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How do climbing beans fit in farming systems of the eastern highlands of Uganda? Understanding opportunities and constraints at farm level

E. Ronner[a,*], K. Descheemaeker[a], W. Marinus[a], C.J.M. Almekinders[b], P. Ebanyat[c], K.E. Giller[a]

[a] Plant Production Systems, Wageningen University, P.O. Box 430, 6700, AK, Wageningen, the Netherlands
[b] Knowledge, Technology and Innovation, Wageningen University, P.O. Box 8130, 6700, EW, Wageningen, the Netherlands
[c] International Institute of Tropical Agriculture, P.O. Box 7878, Kampala, Uganda

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ABSTRACT

Climbing beans offer potential for sustainable intensification in the East-African highlands, but their introduction requires a major change in the cropping system compared with the commonly grown bush bean. We explored farm-level opportunities, constraints and trade-offs for climbing bean cultivation in the eastern highlands of Uganda. We established current food self-sufficiency, income, investment costs and labour, and assessed the *ex-ante*, farm-level impact of four climbing bean options on these indicators. Input for this assessment were a detailed characterization of 16 farms of four types, and on-farm, experimental data of adaptation trials of climbing bean. Climbing beans generally improved food self-sufficiency and income, but often required increased financial investment and always demanded more labour than current farm configurations. Opportunities for integration of climbing beans on small farms were limited. Although some of the poorest farmers accrued the largest absolute benefits from climbing beans, their ability to make the necessary investments is questionable. The analysis was translated into a simple-to-use modelling tool to enable participatory analysis of the outcomes with farmers of the four farm types to understand their perspectives and decision-making. The discussions revealed a recent increase in market prices for climbing bean resulting in growing interest in their cultivation in the eastern highlands. A lack of seed and stakes was limiting climbing bean cultivation, and a sufficient amount of climbing bean seed needs to be ensured through strengthening of farmer cooperatives and improved storage.

1. Introduction

Common bean (*Phaseolus vulgaris* L.) is an important staple crop in the East African highlands providing an important source of protein, calories, minerals and vitamins. While bush varieties have been widely grown in the region for centuries, climbing bean varieties were introduced through a targeted breeding programme in Rwanda since the mid-1980s (Franke et al., 2016; Sperling and Muyaneza, 1995). Climbing beans have a better yield potential (up to 4 to 5 tons ha^{-1}), produce more biomass and fix more nitrogen than bush beans (Bliss, 1993; Ramaekers et al., 2013; Wortmann, 2001). Especially in areas of high population pressure and small farm sizes, climbing beans offer great potential for agricultural intensification (Katungi et al., 2018). In southwestern Uganda, just across the border with Rwanda, climbing beans have now largely replaced bush beans. In eastern Uganda, on the slopes of Mount Elgon, cultivation is less widespread (Ronner et al., 2018).

Compared with bush beans, climbing beans require a major change in cropping system: bush beans are mostly grown in intercropping with maize, but climbing beans have a more prolific growth and smother the maize when planted at the same time (unlike at cooler, high elevations in Latin America, where maize and climbing bean intercropping is common (Clark and Francis, 1985; Davis and Garcia, 1983)). Climbing beans are therefore better grown as sole crops, which means that, in land-scarce areas, they are likely to replace existing crops. Climbing beans also need to be staked, requiring additional labour and capital (Musoni et al., 2014; Ruganzu et al., 2014; Sperling and Muyaneza, 1995). Such disadvantages may provide constraints for farmers when climbing beans are first introduced.

At field level and in terms of agronomic criteria, the benefits of climbing bean over bush bean are clear and the potential of climbing beans has been evaluated in on-farm trials (Franke et al., 2016; Ronner et al., 2018). At farm level, considering the potential replacement of existing crops and criteria other than yield (economic benefits, costs, labour), the comparison may lead to different insights (cf. Sperling and Muyaneza, 1995). Moreover, given the heterogeneity of African smallholders (Giller et al., 2011), advantages and disadvantages of climbing bean cultivation are likely to differ between farms, but this

* Corresponding author.
E-mail address: esther.ronner@wur.nl (E. Ronner).

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diversity has not been studied. By capturing farm diversity, typologies help to disaggregate impacts and opportunities for different types of farmers (Descheemaeker et al., 2016; Franke et al., 2014; Tittonell et al., 2010). A farm-level, multiple criteria exploration could therefore offer insight in the opportunities and trade-offs of climbing bean cultivation for a diversity of farmers.

Discussing the outcomes of such explorations with farmers provides quantitative feedback to farmers about their farming system, and enriches researchers' insights in farmers' priorities and constraints (Defoer, 2002; Falconnier et al., 2017). While researchers may focus on advantages in yields or costs and benefits of a particular crop, farmers may have different priorities based on the allocation of resources over multiple crops on their farm and off-farm activities (Collinson, 2001). An *ex-ante* assessment of which farmers are likely to benefit and how priorities at farm level might hinder or foster climbing bean cultivation could inform rural development projects that aim to expand climbing bean cultivation to new areas.

The objective of this study was to identify farm level opportunities, constraints and trade-offs for climbing bean cultivation among smallholder farmers in eastern Uganda with an *ex-ante* impact assessment tool. Based on a detailed farm characterization we established farmers' current situation in terms of the farm-level indicators food self-sufficiency, income, investment costs and labour. We analysed the effects of four different options for the integration of climbing beans on these indicators. The outcomes of this analysis were discussed with farmers, to understand their priorities, constraints and decision making with respect to climbing bean cultivation. We hypothesized that sole cropping of climbing beans with wooden stakes would provide the largest increase in food self-sufficiency and income, but also the largest trade-offs in terms of investment costs and labour, and that this would therefore not be the most preferred option among farmers.

2. Methodology

2.1. Study area and climbing bean dissemination

The study was conducted in Kapchorwa District (Fig. 1), located on the northern side of Mt. Elgon between 34.30° and 34.55° East and 1.18° and 1.50° North at an elevation of 1500 to 2200 m above sea level (masl). The district can be divided in an "upper" and "lower belt", with the tarmac road situated around 1900 masl as a rough divide. Annual rainfall in the district averages 1600 mm and falls over two seasons: a long season from March to July (Season A) and a shorter season from September to December (Season B). Nitisols are the dominant soil type.

A climbing bean dissemination campaign started in 2013 in two sub-counties of Kapchorwa (Kapchesombe and Kaptanya) where climbing beans were new to many farmers. Improved varieties of climbing beans were planted with manure, phosphorus fertilizer and best management practices (row planting, plant and staking density, weeding) in small demonstrations on farmers' fields. In 2014, the campaign extended to two other sub-counties, Tegeres and Chema. Here, climbing bean cultivation was more common, but with local varieties and largely without mineral fertilizer or manure. The dissemination approach now changed to parish-level demonstrations on visible locations, in combination with numerous farmers trying out technologies in so-called adaptation trials (Ronner et al., 2018).

2.2. Rapid and detailed farm characterization

The study was conducted in Chema sub-county in the first rainy season of 2014 (Season 2014A), just before the extension of the dissemination campaign to this sub-county. A rapid farm characterization survey was conducted in which 75 households were interviewed with questions on household size and composition, education, land and livestock ownership, production orientation, labour hired, sources of income, valuable goods owned, type of housing, food security and crops cultivated. Stratified random sampling was applied, whereby in each of the four parishes in the sub-county at least one village was selected (five villages in total). Households within the village ($n = 15$) were randomly selected. Four farm types were developed manually, based on distinguishing criteria that were also found to be important in earlier typology studies in East Africa (Franke et al., 2014; Tittonell et al., 2010; Tittonell et al., 2005), such as landholding, livestock ownership, type of housing, valuable assets, production orientation and most important sources of income. We focused on easy-to-measure, structural characteristics to allow development or extension agents to rapidly identify these farm types for the scaling of technologies. Resource persons (extension officer, chairman of cooperative, well informed farmers) confirmed that the typology represented farmer diversity (including the poorest and wealthiest) in the community.

A detailed farm characterization was carried out among a sub-selection of 16 households. Stratification was applied to farm type (four farmers per type were randomly selected), and to climbing bean cultivation: per farm type two farmers were selected who cultivated a relatively large area of climbing beans (sole cropping or climbing beans contributing > 30% in intercropping), and two farmers who cultivated no or a small area of climbing bean (intercropping with < 30% climbing bean).

