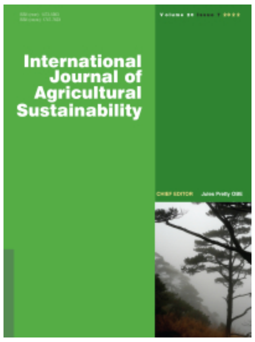

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A stepwise approach to facilitate adoption of climate smart practices for smallholder coffee production in Uganda

David Mukasa[a,b], Leonard Rusinamhodzi[c], Piet. J. A. van Asten[d], David Amwonya[a], Haroon Sseguya[a], Faith Akello Okiror[a*], Diana Kirungi[a], Wilberforce Wodada[a], Victor Komakech[e], Sarah Margiotta[a] and Laurence Jassogne[f†]

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ABSTRACT
Adoption of Climate-smart Agricultural Practices (CSA) enhances crop productivity and livelihoods. Smallholder coffee farmers in Uganda receive training on good agricultural practices (GAPs) through extension programs, but adoption remains low. Adopting all 'best practices' at once may be unrealistic for resource-limited, risk-averse smallholders. This study tested a Stepwise approach, breaking GAPs into manageable, incremental investments. Field trials were conducted in Luweero (Central) and Sironko (East) districts of Uganda, with 16 demonstration sites using randomized treatments and the control (farmer practice), divided into four steps. Each site served 25–30 farmers through experiential learning. A co-design method ensured farmer involvement in the design, development, and testing for sustainability. Results from two harvests (2018–2019) showed significant cumulative yield gains over the control. Arabica yields increased by 31%, 43%, 54% and 65% across Steps 1-4,. Robusta showed gains of 7%, 22%, 23% and 39% respectively. Marginal rate of returns (MRR) was relatively high for Step 1 (563%), 2 (169%) and 4 (122%) for Robusta coffee , and 221%, 217% and 485% for Step 2, 3 and 4 for Arabica coffee respectively. The Stepwise approach demonstrated improved yield gains and increased farmer income.

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KEYWORDS
Coffee productivity; GAPs; MRR; Stepwise approach; Uganda

1. Introduction

Coffee is among the most important cash crops of Uganda with total coffee exports of 345,637MT worth US$ 837 million (UCDA, 2022). The area under coffee production has increased by approximately three times from 245,000 hectares in 2012 to 700,000 hectares in 2021 (FAO, 2024). This could imply that the increased export volumes from Uganda are mainly due to extensification rather than intensification (UCDA, 2023). Coffee produced in Uganda accounts for approximately 5% of global coffee production (UCDA, 2022). It is grown by over 1.7 million smallholder farmers (Mugoya, 2018; Bunn et al., 2019), contributing to over 90% of the country's total coffee production. Uganda is Africa's second largest coffee producer after Ethiopia (Mwesigye & Nguyen, 2020), with more than nine million people deriving their livelihood from coffee-related activities (NCP, 2013). There are two economically important coffee species grown in Uganda, namely Robusta

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coffee (*Coffea canephora* Pierre) and Arabica coffee (*Coffea arabica* L.). Robusta Coffee is grown in the plains of Central, Eastern, Western, and Southeastern Uganda, while Arabica coffee dominates the mountainous area on the slopes of Mount Elgon in the East and Mount Rwenzori and Mount Muhabura in the Southwest. Uganda is a large producer of Robusta coffee, and accounts for 80% of Uganda's coffee volumes. Uganda's Robusta coffee is of a better cupping quality and fetches premium price (UCDA, 2019). Due to its intrinsic taste qualities, it is demanded as a component in certain blends, especially espressos and instant coffee and used to benchmark world Robusta Coffees contributing to the rising global demand for good quality Robusta (Robert, 2020). Coffee provides smallholder farmers with cash that contributes to food security, and allows farmers to pay for larger investments, such as school fees, housing, transport, and agricultural tools and inputs (Okech et al., 2004). Despite the immense potential and importance of coffee to the Ugandan economy and smallholder households, due to sub-optimal application of GAPs, the average national yields of 700 kg/ha green beans per year representing only 20% to 30% of the yield potential (Musoli et al., 2017; UCDA, 2019; Wang et al., 2015). The wide yield gaps are due to resource constraints, poor management, biotic, and abiotic factors, including climate variability (Musoli et al., 2001). Coffee is a tree crop that requires constant good management throughout its growth cycle to provide stable yields. Use of improved technologies, including elite varieties and consistent application of GAPs are needed to increase and maintain productivity (Franzel et al., 2001). Such technologies and practices exist but, in many cases, are not in the hands of farmers partly due to a lack of knowledge about their existence and a lack of investment capacity (Giller et al., 2011; Kijima et al., 2011).

It is estimated that with appropriate investment in good agricultural practices (GAPs), farmers can earn an income of over UGX 10 million (US$ 2,700) per hectare per year as compared to UGX 3.4 million (US $ 918) in the same unit area under poor management (UCDA, 2019).

In addition, conventional extension services offer a 'basket of technologies' which are often complex regardless of the farmers' diverse socio-economic statuses. As a result, most farmers fail to identify an entry point for which technologies to adopt first. This may lead to low adoption levels, hence low crop productivity, which negatively affects farmer livelihoods.

In low-input systems, coffee is often exposed to high pests and disease infestation risks resulting in poor yields and even crop failures where severe attacks occur. GAPs are recommended for adoption to overcome crop production constraints to ensure improved food quality and sustainable production (Vijayakumar et al., 2021). GAPs are aimed at improving crop productivity while CSA practices build system resilience through adaptation and mitigation to offset the impacts of climate change to ensure sustainable production (Safdar et al., 2024). The coffee sub sector recommends 17 management practices to improve coffee productivity and sustainability (Alemu & Dufera, 2017; Jassogne et al., 2018; UCDA, 2019; Kirungi et al., 2023). The recommended management practices for coffee integrate both GAPs and CSA practices for improved productivity and sustainability. Specific GAPs such as mulching, weeding, pruning, fertilizer application, pest and disease control are critical to enable farmers to improve productivity and increase resilience to climate variability and change (FAO, 2009).

The International Institute of Tropical Agriculture (IITA) in Uganda, in collaboration with public and private sector partners, co-designed and tested a Climate Smart Stepwise Investment Pathway (Stepwise approach) that breaks down the recommended GAPs into smaller, more affordable packages that can be implemented in phases in specific agro-ecological conditions. This phased approach reduces the investment burden of the recommended 'basket of technologies' by breaking down the full suite of packages into smaller steps which are more affordable to smallholder farmers and are therefore more likely to be adopted. Stepwise encourages farmers to invest in GAPs and CSA practices sequentially allowing them to build up enough income to eventually apply all the recommended GAPs.

In Uganda, smallholder farmers dominate coffee production, and therefore, it is important to work directly with them to reduce production risks and enhance yields (Chiputwa et al., 2015). The underlying hypotheses: (i) the Stepwise approach is a sustainable pathway for full integration of GAPs in coffee-based systems without increasing the burden for resource-constrained smallholder farmers; and (ii) the phased application of affordable predetermined GAPs units improves the coffee yield incrementally regardless of the agroecological zone and coffee type. Therefore, the main objective of this paper is to define and outline the logical sequence of the Stepwise approach to address low coffee productivity in the context of climate variability and change. The guiding research questions were: (1) What is the most pragmatic approach to breakdown the full package of recommended GAPs into more affordable sets of practices that farmers can incrementally invest in overtime, to increase coffee yields? And (2) Does the application of GAPs units in a phased sequence result in economic gain?

2. Materials and methods

The details of study design are described elaborated by the theoretical basis for the Stepwise approach. The study considered action research and case study research design. It consisted of three main components that helped to shape the Stepwise logic: (a) co-design and co-development, (b) experiential learning, (c) farmers' feedback, and (d) Hypothesis needed for field testing to ascertain its validity and practicality. The combination of these brought about the idea of breaking down the GAPs packages into smaller packages that could be implemented in phases. The process of development of the approach, tools, experiential learning, farmers' feedback, assumptions, and data underpinning Stepwise approach.

2.1. Theoretical basis

The participatory codesign, development, and field testing of the Stepwise approach occurred over three years between 2017 and 2019. The conceptualization and development of the Stepwise approach were based on earlier studies (Kijima et al., 2011; Jayne et al., 2003; Marenya & Barrett, 2009) that reported low adoption of GAPs among smallholder coffee farmers, largely due to limited resources. Additionally, the Uganda Coffee Harmonized Coffee Training materials recommend over 15 management practices bundled together (e.g. weed control, fertilizer application, irrigation management, manure application, mulching, among others) for sustainable production and productivity (NSC, 2014; UCDA, 2019). The current Uganda coffee extension service promotes the entire recommended management package as a single bundle. However, agricultural production is dominated by diverse smallholder farmers who are generally resource-constrained, leading to heterogenous management of fields and significant yield gaps. Similarly, the uptake of GAPs by these farmers is often constrained by a lack of technical know-how on entry points and how the different options can be combined to ensure sustained crop productivity (Nezomba et al., 2014; Franzel et al., 2001). Furthermore, smallholder farmers face various constraints when undertaking potentially profitable activities in the agricultural sector (Alvarez et al., 2014). One size fits all extension service delivery favours only a small percentage of farmers, leading to low adoption rates, especially for manure, irrigation, and fertilizers (Pan & Smith, 2018).

