Agronomy for Sustainable Development (2026) 46:39
https://doi.org/10.1007/s13593-026-01103-z

RESEARCH ARTICLE

Maize-bean row intercropping in Rwanda: labor constraints limit application despite nutritional and economic benefits

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Received: 31 January 2025 / Accepted: 19 March 2026 / Published online: 3 June 2026
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Abstract

Rapid population growth in sub-Saharan Africa is intensifying pressure on food security and reinforcing the need for sustainable agricultural intensification. Maize–bean intercropping presents an opportunity to enhance and stabilize crop productivity in this region. Row intercropping—an arrangement in which two or more crops are planted in intentional row patterns—has been promoted as an efficient alternative to sole crops and traditional mixed intercropping. Yet, evidence of its performance across diverse soils and climates remains limited. This study evaluates the multicriteria performance of maize–bean row intercropping compared with sole cropping and mixed intercropping under contrasting farm conditions. We conducted a large-scale, multiseason on-farm study with 382 trials across a wide range of environments in Rwanda. A novel aspect of this study is to move beyond yield-focused intercropping assessments by jointly considering productivity, nutritional outcomes, labor requirements, economic returns, and farmers' preferences, while uniquely monitoring application rates 4 years after the trials. These dimensions were assessed across a wide range of soil, climate, and socioeconomic farm conditions. Overall, row intercropping had better land use efficiency and higher energy yield and profitability than sole and mixed intercropping systems. It achieved higher land use efficiency in less favorable environments, while its yield stability was comparable to the other cropping systems tested. However, its higher labor requirements, especially at planting, when labor demand peaks, led to only moderate farmer preference. Four years after the trials, application remained limited, with only 30% of participating farmers continuing to use row intercropping despite its higher yields. To enhance adoption, we recommend developing flexible guidelines that allow farmers to adapt practices to their specific needs, introducing labor-saving innovations to reduce the workload at planting, and targeting dissemination to fields with biophysical conditions where row intercropping is expected to deliver the strongest performance.

Keywords Strip intercropping · Mbili-Mbili · Farmer preference · Practice adoption · Multicriteria analysis · On-farm trial · Cereal–legume intercropping

1 Introduction

Sub-Saharan Africa (SSA) continues to face persistent food security challenges despite its agricultural potential (Van Ittersum et al. 2016, 2025). Soil fertility, limited nutrient inputs, and erratic rainfall remain key constraints to crop productivity (Sanchez 2002; Vanlauwe et al. 2015; Couëdel et al. 2026). Maize is the most cultivated cereal by smallholder farmers in SSA (FAOSTAT 2023), providing 30% of the calorie intake of the population (OECD 2016; Ekpa et al. 2019). Despite a large yield potential across the continent, maize yields have stagnated at around 1.9 t ha^{-1} (FAOSTAT 2023), far below the yield potential (Van Ittersum et al. 2016). Closing this gap requires

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sustainable intensification (Vanlauwe et al. 2014)—defined as increasing food supplies while safeguarding biodiversity and other ecosystem functions (Petersen and Snapp 2015).

Cereal–legume intercropping is often promoted as a sustainable intensification strategy with the potential to increase and stabilize yields (Rusinamhodzi et al. 2012; Namatsheve et al. 2020; Li et al. 2021; Ruillé et al. 2026). Yet yield gains remain modest (20–40%) (Himmelstein et al. 2017; Namatsheve et al. 2020) and are insufficient to close yield gaps (Falconnier et al. 2023). Therefore, combining intercropping with adequate, targeted nutrient inputs has been proposed to increase productivity (Affholder 1997; Rötter and Van Keulen 1997; Traoré et al. 2023), but this requires adapted management—such as optimizing crop arrangements, planting densities, and sowing dates—to reduce resource competition (e.g., light and water) (Mudare et al. 2022).

In SSA, mixed intercropping and alternate single-row intercropping are most common (Mudare et al. 2022). These systems often suffer from suboptimal spacing, shading, and competition for water and nutrients, which can reduce yields and profitability compared to sole cropping (Isaacs et al. 2016; Niyomugabo 2019; Madembo et al. 2020).

In contrast, multiple row intercropping—using alternating strips of two or more rows of cereal or legumes—offers a more structured approach that can reduce shading, improve light capture through better repartition, enhance fertilizer use efficiency, and maintain high plant populations (Woomer et al. 2004; Mucheru-Muna et al. 2010; Kinyua et al. 2023; Thierfelder et al. 2024). The effectiveness of multiple row intercropping depends largely on plant traits and crop types (e.g., combining short and tall crops), with maize and beans being particularly suitable for this arrangement (Mucheru-Muna et al. 2010).

Smallholder farmers operate under highly diverse conditions—including variability in weather, soil quality, socioeconomic status, household needs, and social dynamics—that strongly influence both the performance and application of improved management practices (Suri 2011; Suri and Udry 2022), including intercropping (Ha et al. 2023). On-farm trials conducted across multiple locations and growing seasons account for this diversity and are thus essential for understanding the robustness of sustainable intensification strategies (Baudron et al. 2012; Vanlauwe et al. 2019; Lacoste et al. 2022). Numerous studies have examined the yield performance of cereal–legume row intercropping systems on smallholder farms (e.g., Madembo et al. 2020; Mucheru-Muna et al. 2010), but few have conducted a comprehensive multicriteria analysis that considers nutritional, economic, and social dimensions across diverse agroecological and socioeconomic contexts. Additionally, limited research has examined the barriers to application and the lack of fit to farmer conditions, such as increased labor requirements associated with more complex planting arrangements (Kinyua et al. 2023; Thierfelder et al. 2024).

This study addresses these gaps by evaluating the potential of improved intercropping practices, particularly maize–bean row intercropping, to enhance crop production outcomes. Specifically, it asks whether row intercropping can simultaneously improve productivity, nutritional outcomes, profitability, and farmer application under contrasting agroecological and socioeconomic conditions. The novelty of our approach lies in moving beyond yield-focused intercropping assessments by integrating nutritional value, labor requirements, economic performance, and farmers' preferences. We examine these dimensions across a wide range of soil, climate, and socioeconomic farm conditions, while uniquely documenting application dynamics after 4 years.

Our analysis draws on a unique dataset from 382 on-farm trials conducted over two growing seasons across Rwanda. We hypothesized that row intercropping shows better performance than sole cropping and mixed intercropping. Specifically, we hypothesized that row intercropping (i) improves land use efficiency, (ii) provides higher and more stable nutritional outputs (energy, protein, and fat), (iii) generates higher net returns despite higher costs, (iv) has lower labor use efficiency, and (v) faces lower farmer preference due to higher labor requirements.

2 Methods

2.1 Study area

Field trials with the participation of farmers were conducted by "One Acre Fund" (OAF) (https://oneacrefund.org/) as part of their research and development program aimed at supporting their nationwide extension services in Rwanda. The research was conducted in 11 districts of Rwanda (Figure S1.A). A total of 225 farmers (representing 382 farmer fields) participated in on-farm trials over two growing seasons (2019B and 2020A). Rwanda has a bimodal rainfall distribution with rains from September to early January in season "A" and from late February to early June in season "B." Trial locations were stratified according to adapted maize mega-environments (MEs), a classification that combines the International Maize and Wheat Improvement Center's (CIMMYT) MEs with OAF's local knowledge of how maize variety and management interact with altitude and rainfall distribution. We refer to these adapted zones as ME-OAFs hereafter. The number of trials was allocated across ME-OAFs according to the number of OAF field officers in each zone, with larger ME-OAFs having more officers and more participating farmers. Within each ME-OAF, trials were further distributed across districts. A description of the

environmental conditions in each ME-OAF during the two growing seasons of the trials and the number of participating farmers per ME-OAF can be found in Figure S5.

Host farmers were recruited through announcements made during OAF client and nonclient meetings at the cell level (i.e., the administrative unit with an area of 5–10 km^2). Interested farmers could participate only if their fields lay outside the land-consolidated areas of Rwanda's Crop Intensification Program, where priority crops are grown collectively and intercropping is not allowed. OAF trial officers then inspected the fields for suitability, and participating farmers signed consent forms before planting.

