ከተለያዩ መዛግብት መረጃዎች ተወስደዋል፡፡ የግብርና ዘይቤውን ለማሻሻልና ለችግሮቹ የመፍትሄ አማራጭ ለማመንጨት፤ ፋርም ዲዛይን (FarmDESIGN) የተባለ የመረጃ ትንተና ዘዴ ጥቅም ላይ ውሏል፡፡ በዚህ የትንተና ዘዴ መፍትሄ ለማመንጨት ሁለት ሁኔታዎች ታሳቢ ተደርገዋል፡፡ እነዚህም አሁን ባለው የግብርና ዘይቤ ውስጥ ያሉትን የአመራረት ዘዴዎችን መሠረት በማድረግ የተሻለ አማራጭ ማውጣት እና አዳዲስ ተጨማሪ ቴክኖሎጂዎችን በማስረፅ እና በማሻሻል ለአስራ ሁለቱም ማሳዎች የመፍትሄ አማራጭ ማውጣት ናቸው፡፡ የትንተና ውጤቱ እንደሚያሳየው አሁን ባለው አሠራር በሁሉም ማሳዎች ላይ የአፈር ለምነት መቀነስ፣ የቤተሰብ ጉልበት ማነስ እና የገቢ እጥረት መኖራቸው ተረጋግጧል፡፡ ይሁን እንጂ ለእነዚህ ችግሮች በርካታ የተቀናጁ አማራጮች እንዳሉም ውጤቱ ይጠቁማል፡፡ ታሳቢ ከተደረጉ ሁኔታዎች የተሻለ አማራጭ ማግኘት የተቻለው አሁን ያለውን የአመራረት ዘዴ ከአዳዲስ ቴክኖሎጂዎች ጋር አጣምሮ በመስራት ነው፡፡ የተሻለ ለውጥ ማምጣት ካስቻሉ ምክንያቶች ዋነኛው የሰብል ስርዓትን ወይም የሰብል ቦታ ሽፋን ድልድልን ማስተካከል ሲሆን ይህም ከእያንዳንዱ የሰብል የቀደመ አያያዝ ወይም እንክብካቤ ጋር ተያያዥነት ያለው ነው፡፡ ይሁን እንጂ ሰብሎች የሚኖራቸውን የማሳ ሽፋን ስሌት እና ተያያዥ አሠራሮችን በግል ለማስተካከልና ለመተግበር አርሶ አደሩ ሊቸገር ስለሚችል የግብርና ባለሙያ ምክር በእጅጉ ያስፈልገዋል፡፡ ስለዚህ የአርሶ አደሩን ግንዛቤ ማሳደግና ስለሰብል ማሳ ዕቅድና ከሰብል ጋር ተያያዥ የሆኑ የተሻሻሉ የአመራረት ዘዴዎችን፣ የባህር ዛፍን ቦታ አጠቃቀም፣ የሰብል ቅሬት አጠቃቀም እና የፍግ አያያዝና አጠቀቀምን በተሻለ እንዲያውቅ ማድረግ አስፈላጊ ይሆናል፡፡ በተጨማሪም ከግብርና ሥራ ውጪ የሆኑ ቦታ የማይሻሙ የገቢ አማራጮችን መተግበር፣ ጉልበት ቆጣቢ የሆኑ ቀላል የመውቂያ መሣሪዎችን ለአርሶ አደሩ ማስተዋወቅ እና ምርታቸውን በተሻለ ዋጋ መሸጥ እንዲችሉ የገበያ አማራጭና ትስስር መፍጠር ወሳኝ ተግባራት ናቸው፡፡

Abstract

Several constraints affect the performances of the farming system in Chencha suggesting the necessity of adjustments in the farm components. Therefore, an exploration was made to simultaneously optimize operating profit, labour and soil organic matter balances. Data from twelve farms and secondary data on improved technologies were used as bases for the exploration. Using the multi-objective model FarmDESIGN, the optimization was conducted for two scenarios for each farm, i.e., optimization based on the currently existing farm components and practices and by introducing new technologies and practices to amend the current farm management options. The results revealed that the farm operating profit, labour balance and organic matter balance were not yet optimized with the current farm configurations of all farms. But there is ample scope to improve and simultaneously optimize both the economic, social and environmental sustainability either through optimization of management within current farm resources, or through using improved technologies. The highest improvement could be made through combined optimization of management within current farm resources and improved *technologies. The major important factor that influenced the optimization was the cropping plan, which might be associated with the management practices applied for a particular crop. However, adjusting areas of crops and implementation of some other optimized solutions may be difficult for individual farmers and requires advice through agricultural extension programmes. Therefore, there is a need to improve the awareness of farmers to wisely manage: crop area and associated crop and soil management practices, land use for eucalyptus, straw use and storage of farm yard manure. Moreover, it is important to diversify off-farm income sources, introduce alternative threshing machineries and improve market access for farm products.*

Introduction

The world population is estimated to reach about 9.6 billion people in 2050 (United Nations, 2012) and food security will remain a global challenge. Therefore, the increase in agricultural production should match population growth. However, agricultural production is constrained worldwide by several factors including land scarcity due to population pressure and effects associated with climate change. Achieving sustainable food security is a challenge particularly in Ethiopia where the population growth is rapid (3.02%) (United Nations, 2015), the majority (85%) of the population depends on subsistence farming characterized by low productivity of crops and livestock and food price hikes faster than non-food items given the double digit economic growth of the country (Haji and Gelaw, 2012). Constraints to agricultural production in Ethiopia include land scarcity in the highlands (Josephson *et al.*, 2014), land degradation (Gashaw *et al.*, 2014), low levels of input (Taffesse *et al.*, 2011), low efficiency of fertilizer use and erratic rainfall (Bekabil, 2014). Reports indicate that due to the weather shocks in 2015, over 5 millions of people need food assistance in different parts of the country (USAID, 2015).

Potato gives high yield, more calories, vitamins and nutrients per unit area (Knapp, 2008) compared with cereals. Therefore, it has vital role to ensure food security in land scarce areas like Chencha. Potato is one of the most important crops cultivated by the majority of farmers in Chencha and it is used as source of food and income but its productivity is low compared to the national average (Mazengia, *et al.*, 2015). Some of the factors affecting the productivity and production of potato in the area are lack of access to improved variety seeds and fertilizer, shortage of labour, land and cash (Dersseh, *et al.*, 2016), and decline in soil fertility (Mazengia, *et al.*, 2015).Although, mixed crop-livestock system is the dominant farming system in Ethiopia and constraints of production are diverse, most of research works in the country focus on addressing individual constraints.