2.1.1. Co-design and co-development

To address the low adoption of GAPs and the impact of climate change on smallholder farmers in Uganda, IITA used a co-design and co-development approach together with partners to design a national-level Stepwise investment pathway for both Arabica and Robusta coffee in 2016. Co-design for agricultural innovations is crucial as it integrates the perspectives and aspects of diverse stakeholders, including farmers, agro-ecological conditions, and the diverse impacts of climate changes across regions. Sustainability can only be operationalized in context because a 'one size fits all' approach offers limited success due to the diversity of production constraints and farming conditions. It offers a platform for various views on integrating knowledge and capabilities of the relevant partners (Rosca & Bendul, 2016). The process helps farmers and other stakeholders build their systems, adapt them to their own situations, integrate their own knowledge and scientific knowledge (Meynard et al., 2012). As such, an expert group was established comprising representatives from government, research, academia, international and local private sector, not-for-profits and international non-governmental organizations, and farmers who worked together to identify sets of priority coffee management practices for mature coffee, which were ordered into four steps to constitute the generic Stepwise approach. Stakeholders included: the Africa Coffee Academy (ACA), Olam Uganda Limited (OLAM), Hanns R. Neumann Stiftung (HRNS), Café Africa Uganda, the Uganda National Union of Coffee Agribusinesses and Farm Enterprises (NUCAFE), and government partners: the National Agricultural Research Organization (NARO) through its coffee institute the National Coffee Research

Institute (NaCORI), and the Uganda Coffee Development Authority (UCDA).

The generic Stepwise was downscaled and adapted to regionally context-specific production constraints. Through the office of the respective district Chief Administrative Officer (CAO), 40 key regional stakeholders were hosted comprising District Local Government Agricultural Officers (DAO), the District Production and Marketing Officer (DPMO), private sector, and lead farmers. Stakeholders were divided into four groups, each developing a separate Stepwise package. The four Stepwise packages were then consolidated into a hybrid Stepwise package with anticipated yield estimates for each step during a plenary session. The development of site-specific Stepwise packages was informed by focusing on the possible impacts of climate change/ variability and production constraints experienced in the respective regions. The perceived impact of production constraints in each region informed how coffee management practices were prioritized and ordered into the four steps. The development of the site-specific Stepwise was done in six districts, namely: Luweero, Nakaseke, Nakasongola, and Ntungamo in the Robusta coffee growing region, and Sironko and Bulambuli in Arabica coffee growing region.

2.1.2. Experiential learning

The study adopted experiential learning theory to enhance adult learning practice (Dernova, 2019). Experts' knowledge from technical teams at the national level resulted in Stepwise development, validated by researchers through demonstration sites at the field level, and private sector implementing partners provided technical teams for orientation on the Stepwise concept and training to disseminate GAPs to their smallholder farmer networks. Dissemination of GAPs through Stepwise targeted 1000 and 250 coffee farmers organized in groups of 25–30 members in the study sites.

Demonstration sites were established to test Stepwise packages on coffee productivity, profitability, and pest and disease control, and serve as farmer training sites in the two districts of Sironko (Arabica) and Luweero (Robusta) respectively (Figure 1).

2.1.3. Farmers' feedback

Feedback was envisaged to interest farmers to co-own the project outcomes from a more informed position to facilitate implementation, adoption, and the subsequent scaling of Stepwise to coffee farming communities. The outcomes of successful projects motivate new participants to join ongoing and future projects. Feedback from the previous project activity prepares more demand-led rather than supply-driven interest in the application of knowledge and technologies introduced (Dabelstein & Hirono, 2001).

2.2. On-farm testing of the Stepwise packages

2.2.1. Site selection for Stepwise demonstrations

A selection of host farmers for the demonstration sites preceded all other field activities, and sites were selected proportionately but randomly from each cluster to enhance the representative distribution of demonstrations in the community and to reduce biases (Figure 2). Other selection processes for potential demonstration host farmers exist such as the Project field staff providing a checklist of desired indicators that are discussed among Lead Farmers and Extension Officers to determine a choice of the host (Marchand et al., 2019; NARO, 2017). However, there is a high likelihood of selection bias and failure to achieve a fair distribution of demonstration sites to reflect the diverse nature of farmers in the farming community. The site selection process for host farmers involved plot characterization in identifying suitable coffee plots. Quantitative and qualitative indicators were collected during plot characterization. These were: number of coffee trees on a farm, number of productive coffee trees on a farm, coffee variety, coffee age, intercropping status, distance to the main road, shade tree canopy size, land use and farm management status. Cluster analysis (farm segmentation) to categorize fields into uniform clusters was done using the function Factor Analysis of Mixed Data (FAMD) using FactoMineR (Jérôme & Brigitte, 2008). The choice of the analysis method was based on its ability to analyze data containing both quantitative and qualitative variables (Pagès, 2004). During cluster analysis, the final selection of the appropriate number of clusters was based on scree plots, the indexing methods to inform the majority rule of the 'Ward. D2' technique (Kaufman & Rousseeuw, 1990). Plot characterization was done in 25 and 23 households in Robusta and Arabica coffee-growing regions, respectively. The cluster analysis provided insight into the diversity and composition

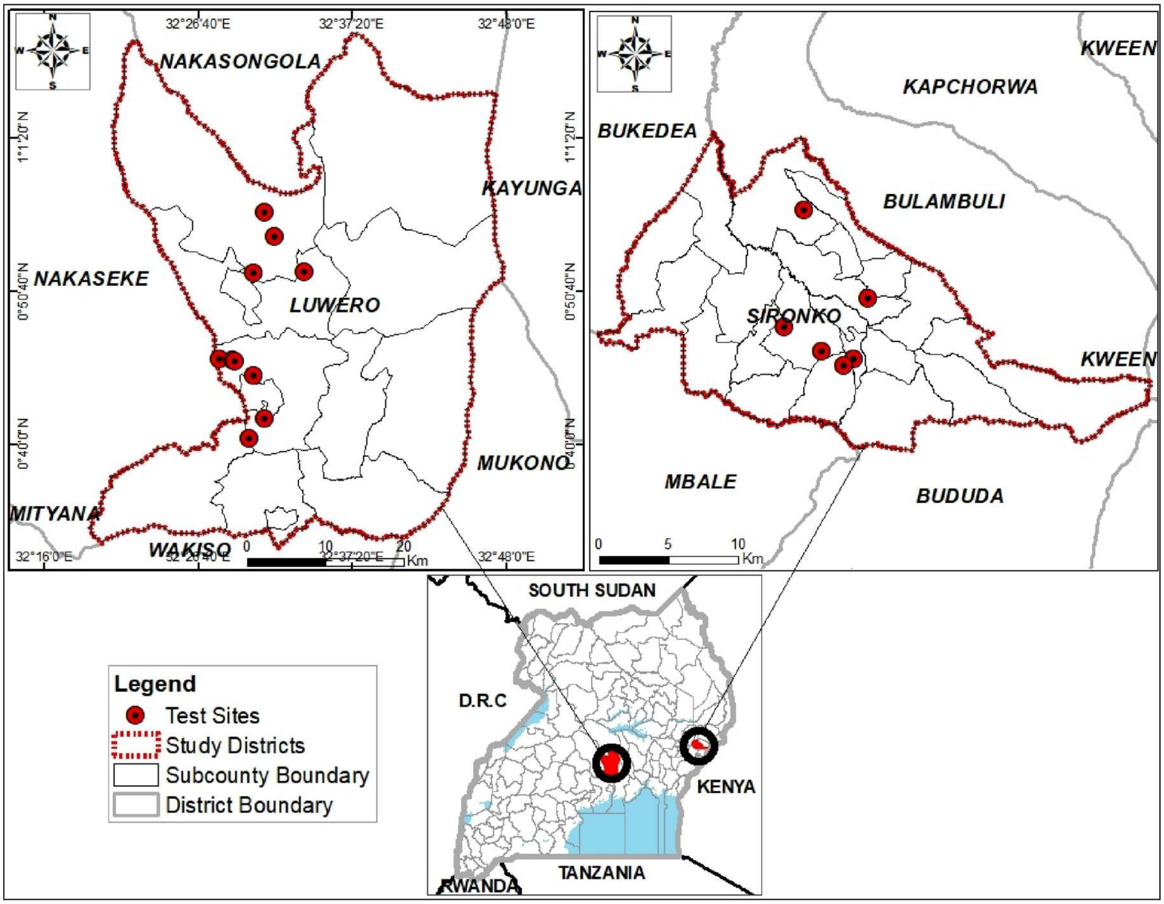

Figure 1. The Stepwise demonstration sites in Luweero (Robusta) and Sironko (Arabica) coffee growing regions in Uganda.

in the coffee farming communities highlighting clusters with the highest and least number of farmers to guide the selection process. A total of 16 households (6 from Sironko and 10 Luweero) were randomly selected from the clusters proportionately to host the demonstration sites for two years. The study ensured that the host farmers selected have similar characteristics when compared to smallholder coffee farmers in the entire country. For example, most of the farmers in Uganda have small coffee plots that range between 0.1 and 1.0 ha (Mukasa et al., 2013; ICO, 2019). This is within the range of plot sizes selected to host the Stepwise demonstration sites. The final host farmer selection was concluded through farmer leaders' participatory meetings that validated the selected farmers and provided opinions on their ability, reliability, and readiness to host the demonstration activities. Potential host farmers that were dropped by validation criteria were replaced randomly from the respective clusters.. Similarly, farmer leaders supported host farmers throughout the study period.