2.2 Experimental design and plot management

The trials were conducted on 382 farmers' fields, 182 in the 2019B season and 200 in the 2020A season, involving a total of 225 different farmers, as the exact group of participating farmers varied between the two seasons. Each field-year was treated as a unique observation in the analysis. On each farmer field, all treatments were established side by side within a uniform area divided into five plots of 5 × 10 m each. Treatments were randomized within each field, and each field-year was considered as a block in the overall experimental design. The trials were rainfed and included the following treatments, (i) sole crop maize (M_SC), (ii) sole crop beans (B_SC), (iii) multiple rows intercropping of maize and beans (RI) (Figure 1), (iv) local practice of intercropping of maize and beans (LI_MB), and (iv) local practice of intercropping of maize with other crops or arrangements (LI_MO) (Figure S1). To reflect local recommendations for producing both maize and beans, performance of sole crop systems (SC) was calculated as comprising half a hectare of maize and half a hectare of beans. Plant spacing for sole maize was on average 0.8 m × 0.4 m with two maize plants per planting hole. Spacing for sole beans was on average 0.4 m × 0.1 m, planted in furrows. However, actual spacing varied among farmers, resulting in average plant densities of 5.9 plants m^{-2} for sole maize (range: 4.9 to 6.8 plants m^{-2}) and 26.1 plants m^{-2} for sole beans (range: 20.1 to 35 plants m^{-2}) (Figure S6). In the first season (2019B), maize and beans in RI were planted in alternating strips of two maize rows and two bean rows. Maize density was slightly reduced compared to sole crop (mean 80% of sole crop density) using narrower rows (0.4 m × 0.4 m), while bean density was almost halved compared to sole crops (mean of 57%; 0.4 m × 0.1 m). In the second season (2020A), farmers had flexibility in the RI treatment to adjust the number of bean rows after two maize rows (either 2, 3, or 4 bean rows), allowing them to tailor the balance between maize and bean yields according to their preferences or needs. In both seasons, farmers were free to choose their crop arrangements and spacing in the LI_MB and LI_MO treatments. In the LI_MO treatment, farmers added a second, third, or even fourth crop such as bean, soybean, Irish potato, sweet potato, peas, or groundnuts (the occurrence of the crops included in LI_MO is displayed in Table S1). When farmers already applied bean and maize intercropping in LI_MO, the arrangement and patterns differed from LI_MB. For example, maize and beans could be planted in the same hole; beans grown on stakes or both crops could have different sowing densities than LI_MB.



Fig. 1 Maize and beans row intercropping in one of the 225 smallholder Rwandan farms included in the study. Photocredit: Diego Cerrudo.

The maize varieties used were Pool 9A (open-pollinated variety) in the high-altitude areas and PAN4M21 (hybrid variety) in the low- to mid-altitude areas, reflecting the most popular certified seeds in each region at the time of the trials. For the bean crop, farmers usually use a mix of varieties based on personal preferences and needs. Bush beans were commonly used in the eastern, southern, and parts of the western region, while climbing beans were used in the western region.

Fertilization followed the recommended rates from MINAGRI (2018) for sole maize and beans. For sole cropping (SC), we assumed that farmers would split a 1-ha plot into 0.5 ha for maize and 0.5 ha for beans. Sole maize received 100 kg ha^{-1} of diammonium phosphate (DAP) and 50 kg ha^{-1} of urea, supplying a total of 41 kg N ha^{-1} and 20 kg P ha^{-1}, while sole beans received 100 kg ha^{-1} of DAP with no urea, supplying a total of 18 kg N ha^{-1} and 20 kg P ha^{-1}. Urea was micro-dosed only to maize in intercrops. For intercropping, the 1 ha was assumed to be fully intercropped and fertilization rates were averaged, resulting in 100 kg ha^{-1} of DAP and 25 kg ha^{-1} of urea, supplying a total of 30 kg N ha^{-1} and 20 kg P ha^{-1}. As such, when comparing the SC system (0.5 ha maize + 0.5 ha bean) to the intercrop system on a per-hectare basis, both systems received the same

amount of nutrients. This approach reflects typical smallholder conditions, where limited land would otherwise be divided between maize and beans, and ensures that observed differences in performance reflect crop (intercropped or not) effects rather than disparities in nutrient inputs. The same fertilization rates were also applied to the LI_MO treatment to ensure consistency and avoid additional variability. DAP fertilizer was broadcast and incorporated at sowing, while urea was micro-dosed at the sixth-vegetative-leaf (V6) growth stage of maize. Farmyard manure was sourced and applied by farmers following their standard practices, broadcast at planting, and applied at the same rate across treatments.

Weed control was done once or twice, as needed, to ensure minimal competition with the crops for each treatment and reflect standard farmer practice. The first weeding was approximately 30 days after planting and the second around 50 days after planting. No pesticides were used.

Crop management activities were carried out by the farmer under the supervision of an OAF trial officer, who supervised the plot demarcation, randomization, setup, and management of the experimental plots and the data collection, to ensure adherence to trial protocols. OAF provided the fertilizers and maize seeds, while the farmers supplied the land, labor, composted manure, and bean seeds. Each trial officer supervised 15–20 farmer fields. Experimental setup, follow-up, and data collection were audited by phone calls for 20% of the participating farmers. Farmers signed consent forms agreeing to host and manage the trials and engage in related surveys, with the option to withdraw at any time.

2.3 Measurements and calculations

2.3.1 Crop yield measurement and calculation

Field data was collected using the cloud-based application, CommCare (Dimagi 2024), to ensure instant data submission. Data was checked every week to identify and correct any errors promptly.

At harvest, maize cobs and bean pods were collected and weighed from the central 25 m^2 (3.2 × 7.8 m) of each 50 m^2 (5 × 10 m) plot, maintaining a buffer zone along plot edges (1.2 m and 0.8 m on the long and short sides, respectively) to minimize border effects. For sole maize and sole bean, with row spacings of 0.80 m and 0.40 m, respectively, four and eight rows were harvested within the 3.2 m width of the central plot. In RI, two rows of maize and two rows of beans were alternately planted with 0.40-m row spacing, allowing for harvesting two sequences of maize and bean rows (4 rows per crop). Subsamples of maize cobs and bean pods were collected from each plot, and their fresh weights were recorded immediately upon harvest. These subsamples were subsequently air-dried at the farmers' homes for 30–40 days before being shelled to obtain dry grain weights at approximately 15% moisture content. The same procedure was applied to the soybean, peas, and peanut seeds and to sweet and Irish potato roots.

The land equivalent ratio (LER) was used to assess intercropping performance relative to sole crops. LER is defined as the relative land area needed under sole cropping to reach the same yields obtained from intercropping (Willey 1979). LER equals the sum of the partial LER (pLER) of each intercropped species:

$$LER = pLER_M + pLER_B \tag{1}$$

$$pLER = \frac{Yield_IC}{Yield_SC} \tag{2}$$

where pLER_M and pLER_B are the pLER of maize and bean, respectively. Yield_IC and Yield_SC are the yields of a specific crop (maize or bean) in intercropping and sole cropping systems, respectively. An LER greater than 1 indicates that intercropping is more advantageous than sole cropping, as it requires less land to obtain the same yields of both crops. In contrast, an LER lower than 1 indicates that intercropping is less advantageous than sole cropping because interspecific competition is higher than intraspecific competition. An LER equal to 1 signifies a neutral outcome, where the interactions between crops neither increase nor reduce overall productivity.

To account for plant density in the analysis, we also computed the relative density (RD), the total relative density (RDT), and the scaled relative density (SRD) in intercrops (Li et al. 2020; van Der Werf et al. 2021) as follows:

$$RDT = RD_maize + RD_bean \tag{3}$$

$$\mathrm{RD} = \frac{\mathrm{d_{IC}}}{\mathrm{d_{SC}}} \tag{4}$$

$$SRD = \frac{RD}{RDT} \tag{5}$$

where RD_maize and RD_bean are the relative density of maize and bean, respectively. d_{SC} and d_{IC} are the plant densities of a specific crop (maize or bean) in intercropping and sole cropping systems, respectively.