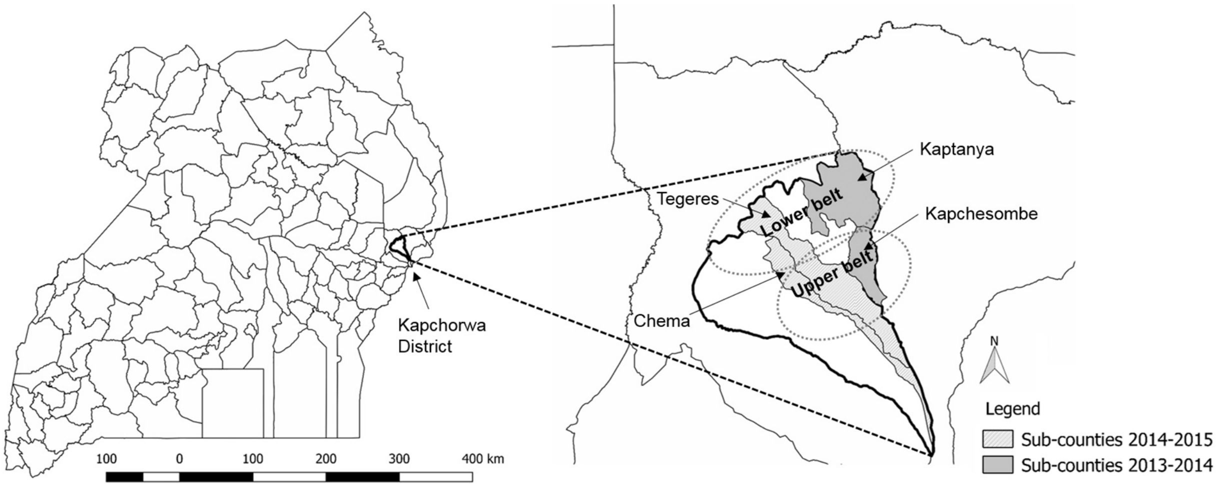


Fig. 1. Kapchorwa District with sub-counties included in the climbing bean dissemination campaign. Grey circles indicate the divide between the lower and upper belt within the district.

The detailed characterization consisted of four surveys, carried out during four visits. The first survey focused on the fields and crops on the farm. Households were asked to record yields for all their climbing bean fields. A cup and recording sheet were handed out to measure fresh bean consumption during the season, and sacks were handed out per field to store dry grains for later measurement. In the second survey, all cultivated fields of the farm were visited to record field history, topography and crop management. Fields were measured using a handheld GPS device, or manually if the field was too small. On climbing bean fields, measurements of stake density, stake length and number of plants per stake were taken on two quadrats of 2 × 2 m (one quadrat on smaller fields). Soil samples were taken from three to four fields per farm (composite samples at 0–20 cm depth) with the most common crops in the area, and from at least one climbing bean field if present. Collected soil samples were air-dried, sieved and ground, and analysed for pH (1:2.5 H_2O), organic carbon (Walkley & Black), total N (Kjeldahl), plant available-P (Mehlich III), Ca, Mg and K (Mehlich III) at the National Agricultural Research Laboratories in Kawanda, Uganda. The third survey contained questions on household income and expenditure and opportunities and constraints for climbing bean cultivation. The fourth survey was conducted at the end of the cropping season (Season 2014A) to assess yields. The climbing bean yield, collected by the farmer and air-dried, was weighed. For all other annual crops, farmers estimated the yield per field. Annual banana yields were assessed by asking for typical weekly yields at the moment of survey, and months in the year in which these yields were larger or smaller than that. Banana yields were reported as the number of bunches harvested per month. Bunch weight was estimated at 19 kg (Wairegi et al., 2009). For a detailed description of the methods and results of the characterization, see Marinus (2015).

2.3. Baseline and four options for climbing bean cultivation

For all 16 farmers in the detailed characterization, we assessed the *ex-ante* impact of four options for climbing bean introduction or expansion (Fig. 2). These options were compared with farmers' current situation based on the detailed characterization. In Option 1, climbing beans were intercropped in a banana/coffee garden (inter). In Option 2, climbing beans would be planted as relay-crop in a field of maize + bush bean intercropping (relay). Bush beans are harvested first. Maize cobs are harvested fresh and stalks are left in the field to serve as stakes for the climbing beans. Option 3 assumed that 50% of a maize + bush bean field was replaced with climbing bean sole cropping (replace). Option 4 represented a sole crop of climbing bean, grown with wooden stakes (sole). The four options were conceived to compare: common practices of farmers already growing climbing beans in the area (Options 1 (inter) and 2 (relay)); the cultivation of climbing beans versus maize and/or bush beans (Options 3 (replace) and 4 (sole)) and the use of different staking methods (Options 2 (relay) and 4 (sole)). For each option, we considered two scenarios: a “current management” scenario with current climbing bean yields, and a “best management” scenario with improved climbing bean yields through fertilizer use and improved management practices, based on results from climbing bean trials (See 2.4.1 for more detail).

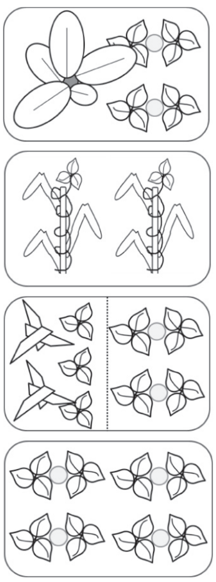
We assumed that each option was applied to all fields on the farm available for that option: in Option 1 (inter) climbing beans were grown on all current coffee and/or banana fields; in Options 2, 3 and 4 on all maize + bush bean intercropping fields. Option 1 (inter) could be applied by farmers in both seasons, Option 2 (relay) only in the second season and Option 3 (replace) only in the first season. To compare different staking materials (Option 2 (relay) versus Option 4 (sole)), we also assumed that Option 4 (sole) was applied only in the second season.

2.4. Data analysis

2.4.1. Data and assumptions for baseline and four options

The comparison between the baseline and the four options was based on food crops produced on the farm. Non-food crops (coffee) and livestock products were not included in the analysis, based on the assumption that decisions on the allocation of land, labour or capital would lead to trade-offs between different cropping activities, rather than with other livelihood activities. Crop yields per field were obtained from the detailed characterization. In case of missing data, the average yield for that crop among all farmers was used.

The four options were established with data from the adaptation trials, for which farmers received a package of seed of an improved climbing bean variety and fertilizer, together with information on best management practices (more detail in Ronner et al., 2018). Yields on farmers' own climbing bean plots planted next to the trial plots were recorded as well. This data set included a total of 235 farmers in Kapchorwa district in Seasons 2014B, 2015A and 2015B.



Option 1 (inter): climbing bean intercropping in banana/ coffee garden. Additive or replacement of bush bean in both the first and second season.

Option 2 (relay): relay cropping of climbing beans in a maize + bush bean field, whereby maize stalks serve as stakes. Additive or replacement of bush bean in the second season.

Option 3 (replace): climbing beans replace maize. Half of a maize + bush bean field is replaced with a sole crop of climbing bean in the first season.

Option 4 (sole): sole crop of climbing bean with wooden stakes. Climbing beans are additive or replace bush bean in the second season.

Fig. 2. Schematic representation and overview of four options for climbing bean cultivation in farming systems of the eastern highlands of Uganda considered in this study.

For the “current management” scenario, we assumed that farmers' current yields per field would give an indication of the quality of the field and the management capacities of the farmer. The climbing bean yield that could be achieved on a particular field was therefore related to the yield of the current crops (bush bean or maize + bush bean) on that field as reported in the detailed characterization. Only in case of missing yield data, average climbing bean yields were used.

Two different methods were used to relate current yields to climbing bean yields. In Option 1 (inter), the current percentage of bush bean in intercropping varied from 10% to 90% ground cover. We therefore considered it most realistic to multiply current bush bean yields (from the detailed characterization) with the average ratio of climbing bean and bush bean yields (found in the adaptation trials):

$$\textit{Current bush bean yield intercropping} \times \left(\frac{\textit{Average climbing bean yield intercropping}}{\textit{Average bush bean yield intercropping}}\right)$$

For Options 2 (relay), 3 (replace) and 4 (sole), we related current maize + bush bean yields per field to the best maize + bush bean yields (10% best yields, $n = 3$), both from the detailed characterization. This ratio was multiplied by the best climbing bean yields obtained in the adaptation trials (10% best yields, $n = 23$):

$$\left(\frac{\textit{Current maize + bush bean yield}}{10\%\textit{best maize + bush bean yield}}\right) \times 10\%\textit{best sole climbing bean yield}$$

In the “best management” scenario we assumed that all farmers would apply the best possible management, and climbing beans yields were therefore no longer related to current (maize +) bush bean yields. For this scenario, we only considered farmers who used TSP or DAP fertilizer in the adaptation trials and calculated their average (Option 1) or 10% best climbing bean yields (Options 2, 3 and 4).

2.4.2. Farm-level indicators

We assessed the effects of the four options for climbing bean cultivation on four farm-level indicators: food self-sufficiency, income, investment costs and labour requirements. Based on these indicators, we also calculated profit, income:cost ratios and returns to labour.

For food self-sufficiency, the yields of the crops produced on the farm were converted to kcal based on a food composition table for Uganda (Hotz et al., 2012). We considered average values for all crop varieties and most frequently used processing forms, resulting in an average of 114 kcal (per 100 g) for banana, 120 kcal for common bean (bush + climbing), 86 kcal for Irish potato and 244 kcal for maize. The total energy produced per farm was divided by the energy required by the household. We assumed that adults would need an average of 2250 kcal per day and children < 18 years 1850 kcal per day (FAO et al., 2001).