2.3. Case study area

The case study sites were in Luweero district in the Central Robusta growing area, and Sironko district, in the Eastern Arabica coffee growing region, respectively. (Figure 1). The Arabica coffee demonstration site lies approximately between latitude 1.1608^0N and longitude 34.2866^0E at an altitude of 1420 m above sea level. In the Arabica coffee growing region, the soils are predominantly sandy clay loams, and the parent rocks underlying these soils are described by Schlüter (2008) as predominantly Cenozoic volcanic. The district experiences a bimodal type of rainfall with the heaviest in the first season of March-July

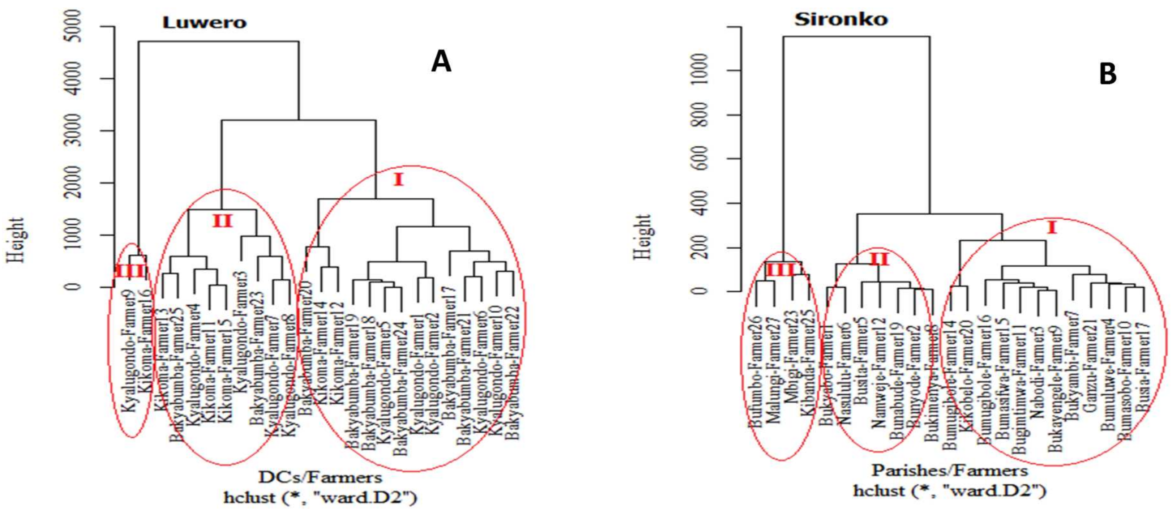

Figure 2. Dendrograms of characterized coffee fields to guide the selection of Stepwise Demonstration plots in Robusta coffee site in Luweero-Central (b); Arabica coffee site-Eastern on slopes of Mt. Elgon (b); I-III are cluster types.

while there is low rainfall in the second season between the months of August–September. The average rainfall is 1550 mm per year. This heavy rainfall supports the agriculture sector, which is the base of the district livelihood. There is a short dry spell between these seasons and a long dry period between the months of January-March. Average annual temperature is reported at 28^{0}C but tend to become lower up the mountainous areas of the district.

The Robusta site lies approximately between latitude 0.8271^{0}N and longitudes 32.6277^{0}E at an altitude of 1100 m above sea level. In the Robusta growing region, the soils are predominantly loams, sandy clay loams, and sandy loams, and the parent rocks underlying these soils are described as Archaen Gneissic-Granulitic-Complex, Proterozoic metamorphic rocks by Schlüter (2008). The climate can be described as modified equatorial climate. Mean annual temperature ranges from 17^{0}c to 29^{0}c. The rainfall is well distributed throughout the year, with the average annual rainfall being 1,300 mm. The peak rain period is March–May and October–November. The reliability of rainfall generally declines northwards. Dry seasons occur from December–February and June–July.

In both study areas, smallholders generally rely mainly on family labour for the application of coffee management practices. Farmers mainly focus on basic management practices such as weed control, de-suckering, pruning, cultural of pests and diseases for coffee production, majorly due to social and economic factors. Labour-intensive management practices such as trenches, water catchment pits, etc., for soil and water conservation are rarely applied adequately. Application of high investment management practices such as manure, fertilizers, mulching, and pesticides vary. A few farmers that try out high-cost practices do so at low doses/rates and frequencies, differently from the recommendations (Benson et al., 2013; Sanabria et al., 2018)

2.4. Data collection from demonstration sites

Each Stepwise demonstration site had five subplots which included the control (farmer's practice) and the four steps (1-4). Each subplot had 20 mature, productive coffee trees from which agronomic data were collected. Biophysical data collected included coffee yield, status of pests and diseases, and frequency of applied management practices. The frequency of application of each management practice was recorded. The recorded GAPs included pruning, de-suckering, manure application, mechanical weed control, and chemical weed control (Table 1). The private sector partners (Olam and HRNS) collected data on the cost of external inputs which included fertilizers, manure, pesticides, and herbicides. The external inputs, namely fertilizers, pesticides and herbicides were purchased in bulk in 2017 sufficient for the entire study period. Application of GAPs was supervised and supported by the private sector technical team and the IITA research team. Labour costs in

Table 1. Site-specific Stepwise package applied in demonstration sites in Luweero (Robusta coffee) and Sironko (Arabica coffee).

	Robusta region					Arabica region				
Applied CSA practices per step under Stepwise approach	Control	Step I	Step II	Step III	Step IV	Control	Step I	Step II	Step III	Step IV
Weed control Freq yr^{-1}	4	4	4	2	2	4	4	4	4	2
De-suckering Freq yr^{-1}	0	12	12	12	12	0	12	12	12	12
Pruning Freq yr^{-1}	0	0	2	2	2	0	2	2	2	2
Cultural control of WCSB and CLR Freq yr^{-1}	0	0	0	0	0	0	0	12	12	12
BCTB cultural control Freq yr^{-1}	0	0	12	12	12	0	0	0	0	0
Mulching Freq yr^{-1}	0	0	0	2	2	0	0	0	0	2
PaD chemical control Freq yr^{-1}	0	0	0	0	10	0	0	0	0	10
PaD chemical control Robusta area: Kohino (Imidacloprid)	0	0	0	0	8.75					
PaD chemical control Robusta area: Orius applied (L $ha^{-1}year^{-1}$)	0	0	0	0	17.5					
PaD chemical control Arabica area: Copper Oxychloride applied (kg $ha^{-1}year^{-1}$)						0	0	0	0	25
PaD chemical control Arabica area cypermethrin applied (L $ha^{-1}yr^{-1}$)						0	0	0	0	25
Manure application Freq yr^{-1}	0	0	0	1	1	0	0	2	2	2
Manure applied (kg $ha^{-1}yr^{-1}$)	0	0	0	11,110	11,110	0	0	32,800	32,800	32,800
Fertilizers NPK Freq yr^{-1}	0	0	0	0	2	0	0	0	2	2
Fertilizers NPK kg $ha^{-1}yr^{-1}$	0	0	0	0	444.4	0	0	0	820	820

Abbreviations: (CSA – Climate smart agricultural practices, BCTB – Black coffee twig borer, CLR – Coffee leaf rust, WCSB-White coffee stem borer, Freq-frequency, yr-Year, ha-Hectare, PaD – Pests and diseases, L – Litres, NPK – Nitrogen, Phosphorus, Potassium).

Uganda shillings (UGX) (converted to US$ at exchange rate of UGX 3720.25 for period 2018/2019) for the management practices were estimated through interviews with demonstration host farmers through a structured questionnaire to determine the cost of production, profitability, and MRR expressed. The variable costs that were considered included labour for weeding, mulching, fertilizer application, manure application and chemical control of pests and diseases, and frequency of application for two years (Table 1). Farmers were responsible for capturing yield data during harvesting using a structured data sheet. Annual yield data for each year were collected; farmers were trained to measure the harvested coffee fresh red cherries using marked plastic cups of known and determined weights (g) whenever harvesting took place. Coffee weight (kg) from each sub-plot (control, step 1-4) was determined and recorded separately. Coffee harvested per step (treatment) was converted to green beans following the International Coffee Agreement (ICO, 2007). Conversion factors of 5 and 6 kg of coffee red cherries is equivalent to one kilogram of green beans for Robusta and Arabica coffee respectively. Coffee yield per ha^{-1} $year^{-1}$ was calculated based on the average yield per tree as productive coffee trees were counted and recorded during the harvest season.