We adapted the pLER to account for contrasting relative plant densities in intercropping versus sole cropping:

$$\mathrm{pLER_{cor.dens}} = \frac{\mathrm{pLER}}{SRD} \tag{6}$$

A $pLER_{cor.dens}$ value below 1 indicates that competitive effects outweigh complementarity, compensation, or

facilitation and/or that interspecific competition is higher than intraspecific competition. A $pLER_{cor.dens}$ value above 1 suggests that complementarity and facilitation surpass interspecific competition and/or that interspecific competition is lower than intraspecific competition.

The environmental index (EI) for each farmer's field (field-year combination) was calculated as an indicator of the combined quality of weather, soil, and management conditions relative to other farmer fields in the same ME-OAF. The EI was derived from the yields of sole maize and beans, with equal weight assigned to both crops. The EI for each farmer's field (i) within ME-OAF (j) was determined as follows:

$$EI(ij) = \frac{Ym(i)}{Ym(j)} + \frac{Yb(i)}{Yb(j)} \quad (7)$$

where $Y_m(i)$ and $Y_b(i)$ are the maize and bean yields from the farmer field i and $Y_m(j)$ and $Y_b(j)$ are the average maize and bean yields across all trials in the ME-OAF j. An EI value of 1 indicates that the growing conditions in the farmer field were comparable to the average conditions of the ME-OAF for seasons 2019B and 2020A. An EI greater than 1 signifies more favorable growing conditions for maize, beans, or both. In contrast, an EI value lower than 1 indicates that the growing conditions in the farmer field were poorer than the average conditions for maize, beans, or both within the ME-OAF. Because crop management practices were highly homogeneous across farmers, the EI serves as a reasonable proxy for underlying field-level growing conditions within each ME-OAF.

2.3.2 Nutritional value

To assess the nutritional performance of the different cropping systems and to enable a comparison of cropping systems with different crops, plant densities, and arrangements, yields were expressed in terms of energy yield (GJ ha^{-1}), protein yield (t ha^{-1}), and fat yield (t ha^{-1}). For this purpose, energy, protein, and fat contents per crop were used as specified in the FAO's Family Nutrition Guide developed by Burgess and Glasauer (2004). Energy yield (GJ ha^{-1}) was calculated as the product of crop grain yield and its energy content (per 100 g): 1.48 MJ for maize, 1.39 MJ for beans and peas, 1.74 MJ for soybean, 0.33 MJ for Irish potato, 0.44 MJ for sweet potato, and 2.37 MJ for groundnut. Protein yield (t ha^{-1}) was calculated using the following protein contents (%): 9.3% for maize, 22.6% for beans and peas, 36.5% for soybean, 2.1% for Irish potato, 1.7% for sweet potato, and 25.8% for groundnut. Fat yield (t ha^{-1}) was calculated using the following fat contents (%): 3.8% for maize, 0.8% for beans and peas, 20% for soybean, 0.1% for Irish potato, 0.3% for sweet potato, and 45% for groundnut. For each cropping system, energy, protein, and fat yields were obtained by summing the respective contributions of all crops included in that system.

2.3.3 Economic indicators

We calculated four key economic indicators: (i) total costs, (ii) gross benefits, (iii) net benefits, and (iv) benefit-to-cost ratio.

Total costs included costs related to inputs (fertilizer, seeds), materials (stakes to support climbing beans, depreciated over two seasons), and labor (planting, weeding, and fertilizer application). Labor costs were estimated following the FAO (2016) framework for calculating labor costs in crop production, considering family labor as hired labor. Planting, weeding, and top dressing were the activities considered. The labor quantity in each plot was recorded by an OAF trial officer and calculated by averaging the number of individuals involved in the activities, multiplying by the time spent, and dividing by a standard 7-h workday (420 min). Average field worker wages for each administrative cell (i.e., the administrative unit with an area of 5–10 km^2) were obtained from a local wage survey.

Gross benefits were calculated by summing the revenue of each crop in the plot, obtained by multiplying the yield of each crop by its respective unit price (USD kg^{-1}). Revenue per crop was calculated based on the local market prices. A market price survey was conducted across all trial districts in April, June, and July of 2019, with averaged values representing market prices for the 2019B season. Due to COVID-19 restrictions, market price surveys for the 2020 A season could not be performed; therefore, we used the 2019B values as proxies. Historically, Season B prices are generally comparable to or slightly higher than those in Season A.

Net benefits were calculated for each plot as the difference between gross benefits and total costs. The exchange rate used for currency conversion was 950 Rwandan francs (FRW) per US dollar (USD). The benefit to labor ratio was calculated as the ratio of net benefits to labor costs.

2.3.4 Preference and application surveys

After harvest, all participating farmers were surveyed in person to assess their preferences regarding the cropping systems. The survey was conducted following a presentation of the harvest results to each farmer. A pairwise comparison approach was used, allowing farmers to give their preference between two systems at a time (e.g., RI vs SC, RI vs LI_MB, and LI_MB vs SC). Based on these comparisons, a ranking from 1 to 3 was generated among the three systems. Farmers were also asked whether they planned to adopt the RI system. Those who answered "no" were asked to specify their reasons, with options including (a) excessive labor requirements,

(b) low production, (c) limited land availability for intercrops, and (d) other (with space to specify additional reasons). These options were designed based on previous experience and surveys conducted by OAF. A follow-up phone survey was conducted in June 2024 (i.e., 4 years after the second-season harvest) to assess the actual application of RI among trial participants and their neighbors. The survey included 83 farmers representing at least 20% of participants in each ME-AEZ and thus broadly reflecting the full sample of 225 farmers. Farmers were asked whether they had implemented RI on any of their fields since the trials. Application was recorded for those who had used RI at least once, and this information was used to estimate the percentage of farmers who applied RI. We also asked farmers what proportion of their land they allocated to RI in the years they applied it. Additionally, farmers were asked how many of their neighbors had applied RI at least once to estimate spillover effects and potential application beyond the original trial participants.

2.4 Data analysis

Analysis of variance (ANOVA) was used to assess the effects of cropping systems (SC, RI, LI_MB, and LI_MO) on agronomic (grain yield), nutritional (energy, protein, and fat yield), economic (total cost, gross benefit, net benefit, and benefit-to-cost ratio), and social (labor requirement, preference rating) variables. Tukey's post hoc test was used to distinguish differences among cropping systems for each variable. Normality was assessed using the Shapiro–Wilk test, while homoscedasticity was evaluated with Bartlett's test. All statistical analyses were conducted using R software (R core team 2023) with differences among treatments considered significant at $p < 0.05$.

We used random forest regression (ranger package in R) to quantify the relative importance of climate, soil, and management in explaining variation in maize and bean grain yield, LER (equation 4), and pLER (equation 6). Random forests are nonparametric models that do not assume a predefined functional form; predictions are obtained by averaging the outcomes of an ensemble of regression trees. For each analysis, we constructed a dataset comprising the outcome variable (maize or bean grain yield in sole crops or in row intercropping, LER, or pLER) and the following predictors: season, agroecological zone (ME-OAF), total seasonal rainfall, altitude, slope, soil texture, landscape position, manure applied, type of bean used, and relative crop densities. Continuous (e.g., rainfall, altitude, slope, manure) and categorical predictors (e.g., soil texture, land position, bean type, management factors) are summarized in Tables S2 and S3, respectively. We ran separate random forest regression analyses for bean and maize in SC and in RI systems (Figure S2), as well as for LER and pLER (Figure S3). Random forest models were trained with 1000 trees, using variance reduction as the split rule and five randomly selected candidate variables at each node (mtry = 5). Variable importance was assessed with the permutation method and scaled relative to the most important predictor (100%). Model performance was evaluated using the out-of-bag (OOB) R^2. This approach allowed us to quantify the relative contributions of rainfall, altitude, slope, soil properties, and management practices to the observed variability in yields, LER, and pLER (Figures S1–S2).