Prices of crops and fluctuations in these prices within and between years were obtained in the detailed characterization. The average price per crop (UGX per kg of produce) was calculated over all farms, and multiplied by the production of each crop per farm. Income was converted to US$ according to the prevailing rate in 2014 (1 US$ = 2600 UGX). The (gross) income per farm (costs not deducted) was related to the poverty line (1.90 US$ per hh member per day), and converted to Purchasing Power Parity (PPP) for Uganda (multiplied with a factor 1089, World Bank, 2015).

Prices and rates for seed and inputs (fertilizer, stakes) per crop were obtained in the detailed characterization and averaged over all farms to obtain investment costs for the current management scenario. For the best management scenario we assumed that in sole cropping, climbing bean seed was applied at a recommended rate of 50 kg ha^{-1}, stakes at density of 40,000 ha^{-1} and fertilizer at a rate of 15 kg P ha^{-1} (Kaizzi et al., 2012; Ronner et al., 2018). For the intercropping plots we assumed that farmers would use 75% of these rates. All rates were applied as an average across farms. We assumed that fertilizer was applied in the form of DAP, as this was the only available fertilizer blend containing P at the time of study. Labour was not included in the investment costs but treated separately. Investment costs were divided over the number of household members for better comparison with food self-sufficiency and income which were also related to household size.

A labour calendar was established for the three most important crops per farm. Labour requirements were reported per activity (land preparation, sowing, weeding, staking and harvest). These were added up to a total per crop (person days ha^{-1}) and multiplied by the estimated percentage ground cover of that crop to obtain a total requirement per field. For the best management scenario, we assumed that fertilizer was applied per planting hole and would require 12 days ha^{-1} (Van Heemst et al., 1981). Additional labour required for staking was obtained by multiplying the current labour for staking with a factor representing the difference between the current average staking density and the recommended staking density. Total labour requirements per farm were divided by the labour available in the household, as for all household members it was known in which months of the year they worked on the farm. Labour productivity was multiplied by a factor 0.5 for household members < 16 years.

2.4.3. Sensitivity analysis

We assessed the effects of variation in climbing bean yield and fluctuations in grain prices on the annual income from crops as percentage of poverty threshold. For each farm, we constructed four additional scenarios by varying the yields and prices of the current management scenario, and compared those with the baseline, current and best management scenarios:

- Poor and good yields. These yields were based on the observed variation in yield in the adaptation trials. Instead of the overall average, we took the average of the 50% lowest and 50% highest yields (Option 1 (inter)), and instead of the average of the 10% best, the average of the 25% and 5% best yields (Options 2 (relay), 3 (replace) and 4 (sole)).
- Poor and good climbing bean grain prices, obtained as the average highest and lowest prices in the detailed characterization.

The variation is presented as the cumulative probability of achieving a certain income with the different options. For simplicity, we assumed that each of the 16 farms represents an equal proportion of the population. Furthermore, we only varied the yields and prices of climbing beans, whereas in reality yields and prices of other crops would also differ.

2.5. Ex-ante impact assessment tool for participatory analysis of options

In 2017, the effects of the four options on the farm-level indicators were discussed with a sub-sample of the 16 farmers from the detailed characterization in Chema sub-county. For this purpose, we constructed a simple spreadsheet model to calculate food self-sufficiency, income, costs, profit and labour for each farm, and to explore the trade-offs associated with the different options. As the discussions took place three years after the detailed characterization, a first step was to update the model input with current household size, crops grown, field sizes and yield. The model output was translated into graphical representations of bags of grain, money (income and costs) and labour to ease the interpretation by farmers (Supplementary material, Fig. S1).

For the discussions, we selected two farmers per farm type (eight in total), of which seven could be retraced. In addition to the seven farmers, we selected eight farmers from Kapchesombe and Kaptanya sub-counties, where climbing beans were new for most farmers. These eight farmers had been part of a participatory wealth ranking in 2014, indicating their farming background and ability to invest in agriculture. We discussed the effects of the different options on the farm-level indicators with these 15 farmers individually. We first asked whether there had been major changes on their farm or in sources of income between 2014 and 2017, which confirmed that no adjustments in farm types were needed. Next, the model input was updated and one to three relevant options were discussed with each farmer. These options depended on whether the farmer already grew climbing beans, the current fields (maize + bush bean or banana/coffee fields), and farmers' own preferences for options. Indicators were discussed one by one, and farmers were asked to compare the baseline and the option per indicator. Next, farmers prioritized the indicators and mentioned constraints for the option. They also indicated which option they preferred. Finally, we discussed implications at farm level, in terms of the importance and contribution of different crops to the farm, diversification and risk spreading versus yield/income maximization and values of climbing beans such as their biomass production, rotational benefits and drought/rainfall tolerance.

2.6. Key informant interviews

We interviewed seven additional farmers individually as examples of “successful” climbing bean farmers. Most of these farmers grew climbing beans since the start of the climbing bean dissemination campaign, and were farmers who tried innovative staking methods, grew climbing beans in the dry season with irrigation or grew climbing beans on a large scale. These interviews were held to explore whether these farmers continued to grow climbing beans and in what way, what role climbing beans currently played in their livelihood, if they marketed the beans collectively and so on.

Two focus group discussions with key informants were held to enrich our understanding of trends in climbing bean cultivation since the start of the dissemination campaign; the availability of seeds, inputs and output markets; prices of inputs and outputs in 2017; changes in demand or volumes traded and the role that climbing beans could play in farming systems. Informants participating in the discussion were team members of the dissemination project, community based facilitators, agro-input dealers, local buyers, successful climbing bean farmers and chairmen of cooperatives.

3. Results

3.1. Farm and field characteristics

3.1.1. Farm types

Four farm types were distinguished to describe the diversity of households in Chema (Table 1). Farm types (FT) 1 and 2 were the wealthiest households based on resource endowment; the high resource endowed (HRE) farm types. FT3 and FT4 were the medium (MRE) and low (LRE) resource endowed households. Farmers in FT2 had the largest landholdings, and the sale of farm produce was their most important source of income. In terms of landholding and livestock ownership, FT1 was comparable to FT2 and FT3. The main source of income of FT1 however, was off-farm income from a salary, pension or remittances. FT1 and FT2 are therefore referred to as HRE – off-farm and HRE – farm respectively. LRE farmers mostly depended on income from casual labour off-farm and had some income from selling small amounts of farm produce. MRE farmers also sold farm produce and had additional income from small businesses or petty trade. Another specific characteristic was the ownership of fields in the lowlands (around 1400 masl), in addition to the fields closer to the homestead in the highlands (around 1700 masl). Ownership of lowland fields was highest for HRE – farm and lowest for LRE farmers. In comparison with the total population surveyed, MRE farmers represented the largest group (40%), followed by HRE – off-farm (25%), LRE (20%) and HRE – farm (15%).

3.1.2. Crop cultivation and field characteristics

The most commonly cultivated crops for all farm types in Season 2014A were banana, coffee, maize, bush bean, climbing bean, and Irish potato (HRE and MRE farmers only). Maize and banana were considered the most important crops, followed by bush bean and coffee. At the start of the study, climbing beans were therefore not considered of major importance to farmers. Despite this, 68% of the farmers (in the rapid characterization) grew climbing beans, on 28% of fields. Only 7% of the farmers growing climbing beans grew them as sole crop; the majority intercropped climbing beans with coffee, banana or other crops. Climbing beans in intercropping usually comprised < 30% ground cover.

Fields with climbing beans were smaller than average, both in sole and intercropping (Table 2). Fields with maize + bush bean were generally largest. These fields were located at lower elevation, further away from the homestead. Climbing beans intercropped in banana/coffee gardens were grown closest to the homestead, followed by coffee banana gardens with other or no intercrops, and sole climbing beans. Main soil fertility parameters did not differ among fields or farm types (Supplementary material, Table S1).

Common crop rotations were maize + bush bean intercropping in the first season, followed by sole bush bean in the second season (23% of fields) and maize + bush bean or Irish potato (on fields at higher elevation) in the first season of the next year. A few farmers grew maize every year, but left their land fallow in the second season (9%). In banana/coffee gardens, two consecutive seasons of bush bean were common (34% of fields). None of the farmers grew climbing beans in the second season; only bush bean or fallow were mentioned. The use of fertilizer was limited to fields with maize or Irish potato. Only one farmer applied DAP specifically to bush bean. Manure was only applied to banana/coffee gardens.

3.2. Climbing bean yields, prices, investment costs and labour for the four options

3.2.1. Climbing bean yields

Crop yields used to calculate the different options under current and best management are given in Table 3, with the variation in climbing bean yield in brackets. Climbing bean yields in intercropping represent different densities of climbing bean ground cover (30% climbing beans on average). For Option 2 (relay), we derived yields of climbing beans grown on maize stalks from a comparison of the measured yields of climbing beans on maize stalks and on wooden stakes in the adaptation trials. The yields of climbing beans planted with wooden stakes was 1200 kg ha^{-1}, with maize stalks 890 kg ha^{-1}. The relative difference (890 kg ha^{-1}/1200 kg ha^{-1} = factor 0.65) was applied as a yield penalty for the use of maize stalks in Option 2 (relay), compared with Options 3 (replace) and 4 (sole).