For pests and diseases, data was collected monthly for both years (2018 and 2019). In the Robusta coffee demonstration sites, the Black Coffee Twig Borer (BCTB) and Coffee Wilt Disease (CWD) were the key monitored biotic production constraints. Monthly assessments focused on pest infestation and disease severity. For data on BCTB, dry branches with signs of the pest were counted and expressed as a proportion of the total number of branches (Kagezi et al., 2013). Five coffee trees were randomly selected and marked for monitoring pests and diseases. In case a marked coffee bush died, it could be replaced with a new one selected within the subplot. In Arabica demonstration sites, Coffee Berry Borer (CBB) and Coffee Leaf Rust (CLR) were monitored following the standard protocols on scoring pests and diseases (Avelino et al., 2012).

2.4.1. Baseline survey

The Stepwise results were compared with coffee yield figures collected during 2016 baseline household survey. The survey covered 693 households in the two regions: 355 and 338 in Central and Eastern Uganda respectively. Data were collected on indicators of human, financial, physical, natural and social capital, level of adoption of coffee GAPs and yields. The coffee yield results for each of the four steps (1-4) of Stepwise were compared with coffee yield determined per farmer typology generated from baseline data.

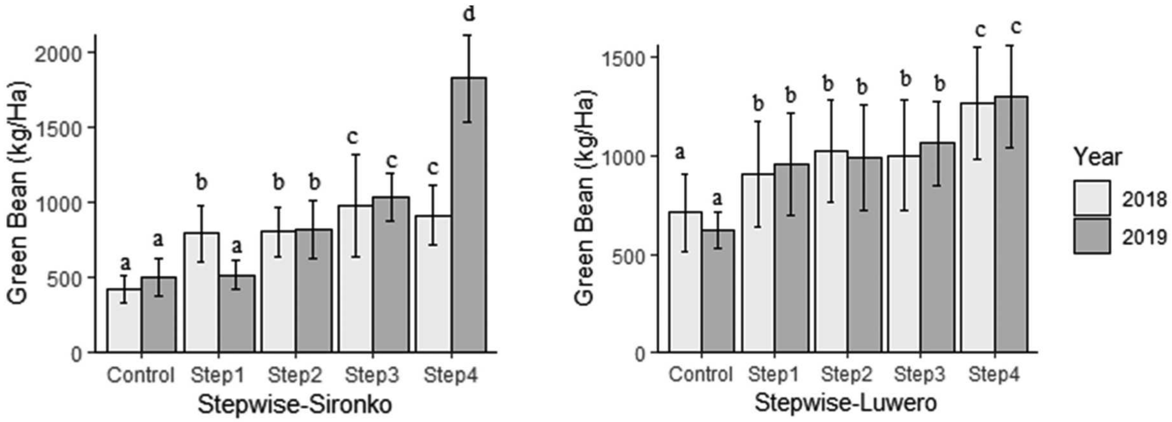

Figure 3. Coffee yield trends in Sironko and Luweero demonstration learning sites for the year 2018 and 2019. For a given annual coffee yield followed by the same lowercase letter are not significantly different at 95% confidence level. Different steps with different letters (a, b, c, d) on the error bars indicate significant differences.

2.5. Statistical analysis

2.5.1. Coffee yield data analysis

Coffee yield from the demonstration plots (Figure 3) was analyzed using a general linear mixed model (GLMM). In this model, the season was the time variable, demonstration sites were considered as the random effect, the steps within the Stepwise packages were included as treatments (or groupings), the coffee yield was the response variable. In contrast, management practices were considered as fixed effects. The BCTB, CBB, CWD pests and diseases, and cultural vs chemical control (CLR) assessed under the different Stepwise steps were compared (Table 2). Statistical analysis of data was conducted using R version 3.6.2 with various packages such as 'Cluster', 'factoextra' and 'FactoMineR' set at 5% level of significance (R Core Team, 2020).

2.5.2. Baseline and Stepwise coffee yield

Since coffee farming communities are diverse (Alvarez et al., 2014), the level of adoption of GAPs and coffee yield is likely to differ among farmer types. The 2016 baseline household survey data was used to generate farmer typologies by classification and regression trees (CART) statistical method – a non-parametric approach a suitable model for uncovering complex dependencies among predictor variables (Gareth et al., 2017). The generated farmer typologies were mainly based on two variables: the summed-up management practices into an average percentage score and coffee yield as response variable. Further analysis was done to determine the average coffee yield per typology (Table 2). The coffee yield results per each step of the Stepwise approach (Figure 3) were compared with coffee yield per farmer typology (Figure 4).

2.5.2. Economic analysis

The profitability of the Stepwise approach was evaluated using a partial budget analysis as described by CMMYT (1988). The variable costs included labour and input costs and factored in the frequency of application for all implemented practices under the Stepwise approach (Table 1). Opportunity costs and fixed costs were not included in the analysis. Although farm gate coffee prices kept fluctuating during the coffee harvest season, a fixed price which was most prevalent for Arabica and Robusta coffee of US$ 1.68 and US$ 1.37 per kg of coffee green beans, respectively, was used (a local price of UGX 6,250 and UGX 5,100 per kg green bean) to determine the yield value during the study period.

The yield increase was calculated as difference between control (farmer practices) and for each Step (1-4). The additional variable input costs attributed to an increase in coffee yield value for each Step was determined as a difference between total input costs for each Step (1-4) less the total input costs of the control. The change in benefits of the different steps in the Stepwise approach were compared to control. This was calculated as the change in the value of the yield less the change in the total variable input costs due to each Step. The change in benefits

Table 2. Farmer typologies for both Robusta and Arabica coffee farming communities and the corresponding coffee yield during the baseline survey.

	Robusta					Arabica					
	I(35.20%)	II(34.08%)	III(13.97%)	IV(16.76%)	*P*-value	I(2.01)	II(45.73%)	III(36.59%)	IIV(10.06%)	V(5.61%)	*P*-value
Yield (kg/ha)	106.51± 3.09^{a}	292.84± 3.89^{b}	560.29± 6.86^{c}	714.82± 1.48^{d}	<0.0001	210.98± 7.34^{e}	450.90± 2.68^{f}	691.72± 3.44^{g}	860.68± 6.27^{h}	912.51± 63.53^{i}	<0.0001
[j]GAPs (%) application score	8.45± 0.64^{j}	10.69± 0.78^{j}	11.48± 1.22^{j}	11.92± 1.11^{j}	0.5405	8.17± 1.01^{k}	17.19± 1.33^{k}	27.87± 1.84^{jk}	34.41± 4.96^{jk}	27.61± 5.71^{k}	0.0179

Note: Different letters (a, b, c, d, e, f, g, h and i) in the same column indicate significant differences.
[j]Abbreviation for Good Agronomic practices percentage application score; Farmer typologies (I, II, III, IV and V).

over change in total variable input costs for each Step (1-4) gave the marginal rate of return (MRR).

Sensitivity analysis was performed to evaluate how changes in coffee prices, input costs (labour and inputs) affected profitability using the approach described by Alimi and Manyong (2000). Marginal rate of returns (MMR) was calculated based on 50%, 100%, and 200% of the coffee prices and 100%, 150% and 200% of the input rates of 2018/2019.

Furthermore, price scenario analysis was carried out using coffee prices for five years between 2017 and 2021(UCDA Website). Input costs were assumed to be stable, and input prices did not differ significantly during the study period (2018–2019). A five-year period was considered, and the inflation rate was reported between 5.64% and 2.16% in 2017 and 2021 respectively (Statista, 2021).