3 Results

3.1 Multicriteria analysis of the performances of cropping systems

The multicriteria assessment across 382 on-farm trials covering diverse environments in Rwanda revealed clear differences in the performance of cropping systems (Figure 2). RI consistently ranked highest in cereal yield, nutritional outputs, and economic returns, but it required the most labor input and was not the system most preferred by farmers, despite its clear agronomic and economic advantages. Sole crops required less labor, but underperformed in overall system productivity. Notably, although widely practiced by farmers, LI_MB and LI_MO generally showed lower performance across indicators, with LI_MB in particular combining low yields, poor nutritional performance, and low profitability (Figure 2). Farmers' preference patterns reflected these trade-offs: While farmers valued the benefits of RI, its higher labor demand reduced its appeal (Figure 2). In the following sections, we examine the different performance indicators in more detail.

3.2 Grain yield and land equivalent ratio

Across the 382 on-farm trials, maize and bean grain yields were significantly greater in sole cropping (M_SC and B_SC) than in the intercropping systems (Figure 3A, B). Among the intercropping systems, maize yields were significantly higher and bean yields significantly lower in RI compared with LI_MB and LI_MO (Figure 3A, B). Yields varied greatly across farmers, and the factors explaining this variability were similar in SC and RI. Total seasonal rainfall was the most important factor explaining yield variability for beans in SC and RI (Figure S2), albeit with a low explanatory power (R^2=0.17–0.27). On the other hand, altitude and slope were the most significant factors for maize in SC and RI, respectively, with similarly low explanatory power (R^2=0.23). The ME-OAF agroecological zones did not significantly explain maize and bean yields in either sole crop or intercrops (Figure S2).

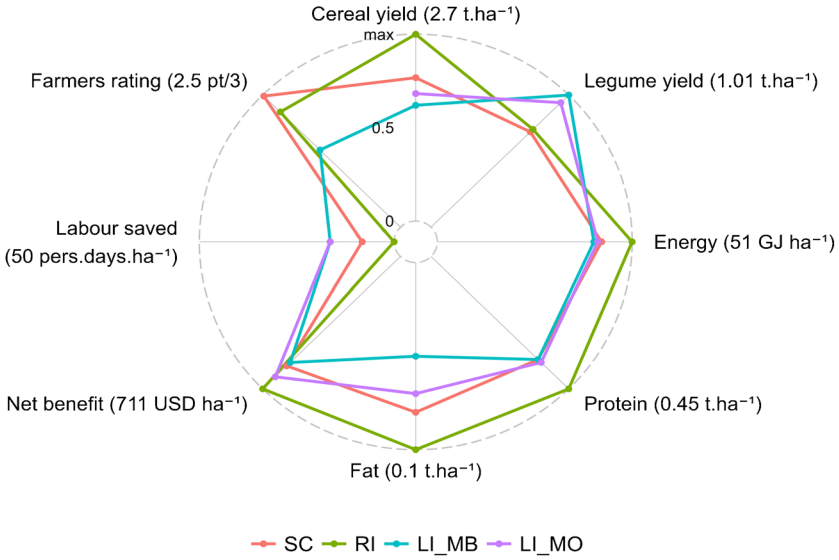


Fig. 2 Cropping systems' multicriteria performances averaged across 225 farms and two growing seasons in Rwanda (382 farmers' fields). The scale is relative to the maximum average performance achieved among the four cropping systems for each indicator. The only exception is labor saved, where the reference corresponds to the system with the highest average labor requirement and where values are inverted so that systems requiring less labor plot closer to the maximum. This ensures that higher values consistently indicate better performance across all indicators. Abbreviations: SC = sole crop as half a hectare of maize and half a hectare of beans; RI = row intercropping of maize and beans; LI_MB = local intercropping maize and bean; LI_MO = local intercropping maize and other crops.

The mean LER was greater in RI (1.22) compared to LI_MB (1.11), with LER exceeding 1 in 74% of cases for RI and 62% of cases for LI_MB (Figure 3C). The mean pLER of maize was higher in RI (0.68) than in LI_MB (0.41), while the pLER of beans was higher in LI_MB (0.70) than in RI (0.54) (Figure 3C). These differences in pLER are explained by farmers using higher bean densities and lower maize densities in LI_MB compared with RI (Figure S6). LER and pLER varied greatly across farmers, and the factors explaining this variability had low explanatory power (R^2 from 0.02 to 0.12) (Figure S3). pLER corrected by scaled relative density was greater than 1 in RI and LI_MB for both crops, indicating that both systems achieved better yields per plant than in SC. The pLER corrected by scaled relative density was slightly higher in RI for maize and in LI_MB for beans, indicating that RI is more effective than LI_MB at increasing maize yield, whereas LI_MB is comparatively more effective for beans (Figure S4).

Notably, the likelihood of obtaining an LER greater than 1 in RI decreases as the EI increases (Figure 3D), indicating that the benefits of RI tend to decrease as growing conditions become more favorable.

3.3 Nutritional outputs

RI had significantly higher yields for energy (+32%), protein (+15%), and fat (+47%) compared with both SC and LI_MB (Figure 4). In contrast, LI_MO had a significantly lower energy yield (−31%) than RI, and there were no significant differences in protein and fat yield between the two. Surprisingly, LI_MB provided the lowest nutritional performance, with the lowest energy, protein, and fat yields of all systems (Figure 4).

The higher nutritional performance of RI came with higher variability in energy, protein, and fat yields across farmers and seasons but without lower minimum values compared with SC (Figure 4). This higher variability was primarily driven by higher fluctuations in maize yields in RI compared with SC.

3.4 Economics and workload

RI had significantly higher net benefits (716 USD ha^{-1}) than the other cropping systems (Figure 5C), due to significantly higher gross benefits (Figure 5A) driven by maize sales (Figure 6A). Yet, RI also incurred significantly higher costs (235 USD ha^{-1}) than all other systems (Figure 5B), primarily due to increased labor requirements. As a result, the benefit-to-cost ratio was similar across systems, except for LI_MB, which had a significantly lower benefit-to-cost ratio than SC (Figure 5D).

The workload in RI was 22% greater than in SC (Figure 6B), mainly due to additional labor needed for planting