3.2.2. Prices, investment costs and labour

Prices for climbing bean were comparable to bush bean: 0.61 versus 0.64 US$ kg^{-1} in 2014. Climbing bean prices varied from 0.34 US$ kg^{-1} as lowest, to 0.91 US$ kg^{-1} as highest price. Prices for maize were 0.30 US$ kg^{-1}, for Irish potato 0.19 US$ kg^{-1}. Banana had an average price of 3.50 US$ per bunch.

Investment costs were only considered for the annual crops (not for banana). The information for Irish potato was insufficient to make a good comparison, so only climbing bean, bush bean and maize were compared (Table 4). Investment costs for climbing beans in the current management scenario consisted of seed and stakes. Different seeding and staking rates were found for sole and intercropped climbing bean fields, indicating that management of climbing beans in intercropping was generally poorer than in sole cropping (larger numbers of plants per stake). In general, seeding rates were larger than the recommended rate of 50 kg seed ha^{-1} (to compensate poor emergence) and the number of stakes smaller than the recommended 40,000 stakes ha^{-1}. The only investment cost considered for bush bean was seed. All farmers used hybrid maize seed, which is considerably more expensive than seed of bush or climbing beans. Fertilizer was used on half of all

Table 1
Farm types in Chema based on a rapid farm characterization survey (n = 75).

	Characteristics	Farm type 1 (HRE – off-farm)	Farm type 2 (HRE – farm)	Farm type 3 (MRE)	Farm type 4 (LRE)
	n	18	12	30	14
Resource endowment	Cultivated land*	0.4–2 ha	1.2–3.6 ha	0.4–1.2 ha	< 0.4 ha
	Type and number of livestock*	0–5 cows, 0–3 goats, 1–15 chickens	0–8 cows, 0–8 goats, 5–15 chickens	1–3 cows, 1–4 goats, 2–5 chickens	1 local cow[a] or 1 goat, 1–2 chickens
	Type of housing*	Iron sheet roofs, semi- permanent and permanent walls	Iron sheet roofs, semi-permanent walls	Iron sheet roofs, semi-permanent walls	Thatched or iron sheet roof, semi-permanent walls
	Valuable goods owned*	Ranging from only cell phone and radio to motor bike or car	Cell phone, radio, sofa and plough	Cell phone, radio and/or sofa	Max. one cell phone or radio
	Households hiring labour during the season	94%	83%	67%	53%
Household characteristics	Average age household head	44 (28–90)	50 (29–74)	43 (24–70)	39 (20–70)
	Education level household head	Most secondary, part primary and some university	Primary and secondary	Most secondary, part primary	Most primary, part secondary and some none
	Average months of food insecurity	2.4 (0–4)	1.1 (0–3)	2.0 (0–3)	2.3 (2–3)
Production orientation, sources of income	Type of crops (season 2014A)	Banana, coffee, bush bean 33% has lowland fields	Banana, coffee, bush bean 75% has lowland fields	Banana, coffee, bush bean 47% has lowland fields	Banana, coffee, bush bean No lowland fields
	Production orientation*	Most home consumption, part sold	Half sold, half for home consumption	Most home consumption, part sold	Mostly for home consumption
	Most important source of income*	Off-farm income most important (> 50%)	Farm produce most important, other source < 30%	Farm produce most important, some other source of income (0–50%)	Casual labour and some farm produce

Characteristics marked with "*" were used to construct farm types. Other characteristics were analysed to assess additional differences between farm types. Values shown between brackets are minimum and maximum values.

[a] FT1 only owned local cattle breeds whereas other farm types sometimes also owned improved breeds.

Table 2
Field size, elevation and distance to the homestead of fields with the most commonly cultivated crops in Chema.

Main crop	n	Field size (ha)	Elevation (masl)	Distance to homestead (m)[a]
Climbing bean intercropping	6	0.10	1801	280
Climbing bean sole cropping	4	0.11	1807	540
Banana/coffee	13	0.12	1819	340
Maize + bush bean[b]	16	0.40	1539	2580
Total/average	39	0.30	1723	990
P-values		< 0.001	< 0.001	< 0.001

[a] As the crow flies.
[b] Includes one field with Irish potato. Taken together as common rotation is maize and Irish potato on the same field.

maize fields. All farmers applied DAP in combination with either urea or CAN. Prices of urea and CAN were comparable.

Farmers' estimated labour requirements for climbing bean were much larger than for maize + bush bean fields (Table 5). Not only staking and harvest required more labour, but also land preparation, sowing and weeding. Estimates differed considerably for crops grown on small and large fields, however, reflecting economies of scale. To simplify comparisons among crops, median labour requirements were allocated across all options, irrespective of field size. This median may underestimate labour costs on the generally smaller fields in Option 1 (inter), and overestimate them on the larger fields in the other options.

3.3. Effect of the four options on farm level indicators

3.3.1. Food self-sufficiency

In the baseline, three of the HRE – off-farm and LRE households were not food self-sufficient (Fig. 3A). HRE – farm and MRE households were generally most food self-sufficient. Banana and maize contributed most to food self-sufficiency, the contribution of climbing beans was small. Under current management, food self-sufficiency increased in all options, except Option 3 (replace). As maize yields more than climbing bean, both in terms of kg of produce and calorific value, replacing 50% of the maize + bush bean field with climbing beans reduced food self-sufficiency. In Option 1 (inter) the increase in food self-sufficiency was modest, as banana/coffee fields were generally small. Option 4 (sole) provided the largest increase in food self-sufficiency, because of the larger sizes of maize + bush bean fields and because of the 65% reduction in yields in Option 2 (relay) resulting from the use of maize stalks. Under best management, the increase in food self-sufficiency of Option 1 (inter) remained modest, but in the other options climbing beans gained a much larger share of the total produce. Food self-sufficiency also increased in this scenario for most farms in Option 3 (replace) compared with the baseline.

3.3.2. Income

The price differences between crops resulted in a different picture for income than for food self-sufficiency (Fig. 3B). Banana still contributed an important share of the total income, but bush and climbing beans were relatively more important than maize for income compared with food self-sufficiency. In the baseline, a few HRE – farm and MRE farms had an income from cropping larger than the poverty threshold (NB: gross income; costs not deducted). With current management, income increased in all options. The increase in Option 3 (replace) resulted from the better price for climbing bean than for maize, which compensated for the loss in kg of produce. In Option 1 (inter), the increase in income was again modest, with the exception of a few farms. These farms had a considerable share of their farm under banana/coffee, and the better yields for climbing beans compared with bush beans caused a large increase. On average, the gross income obtained from climbing beans was 100 to 450 US$ per farm in options 1 (inter) and 4 (sole) respectively. From maize, this was about 340 US$. Income from coffee, the most important cash crop in the area, averaged 350 US$ per farm and off-farm activities contributed almost 1000 US$ (data not presented). Under best management, in Option 4 (sole) 11 out of the 16 farms could earn an income from farming larger than the poverty threshold. Also in the other three options, climbing beans gained an important share of the total farm income, up to half of the total income from cropping.

3.3.3. Investment costs

For the baseline, investment costs for maize were often about three times as high as investment costs for bush bean (Fig. 4A). Investment costs for climbing bean ranged from 4 to 55 US$ per household member, for bush bean from 2 to 30 US$. With Option 1 (inter) under current management, investment costs increased considerably, even though field sizes in intercropping were generally small. The contribution of staking to the total costs becomes visible through the comparison with Option 2 (relay). In this option, the additional investment in climbing bean remained relatively small and comparable to the total investment in bush bean. Option 3 (replace), where investment costs generally decreased, indicated that investment costs for the same piece of land were smaller for climbing bean than for maize. However, farmers who did not apply fertilizer on their maize had relatively small costs and increased their investment costs with climbing beans because of the cost of staking. The increase in investment costs was largest for Option 4 (sole), as field sizes were generally larger than for Option 1 (inter), and farmers would have to make a considerable investment in stakes compared with Option 2 (relay). The costs for climbing beans in Option 4 (sole) contributed up to half of the investment costs, and increased to up to 140 US$ per household member. Under best management, investment costs remained moderate for Option 2 (relay). With Option 3 (replace), costs were larger than in the baseline. In Option 4 (sole), costs for climbing beans rose to over 200 US$ per household member.