Improvements in farm productivity can be achieved through increased yields of individual crops and animals, or by reconfiguration of existing or new components at farm level (areas of crops, numbers of animals, allocation of products, amounts of applied manures and fertilizers, etc.) to close the farm productivity gap (Cortez-Arriola*et al.,* 2014). Components of a farming system are interrelated and solutions to certain components may positively or negatively affect the other components in the system and this necessitates optimized solutions. Moreover, agricultural production is influenced by different biophysical, socioeconomic and climate factors and thus redesigning the current farming systems is important. Martin *et al.* (2013) have identified two categories of farming system design approaches: i) optimization approaches in which emphasis is placed on exhaustive computational exploration of the solution space by a problem-solving algorithm; and ii) participatory and simulation-based approaches in which problem situation analysis and exploration of the solution space rely on the creativity of humans. FarmDESIGN (Groot *et al.,* 2012) is a model that serves as a farm diagnosis and exploratory tool to generate large sets of Pareto optimal alternative management options in search of improved farm performance. The model is used as an interactive application which supports iterative cycles of learning and adaptation of the structure of a mixed farm. It has demonstrated its usefulness for multi-objective optimization in the design of mixed farming systems (Groot *et al.,* 2012). Flores-Sánchez *et al.* (2014) and Cortez-Arriola *et al.* (2016) have used the model to simultaneously improve income, labour and soil organic matter.

In Ethiopia, there are few experiences of exploring solutions for constraints using optimization (Adane, 2014; Yihun, 2015) and multi-objective optimization (Awulachew *et al.,* 2009; Hassaballah *et al.,* 2012; Saliha, 2012; Seitz and Torre, 2014) but most of them focus on water productivity and use. Yirga and Hassan (2010) have worked on optimization of soil nutrient. Amede and Delve (2008) used an optimization model to address food security and cash income. However, approaches that simultaneously address multiple production constraints related to biophysical (crop, livestock, soil) and socioeconomic (labour and farm income) issues are rare.

In our previous study, we identified a number of constraints in the performances of the farming systems in Chencha, indicating the necessity of adjustments in all farm components (Waga, 2017). The current study aims at optimizing operating profit, labour and organic matter balances. We identify management practices and technologies that could resolve these issues, and conduct model-based tests of these potential innovations in a whole-farm context. Moreover, we explore how further reconfiguration of current and newly introduced practices and technologies can contribute to better production, socio-economic and environmental performance of farms using cash, labour and soil organic matter as indicators.

Materials and Methods

Description of study area

Chencha is a district in the southern Ethiopia having an area of 373.5 km^2 and a human population density of 388 person km^{-2} (CSA, 2011). The altitude ranges from 2000 to 3000 meter above sea level (masl). Based on the altitude, the agro-ecology is classified as highland (>2500 masl), which accounts for 82% of the total area, and midland (2000 – 2500 masl) accounting for the remaining 18%.The minimum air temperature ranges from 11 to 13 °C and the maximum ranges from 18 to 24 °C. The long-term average annual rainfall is 1172 mm with a peak in April followed by one in September, whereas the total rainfall and average temperature during the study period were 868mm and 13.7 °C. Thus, there are two cropping seasons known as *Belg* (March to May) and *Meher* (June to October). Crops cover about 35 and 65% of the farmlands in the two seasons, respectively. Most plots have been cultivated for centuries and the soils are degraded. Most soils have a reddish brown colour and clay loam texture. Mixed farming is the major farming system and the major crops grown are enset [*Enset ventricosum* (Welw.) Cheesman], wheat (*Triticumaestivum* L.), potato (*Solanum tuberosum* L.) and barley (*Hordeum vulgare* L.) while the major livestock are cattle, horse, sheep and chicken (Dersseh *et al.*,2016).

Farm selection and data collection

The majority of the data used for this study were adopted from our previous farm surveys on twelve farms selected using stratified sampling (Waga,2017). The main criteria used to select the farms were the farm owners' gender, age and education level, household size, wealth class, off-farm income levels, mineral fertilizer usage and diversity of livestock and crops. The data were collected mainly through interviewing the farm owners, taking soil and plant samples and reviewing secondary sources. The interview data were related to crop, animal, soil and socioeconomic aspects of the farms and the households. Additional data were collected on management practices and technologies from secondary sources.

Characteristics of the original farm configurations

Each farm had a total land area ranging from 0.3 to 4.3 ha (on average 1.1 ha) divided over, on average10 plots planted with different annual and perennial crops. Sequential double-cropping was practised on most plots. In different farms, a total of fifteen types of food crops, one feed crop (natural grass) and two trees (eucalyptus and bamboo) were grown. Enset, potato and barley were grown in all the farms and wheat and vegetables were grown in 92 and 67% of the farms, respectively. The most common cropping system was sole enset grown by all of the farms followed by Fallow-Barley, Fallow-Wheat and Fallow-Potato each practised by 83, 83 and 50% of the farms, respectively. Average plot sizes range from 0.01 ha of apple or vegetables to 0.51 ha of eucalyptus with a median of

0.075 ha. Crop products were used partly for home consumption (particularly enset and barley) while the remaining were exported from the farm through sale (particularly fruits and vegetables). Depending on the crop type, straws were used for animal feed and bedding, fire wood or other home uses or for sale in a few cases.

Average fertilizer rates used to produce different crops per farm were 94, 57 and 5608 kg ha^{-1} DAP, urea and farm yard manure (FYM), respectively. Rates varied across farms from 30 to 201 kg ha^{-1} for DAP, 20 to 158 kg ha^{-1} for urea and 457 to 20929 kg ha^{-1} for FYM. Only FYM was applied mainly to enset and fruit trees plots whereas no fertilizer was applied to eucalyptus and grass plots.

The animal herd consisted of mainly cattle, horse and sheep. All of the farms had cows and the majority (92%) of the cows had claves. About 33, 17 and 42% of the farms had heifer, bull and ox respectively. Most (67%) of the farms had sheep whereas less percentage (33%) of the farms had horses. Average numbers of cattle, sheep and horses (including young) kept per raring farm were about 5, 6 and 1.5, respectively. Whereas, the average numbers of the adult ones were about 2, 5 and 1, respectively. All of the farms had animal feed shortage and the average feed self-sufficiency was 28%. Animals graze for 8 hours during the day throughout the year. Animals, particularly young ones, were used for sale while nearly all of the milk products were used for home consumption. FYMs were used only for crop production in all farms.