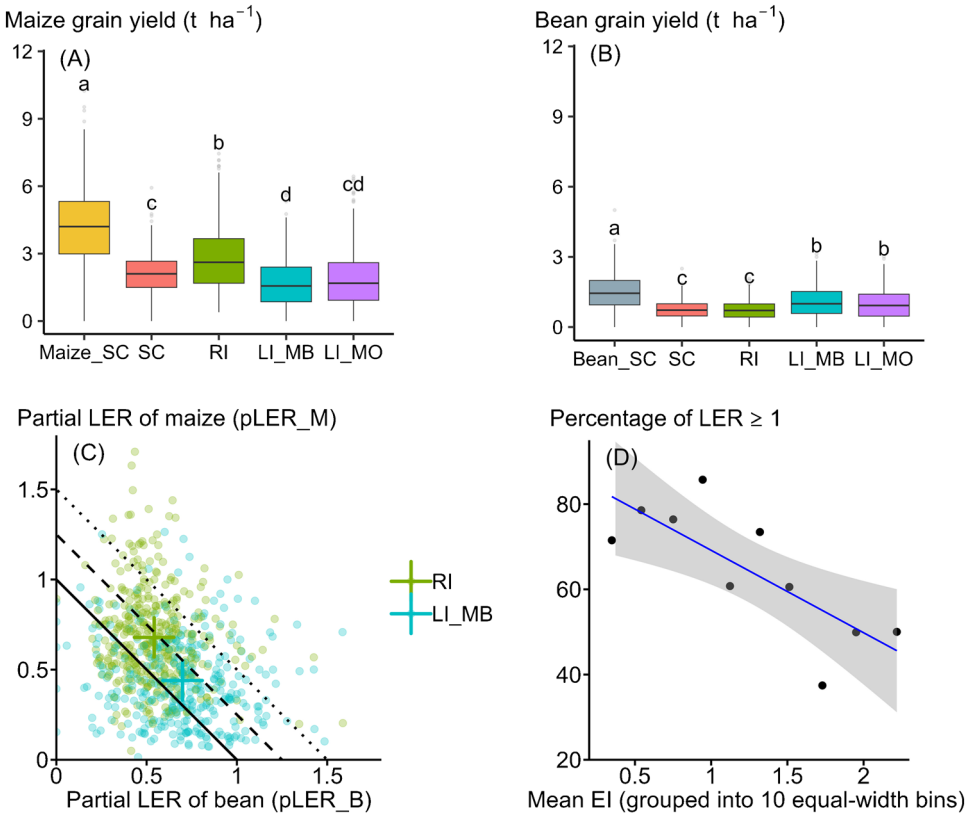


Fig. 3 Maize (**A**) and bean (**B**) yield for the different cropping systems, partial maize LER versus partial bean LER for row intercropping (RI) and local maize and bean intercropping (LI_MB) systems (**C**) and percentage of LER greater than 1 as a function of environmental index when the LER data is divided into deciles ($y = -19.27x + 88$; R^2=0.61; p value < 0.001) (**D**). Data are for 382 farmer trials over two growing seasons in Rwanda. Distinct letters signify statistically significant differences between groups at the 5% significance level. The cross represents the average partial LER of maize and bean for RI (in green) and LI_MB (in blue). Solid, dashed, and dotted lines represent LER of 1, 1.25, and 1.5, respectively. Abbreviations: Bean_SC = sole crop bean; Maize_SC = sole crop maize; SC = sole crop as half a hectare of maize and half a hectare of beans, RI = row intercropping of maize and beans; LI_MB = local intercropping maize and bean; LI_MO = local intercropping with maize and other crops.

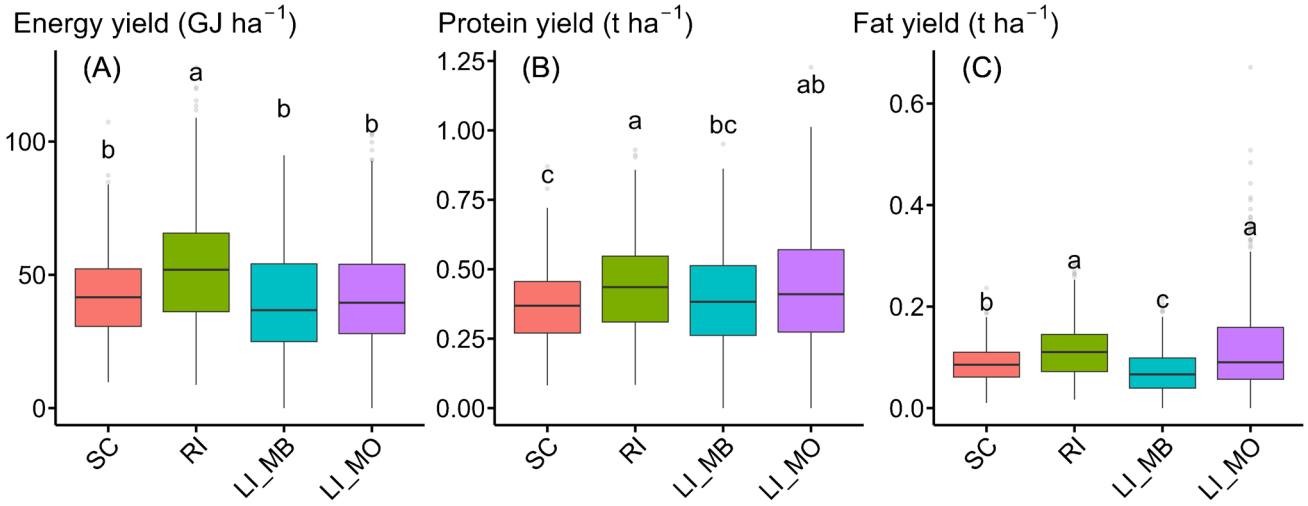


Fig. 4 Cropping systems' energy, protein, and fat yield for 382 farmers' trials over two growing seasons in Rwanda. Distinct letters signify statistically significant differences between groups at the 5% significance level. Abbreviations: SC = sole crop as half a hectare of maize and half a hectare of beans; RI = row intercropping of maize and beans; LI_MB = local intercropping maize and bean; LI_MO = local intercropping with maize and other crops.

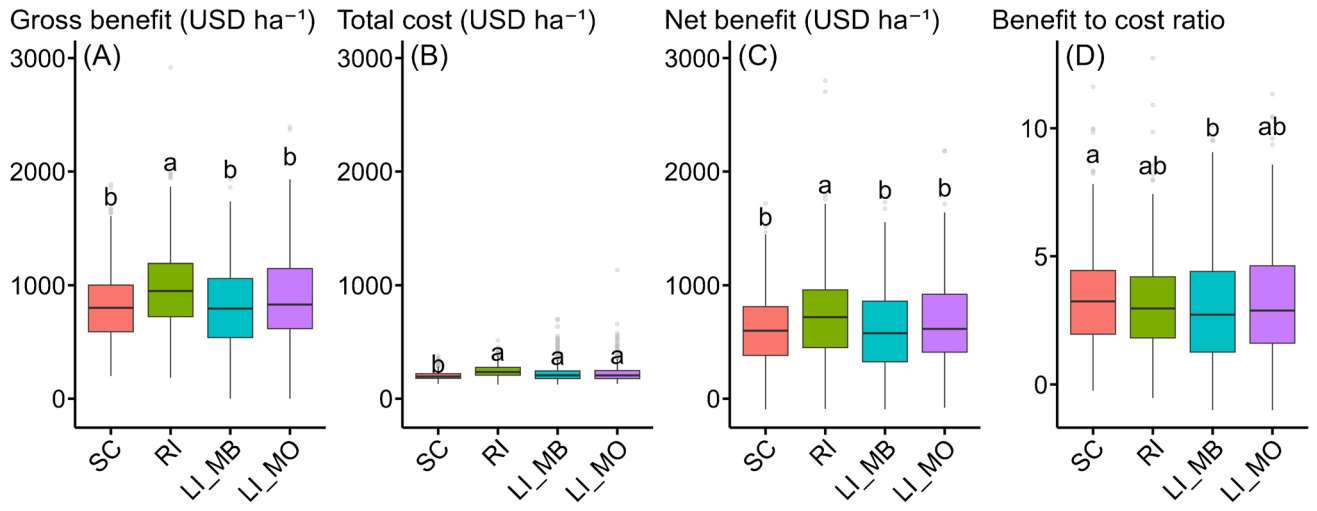


Fig. 5 Cropping systems' total cost, total revenue, net return, and benefit-to-cost ratio for 382 farmers' trials over two growing seasons in Rwanda. Distinct letters signify statistically significant differences between groups at the 5% significance level. Abbreviations: SC = sole crop as half a hectare of maize and half a hectare of beans; RI = row intercropping of maize and beans; LI_MB = local intercropping maize and bean; LI_MO = local intercropping maize and other crops.