Table 3
Crop yields (kg ha^{-1}) used for the calculation of four options for climbing bean cultivation under current and best management in the eastern highlands of Uganda

	Grain yield (kg ha^{-1})			Data source	Comment
	Option 1 (inter)	Option 2 (relay)	Option 3 (replace) & 4 (sole)		
Current management[a]	815 (285–1015)	3000 (1015–4270)*0.65	3000 (1015–4270)	Adaptation trials	Measured
Best management[b]	1620	5000*0.65	5000	Adaptation trials	Measured
Bush bean	400	–	–	Adaptation trials	Farmer reported
Maize + bush bean	–	–	2570	Detailed characterization	Farmer reported

Climbing bean yields in brackets indicate the average 50% poorest and 50% best yields (Option 1) and 25% and 5% best yields (Options 2, 3 and 4) as measure of variation.
[a] Figures presented in table related to current yields on farmers' fields.
[b] Figures presented in table applied across all fields, unrelated to current yields on that field.

Table 4
Inputs, rates and prices used for the calculation of investment costs for four options for climbing bean cultivation under current and best management in the eastern highlands of Uganda.

Crop	Input	Unit	Rate (unit ha^{-1})	Price per unit (USD)
Climbing bean (current management)	Seed (sole cropping)	kg	75	0.85
	Seed (intercropping)	kg	100	0.85
	Stakes (sole cropping)[a]	stake	27,850	0.04
	Stakes (intercropping)[a]	stake	22,500	0.04
Climbing bean (best management)	Seed (sole cropping)	kg	50	0.85
	Seed (intercropping)	kg	38	0.85
	Stakes (sole cropping)[a]	stake	40,000	0.04
	Stakes (intercropping)[a]	stake	30,000	0.04
	Fertilizer (DAP)	kg	75	0.91
	Fertilizer (DAP)	kg	56	0.91
Bush bean	Seed	kg	80	0.67
Maize	Hybrid seed	kg	22	2.44
	Fertilizer (DAP + Urea/CAN)	kg	143	1.75

[a] Stakes were generally used for four seasons, so total staking costs were divided by four.

Table 5
Median labour requirements (person days ha^{-1}) for farm operations and total labour requirements per season per crop.

	n	LP	SO	ST	W1	W2	W3	W4	HA	Total
Climbing bean	11	129	70	122	83	71			122	596
Maize + bush bean	11	32	37		44	44			59	216
Bush bean	4	125	148		117	109			63	561
Maize	3	160	80		160	160			84	644
Banana	15				114	116	117	121		468
Irish potato	1	319	53		106	106			266	850

LP = land preparation, SO = sowing, ST = staking, W1–4 = weeding 1–4, HA = harvest.

3.3.4. Labour

In the baseline, all but one of the farms had sufficient household labour to cover annual requirements (Fig. 4B). Maize and bush bean generally required the largest share of labour. For Option 1 (inter) under current management, the additional labour requirement for climbing beans was small and comparable with bush bean. With Option 2 (relay), the labour required for staking was deducted from the total, as stakes were already in the field. Nevertheless, climbing bean labour requirements increased to about 50% of the total labour because climbing beans were additive on most farms in this option. The labour demand for Option 3 (replace) was larger than in the baseline, which reflects the large difference in labour on maize + bush bean and climbing bean fields (Table 5). Labour demands for Option 4 (sole) were largest. With this option, five farms exceeded their annual household labour availability. These farms would have to hire labour to

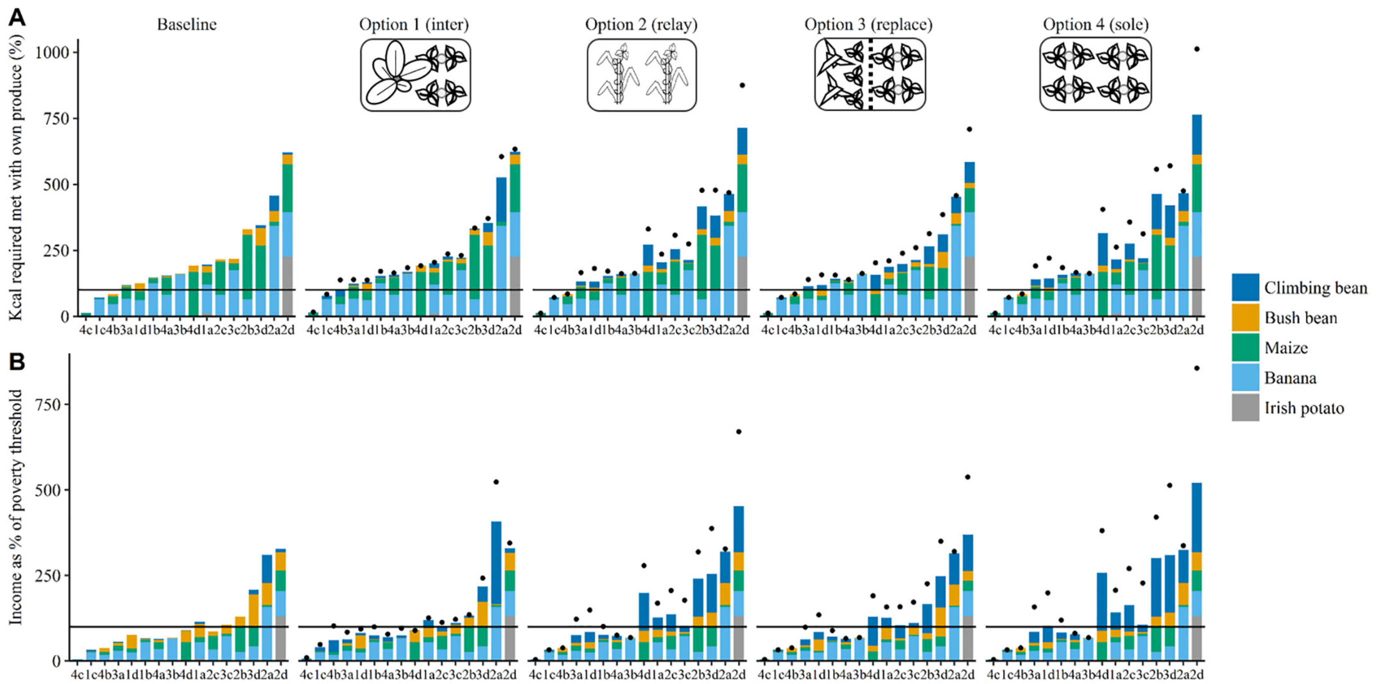


Fig. 3. A&B: Effects of four options for climbing bean cultivation on food self-sufficiency (annual kcal required by household divided by kcal supplied by crops from farm (%)) (A) and annual income from crops as percentage of poverty threshold (1.90 US$ in purchasing power parity per household member per day) (B) under current management. Black dots per option show effects under best management. Numbers on the x-axis represent Farm types 1 (HRE – off-farm), 2 (HRE – farm), 3 (MRE) and 4 (LRE), letters a-d the four farms within the type. Farms in all graphs are ordered from least to most food self-sufficient in the baseline.

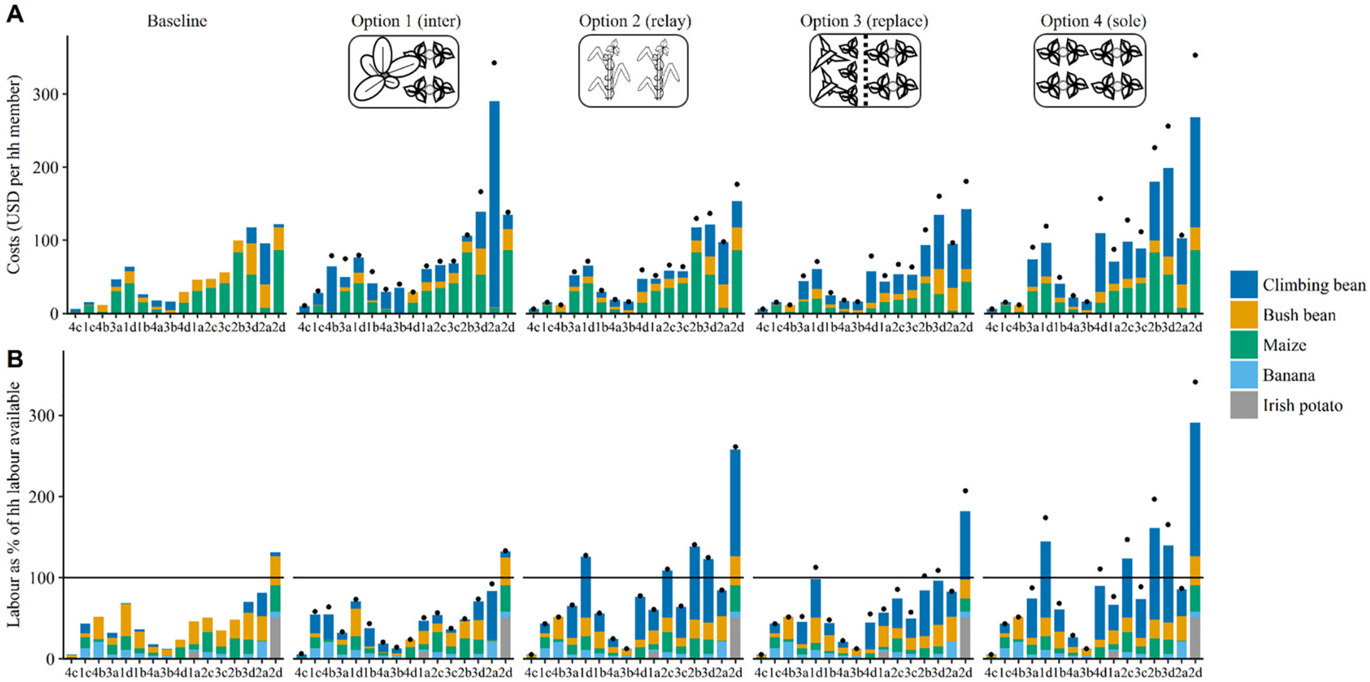


Fig. 4. A&B: Effects of four options for climbing bean cultivation on annual investment costs for climbing bean, bush bean and maize (USD per household member) (A) and annual labour requirements per crop as % of total labour available in the household (B) under current management. Black dots per option show effects under best management. Numbers on the x-axis represent Farm types 1 (HRE – off-farm), 2 (HRE – farm), 3 (MRE) and 4 (LRE), letters a-d the four farms within the type. Farms in all graphs are ordered from least to most food self-sufficient in the baseline.