Modelling improved management practices and technologies

The multi-objective optimization was used for each farm to explore possibilities to improve farm performance on the basis of only the currently existing farm components and practices or resources (Scenario-1) and by introducing new or improved technologies and practices to amend the current or existing farm management options (Scenario-2). The proposed interventions are described below and Table 1 shows the specific changes made for one farm.

Frequency of potato in rotation: In all farms, the maximum frequency of planting potato was set at 0.66 so that potato appears in a plot utmost once in every one and half years (or once in every three growing seasons) which is practised by most farmers. The frequency can be also related to the proportion of plot area of potato relative to the total farm area.

Improved crop varieties: Improved varieties with associated management practices were considered for annual crops including potato, wheat, barley, faba bean, field pea and grass. The average yields of the improved crop varieties attained on farmers' plots at national level were considered as interventions (MoARD, 2014). Interventions were proposed for farms mainly where the productivities of crop varieties were less than the average on-farm yields of the improved varieties. In one farm (Farm-6), the productivity of improved potato variety in one plot was below the average potential due to management problems. Therefore, proper management practices, including fungicides, were considered as intervention. Generally, for six farms, 75 to 100% of the above mentioned crops were replaced by improved varieties and practices, whereas in the remaining farms, 20 to 71% of the plots were replaced by improved varieties and practices.

FYM management: To improve management of on-farm produced manure, covering FYM with impermeable plastic sheet was assumed to create anaerobic condition to reduce N loss (Shah *et al.,* 2012). Therefore, the originally used fraction (0.27) of mineral N loss during storage in aerobic condition was adjusted to 0 in the model for all farms.

Improved cattle breed: For all farms, the productivity of the current lactating cow breed was replaced by a cross-breed (indigenous with exotic) which produces about three folds more milk per day and has a longer lactation period compared with the local breed (Mulugeta Ayalew and Misaye Badasso, 2014).

Machine threshing: To reduce labour requirement, manual threshing of wheat, barley and triticale was assumed to be replaced by threshing with small machinery (Asella multi-crop thresher) which is being promoted in the country. The time saved, compared with manual threshing of the same product, was calculated and the total hours of labour required to produce respective crops was adjusted accordingly in the model. The cost of machine threshing (on hiring basis) was considered as cost of contract work in the model.

Variables and steps for optimization

The main production constraints identified by our previous studies (Dersseh *et al.,*2016; Waga, 2017) were considered as objectives in the model. These constraints were cash and labour shortages and low soil fertility. Accordingly, the objectives of the optimization were to maximize the operating profit to generate sufficient income, to maximize the farm labour balance (decrease labour requirement) and to maximize the soil organic matter balance.

The decision variables that were changed to attain the above objectives were crop land area, fertilizer (DAP, Urea and FYM) amount, animal number and amount of fresh grass to feed animals. The minimum value for each of the decision variables was set to zero except for the plot areas of permanent crops and trees (enset, apple, plum, eucalyptus and bamboo) which were fixed at the original plot sizes of respective farms, as well as the number cows which was fixed at one.

Table 1. Proposed introductions of improved technologies and their productivities or efficiencies relative to the current practices in Farm-11

Plot, practice, animal	Type of introduced technology	Productivity (kg ha^{-1}) /efficiencies		Seed rate, kg ha^{-1}		DAP, kg ha^{-1}		Urea, kg ha^{-1}	
		Current	Introduced	Current	Introduced	Current	Introduced	Current	Introduced
Enset	No					0		0	
Kale	No					0		0	
Potato-Triticale	Potato variety*	2667	20000	1333	1900	220	195	220	165
	No for triticale	2000		120		20		10	
Fallow-FB	Variety	1000	3100	170	275	41	100	0	50
Potato-Wheat	No for potato	19048	2000	1667	2000	119	195	95	165
	No for wheat	3571	2770	238	175	0	100	0	150
Barley-Wheat	Barley variety	560	2600	80	125	0	50	0	50
	Wheat variety	2400	2770	80	175	0	100	0	150
Fallow-Barley	Variety	1875	2600	128	125	0	50	0	50
Barley-FP	Barley variety	208	2600	100	125	0	50	0	50
	FP variety	1042	2900	150	150	0	100	0	50
Barley-FB	Barley variety	450	2600	100	125	0	50	0	50
	FB variety	759	2770	100	275	0	100	0	50
Potato-Barley	Potato variety*	9167	20000	1800	1900	133	195	100	165
	Barley variety	833	2600	100	125	0	50	0	50
Potato rotation	Frequency	The highest frequency was set at 0.66							
FYM storage	Plastic cover	Fraction of mineral N storage loss in aerobic condition = 0							
Cereal threshing	Machinery	The machine threshes 400 kg hr^{-1} wheat and 500kg hr^{-1} barley							
Lactating cow**	Cross breed	1.75 l day^{-1}	5.2 day^{-1}						

*Fungicide used; **lactating periods of local and cross breed are 7 and 8 months, respectively; FB=Faba bean; FP=Field pea

The maximum values for permanent crops areas and amount of fertilizer and fresh grass to feed animals were set to about twice the original values of respective farms. The maximum areas of annual crops were set at the total area of the farm less the sum of the areas of permanent crops while the maximum numbers of animals were set to four times higher than the original values.

The constraint variables in the model were total farm area, percent feed balance [percent deviation between required and available dry matter intake, energy and protein (CP) for maintenance and production] and soil nutrient (N, P and K) losses. The minimum allowed nutrient loss was zero to avoid mining, except for farms that originally had negative values for K losses indicating mining. The exploration was conducted using FarmDESIGN model (Groot *et al.,* 2012). Pareto-based Differential Evolution (DE) was used as selection strategy in the exploration. For each farm, the model was run to explore alternative solutions relative to the original farm configurations with 1000 iterations. The parameters for the evolutionary algorithm (DE) were F=0.15 (mutation amplitude) and CR=0.85 (crossover probability). The number of solutions generated depends on the number of decision variables and multiplication factor (MP). MP was adjusted so that the number of solutions for each optimization was ca. 700 (varying from 690 to 726 with an average of 714).

Results and Discussion

Optimized solutions and their relationship

A number of optimized solutions were generated simultaneously for the three objectives for each farm (Fig. 1). The relationships between the optimized solutions for different objectives were different across farms.