3. Results

3.1. Coffee productivity

In both sites, the Stepwise approach demonstrated yield increases when compared with the control and between steps. Yield in the Robusta coffee site for year one of the study in 2018 did not differ between Steps 1, 2 and 3, respectively (Figure 3). However, in the Arabica coffee demonstration site, Steps 3 and 4 yield was significantly higher when compared to Steps 1 and 2 ($P < 0.05$) for 2018 (Figure 3, Table 3). Steps 1–4 yields for 2018 were significantly higher than the control yield ($P < 0.05$) in the Arabica and Robusta coffee demonstration sites (Figure 3, Table 3). Similar trends were observed in 2019 for the Arabica coffee site of which Steps 2–4 registered higher yields than the control except in Step 1 the gain did not differ from control. Similar yield trends were observed in the Robusta site as the gain between Step 1 and Step 3 did not differ significantly in either 2018 or 2019 except in Step 4 which demonstrated significant yield gain in response to the additional application of GAPs along an application intensification gradient from control to Step 4 (Figure 3). In 2019, the second year of the Stepwise testing, in the Arabica site, Step 4 demonstrated significant yield gain ($P < 0.05$) when compared to Steps 1-3, including the control of 2018. Step 4 yield increase for two years (2018 and 2019) in Robusta was significantly higher compared to other steps, including the control. Overall yield gain within Steps 1–3 for the study period did not differ significantly

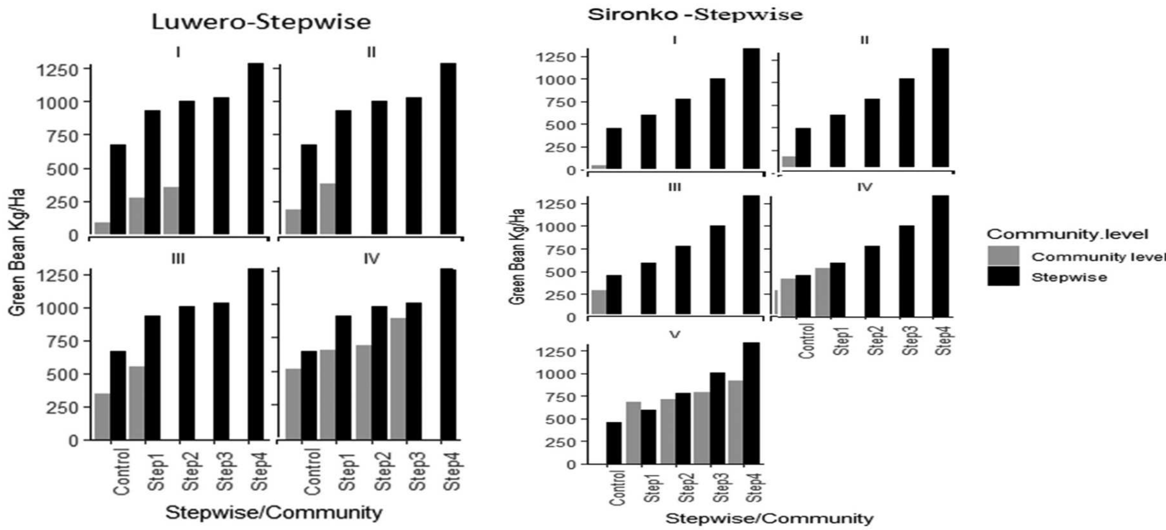

Figure 4. Stepwise coffee productivity compared with community coffee productivity for the 2016 baseline survey in Robusta and Arabica coffee growing sites. Coffee productivity in 2018 for Stepwise (control and steps 1-4) compared with baseline coffee productivity under different farm types (I-V) in Robusta and Arabica coffee sites.

($P < 0.05$) for the Robusta site (Figure 3). Step 4 in the Robusta site consistently scored the highest yield gain for both years. For year 2 in the Arabica site, there was a significant yield gain in Step 4 ($P < 0.05$) when compared to the rest of the Steps (1-3), including the control. Provided the observed yield gains in response to intensification along the Stepwise gradient (control to Step 4), the significant yield gain seems to be more realistic with sustainable use of GAP packages, for example, in the second year the yield gain was significantly higher in Arabica. Robusta appears the same though the yield did not differ significantly between years. However, Step 4 tends to gain more in terms of yield for the second year with the sustainable use of the Stepwise approach. Improvement in coffee yield gain in both sites correlates with sustainable use of the full suite of GAPs annually when control (farmer practices) was compared with subsequent steps in the Stepwise approach.

3.1.1. Comparison of baseline and Stepwise coffee productivity

The CART analysis generated four and five farmer typologies for Robusta (Central) and Arabica (East) coffee farming communities respectively. Type I and II farmers for Robusta and Type II and III for Arabica coffee constituted the largest percentage. Type I and II farmers for Robusta constituted 35% and 34% while for the Arabica site, Type II and III had 45% and 36% respectively (Table 2). Type I and II farmers average yield was 106 kg ha–^{1}year^{-1} and 292 kg ha^{-1}year^{-1} for Robusta coffee production respectively. In the Arabica site, Type II and III farmers' average yield was 450 kg ha^{-1}year^{-1} and 691 kg ha^{-1}year^{-1} respectively. Type IV farmers had the highest yield of 714 kg ha^{-1}year^{-1}in Robusta. Type V farmers in the Arabica site constituted the smallest percentage with the yield of 912 kg ha^{-1}year^{-1}. The coffee yield differences between farmer Typologies were significant for both coffee farming communities ($P < 0.001$) (Table 2).

Average coffee yield results from farmer typologies were then compared with the yield from Stepwise (Figure). The community coffee yield was generally low when compared to Stepwise yield. Similar trends were observed in both Robusta and Arabica coffee-growing communities. Typologies I to III in both regions, farmers' yield performance and distribution can only be comparable up to Step 2 of Stepwise. Typologies I to III combined constitute over 80% of the farming community implying that adoption and application of GAPs is still low among the coffee farming communities.

Typology IV and V farmers had relatively high yields that matched with yield gained from different steps (1-4) along Stepwise for Robusta and Arabica coffee sites respectively (Figure 4). However, these

Table 3. The Effect of Stepwise application of Good agronomic practices on Arabica and Robusta annual coffee productivity.

Coffee variety	Year	Control Mean ± SE (kg/ha)	Step 1 Mean ± SE (kg/ha)	Step2 Mean ± SE (kg/ha)	Step3 Mean ± SE	Step4 Mean ± SE
Arabica	2018	426.98± 89.86[a]	793.91± 97.77[a]	805.05± 68.01[a]	977.9± 38.85[a]	913.64± 94.69[a]
	2019	499.05± 93.71[c]	518.9± 82.12[bc]	819.79± 96.85[bc]	1032.58± 154.9[b]	1823.62± 87.79[a]
	Overall	459.74± 74.03[c]	670.43± 98.8[bc]	811.73± 126.81[bc]	1002.75± 96.2[ab]	1327.26± 77.87[a]
Robusta	2018	710.86± 97.39[a]	909.43± 66.84[a]	1024.29± 61.38[a]	999.71± 79.93[a]	1262± 83.71[a]
	2019	623.59± 99.33[a]	956.15± 259.85[b]	990.49± 105.71[b]	210.81± 24.21[c]	1301.55± 98.03[d]
	Overall	670.58± 92.01[b]	932.79± 79.04[ab]	1007.39± 89.11[ab]	1030.48± 98.56[ab]	1281.77± 84.31[a]

two typologies constituted the smallest percentage of 16% and 5% in Robusta and Arabica farming communities respectively.

3.2. Pest and disease incidence – BCTB, CLR

Results from the Robusta coffee site showed that the use of cultural methods is as effective as the use of pesticides (chemical control) for controlling BCTB as there were no significant differences between cultural methods in Steps 2 and 3 from Step 4 where the pesticides application was done (Table 1). Intensive cultural control of BCTB monthly by trimming and burning the infested coffee twigs significantly reduced BCTB prevalence ($P < 0.05$) when compared with control (Table 4). On average, the BCTB infestation was reduced to one infested twig (primary branch) per coffee tree when compared with over 4 infested primary branches per coffee tree in the control (Table 4). Chemical control of pests and disease produced similar results as the cultural control, and yet pesticide use increases investment costs for farmers. BCTB proved difficult to successfully manage by pesticide control at farm level as BCTB is reported to have several alternative hosts found on the farm, such as some species of shade trees.

Results from the Arabica sites showed seasonal (monthly) variability in CLR incidence and severity were observed in all Steps with similar high prevalence levels except for Step 4, with significantly low levels in disease prevalence due to the use of pesticides to control CLR. CLR control in Steps 1, 2, and 3 were all under cultural methods (Table 1) implying that controlling CLR by cultural methods is not plausible because when pesticide application was only done in Step 4, the disease prevalence was significantly reduced (Table 4). The selection of management methods for pests and diseases is a case-by-case study. Whereas cultural control was successful in controlling BCTB, CLR control was effective by pesticide use.

Table 4. Prevalence of black coffee twig borer and coffee leaf rust in Robusta and Arabica coffee growing regions.

BCTB[d] prevalence Robusta coffee growing region		CLR[d] prevalence in Arabica growing region	
Stepwise	mean ±se	Stepwise	mean ± se (%)
Control	4.24 ± 0.32[a]	Control	17.90 ± 0.70[b]
Step 1	3.73 ± 0.36[b]	Step 1	17.69 ± 0.74[bc]
Step 2	1.36 ± 0.15[c]	Step 2	20.28 ± 0.82[a]
Step 3	1.14 ± 0.11[c]	Step 3	18.27 ± 0.78[ab]
Step 4	1.34 ± 0.15[c]	Step 4	15.99 ± 0.72[c]

Note: Different steps with different letters (a, b, c) in the same column indicate significant differences.
[d]Abbreviations for Black coffee twig borer (BCTB) and Coffee leaf rust (CLR).