meet the additional demand. However, as labour requirements for climbing bean coincide with land preparation, sowing and weeding of maize and bush bean (Supplementary material, Table S2), many more households would have to hire labour during these seasonal labour peaks (which also shows from Table 1). Under best management, the increase in labour for Option 2 (relay) was barely noticeable, considering the modest additional labour for fertilizer application. The labour required for staking increased considerably in Options 3 (replace) and 4 (sole), and labour for climbing beans went up to a third of the total labour requirement on some farms.

3.3.5. *Profit, income: cost ratio and returns to labour*

The average income that could be obtained from one ha of climbing beans was larger than from one ha of (maize +) bush bean in all options under current and best management (Table 6). The average costs for climbing beans were also (considerably) larger, however, meaning that the benefits from climbing beans can only be realized when farmers are able to make the necessary investment. If farmers could afford the investment, all options resulted in a larger profit than (maize +) bush bean cultivation. The income:cost ratios for climbing beans were, however, not always more favourable than for (maize +) bush bean – see Option 1 (inter) and Option 4 (sole). This is especially the result of the small investment costs for bush bean, consisting of seed only. Returns to labour were larger for climbing bean cultivation than for (maize +) bush bean in Option 1 (inter) and Option 4 (sole), but smaller for Option 2 (relay) and especially Option 3 (replace) under current management. Maize + bush bean cultivation had more favourable returns to labour than any of the climbing bean options under current management, which could explain its popularity. With climbing beans under best management, returns to labour were comparable or larger than maize + bush bean for all options except Option 1 (inter).

3.4. *Opportunities and trade-offs: which farmers benefit most?*

The quantitative analysis of the four options showed that climbing bean cultivation generally improved food self-sufficiency, income and profit, but often at the expense of larger investment costs and always with a larger labour demand (Fig. 5). An exception was Option 3

Table 6
Average seasonal income, cost, profit (USD ha^{-1}), income:cost ratio and returns to labour (USD day^{-1}) for four options for climbing bean cultivation under current and best management, and comparison with (maize +) bush bean cultivation in the eastern highlands of Uganda.

	Average income (USD ha^{-1})	Average cost (USD ha^{-1})	Profit (USD ha^{-1})	Income:cost Ratio	Returns to labour (USD day^{-1})
Baseline: bush bean intercropping	279	54	225	5.2	0.5
Option 1 (inter) – current	558	282	276	2.0	0.9
Option 1 (inter) – best	988	342	646	2.9	1.7
Baseline: bush bean sole cropping	458	54	404	8.5	2.1
Option 2 (relay) – current	868	64	804	13.5	1.8
Option 2 (relay) – best	1981	103	1878	19.3	4.1
Baseline: maize + bush bean	888	241	647	3.7	4.1
Option 3 (replace) – current	1300	303	997	4.3	3.2
Option 3 (replace) – best	2157	400	1757	5.4	5.3
Baseline: bush bean sole cropping	458	54	404	8.5	2.1
Option 4 (sole) – current	1336	293	1043	4.6	2.2
Option 4 (sole) – best	3050	457	2593	6.7	5.1

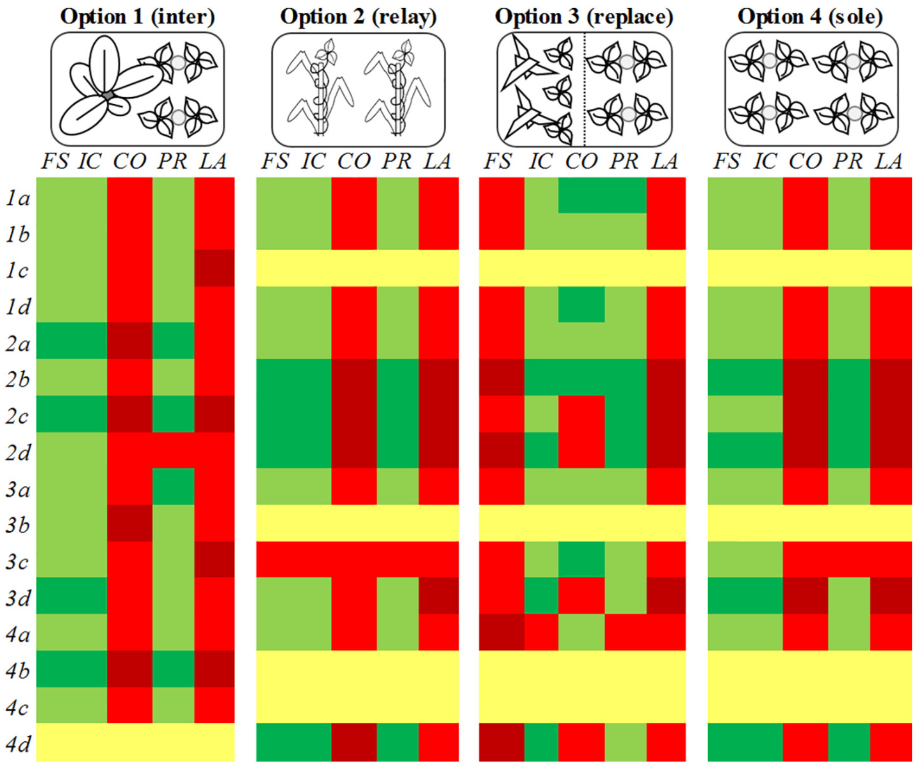


Fig. 5. Positive (green) and negative (red) effects of four options for climbing bean cultivation on food self-sufficiency (FS), income (IC), costs (CO), profit (PR) and labour (LA) at farm level. The four farms with the largest absolute advantage (dark green) and disadvantage (dark red) are highlighted. Yellow = no change. Numbers on the left represent Farm types 1 (HRE – off-farm), 2 (HRE – farm), 3 (MRE) and 4 (LRE), letters a-d the four farms within the type. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(replace): food self-sufficiency decreased, but income increased. Investment costs in this option were only larger for farmers who did not use fertilizer on their maize; their investment costs for maize + bush bean were relatively small and increased with costs required for climbing bean staking.

For LRE farmers, not all options were applicable: three out of four farmers had no banana/coffee or maize + bush bean fields. This is the result of their small farm sizes and number of fields. The opportunities for the integration of climbing beans on small farms were therefore limited, unless climbing beans replace a different crop. Despite this, some LRE farmers were among the four farms with the largest increases in food self-sufficiency, income and profit. The other farms with large increases were mostly from HRE – farm, because of the large farm sizes. Yet, this also resulted in the greatest increase in investment costs and labour for this group. The picture for MRE farmers was more diverse: some farmers had increasing, some decreasing costs with Option 3 (replace). None of the HRE – off-farm households used fertilizer on their maize, so investment costs decreased in Option 3 (replace). For the HRE – off-farm group, climbing bean cultivation therefore provided the least trade-offs.

3.5. *Sensitivity analysis of climbing bean yields and prices*

Although farmers generally increased their income with the cultivation of climbing beans compared with the baseline, the benefits may be different with variations in climbing bean yields or output market prices. A sensitivity analysis showed that generally, differences between farms were larger than the effects of yield or price differences for individual farms (Fig. 6). For farmers with larger incomes the fluctuations resulted in greater variation, however, but largely in a positive sense and with low risks associated with poor yields or prices. Only in Option 3 (replace), poor climbing bean yields would result in a (modest) reduction in income compared with the baseline. As the income from climbing beans was relatively small in Option 1 (inter), the effects of yield or price differences were also small. In all options, the effect of improved management was larger than the effect of better market prices.

3.6. *Farmers' priorities, constraints and decision-making*

During the follow-up visits to discuss the four options with farmers in season 2017A, seven out of the 15 farmers that were interviewed grew climbing beans. Most of them were HRE – off-farm, HRE – farm and MRE farmers. Option 1 (inter) was the most popular in practice: six out of the seven farmers grew climbing beans intercropped with banana/coffee. All seven grew climbing beans on a relatively small piece of land because the availability of seed and stakes limited the area they could plant.