OM and labour balances

The relationships between the optimized solutions for organic matter (OM) and labour balances (LB) (the difference between available and required labour) were negative in half of the farms in both the current farm management (scenario-1)and introduction of improved technologies(scenario-2) (Figs 1 a and b). For example, the correlation between optimized solutions of OM and LB were -0.98 and -0.77 for Farm-6 and Farm-7, respectively (Figs 1 a and b). However, the degree of association varied across farms. The mean optimized estimates and original values of the OM balance in the two scenarios showed that optimizations of the current farm configurations increased OM balance in the top 20 cm by 108 to 351 kg $ha^{-1}yr^{-1}$ or by 5 to 319% (average: 59%) compared to the original values Fig. 1(c). But technological intervention alone increased OM balance by less than 1% compared to the original values in the current management practices (scenario-1) for all farms. In contrast, optimizations of farm configurations in scenario-2 brought OM balance increments ranging from 10 to 387% (average: 78%) compared to the original values in scenario-1.

Likewise, optimizations of the current farm configurations decreased labour balance by 120 to 315 hr. ha^{-1}yr^{-1} or by -9 to -137% (average: -35%) compared to the original values (Fig. 1d). Technological intervention alone decreased labour balance on average by -16% compared to the original values in scenario-1. Optimizations of farm configurations in scenario-2 decreased labour balance by -15 to -106% (average: -51%) compared to the original values in scenario-1.

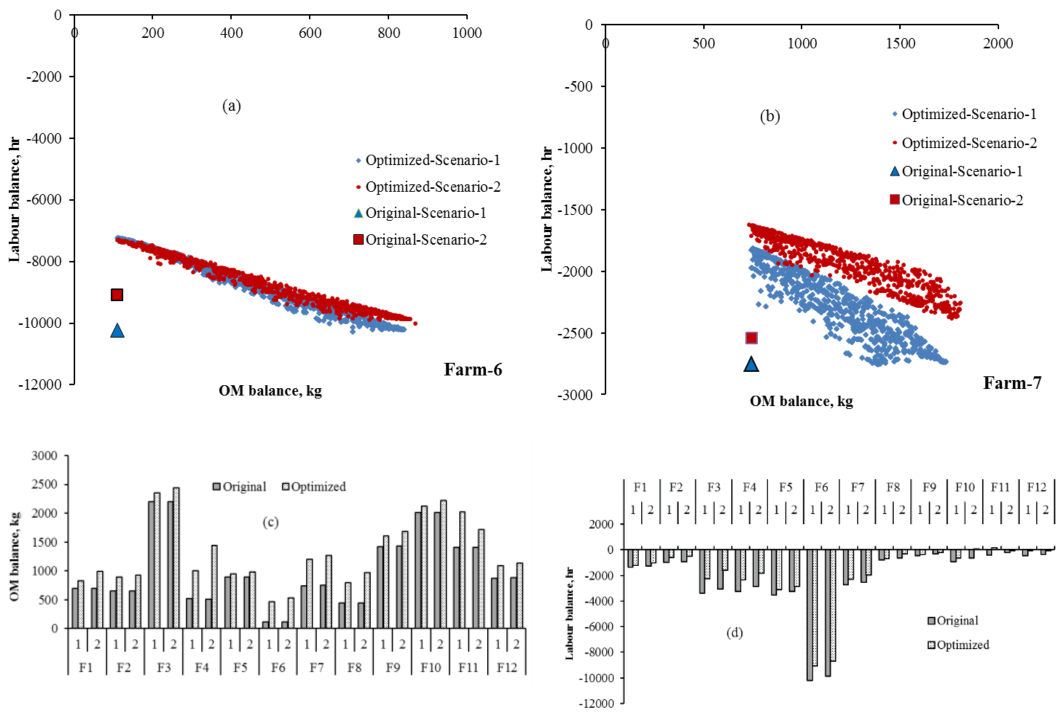

Figure 1. Relationship between optimized solutions of OM and labour balances and their mean optimized estimates (c) compared to their original values in scenario-1 (1) and scenario-2 (2) across farms (F). Each dot in the figure (a and b) represents an alternative optimized solution to attain the specified objectives through adjusting crop area, number of animal, amount of fertilizer and frequency of potato planting.

OM balance and operating profit

The relationships between the optimized solutions for OM balance and operating profit (OP) were negative in the majority (75%) of the study farms in the two scenarios (Figs 2 a and b) though the degree of their association varied across farms and scenarios. For instance, the correlation between optimized solutions for OM and OP in Farm-3 and Farm-6 were -0.84 and -0.97, respectively (Figs 2a and b). Optimizations of the current farm configurations increased operating profit by 928 to 8373 BR ha^{-1}yr^{-1} (1Br = 0.05 USD) or by 7 to 742% (average: 149%)

compared to the original values (Fig. 2c). Technological intervention alone increased operating profit by 13519 to 29055 BR $ha^{-1}yr^{-1}$ compared to the original values in scenario-1. Whereas, optimizations using improved technologies increased operating profit by 32729 to 373451 BR $ha^{-1}yr^{-1}$ compared to the original values using the current management system. One farm that had the lowest and negative initial operating profit showed the highest percent increment in operating profit.