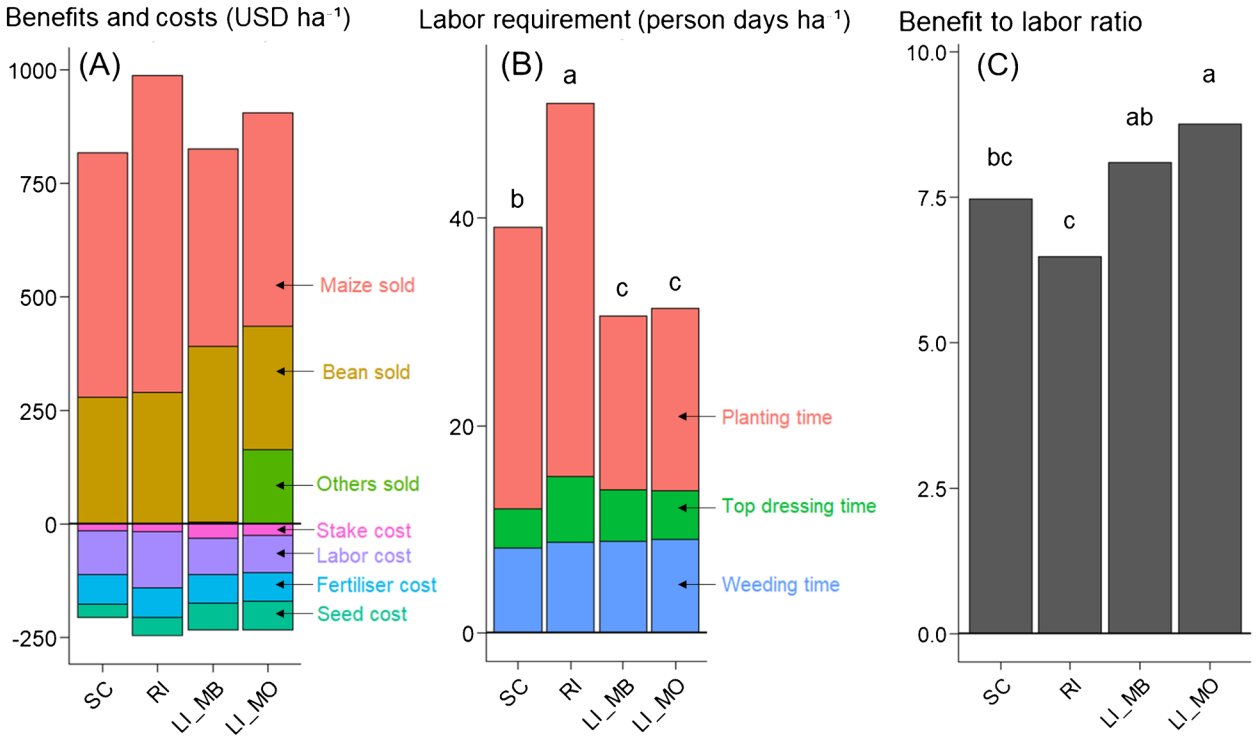


Fig. 6 Cropping systems benefit per crop and cost per management operation (**A**), labor requirement for planting, topdressing, and weeding (**B**), and benefit to labor ratio (**C**). Distinct letters signify statistically significant differences between groups at the 5% significance level. Abbreviations: SC = sole crop as half a hectare of maize and half a hectare of beans; RI = row intercropping of maize and beans; LI_MB = local intercropping maize and bean; LI_MO = local intercropping maize and other crops.

(Figure 6B). Consequently, RI had the lowest labor productivity among all cropping systems (Figure 6C), showing a clear trade-off between high net benefits and reduced efficiency of labor use.

3.5 Preference and application

At the end of the trials, farmers most often preferred SC over RI (Figure 7A). Yet, when compared to their current

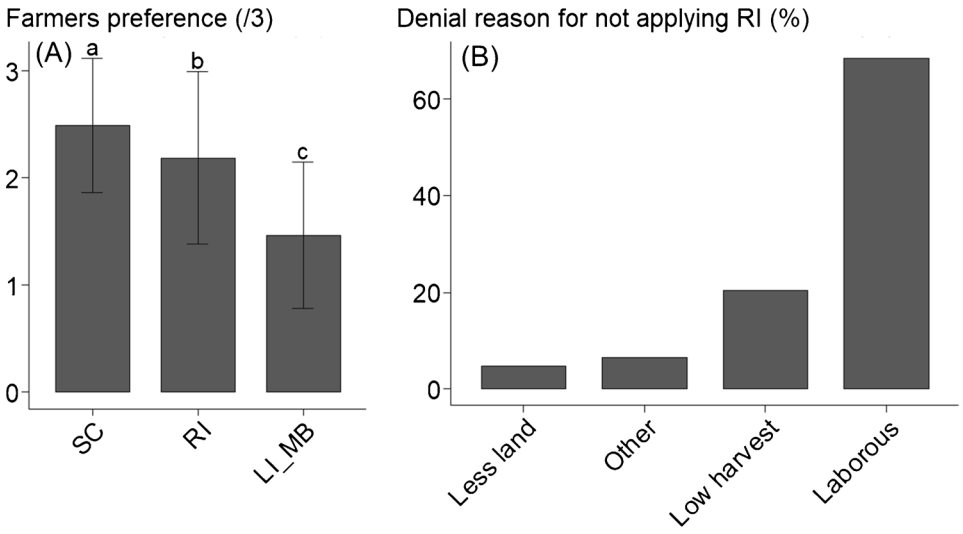


Fig. 7 Farmers' preferred cropping system (**A**) and reason for not applying row intercrops (**B**). Preference ranks were averaged across farmers, with cropping systems ranked on a scale from 1 to 3 based on a farmer survey (1 is low preference and 3 is highly preferred). SC = sole crop as half a hectare of maize and half a hectare of beans, RI = row intercropping of maize and beans; LI_MB = local intercropping maize and bean.

practice of intercropping of maize and beans (LI_MB), RI was preferred by the farmers (Figure 7A). Increased labor demand was identified as the main constraint limiting preference for RI (Figure 7B).

Four years after the end of the trials, 30% of the surveyed farmers had applied RI for at least one season (Figure 8A), on an average of 27% of their land. Application rates 4 years after the trials were similar to the proportions of farmers who had expressed intention to apply during the trials, though actual uptake did not align directly with stated intentions (Figure 8A). Among those who applied RI, half had expressed willingness to do so during the trials, while the other half had not. Additionally, appliers tended to have more neighbors who also applied RI, whereas the majority of nonappliers were surrounded by neighbors who similarly did not apply (Figure 8A).

Interestingly, pioneer farmers who applied RI in the four post-trial years achieved significantly higher LERs in their trials compared to nonappliers (1.39 vs 1.19). Notably, among the appliers, only one farmer had an LER below 1 (Figure 8B). On average, 0.57 neighboring farmers applied RI when trial farmers had an LER < 1, whereas 2.05 neighboring farmers applied RI when trial farmers had an LER > 1 (Figure 8A).

4 Discussion

4.1 Multicriteria benefits and limits of row intercropping systems

Previous studies on RI have primarily focused on a small number of farms in contrasting conditions (Kinyua et al. 2023; Thierfelder et al. 2024) or examined only a limited set of criteria in controlled on-station trials (Namatsheve et al. 2020). Here, we provide robust evidence that RI can improve multiple performance indicators compared with sole cropping and farmers' current mixed intercropping practices across diverse and contrasting growing conditions (summarized Figure 2), although the magnitude and direction of benefits vary across farms and indicators. To the best of our knowledge, this is the first large-scale multiseason on-farm study of RI in SSA. The greater efficiency of RI compared with sole crops highlights that the benefits of intercropping (mixed and RI) arise from cultivating both crops on the same unit of land, thereby enhancing resource-use efficiency. Our study further shows that improved intercropping management through RI reduces interspecific competition relative to intraspecific competition, likely through more efficient resource partitioning. This is reflected in the consistently greater LER and pLER values of RI compared with current mixed intercropping. Using pLER corrected by scaled relative plant density, we show that both RI and the local maize–bean intercropping produced higher per-plant yields than expected from their sowing densities, even though their overall plant densities exceeded that of the sole crops. These findings align with global evidence that RI outperforms mixed intercropping in terms of LER (Yu et al. 2015) and that increased planting density can enhance productivity over sole cropping for diverse intercropping patterns (Yu et al. 2016).