The use of maize stalks (Option 2 (relay)) was preferred by five out of the 12 farmers (40%) with whom this option was discussed. Most of these were MRE and LRE farmers and indicated that they knew wooden stakes would give a better yield, but could not afford to buy them. Option 2 (relay) was considered as a good start for climbing bean cultivation, as the use of wooden stakes could be expanded in subsequent seasons. The 60% farmers who preferred (and could afford) wooden stakes mostly mentioned the better yield and profit from wooden stakes, or practical constraints such as destruction of maize stalks by termites, the location of the maize field in the plains (too hot and dry for climbing beans in the second season), and the fact that in the common rotation of maize, beans and Irish potatoes, maize would not be available every year.

Based on the quantitative analysis, we assumed that the decrease in food self-sufficiency in Option 3 (replace) would make this option less attractive for LRE farmers who produced for home consumption, but interesting for market oriented farmers from HRE – farm. All ten farmers from different farm types with whom Option 3 (replace) was discussed, however, were interested in replacing their maize because of the better income from climbing bean. The reduction in food self-sufficiency did not matter to most: they were willing to buy maize. Most farmers did not produce enough maize for the whole year, or indicated that they sold their maize anyway because of poor storage facilities. In addition, cash crops were considered of great importance to provide income for school fees. An advantage of climbing beans was therefore also that climbing beans can be grown (and provide income) twice a year, in contrast to maize or coffee. The additional labour demand and

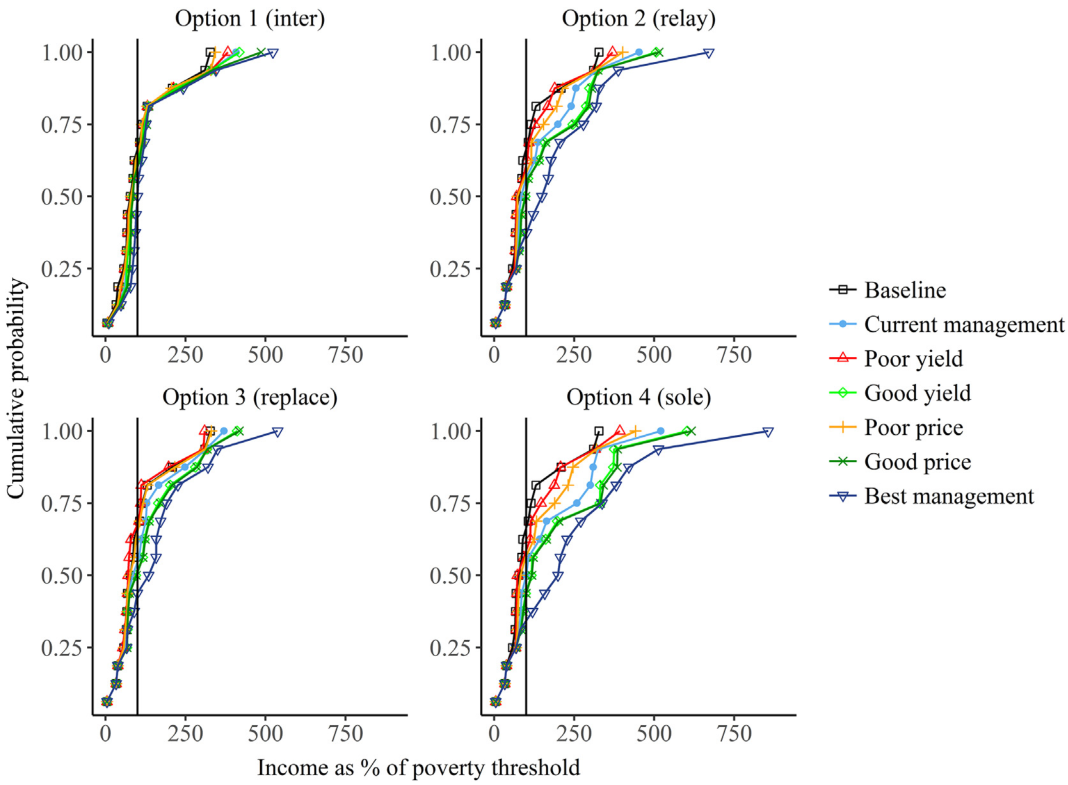


Fig. 6. Sensitivity analysis of the effects of variation in climbing bean yields and grain prices on the cumulative probability of a certain annual income from crops as percentage of poverty threshold (1.90 US$ in purchasing power parity per household member per day) for individual farms.

costs for staking were considered to be compensated by the larger profit (although Table 6 shows that for labour, this may not be the case).

Also in Option 4 (sole), farmers of all types pointed out that climbing beans would give a better yield, income and profit than bush bean, and that the additional costs and labour were worth the investment. However, two farmers who grew climbing beans on a large area (0.5 ha) during the detailed characterization indicated that they had not grown such large areas again, as the market prices for climbing beans were not good and they struggled to sell the beans. Interestingly, farmers indicated that the market demand for climbing beans had increased considerably in 2017 compared with 2014, resulting in a much better price for climbing bean (0.63 US$ kg^{-1}) than bush bean (0.15 US $ kg^{-1}) and maize (0.17 US$ kg^{-1}). The seed type of the climbing bean varieties had gained local popularity after people got used to them, and demand from Kampala also increased. Many farmers therefore indicated to be interested in an expansion of climbing bean production, replacing bush bean in the second season. The main constraint was a lack of seed. Only a few farmers still had small quantities of seed of the varieties distributed during the dissemination campaign, and people did not know where to get additional seed from. A better link to cooperatives focussing on climbing bean production was just established in 2017 and should help to address this problem. As Option 4 (sole) comprised climbing bean cultivation on a large scale (0.25 to 0.5 ha), farmers mentioned the need for stakes as disadvantage.

Next to better income and profit, other perceived advantages of climbing beans were their taste, cooking time, biomass production and soil fertility benefits. Most farmers were aware of these benefits, but did not grow climbing beans for this purpose. Despite these advantages, all farmers mentioned that they would still prefer to grow a variety of crops 'because that is what we eat'. In addition, the majority of farmers would not want to replace all of their bush bean with climbing bean because bush beans are early maturing and provide food during the hunger period in the middle of the growing season. Some also preferred the taste of bush bean varieties. Farmers did not perceive the larger investment costs for climbing bean than bush bean to be a risk. They pointed out that stakes – the largest share of the additional investment – can be re-used, so even with a harvest failure the loss would not be much more than for bush bean.

4. Discussion

4.1. How do climbing beans fit in farming systems in the eastern highlands of Uganda?

Option 1 (inter) was the most common current cultivation method for climbing beans in the eastern highlands of Uganda. Intercropping is a common practice in land constrained areas to optimize production (Lithourgidis et al., 2011; Willey, 1990). In combination with a lack of access to seed and capital required for staking this explains why climbing beans are grown on a small scale in home gardens. The lack of access to seed was especially problematic in Kapchesombe and Kaptanya sub-counties, where climbing beans were newest. Seed of climbing bean varieties was introduced through the dissemination campaign, but harvest failures and problems in storage (bruchid beetles) reduced the quantities of seed available (cf. David et al., 2002; Sperling and Loevinsohn, 1993). The better market prices for climbing beans in 2017 compared with 2014 enhanced farmers' interest in climbing beans, and with increasing production volumes more seed would be available in the system, facilitating informal seed sharing. Reducing damage of seed in stores through the use of multi-layered grain storage bags could also improve the availability of seed (Murdock and Baoua, 2014).

The lack of stakes is a constraint frequently heard for climbing bean cultivation (Musoni et al., 2014; Ruganzu et al., 2014), and particularly in eastern Uganda (Ronner et al., 2018). Farmers commented, however, that if climbing beans give a good profit they are willing to invest in them. With improved marketing opportunities this constraint may therefore diminish, as also seen in southwestern Uganda and Rwanda

(Sperling and Muyaneza, 1995). Moreover, despite attempts to introduce alternative staking materials (Musoni et al., 2014; Ronner et al., 2018), wooden stakes seem to be the easiest and least labour intensive method leading to the largest yields. Only maize stalks are an alternative staking material currently used by a reasonable number of farmers. Some farmers described the use of maize stalks (Option 2 (relay)) as a last resort option for poorer farmers, because costs are small but climbing bean yields are often reduced as well. However, with a hybrid maize variety and the use of fertilizer – particularly potassium (Li et al., 2012; Melis and Farina, 1984) – the maize could be strong enough to avoid lodging and minimize yield losses. Most farmers in the eastern highlands already use hybrids and fertilizer (although DAP and urea/CAN do not contain potassium), and the free source of staking material could be an additional incentive for adequate investments in fertilizer.