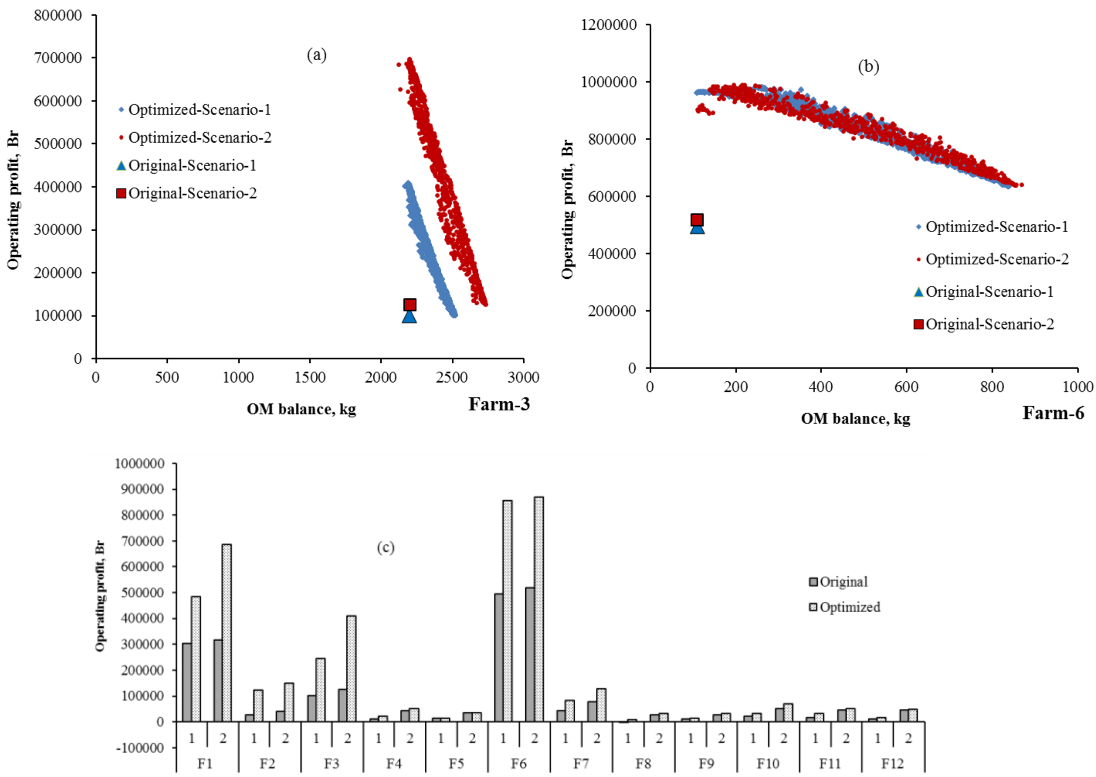

Figure 2. Relationship between optimized solutions for OM balance and operating profit and mean optimized estimates (c) of operating profit compared the original values in scenario-1 (1) and scenario-2 (2) across farms (F). Each dotin the figure (a and b) represents an alternative optimized solution to attain the specified objectives through adjusting crop area, number of animal, amount of fertilizer and frequency of potato planting.

Labour balance and operating profit

The relationships between the optimized solutions for labour balance (LB) and operating profit (OP) were positive in 50% and 58% of the farms in scenario-1 and scenario-2, respectively (Fig. 3), indicating that an increase in labour balance (i.e., a decrease in labour requirement of the farm) is associated with an increase in profit. The degree of association was relatively high in the scenario-2 in the majority of the farms. For instance, the correlation between optimized solutions for LB and OP in Farm-6 was 0.91(Figs 3).

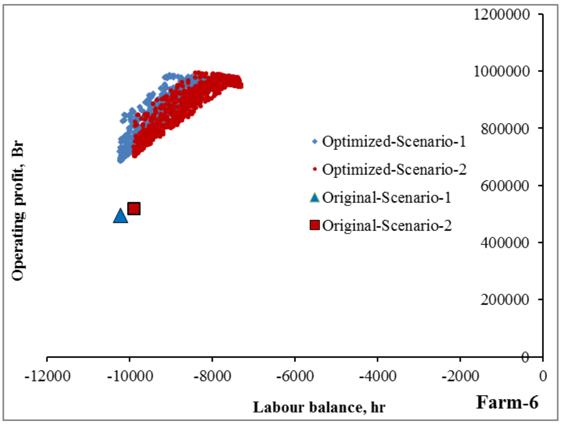

Figure 3. Relationship between optimized values of labour balance and operating profit in scenario-1 and scenario-2 for Farm 6.Each dot in the figure represents an alternative optimized solution to attain the specified objectives through adjusting crop area, number of animal, amount of fertilizer and frequency of potato planting.

Generally the differences between the optimized solutions and the original values for all objective variables in the current systems imply that the current farm configurations of all farms are not yet optimized and this signifies the room and the need for simultaneous, synergetic improvements for the three objectives. Therefore, the solution spaces that were explored in the current study suggest that each farm can have a wide range of options from which farmers can select based on their needs.

Relationship between management practices and optimized solutions

Adjusting crop areas and organic matter balance

The model uses "crop area" as proxy for "contribution to the cropping plan" and thus as the plot area of one crop increases, the plot areas of other crops automatically reduces. Depending on crop type and associated management practices, adjusting the crop composition, by changing the plot areas of individual crops, played a major role in optimizing the three objectives. The relationships between plot areas and optimized solutions for OM balance in scenario-2 varied among crop types (Fig. 4).

For barley, the relationships were positive with change in areas of the majority of plots although the relationship varied across plots (Figs 4-a and b). The positive association of the plot area of barley with OM balance might be related to the prevailing soil fertility and straw management practices for barley production. In most farms, barley is produced using FYM with little or no chemical fertilizer.

Moreover, the majority of the straw yield of barley is used for animal feed and bedding in most farms; this reflects common practice in other parts of the country (Brink and Belay, 2006). Barley straw is not used for fire or burned on the field like the straw of some other crops. Therefore, the portion of the straw product used as bedding material and for animal feed is returned to the soil with and through FYM and might increase the OM balance.

Conversely, adjusting the areas of potato resulted in mixed responses of the OM balance (Figs 4b and c): the relationship was negative when potato was grown in mono-cropping (Fallow-Potato), whereas it was positive when potato was double cropped with triticale, wheat and barley in most farms. The negative association of potato production in mono-cropping with OM balance in most plots suggests that it played a less positive role in environmental sustainability. This might be because potato is mostly produced using inorganic fertilizers (Mazengia *et al.*, 2015) which have no direct role in maintaining OM. Moreover, potato has a very high harvest index and small root system and thus less biomass remains in the farm leading to OM depletion. However, the positive association of OM balance with potato in double cropping with other crops shows the importance of crop rotation in soil fertility management and the possibility of reducing the nutrient mining effect of potato in ensuring sustainable production.

OM had a negative association with an increase in areas of crops of which the straw products are mainly burned, as observed with faba, or the products of which leave the farm through sale, such as apple seedling, vegetables and eucalyptus (Figs 4c and d). Moreover, it is not common to apply fertilizer to eucalyptus and little or no fertilizer is applied to faba bean, as it is a nitrogen fixing crop. Therefore, one way to improve the soil OM balance might be by increasing the area of barley plots that might attract FYM and increase the availability of feed and bedding material. However, an increase in the plot area of barley was associated with high labour demand and low operating profit as evidenced in most farms. Thus, improving labour use and economic efficiency of crop production, particularly for barley, and adjusting the destination of crop straws would be important. It might be important to distribute the available FYM to other crop plots too.