Improved management practices, combined with fertilizer micro-dosing (30 kg N ha^{-1} and 20 kg P ha^{-1}), can double yields of maize and beans (NISR 2019) compared with current farmers' yields in Rwanda, a trend consistent with findings from other regions in SSA (Kinyua et al. 2021; Mbanyele et al. 2021; Kinyua et al. 2023). Yet, this yield increase remains insufficient to close the yield gap, and we lack evidence on how intercropping benefits would evolve under higher levels of nitrogen intensification (Yu et al. 2015, 2016; Mudare et al. 2022). RI offers a promising approach to optimize light utilization, particularly in

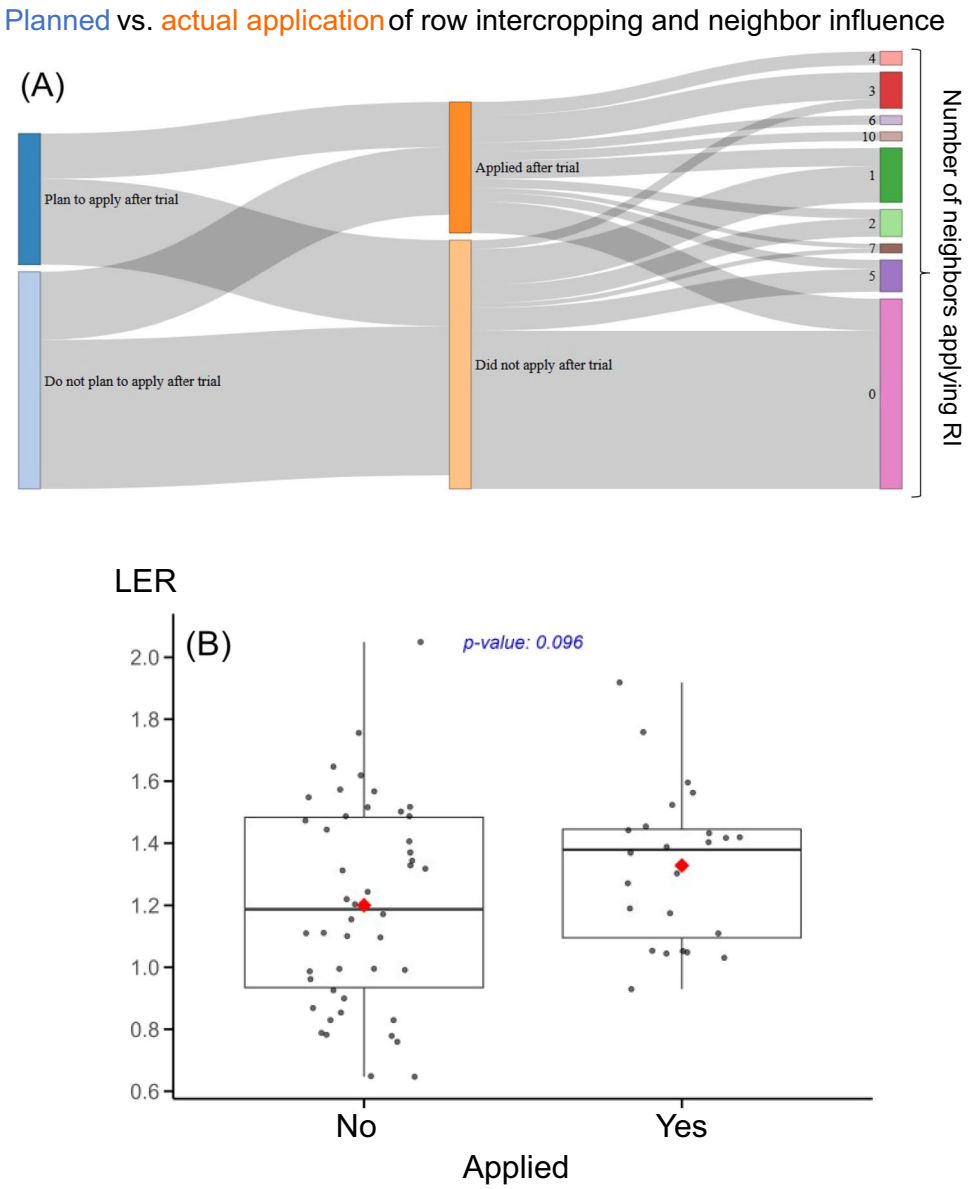


Fig. 8 Evolution of the proportion of farmers who planned to apply row intercropping (RI) versus those who applied it 4 years later, along with the number of neighboring farmers who applied the practice (**A**). Land equivalent ratio (LER) for farmers who applied row intercropping compared to those who did not (**B**).

intensified systems with strong competition for light among crops. Additionally, RI allows for targeted fertilization of cereals and beans at different rates, further enhancing resource efficiency. The productivity gap between RI and mixed intercropping could potentially widen further under higher nitrogen intensification. However, at the current level of fertilization (30 kg N ha^{-1}), the benefits were inconsistent across the on-farm trials, and relatively small compared with the overall variability observed across the trial network. Intercropping performance appeared to be more strongly influenced by contextual factors such as harvest year, temperature, rainfall, solar radiation, soil type, and landscape position, than by the specific intercropping systems tested (RI or mixed). This is consistent with the complex and variable nature of smallholder farming systems, where many interacting and often unmeasured factors influence crop performance.

In this study, the spatial and temporal stability of RI productivity was not higher compared with that of the sole crops, contrary to previous literature suggesting that crop complementarity enhances stability (Raseduzzaman and Jensen 2017). Here, we mostly present data on the spatial variability of intercropping, an aspect that remains underexplored, even in meta-analyses of on-station research data (Himmelstein et al. 2017; Namatsheve et al. 2020; Mudare et al. 2022). Most previous studies have evaluated by comparing intercropping to sole cereals (Raseduzzaman and Jensen 2017), rather than adopting a full cropping systems perspective that compares intercropping to the two sole crops grown on the farm at the same time (Traoré et al. 2023).

Further research is needed to understand the impact of climate and soil fertility on intercropping performance. While some studies suggest that intercropping is beneficial in drought conditions (Renwick et al. 2020; Kwenda et al. 2025), others report conflicting results (e.g., Nelson et al. 2021). The EI utilized in this study provides a preliminary framework for capturing environmental effects and indicates that the benefits of RI may diminish under more favorable growing conditions. Still, this approach requires refinement through targeted experiments (e.g., Temesgen et al. 2015) and, specifically, through on-farm studies that incorporate measured rainfall and soil characteristics.

We demonstrate that RI delivered higher nutritional and economic outcomes than sole crops, supporting findings from Mucheru-Muna et al. (2010) and Thierfelder et al. (2024). However, RI required more labor and higher input costs compared with the other systems, consistent with Woomer et al. (2004), who reported a 20% labor increase in RI systems. Unlike studies conducted in Zambia and Malawi (Thierfelder et al. 2016, 2024; Mupangwa et al. 2019; Mutenje et al. 2019), we did not observe higher returns on investment for intercropping and, in fact, found the lowest return on labor for RI. These findings suggest that increased labor investment does not necessarily translate into improved economic performance for RI. Consequently, future efforts should prioritize strategies to reduce the labor demands of RI rather than intensifying labor input. Although this study did not actively test labor-saving practices, two options have since been identified for Rwandan conditions. These are (a) adjusting in-row spacing for maize and beans to make planting holes easier to visualize for farmers (e.g., maize at 40 cm and beans at 20 cm) and (b) using manual planting tools that facilitate row planting.

4.2 Farmers' preference and application

Although RI demonstrates higher multicriteria performance on most farms, farmers have a relatively low preference for it compared to sole crops, with only about 30% reporting having applied it. The main reason indicated by farmers for nonapplication is the extra labor required for RI, particularly at planting, which is a peak period in the farm calendar with many competing activities. Labor shortages at planting reflect farmers' cash constraints: High demand for hired labor increases daily wage rates, family labor is limited, and essential purchases such as seeds and fertilizers compete for the same limited funds. Additionally, the narrow planting window at the onset of rains requires farmers to balance land preparation and sowing, further constraining labor availability for RI.