3.3. Economic evaluation of Stepwise

The average marginal rate of return (MRR) in the Robusta coffee growing area was 563%,169%, 95% and 122% for Steps 1, 2,3 and 4, respectively. In the Arabica coffee growing areas, the MRR was 7%, 221%, 217% and 485% for Steps 1, 2,3 and 4, respectively (Table 5). MRR calculated using 50% of coffee prices of 2018/2019 was 232%, 35%, −3%, 11% and 1226%, 438%, 290%, 343% for Steps 1, 2, 3 and 4, and −46%, 61%, 58% and 173% for Steps 1, 2, 3, and 4 in Robusta and Arabica growing areas respectively (Table 5). Similar calculations using 200% increase of coffee prices showed MRR was 1226%, 438%, 290%, 343% and 98%, and 115%, 542%, 533%, 1109% for Steps 1, 2,3, and 4 respectively in

Table 5. Partial budget comparing the Stepwise packages in the Robusta and Arabica coffee growing regions in Uganda (US$ ha^{-1} $year^{-1}$).

	Robusta					Arabica				
	Coffee prices[a]			Input costs[a]		Coffee prices[a]			Input costs[a]	
Gross revenues	100%	50%	200%	150%	200%	100%	50%	200%	150%	200%
Price of coffee (USD kg^{-1})	1.37	0.69	2.74			1.68	0.84	3.36		
Value of coffee farmer practice (control)[b]	882	441	1764	882	882	1370	685	2741	1370	1370
Value of coffee Step 1[b]	1742	871	3484	1742	1742	1596	798	3191	1596	1596
Value of coffee Step 2[b]	1950	975	3899	1950	1950	2302	1151	4603	2302	2302
Value of coffee Step 3[b]	2136	1068	4271	2136	2136	2881	1441	5763	2881	2881
Value of coffee Step 4[b]	2679	1339	5357	2679	2679	4692	2346	9383	4692	4692
Variable costs associated with Stepwise										
Total variable costs control[c]	270	270	270	405	541	589	589	589	884	1178
Total variable costs Step 1[c]	400	400	400	600	800	799	799	799	1198	1598
Total variable costs Step 2[c]	667	667	667	1001	1334	879	879	879	1319	1758
Total variable costs Step 3[c]	913	913	913	1370	1827	1066	1066	1066	1600	2133
Total variable costs Step 4[c]	1080	1080	1080	1621	2161	1331	1331	1331	1996	2662
Economic returns										
Increased value of yield for Step 1[d]	860	430	1720	860	860	225	113	451	225	225
Increased value of yield for Step 2[d]	1068	534	2136	1068	1068	931	466	1863	931	931
Increased value of yield for Step 3[d]	1254	627	2508	1254	1254	1511	756	3022	1511	1511
Increased value of yield for Step 4[d]	1797	898	3593	1797	1797	3321	1661	6643	3321	3321
Net benefits Step 1[e]	730	300	1591	666	601	16	−97	241	−89	−194
Net benefits Step 2[e]	671	137	1739	473	274	641	176	1573	496	351
Net benefits Step 3[e]	611	−16	1864	289	−33	1034	278	2545	795	556
Net benefits Step 4[e]	986	88	2783	581	176	2580	919	5901	2209	1838
Marginal rates of returns Step 1[f]	563	232	1226	342	232	7	−46	115	−28	−46
Marginal rates of returns Step 2[f]	169	35	438	79	35	221	61	542	114	61
Marginal rates of returns Step 3[f]	95	−3	290	30	−3	217	58	533	111	58
Marginal rates of returns Step 4[f]	122	11	343	57	13	485	173	1109	277	173

[a]Calculations for 100% based on coffee prices and input costs for 2018/2019, coffee prices were decreased by 50% and increased by 100% in 'Coffee price' and input costs were increased by 50% and 100% in 'total input cost'.
[b]Yield value based on coffee yields presented in Figure 3 for 2019 and coffee prices.
[c]Total costs (combined costs of labor, frequency and input costs for different steps including control (Table 1)).
[d]Increased value of coffee yield by each Step (1-4) less by yield value of control.
[e]Net benefits due to increased yield value less by input costs.
[f]Marginal rates of return of investment for different Steps as a product of Net benefits divided by input costs expressed as a percentage.

Robusta and Arabica growing areas. MRR calculated using 150% and 200% of input variable costs were 342%, 79%, 30% and 57%, and 232%, 35%, − 3%, 13% for Steps 1, 2, 3, and 4 respectively in the Robusta growing region, and − 28%, 114%, 111% and 277%, and − 46%, 61% 58% and 173% respectively in the Arabica growing region (Table 5).

3.4. Net income from phased investment in CSA packages

Arabica and Robusta coffee cumulative annual yield trends per hectare per year for the 2018 and 2019, respectively, are shown in Figure 5. Figure 5 represents 2018 and 2019 cumulative yields for the different Steps, while the line graph represents the profit equivalent to US Dollars. Profit was calculated based on a partial budget analysis of variable costs that included labour and input costs and factored in the frequency of application for all implemented practices under the Stepwise approach in Table 1, i.e. weeding, mulching, fertilizer application, manure application and chemical control of pests and diseases for two years. Opportunity costs and fixed costs were not included in the analysis. Although farm gate coffee prices fluctuated during the coffee harvest season, a fixed price which was most prevalent for Arabica and Robusta coffee of US$ 1.68 and US$ 1.37 per kg of coffee green beans, respectively, was used (a local price of UGX 6,250 and UGX 5,100 per kg green bean) to determine the yield value during the study period. Subsequent application of the Stepwise approach positively impacted yield gain in both sites (Figure 5). Stepwise investment in GAPs for coffee production was costly when Steps 1–4 were compared to the control (Table 5). However, the cumulative profit in all Steps (1- 4) was higher than the control in both the Arabica and Robusta sites. There was an income gain of 76% and 148% in Step 4 when compared to control for both sites (Figure 5). A phased investment

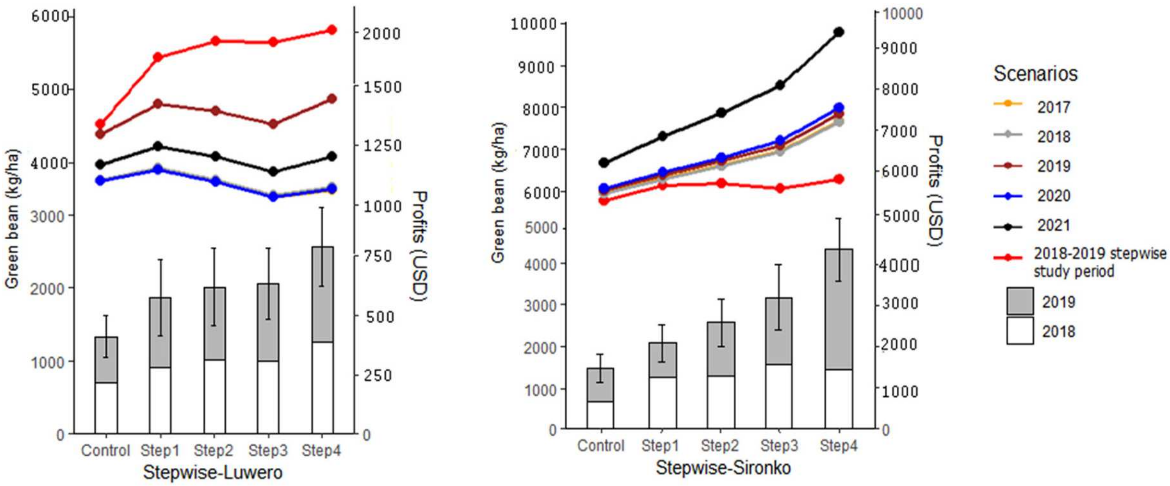

Figure 5. Cumulative coffee yields ($ha^{-1}yr^{-1}$) for the different steps for 2018 and 2019, with line graphs for profit in USD depicted by farm gate price scenarios between 2017 and 2021 for Robusta (Luweero) and Arabica (Sironko) coffee sites.

in the Stepwise approach indicates a gradual profit gain when control was compared to all Steps. However, investing in Step 2 and Step 3 tends to have reduced profit gain for Robusta (Figure 5). Although, incorporating the use of fertilizers in Step 4, profitability increased again. Similar trends were observed when the GAPs were subjected to price scenario analysis using farmgate coffee prices for five years between 2017 and 2021 (UCDA, 2022).

In the Arabica growing area profitability increased gradually alongside the incremental investment in GAPs. In Step 4, the profitability was more pronounced with the introduction of pesticides to manage pests and diseases. Arabica coffee is more sensitive to pests and diseases, implying that using manure and fertilizers to boost nutrient availability before chemical control of pests and diseases does not improve coffee productivity significantly. However, when the pesticide was introduced in Step 4 the disease prevalence of CLR was significantly reduced (Table 4). As a result, there was a significant yield increase ($P < 0.05$) observed in Step 4 for the 2019 coffee yield season (Figure 3). Overall, investing in the Stepwise approach seems to be profitable at any Step despite the volatile nature of annual farm gate coffee prices (Figure 5).