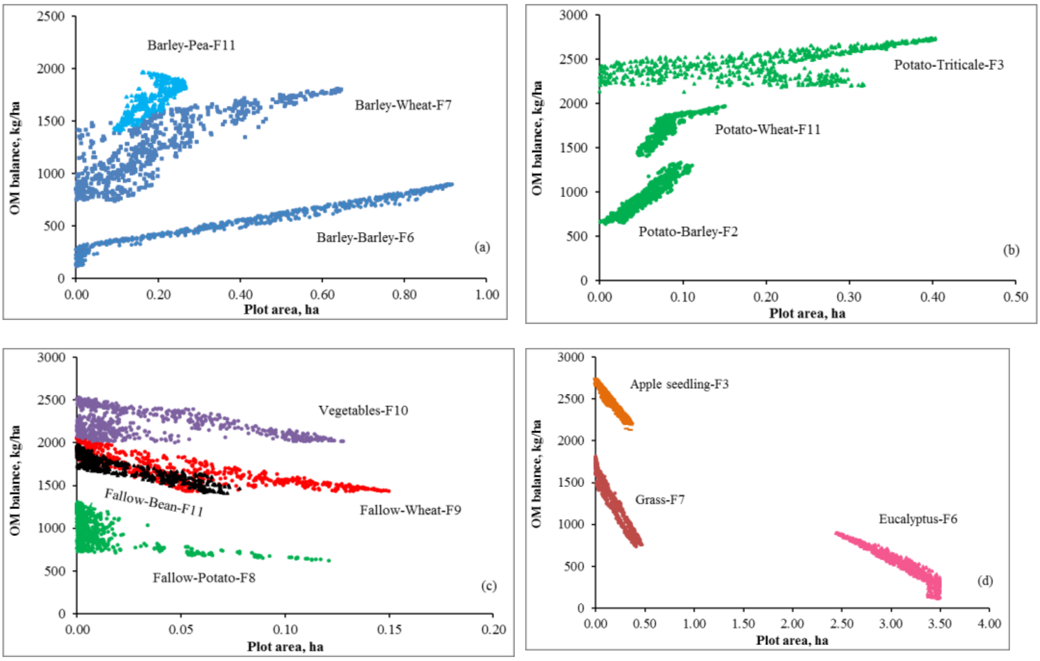

Figure 4. Relationship between crop area and optimized OM balance in scenario-2 across farms (F). Each dot in the figure represents an alternative optimized solution to attain the specified objectives through adjusting crop area, number of animal, amount of fertilizer and frequency of potato planting.

Adjusting crop areas and labour balance

The relationship between optimized solutions for labour balance and plot areas in scenario-2 varied based on crop types and cropping systems (Fig. 5). In most plots, the labour balance was negatively associated with the areas of mainly barley grown particularly in double-cropping (Figs 5a and b). Labour balance was also negatively associated with the areas of potato when it was double cropped with other crops signifying the social importance of potato intervention in reducing labour demand. Labour balance, however, was mostly weakly and positively associated with areas of potato and wheat in mono-cropping (Fig. 5c) and triticale (data not shown). Generally, mono-cropping had a positive association with labour balance for most crops. The labour balance was also strongly and positively associated with plot areas of grass and eucalyptus in almost all farms where they were grown (Fig. 5d).

Increasing the areas of plots with relatively less labour requirement played an important role in the optimization of labour balance. This was demonstrated by the positive association between eucalyptus and grass plots with labour balance. Based on the local practice, cultivation of eucalyptus requires less labour, which is mainly for land preparation and planting, whereas minimum labour input is required for grazing grass. Thus it appears that labour requirement of farms could be minimized by expanding the areas of primarily eucalyptus and grass. However, optimization of the labour balance was associated with reduction in OM balance which might be due to the removal of OM from the farms through the biomasses of mainly eucalyptus and to some extent grass. Moreover, increasing the area of grass plots might not be practical due to land scarcity and its negative association with operating profit. Therefore, it might be important to improve both labour and economic efficiencies of farms focusing on food crops that proved to contribute more to OM. One of such crops was barley, but increasing the areas of barley plots was associated with high labour demand in most farms. This suggests that threshing of barley using a machine did not bring significant reduction in the overall labour requirement for barley production for some farms. This in turn implies the presence of labour inefficiencies in other management practices which might include harvesting of barley by uprooting and weeding. In a previous study in Chencha, the labour and economic efficiencies of barley production were lower than for other crops (Waga, 2017). In addition, collecting weeds for animal feed in the fields of cereals (mainly barley) is a common practice in the area and this might require extra labour. Therefore, improving the method of harvesting of barley and feed management may also be crucial to improve the labour balance.

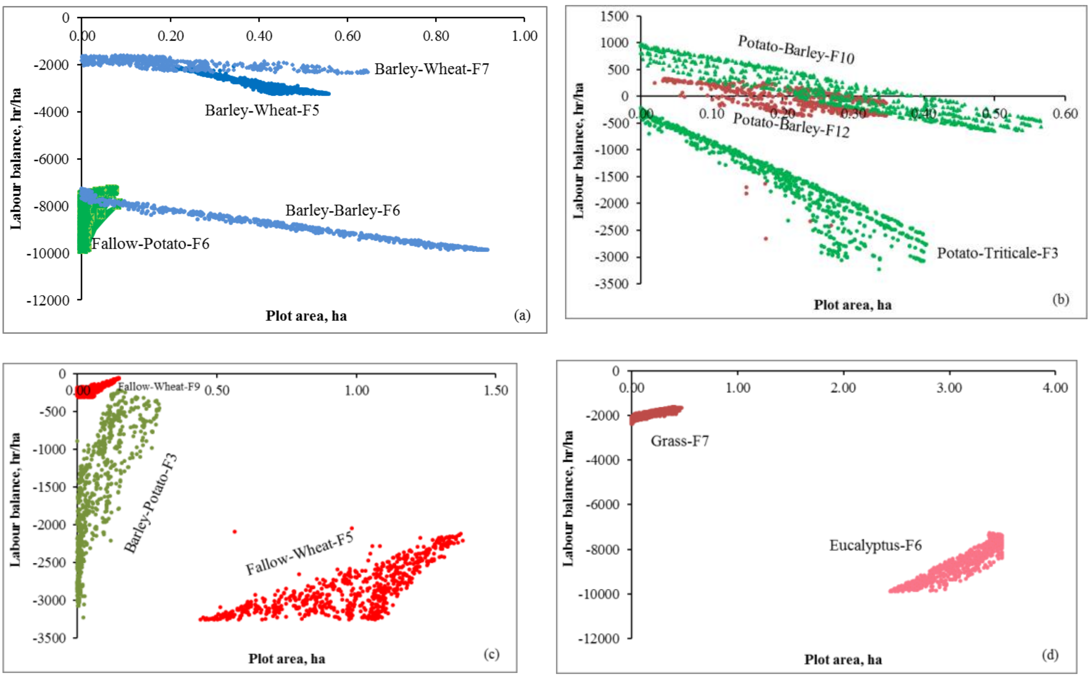

Figure 5. Relationship between crop area and optimized labour balance in scenario-2 across farms (F). Each dot in the figure represents an alternative optimized solution to attain the specified objectives through adjusting crop area, number of animal, amount of fertilizer and frequency of potato planting.