Farmers of all types were interested in Option 3 (replace) because of the relatively better prices for climbing bean compared with bush bean and maize. This finding shows how adoption and crop choices greatly depend on market opportunities (Hockett and Richardson, 2018; Ortega et al., 2016; Udoh and Kormawa, 2009). The decrease in maize yield and food self-sufficiency with this option was not considered problematic, which is in contrast to farmers' preference for maize over legumes, and food self-sufficiency versus income in other studies (Leonardo et al., 2015; Ortega et al., 2016). The preference for income can be explained by access to legume grain markets (relatively good in eastern Uganda), and the value that farmers in this study attached to cash income for school fees and to the poor storage facilities that forced people to sell maize. At a larger scale, the reduction in food self-sufficiency could mean that maize would have to be bought from other regions. It should also be noted, however, that a rotation of maize with climbing bean would enhance yields compared with continuous maize. After a legume, cereal yields in Africa were found to increase with an average of 0.49 t ha^{-1} compared with cereal yields after a cereal (Franke et al., 2018). If this average is applied across the farms in this study, the 50% loss in area of maize would be largely compensated in the subsequent season.

Option 4 (sole) showed the potential contribution of climbing beans to food self-sufficiency and income when grown as sole crop on relatively large fields. With the aforementioned increase in demand for climbing beans and good market prices, all farmers commented that this could be an attractive option. However, as the option would also require the largest increase in investment costs and labour, the extent to which farmers (especially MRE and LRE farmers) can afford this is questionable. In the discussions, farmers generally stated that they would be able to make these investments as long as the profit was good. Numerous studies have shown, however, that a lack of access to capital and labour are important constraints for adoption of agricultural innovations (Doss, 2006; Farrow et al., 2016; Feder and Umali, 1993). This implies that farmers may be ambitious but face constraints along the way and compromise on management, or that farmers' preferences and 'willingness to invest' are not necessarily good indicators for adoption (cf. Pircher et al., 2013; Waldman et al., 2014).

4.2. Putting food self-sufficiency and profit in context

In our assessment of food self-sufficiency we assumed that households would first use the produce from the crops on their farm for home consumption, and only then sell any surplus. This resulted in all but three households (80%) being food self-sufficient in the baseline. Table 1 shows that this assumption is a simplification of reality, as farmers indicated that they also sold crops due to urgent cash needs or because of storage problems. The 80% is also larger than the average found for Uganda in Wichern et al. (2017), but considering the fertile soils in Kapchorwa and the two cropping seasons per year this may be expected.

The average annual profit from climbing bean cultivation ranged from about 275 US$ per ha in Option 1 (inter) to 1040 US$ per ha in Option 4 (sole) under current management. These figures are around the average profit of agricultural innovations of 558 US$ per ha per season found by Harris and Orr (2014). The latter study included costs for labour, however. If we value labour costs in this study (casual labour equated to 1.90 US$ per day in 2014), both climbing bean and bush bean cultivation would result in a loss (only maize + bush bean cultivation would have a profit of 200 US$ per ha). Compared with other studies (Franke et al., 2006; Van Heemst et al., 1981), the labour requirements in our study seem to be overestimated (by a factor 2 for maize + bush bean cultivation), probably because of the small field sizes. If we assume that labour requirements for climbing beans are roughly 1.5 times the average for maize in Franke et al. (2006) and Van Heemst et al. (1981) – 162 days per ha – profitability would range from 60 to 750 US$ per ha in Options 1 (inter) and 4 (sole).

In the best management scenario, the average profit of climbing beans ranged from 650 to 2590 US$, far above the 558 US$ per ha per season reported by Harris and Orr (2014). Although some farmers in the area indeed achieved yields of 5 t ha^{-1} in the adaptation trials, such yields require capital investments in fertilizer (which was provided in the adaptation trials) and stakes, and labour investments in timely management operations. Considering the generally small yields of other crops, farmers are constrained in capital and labour and will probably choose for an optimal allocation of resources over all these crops (and off-farm activities) rather than maximum investments in one crop (Barrett et al., 2001; Collinson, 2001).

4.3. Added value of multi-criteria, farm level and participatory ex-ante impact assessment

Our *ex-ante* assessment of the impact of four options for climbing bean cultivation on multiple criteria clearly demonstrated the trade-offs associated with a change in farming system (Groot et al., 2012; Tittonell et al., 2007). If we compare climbing bean with bush bean based solely on yield, most would agree that climbing beans are a better option. However, relatively large additional investments (up to half of the total investment or labour in farming) need to be made before such benefits can be realized. Given irregular patterns of production and income, people often face major challenges in matching income to be accrued in future with current investment needs in inputs or labour (Dorward et al., 2009).

The identification of such trade-offs also shows the relevance of an analysis at farm level. Even though a technology may lead to a positive outcome at the field level, the required resources may not be available at the farm level. For instance, farmers would have to switch from relying on household labour to spending money on hired labour, or they may prefer to spend their money on more profitable activities. The comparison of income from climbing beans in relation to other sources of income (coffee, off-farm income) therefore also gave an impression of the relative importance of climbing beans in the total household income. In addition, the introduction of climbing beans would lead to the substitution of another crop on some farms. Even when the economic analysis showed that climbing beans were more profitable than maize or bush beans, farmers valued a diversity of crops for different purposes (Dorward et al., 2009; Groot et al., 2012; Ondurua and Du Preezb, 2007).

The latter priority also surfaced during the discussions with farmers. Based on the quantitative analysis, Option 4 (sole) was the option with the largest yields and profit. Yet, farmers had different arguments that led to different choices such as the preference for intercropping or the use of maize stalks. Other insights from discussions with farmers were the importance of income versus food self-sufficiency, and the positive feedback loop of increasing demand, increasing market prices and increasing interest in climbing bean cultivation. The combination of a quantitative exploration of impacts at farm level with qualitative feedback from farmers and other informants contributed to a better understanding of the actual benefits, constraints and potential adoption of technologies.

Finally, the use of farm types was useful to describe the diversity of farmers in Chema sub-county and to show how the effects of the four options differed between farm types. It allowed recognizing the limited options available to LRE farmers with the smallest farm sizes, and the accrual of benefits to farmers from HRE – farm with the largest farm sizes and who derive most of their income from farming. Although LRE farmers were also among the farmers with the largest absolute benefits (Fig. 4), their limited resources probably impede them to make the necessary investments (Langyintuo and Mungoma, 2008; Tittonell et al., 2007). The latter was also reflected in the preference for Option 2 (relay) among MRE and LRE farmers. In contrast, given their dependence on farm income, the wealthier farmers of HRE – farm are likely to re-invest the additional income in the farm, which in turn leads to increased production (Govereh and Jayne, 2003; Wichern et al., 2017). Recognizing diversity among smallholders is important and farm types can be useful to describe and categorize this diversity in terms of wealth and farming strategies (Bidogeza et al., 2009; Franke et al., 2014). The differences between farm types could help government or development organisations to tailor their interventions to e.g. providing financing options for poorer farmers who cannot afford to make initial investments or alternatives outside agriculture, and supporting collective marketing among farmers largely depending on agriculture and producing for the market.

However, our results also showed that the effects differed within the farm types. The ranking of farms according to food self-sufficiency indicated that LRE, followed by HRE – off-farm households were the least food self-sufficient, but with some exceptions. For the other indicators, the ranking was different, and there was no clear pattern in the effects for the different farm types. Our study therefore also showed that farm types based on (mostly) structural farm characteristics did not explain the variation in the effects of agricultural innovations. Our focus on easy-to-measure variables could have facilitated the scaling of technologies, but with their limited explanatory power this could mean that other variables should also be collected, such as functional characteristics (dynamics of production orientation and livelihood strategies), farmers' intrinsic motivations or their risk perception (Meijer et al., 2015; Tittonell et al., 2010). Additionally, the discussions with farmers revealed that farmers make decisions based on factors that cut across farm types, such as the enhanced market prices for climbing beans. Moreover, changes in weather conditions or pest and disease pressure may affect farmers' decisions to invest in climbing beans in a particular season (Hockett and Richardson, 2018; Misiko and Tittonell, 2011). Such season-to-season dynamics are hard to capture in one-off typologies, stressing the value of qualitative explorations to determine the most important factors in farmers' decision-making.

5. Conclusion

The *ex-ante*, multi-criteria exploration of climbing bean options showed that climbing beans generally improve food self-sufficiency and income, but often require increased investment and always demand more labour. The small farm sizes of the poorest (LRE) households resulted in fewer options for the inclusion of climbing beans than for larger farms. Moreover, poorer farmers may be unable to make the necessary investments in climbing bean cultivation. The combination of quantitative and qualitative information improved our understanding of farmers' decision-making, showing that farmers prioritized income over food self-sufficiency and that cash constraints were more important than labour constraints for climbing bean cultivation. The recent increase in market prices for climbing bean in the eastern highlands resulted in growing interest in their cultivation, but a lack of seed, next to a lack of stakes, is currently limiting climbing bean cultivation. Strengthening of farmer cooperatives to ensure large enough volumes of climbing bean seed and improved storage of seed are essential next steps to enhance climbing bean cultivation in the area.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.05.014.

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