4. Discussion

4.1. Options for improving coffee productivity and field testing of the Stepwise approach

The recommended GAPs for coffee are complementary functioning through synergistic effects to enhance optimal crop productivity (Thierfelder et al., 2018). Application of basic management practices (weed control, desuckering, pruning) are the fundamentals to build complementarity so that subsequent application of GAPs with significant potential (fertilizers and manure) to increase productivity become more effective. Much as the earlier studies confirmed that the application of GAPs results in increased crop (coffee) productivity (Pillai et al., 2015; Wagner et al., 2021), this application should be implemented judiciously to account for synergistic functionality of GAPs. During co-design and co-development of the Stepwise approach, complementarity effect of GAPs was emphasized in the guiding protocols. Stepwise application of GAPs generally demonstrated a gradual increase in coffee productivity as more yield was realized when the entire set of GAPs was applied in Step 4. Implying that all the recommended practices for coffee should be adopted for better productivity. Benefits of applying GAPs such as manure, fertilizers, and mulch which are considered in the topmost Stepwise intensification pathway are reported to have residual effects that contribute to increased production in subsequent seasons and improvement in soil properties (Eghball et al., 2004). Furthermore, the combination of these management practices such as organic manure and fertilizers enhances crop productivity, soil organic matter content, and soil water retention, which builds up through the sustainable use of inputs (Tittonell et al., 2008; Vågen et al., 2005). Thus, low productivity among the smallholder farmers is attributed to inability to adopt all the recommended GAPs at once due to the associated capital and transaction costs (Giller et al., 2011; Nachibi et al., 2024). Thus, the Stepwise approach has demonstrated the potential to improve coffee productivity through incremental adoption of GAPs in affordable small sets of practices. The phased application of the Stepwise GAPs packages is likely to transition farmers from low adoption to improved adoption as gained productivity from each step encourages them to consider applying next step and so on, until they can afford to apply the entire set of recommended GAPs. The yield gain in Step 4 of Stepwise corroborates the attainable coffee yield observed in Uganda (Bekunda et al., 2002; Wairegi et al., 2016) for Arabica and Robusta coffee. To optimize coffee productivity, the entire package of GAPs must be adopted by farmers. The study findings demonstrate that applying a predetermined unit of basic management practices improved the coffee yield when compared with the control. The basic GAPs such as weed control, pruning, and desuckering which require minimum capital investment are useful to reduce competition for nutrient resources crucial for plant growth and productivity. Resource use efficiency is likely to improve when farmers are guided on how to apply GAPs that fit within their means and capabilities. Adoption of GAPs is a key driver of enhanced productivity reducing the gap between potential and actual farmers' yields (Manda et al., 2016). Improved coffee productivity provides an economic knock-on effect across the entire coffee value chain benefiting farmers, processors, exporters, offering employment opportunities and the overall economy through increased income, and foreign exchange earnings (Koutouleas et al., 2023). The Stepwise approach thus presents potential fundamentals for improving adoption and productivity among smallholder coffee farmers in Uganda. Similarly, previous studies have predicted that approximately 80% of future production gains will be made through intensification pathways to enhance systems resilience rather than through land expansion (de Haen et al., 2003; Mishra et al., 2021) to reduce poverty and improve rural livelihoods. However, agroecological intensification that integrates social capital, and farmers' aspirations is generally considered more equitable for sustainability (Haggar et al., 2021; Lamboll et al., 2021). Previous studies concluded that collaborative and interdisciplinary interventions prioritizing farmers in their design and implementation is key to the continued success and longevity of the coffee subsector (Smith et al., 2022; Karr et al., 2017).

The study approach corroborates the Social Capital Theory (van Bakel & Horak, 2024) that suggests building relevant social networks. This study inclusively involved different stakeholders throughout the stages of co-design, co-development and co-learning of Stepwise. This created an understanding of the potential benefits and challenges associated with incremental investment in coffee management. Previous studies concluded that collaborative and interdisciplinary interventions prioritizing farmers in their design and implementation are key to the continued success and longevity of the coffee subsector (Karr et al., 2017; Smith et al., 2022). Collaborations enable different actors to support each other by leveraging, combining, and capitalizing on their complementary strengths and capabilities (Lasker et al., 2001). Furthermore, collaborations provide more innovative solutions to complex issues, reducing duplication of efforts, bringing together multiple human and financial resources, and creating higher-quality programs (Marek et al., 2014; Peterson et al., 2021).

Partners contributed towards the successful outcome of this study: Research partners identified the gaps in GAPs adoption and conceptualized the approach. Knowledge experts guided the phasing of the recommended GAPs into unit packages that smallholder farmers could potentially afford to apply in phases. Regional technical stakeholders adapted the packages to a site-specific context to prioritize the control of the most limiting production constraints. For example, in the Robusta growing area soil and water conservation practices were prioritized to enhance soil water infiltration and moisture retention. In the Arabica growing area, soil fertility amendments were given priority as the use of mineral (inorganic) fertilizer is recommended in Step 3 compared to the Robusta growing area where this practice starts in Step 4.

The participation of public and private sector players provided the platform and infrastructure to pilot and scale the Stepwise approach beyond the immediate project area. This participatory action research utilized the existing private and public sector structures and networks of extension staff and farmer groups to enable a consistent delivery of knowledge to farmers. Farmers were mobilized for training by private sector partners at demonstration sites for visual observation and assessments to facilitate practical learning and potential adoption. The field testing of the Stepwise packages at the demonstration sites provided empirical evidence and learning to the farmers. As a result of this study, private sector partners HRNS and Olam Ltd through their existing extension service structures, trained 13,672 (8,149 males and 5,523 females) farmers in the Central and Southwestern Uganda; and 260 farmers (160 males and 100 females) in Sironko district on Stepwise between 2018 and 2020 respectively (IITA, 2020). This resulted in many early adopters including demonstration host farmers that expanded the learning beyond the demonstration sites (IITA, 2020; Mukasa et al., 2020). At the national level, the Stepwise approach is acknowledged by the Uganda Coffee Platform as one of the novel approaches to increasing investment in coffee farming systems (Mugoya, 2018). The Stepwise approach has been incorporated into the Uganda Coffee development Authority technical handbooks for Arabica and Robusta coffee to guide farmers on the adoption of GAPs (UCDA, 2019).

4.2. GAPs practices on management of pests and diseases (BCTB and CLR)

The Stepwise GAPs tested were effective in reducing the impact of BCTB to almost one infested twig per coffee tree than when the pest was not controlled at all. Cultural control through trimming and burning of infested twigs was as effective as chemical (pesticide) control. This could be attributed to farmers reluctance in the community to control BCTB, offering a wider breeding ground for pest multiplication and spread, overwhelming the efficacy of pesticides. Thus, controlling BCTB by a pesticide approach in such an environment only increases the cost of production. Therefore, a timely cultural method (on a monthly basis) for BCTB control appears to be more cost-effective and environmentally friendly to cash constrained coffee farmers.

Based on observed results in the Arabica site, no GAPs package (cultural versus chemical) offered a significant control over CLR based on developed disease rating scale (1-4) to score for severity of infection per tree as follows: 1 = No CLR or Coffee Berry Disease (CBD), 2 = < 10% diseased leaves or berries, 3 = 10-30% diseased berries or leaves, 4 = > 30% diseased leaves or berries (Phiri et al., 2001) as disease scores in all Steps were in category 3 (high) of the rating scale. CLR control by pesticides (fungicides) in Step 4 had a low impact on controlling seasonal disease outbreaks, even though the results for the pesticide application demonstrated a significant reduction in incidences and severity when compared with cultural control. However, when scores were rated to the disease scale (Phiri et al., 2001), the average proportion of CLR-infected leaves in the demonstration sites, was high across all Steps. The highest severity (scale 4) seems to occur in dry seasons (January and February) results not shown. This could imply that the CLR when the inoculum within the neighbouring coffee farmer fields is high (not managed) for an airborne disease, the efficacy of pesticides-Copper Oxychloride 50% WP (Wettable Powders) as active ingredient used to control the infection and spread is reduced. CLR is reported to cause about 10–50% yield loss in farms where no control measures are undertaken (Van der Vossen, 2001; Silva et al., 2006).

4.3. Economic benefits of adopting GAPs

The two-year study demonstrated the economic advantages of the Stepwise approach. The phased application of GAP packages resulted in incremental yield increases and profitability despite price volatility in the coffee market which was depicted by a 5-year period scenarios analysis. The results from both sites indicate that coffee is a profitable enterprise. Profitability increased when more investments were made in mulching and chemical control of pests and diseases in Step 4 in both sites. Similarly, Marginal rate of returns (MRR) was relatively high for Step 1, 2 and 4 for Robusta coffee 563%, 169% and 122%, and 221%, 217% and 485% for Step 2, 3 and 4 for Arabica coffee respectively, implying that a Stepwise investment in GAPs is generally profitable except for Step 3 and Step 1 in Robusta and Arabica which showed low returns respectively. Sensitivity analysis performed to evaluate changes in coffee prices and input variable costs affected the benefits of Stepwise investments in GAPs. Fluctuations in coffee prices by 50% had negative effect on benefits of all Steps in both regions except Step 4 in the Arabica growing region. However, in a scenario when coffee prices increase by 200%, all Steps in both regions registered the highest returns on investment.