Adjusting crop areas and operating profit

Operating profit was negatively associated with the areas of barley (Figs 6a and b). It showed a weak and varied relationship with the areas of most potato plots across farms. However, it had a positive association with plot areas of potato particularly in a mono-cropping system and this shows the relative economic importance of potato which covers the largest portion of the land allotted for food crops. Operating profit had also strong and positive association with the areas of apple seedling, vegetables and eucalypts in the majority of the farms where they were grown (Figs 6c and d).The large variation in profit over plots might be partially related to the difference in the original management of crops and land across farms.

The positive association of plot areas of some crops with operating profit may be related to the productivity, input and product use of such crops. Eucalyptus requires less labour and fertilizer inputs and it gives a high-value product which is used mainly for sale. As a result, it has high labour and economic efficiency (Waga, 2017) and this might be a reason why eucalyptus plantations are expanding fast throughout the country. Matthies (2013) reported that the equivalent annual income of eucalyptus exceeds that of other crops. However, expanding the area of eucalyptus may not be practical due to land scarcity in Chencha. Moreover, eucalyptus is considered by the government as a threat for competing crop land and exhausting soil fertility and thus some regional states have banned eucalyptus tree planting on farm-lands (Jagger and Pender, 2000). Apple seedlings also require fewer inputs (including land) and the majority of its produce is used for sale. A small increase in an area of apple may generate high profit and may not have much effect on the overall OM balance on the farm. However, access to market may be a potential challenge for apple production. Although Chencha was known to be the major source for apple seedling in the country, currently there is less market for apple seedlings in the area which may be caused by the emerging competition among growers within and outside the district. Thus investigating the challenge and improving market access is essential.

The majority of the products of vegetables (cabbage, carrot and beet root) are used for sale and thus had positive association with operating profit. However, vegetables are currently grown in a small area per farm and may not generate adequate income to the household. But there is a possibility of increasing the areas of vegetables with proper soil fertility management to maintain OM balance as vegetables showed negative association with OM balance. In contrast, the negative association of operating profit with other crops might be related to the use of all or most of the products of these cops for home consumption. A good example is barley which was produced by the majority (67%) of the farms only for home use. This might be one reason why operating profit had negative relationship with the plot areas of barley in mono- or double-cropping with other crops such as potato. Overall, the positive association of operating profit with the plot areas of several crops shows that there are many options to improve the operating profit. However, most of the crops were associated with a negative OM balance and this means that optimized crop management is conditional on proper soil management practices being in place. Alternatively, augmenting off-farm income generating activities could play a role in improving profit.

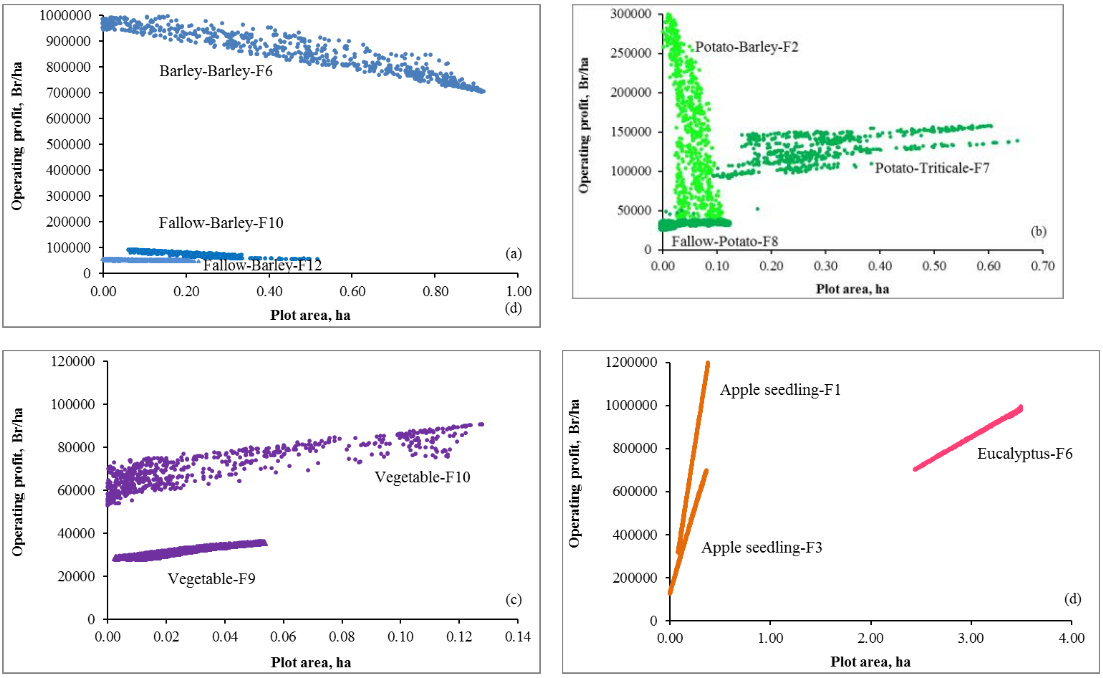

Figure 6. Relationship between crop area and optimized operating profit in scenario-2 across farms (F). Each dot in the figure represents an alternative optimized solution to attain the specified objectives through adjusting crop area, number of animal, amount of fertilizer and frequency of potato planting.

Improved FYM storage on N loss

Improved storage of FYM reduced the amount of N loss in all farms (Fig. 7). The reduction in N loss between the current and introduced improved storage methods ranged from 4 to 16 kgha^{-1}year^{-1} equating to 26 to 32%. The relative reduction in N loss was weakly and positively correlated with the total amount of FYM used per farm. Similarly, N loss was weakly associated with wealth status and gender of the farm owners.