Despite ongoing efforts to promote agroecological practices, here referring to management approaches that enhance ecological processes through measures such as intercropping, crop diversification, conservation agriculture, low adoption rates are common. For example, Ortega et al. (2016) reported limited uptake of maize–legume intercropping in Malawi. Farmers' decisions do not always follow the "best trade-off" logic. Some farmers may overlook certain attributes altogether (attribute nonattendance strategy, e.g., Rodríguez-Entrena et al. 2018), while others may reject a system because of one undesirable feature, even when other advantages are offered (elimination-by-aspects strategy, Tversky 1972). For example, high labor demand at periods when labor is scarce or costly often becomes a deal breaker, regardless of agronomic or economic benefits (Anders et al. 2020). Kassie et al. (2014) similarly noted that farmers' perceptions on labor demands often outweigh agronomic advantages in decision-making processes. This preference for less labor-intensive systems suggests that labor constraints (availability or costs) are significant and a major limiting factor in Rwanda, alongside land size and access to inputs. Regional differences in land and labor availability likely contribute to the variation observed in farmer preferences.

To enhance application, it is crucial to provide farmers with the flexibility to adjust the design of RI to their specific needs; indeed 30% of farmers changed their RI design between the first and second seasons. This highlights the value of involving farmers in fine-tuning technologies at the local level to minimize agronomic and labor-related drawbacks. The approach used here, based on on-farm trials led by scientists but with active participation and effective feedback loops from farmers, strikes a balance between full co-creation processes, which can be time- and resource-intensive, and top-down, nonconsultative designs (Bakker et al. 2021). Flexible recommendations, allowing farmers to adjust crop management to suit their environmental context and household needs (e.g., Bagagnan et al. 2024; Sunday et al. 2024), can significantly enhance uptake. A sub-optimal design (in terms of agronomic performance) that is easy to adopt may be more effective and impactful than an optimal design that is difficult to implement. Examining application rates over several years can also help to understand the long-term determinants of adopting a practice (Pangapanga-Phiri et al. 2024). In this study, we focused primarily on application rather than true adoption, as the latter would require a longer timeline.

A key novelty of our study is the identification of positive relationships between EI and LER, between LER and application, and between application and diffusion (via neighbor application). The high variability in LER—where 26% of farmers achieved LER < 1 in "scientist-led" plots is similar to what is obtained in meta-analyses (e.g., Namatsheve et al. 2020) and emphasizes the need to further refine RI practices to enhance land productivity. With an application rate of only 30%, the scalability of RI appears constrained. To address this, mapping and understanding the biophysical and social contexts that foster LER > 1 would allow

RI to be promoted where it is most likely to succeed. Such targeting could not only increase the application potential—by reducing the proportion of farmers with LER < 1—but also enhance dissemination efficiency. Notably, our findings indicate that farmers achieving LER > 1 in trials are more likely to apply RI practices and that their dissemination to neighbors is four times higher compared to farmers with LER < 1. Thus, prioritizing demonstration plots and extension campaigns in areas and field conditions with higher expected LER outcomes could substantially boost both application and diffusion. Furthermore, the effectiveness of these interventions is hindered by the current structure of the extension system in Rwanda, which focuses on sole cropping despite the widespread practice of intercropping. This disconnect leaves a considerable number of farmers underserved, lacking specific recommendations tailored to their needs or preferences. Establishing dedicated extension support for intercropping could bridge this gap, ensuring that RI practices are more effectively implemented and scaled to benefit a broader population of farmers.

4.3 Avenues for future research

To facilitate a significant transition from mixed cropping systems to the application of RI, innovations that reduce planting labor are essential. Simple, cost-effective tools such as hand seeders or row openers could streamline planting and reduce labor demands. Alternatively, more advanced, but also more costly, mechanization, such as two-wheel tractors or animal traction systems, could drastically reduce labor demands and alleviate drudgery. Such mechanization efforts in parts of southern Africa have demonstrated their potential to lower labor requirements (Baudron et al. 2015, 2019).

A more integrative multicriteria analysis should also include environmental factors. However, indicators such as changes in soil fertility or pH may not show significant differences between systems over short periods (e.g., Thierfelder et al. 2024). Long-term experiments are therefore required to assess the environmental performance of intercropping systems (e.g., Laub et al. 2024). Additionally, soil-crop modeling can complement on-farm data by assessing the effects of long-term climate variations on intercropping performance (e.g., Traoré et al. 2023; de Freitas et al. 2025; de Freitas et al. 2026) and by evaluating the impact of intercropping on soil health (e.g., Fuchs et al. 2024).

5 Conclusions

This study, based on an unprecedented large-scale, multiseason on-farm trial encompassing 382 fields across diverse environments in Rwanda, evaluated the multicriteria performance of multiple row intercropping (RI) compared to sole cropping and traditional mixed intercropping. Our key question was whether RI can simultaneously improve productivity and profitability, while remaining feasible for smallholder farmers to implement. Consistent with our hypotheses, our results show that RI has a clear advantage over sole cropping and mixed intercropping systems in terms of land productivity, nutritional outputs, and economic returns across diverse agroecological zones in Rwandan smallholder farmers' fields. By optimizing resource use and enhancing complementarity between crops, RI offers a promising pathway for sustainable intensification.

The novelty of our work lies in combining multicriteria performance assessment with monitoring of farmer preferences and application of an innovation. Despite its agronomic and economic advantages, only 30% of farmers have applied RI at least once within 4 years after the trials. This relatively low application is primarily due to the expected increased labor demands with RI, particularly during planting, a critical period of other competing farm activities. To increase application and unlock the full potential of RI, future efforts should prioritize labor-saving innovations, such as mechanized or semi-mechanized planting tools, and provide flexible recommendations that allow farmers to tailor RI designs to their unique environmental conditions and household needs. Additionally, targeting interventions in areas where RI consistently achieves higher land productivity could significantly boost farmer uptake and diffusion.

Finally, this research highlights the value of combining rigorous researcher-led experimentation with active farmer participation and feedback loops. Finding a cost-effective balance between linear, top-down research and participatory co-design will be essential to ensure that RI evolves into a practice that is not only agronomically efficient but also socially feasible and widely applied. By addressing these challenges, RI can move from being a technically efficient practice to one that is widely adopted, making a tangible contribution to food security, profitability, and sustainable intensification for smallholder farmers in Rwanda and similar smallholder farming systems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-026-01103-z.

Acknowledgements Dr. Claver Ngaboyisonga (RAB) and Dr. Milindi Sibomana (OAF) provided critical feedback on trial design and result interpretation. Gratitude is also extended to the local government authorities and Feed the Future Hinga Weze for their valuable contributions to this research. We also acknowledge the essential role of participating farmers, farmer promoters, village leaders, and Sector Economic Development Officers (SEDOs) for their constructive feedback on the trial performances.

Authors' contributions Antoine Couëdel: formal analysis, investigation, validation, visualization, writing—original draft. Jean de Dieu Mbarushimana: conceptualization, formal analysis, funding

acquisition, investigation, methodology, writing—review and editing. Alphonse Nyombayire: conceptualization, formal analysis, funding acquisition, investigation, methodology, writing—review and editing. James Ellison: conceptualization, formal analysis, funding acquisition, project administration, investigation, methodology, writing—review and editing. Marc Corbeels: validation, visualization, writing—review and editing. Juliette Lairez: investigation, validation, visualization, writing—review and editing. Diego Cerrudo: conceptualization, formal analysis, funding acquisition, project administration, investigation, validation, visualization, supervision, methodology, writing—original draft. Elyse Tuyishime: conceptualization, formal analysis, funding acquisition, project administration, investigation, validation, visualization, supervision, methodology, writing—review and editing.

Funding Open access funding provided by CIRAD. This study was funded by the CANALLS project "Agroecological practices for sustainable transition" (funded by the European Union under GA no.101083653). This article was also supported by the IntercropVALUES project, funded by the Horizon Europe Research and Innovation programme (funded by the European Union under GA No.101081973).

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Farmers signed consent forms agreeing to host and manage the trials and engage in related surveys while being allowed to drop the trial anytime.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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