The increase in input costs by 50% negatively affected the MRR in Robusta growing region except for Step 1(342%) implying that investing in GAPs was not beneficial for Steps (2-4). However, Arabica coffee growing regions had good MRR at price fluctuation as low as 50% and at increase input costs by150%

except for Step 1. Stepwise investment in GAPs was unacceptable (i.e. MRR < 1) for Steps (2-4) except for Step 1 in Robusta. Arabica growing regions only Step 1 (package) was unacceptable for investment.

Sustainable coffee production amidst the impacts of climate variability demands investment in mulching, manure application, and fertilizer usage and these practices tend to be costly. Coffee is a high-investment crop, so to realize increased crop agronomic efficiency and sustainable economic yield, the application of the entire set of GAPs including practices is key for sustainability, yet investment in high end GAPs negatively affects MRR, especially with Robusta coffee. Costly inputs such as mulching materials can be substituted with cover crops and recommended shade trees to improve the in-situ mulch layer due to leaf litter and biomass turnover. Importantly, coffee is a tree crop that requires good management throughout its growth cycles; poor investment in GAPs can result in coffee being exposed to high risks of pest infestation and disease severity (Theresa Ines Liebig, 2017) reducing coffee quality and quantity. Furthermore, low investment in GAPs can lead to nutrient mining; for example, to produce 1t ha^{-1} of coffee green beans, the nutrient uptake and consumption by different parts of the Arabica coffee tree requires 112 kg N, 18 kg P, 125 kg K, 36 kg Ca, 15 kg Mg and 9 kg S (FAO, 2005). Moreover, nutrients removed in harvested cherries equivalent to 1000 kg of Arabica green beans are reported as 63.1 kg N, 3.25 kg P, and 33.59 kg K (Ripperton et al., 1935). For Robusta coffee, without returning coffee husks to the plantation, 1t ha^{-1} of coffee green beans removes 30 kg N,1.05 kg P and 18.25 kg K (Forestier, 1969). Low input use in coffee production is not sustainable in the long run because of the high nutrient demand by coffee plants to remain productive. Good coffee management practices contribute to the resilience of coffee trees to pest and disease attacks (Altieri & Nicholls, 2003). For example, the availability of nutrients activates and regulates metabolic activity associated with plant resistance, hence the first and foremost line of defence against plant pests and diseases (Huber & Haneklaus, 2007).

Tree shade cover is an appropriate GAP in coffee-based cropping systems suitable for climate variability as it reduces CLR prevalence (Huber & Haneklaus, 2007; van Asten et al., 2012). The current impacts of climate change have resulted in high pest and disease prevalence, with observed trends of CLR becoming more prevalent even at higher altitudes (Iscaro, 2014). Therefore, producing coffee by applying basic GAPs alone will not work for farmers when the impacts of climate change become more prevalent. Although investing in only basic GAPs appears to attract higher returns than the costly practices applied in Steps 3 and 4, the benefits of investing in these basic practices are short-lived when climate change elements expose the coffee plants to production constraints such as erratic rainfall, increased temperature, increased soil temperature, and evapotranspiration. The costly GAPs such as mulching, manure, and fertilizers are potentially effective to off-set climate change impacts and contribute to improved yields. Therefore, it is plausible to invest in the entire GAPs package for coffee in Uganda to survive the threat of climate change impacts especially with Arabica coffee which had high MRR with increase in investment (Step 4) when compared to Step 1. Overall, the observed low MRR could be attributed to the higher cost of inputs such as manure, mulching materials, mineral fertilizers, and pesticides applied in Step 4 concerning the low prices of Robusta during the study period. MRR is arguably one of the most popular metrics, and MRR analysis (when applied correctly) is a powerful tool for making informed decisions in line with the profitability of incremental adoption of GAP practices (Timothy & Joseph, 2003). The costs incurred in purchasing materials and labour in the application of GAPs per Step (Table 1) constituted the variable costs to determine the MRR. The GAPs considered in the MRR per step included weed control, pest, and disease control, purchased manure and cost of application, purchased fertilizer and cost of application, mulching materials and cost of application, herbicides, and pesticides used for the two years of the Stepwise testing. However, the cost of harvesting coffee was not included among the variable costs as it was assumed that for smallholder farmers harvesting is mainly by family labour.

4.4. Agronomic recommendations

Stepwise application of GAP packages concomitantly increased coffee productivity in both study sites. However, it appears that when the entire GAPs were applied, the MRR was reduced due to costly practices such as mulching, pesticides, manure, and fertilizer application as well as low prices for Robusta. Much as the mentioned practices are expensive, their contribution and benefits to sustainable coffee production and ability to offset climate change impacts are also important. For example, mulching accounted for 30% and 37% of the total investment costs in the Arabica and Robusta regions, respectively. Exploring alternatives to mulching materials, such as cover crops with similar potential to retain adequate moisture, improve soil fertility through nitrogen fixation, suppress weeds, encourage high biomass turnover, and provide soil surface cover throughout the year could reduce investment costs.

Furthermore, investment costs can be reduced by dropping practices that did not add value, for example, the control of BCTB by pesticide use (Orius and Imidacloprid), which cost about 19% of the investment budget per hectare in the Robusta site. Cultural pest and disease control methods were cheap to apply and provided good results in reducing BCTB prevalence in the Robusta site. This investment plan supported by sap-exuding shade trees has the potential to narrow the spectrum of BCTB alternative hosts in the Robusta growing region. Bukomeko et al. (2018) reported that a unit increase in the density of sap-exuding trees on the farm has the potential to reduce BCTB infestation by 0.35% on coffee trees. A combination of these types of trees and the application of the full Stepwise package is likely to improve MRR. Also, the integration of coffee-banana systems is likely to bring added value because bananas are not alternative hosts of pests and diseases that attack coffee, as is the case for certain agroforestry trees, for example, *Albezia chinesis* (Chocolate heart albizia). van Asten et al. (2015) reported that banana-shaded coffee experiences a 50% lower incidence of CLR (Hemileia vastatrix) and BCTB (Xylosandrus compactus) when compared to tree-shaded systems.

Improving the coffee-based cropping system through diversification options is likely to boost MRR per unit area; for example, coffee-banana intercrops have been shown to bring added economic benefits compared with their respective sole crops (van Asten et al., 2011). The intercrops provide both food from bananas and income from the sale of bananas, in addition to that from the sale of coffee (van Asten et al., 2011). This gives farmers flexibility in maintaining revenue flows and standards of living, despite the boom-or-bust cycles of the world market for coffee (van Noordwijk et al., 2002). The coffee-banana agroforestry system can potentially increase carbon sequestration, thus contributing towards combating global warming and the associated climate change production constraints.

Breeding for resistance against CLR appears to be the best option for managing disease outbreaks. The results suggest that no single practice was effective in dealing with CLR including the application of pesticides that had only a marginal impact on the disease. Additionally, smallholder coffee fields are randomly scattered across the farming community, providing an opportune environment for CLR massive inoculum build-up which is difficult to control. It is worse when a few farmers decide to apply pesticides.

5. Conclusions

This study reflects the importance of co-design and co-development approaches to address complex agricultural challenges inclusively. More specifically, the study shows that in taking an incremental – Stepwise approach – farmer adoption of recommended coffee GAPs can effectively address challenges faced by resource-limited smallholders. It was observed that breaking down the full suite of recommended GAPs, into more manageable steps resulted in significantly improved coffee productivity and profitability for smallholder coffee farmers. The study shows significant yield improvements and MRR observed in both Arabica and Robusta coffee.

In conclusion, the adoption of the Stepwise approach in Uganda's national extension programs will significantly improve smallholder coffee farmer adoption of GAPs and CSA practices, improve coffee yields and smallholder farmer income. The approach contributes to the sustainable development of Uganda's coffee sector.

However, further studies are required to fully understand the interplay between the different GAPs, coffee varieties and environmental factors to optimize resource use efficiency and maximize the benefits of climate-smart coffee production.

Author contributions

CRediT: **David Mukasa:** Conceptualization, Investigation, Writing – original draft; **Leonard Rusinamhodzi:** Validation, Writing – review & editing; **Piet. J. A. van Asten:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing; **David Amwonya:** Data curation, Formal analysis; **Haroon Sseguya:** Supervision, Visualization, Writing – review & editing; **Faith Akello Okiror:** Investigation, Writing –

review & editing; **Diana Kirungi:** Visualization, Writing – review & editing; **Wilberforce Wodada:** Data curation, Methodology, Writing – review & editing; **Victor Komakech:** Supervision, Writing – review & editing; **Sarah Margiotta:** Project administration, Supervision, Visualization, Writing – review & editing; **Laurence Jassogne:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.**Laurence Jassogne:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – review & editing.

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Data availability statement

The data will then be available in a depository on the Consultative Group for International Agricultural Research (CGIAR) website. The data set associated with the paper can be found at google drive; https://drive.google.com/drive/folders/1ndu0Jrlyfv-Hau2tik0KaHkEkp3P4IrG?usp=drive_link.

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