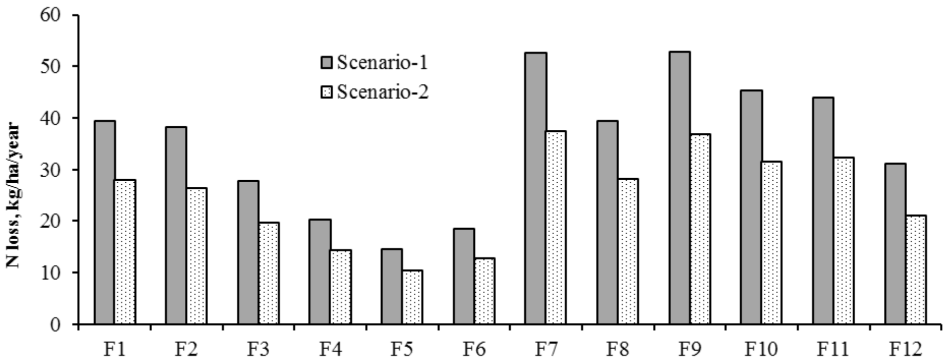

Figure 7.Comparison of estimated N loss through volatilization from FYM with the current (scenario-1) and improved (scenario-2) storage method across farms.

Other management practices

On the majority of farms, other management practices had only weak associations with the objective variables with the exception of the amount of fresh grass to feed to animals (data not shown), which had a relatively strong positive relationship with the organic matter balance and negative relationship with the operating profit on some farms.

Sources of improvement for optimization

Our scenario analyses consider two sources of improvement in the exploration. The first one is management optimization within the current farm resources, which was demonstrated by the wide variation between the mean optimized solutions and the original values of the three objective variables in scenario-1. The wide variation indicates the possibility and the extent of improvement that can be made in each farm by redesigning the current farm management within the current resources. However, the scale of the potential improvements varied across farms, and may be associated to certain farm characteristics for each objective. The percent improvement in OM balance was related to the original OM balance and the total areas of the farms. Therefore, the improvement was relatively large for farms having a low original OM balance and a large area. Farms of most of the wealthier households were low in OM balance and this might be related to the tendency that such households use more inorganic than organic fertilizer for crop production (Mazengia *et al.*,2015). Moreover, the farms of most of the rich households were relatively large and might be constrained with insufficient organic material to cover the whole farm. Similarly, the improvement in labour balance was high for farms originally having high ratio of family labour and farm size suggesting that such farms had low original labour use efficiencies which were the characteristics of most of the farms of households of low to medium wealth (Waga, 2017). On the other hand, the improvement made in operating profit had no clear relationship with farms although there was a tendency that farms with low original profit had relatively high improvement indicating that farms of relatively most rich households were already optimized.

The second source of improvement is through using improved resources or practices. This is the improvement made as a result of intervention or introducing improved farm practices and technology. It is the difference between the original values of the three objectives in scenario-2and scenarios-1. The percent improvement in OM balance, arising from these improved technologies, was low and had no significant variation across farms. In scenario 2, inorganic fertilizers were used to amend soil fertility and thus might not have significant effect in changing the OM balance. The use of machine thresher for cereals was the only introduced practice used to improve the labour balance. Therefore, the variation in improvement across farms could be partly associated with the proportion of cereals in each farm. Similarly, farms with a high proportion of introduced technologies had a relatively high percentage of improvement in operating profit. Generally, the improvements made on the three objectives using this method were relatively low suggesting that use of improved practices/technologies with the current farm configuration alone cannot bring enough change and reconfiguring the farms is essential to further maximize benefits.

Finally, we considered the potential of ‘double optimization’ in scenario two, i.e. the combined effects of Improved Technologies and subsequent Optimized Management. In this scenario, the scope for improvements, quantified as the difference between the mean optimized values in Scenario 2 and the original values, was quite high compared to the improvements made by Optimized Management or Improved Technologies in isolation. This suggests that combined use of improved technologies and reconfiguring farm structure is indispensable to maximize benefits. However, the scale of the improvements varied across farms, for the same reason as those described in the above two sources of improvement.

In conclusion, the current study revealed that the farm operating profit, labour balance and organic matter balance were not yet optimized with the current farm configurations of all farms. It also showed that there is ample scope to improve and simultaneously optimize both the economic, social and environmental sustainability (as indicated by the organic matter balance, labour balance and operating profit) for each farm. Improvements could either be achieved through optimization of management within current farm resources, or through using improved technologies. However, the highest improvement could be made through optimization combination of management optimization and improved technologies. Depending on the management practices used per farm, the solutions for each objective can either be antagonistic or synergetic. The major important factor that influenced the optimization was the cropping plan, which might be associated with the management practices applied for a particular crop. However, adjusting areas of crops and implementation of some other optimized solutions may be difficult for individual farmers and requires advice through agricultural extension programmes. Therefore the following may be considered to enhance the practical implementations of solutions for the three objectives: 1) Although eucalyptus played an important role in improving profit and labour balance, its expansion might not be practical with the current land scarcity and for it exhausts organic matter unless proper land use is in place.2) The current soil fertility management and straw use of barley improves the OM balance and this role of barley might be sustainable if the current productivity and labour efficiencies of barley are improved. 3) The implementations of most of the optimized solutions will be practical if the current labour use and economic efficiencies of production are improved. 4) Expansions of the areas of apple seedling and vegetables with proper soil fertility management practices can play an important role in improving income if access to market is facilitated.

The district Office of Agriculture of Chencha, supported by research institutions, has been working on multisector extension service to improve the livelihoods of the farming communities. The following considerations may accelerate the ongoing development work in the district, by creating awareness on:1) the pros and cons of optimizing the cropping plan and their management practices from the perspective of improving OM, labour requirement and profit; 2) planting eucalyptus where it is not suitable for other crops or where it has less competitive impact on crops; 3) the role of using crop straws for animal bedding and feed in improving organic matter and the disadvantages of burning crop residues; 4) improving the storage of FYM using plastic cover; 5) the distribution of FYM across different crops similar to barley plots; 6) strengthening the introduction of improved crop (food and feed) varieties with their improved management practices; 7) in collaboration with cooperatives and NGOs, facilitate introduction of small threshing machineries and easy methods for harvesting of cereals; 8) improving market access for vegetables and apple seedlings; 9) introducing or strengthening different off-farm income generating activities that do not require much land.Moreover, research institutes need to determine economic and labour efficient management practices for crop production and evaluate and adapt threshing machineries to the local situation. Based on the major change in the farming system, re-exploration using updated tools is important.

Acknowledgements

This study was financially and technically supported by the Wageningen University and Research Centre, the Teagasc Walsh Fellowships Programme and Vita.

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