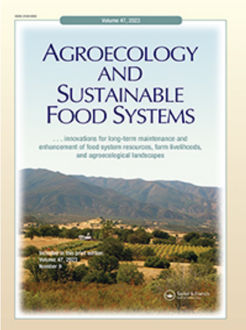

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Agroecology and Sustainable Food Systems

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/wjsa21

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To cite this article: Angelika Hilbeck, Eugenio Tisselli, Simon Crameri, Kallunde P. Sibuga, John Constantine, Mawazo J. Shitindi, Method Kilasara, Ayubu Churi, Camillius Sanga, Luambano Kihoma, Gladness Brush, Fadhili Stambuli, Rainard Mjunguli, Blaise Burnier, Janet Maro, Angelina Mbele, Suleyman Hamza, Mary Kissimbo & Ayoub Ndee (06 Oct 2023): ICT4Agroecology part I: Outcomes for cassava production system, Agroecology and Sustainable Food Systems, DOI: 10.1080/21683565.2023.2265318

To link to this article: https://doi.org/10.1080/21683565.2023.2265318

Published online: 06 Oct 2023.

AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS
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ICT4Agroecology part I: Outcomes for cassava production system

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ABSTRACT

This study discusses the results of a 5-year Agroecology Research and Advocacy project at three Tanzanian field sites in different agroecological zones. We investigated four common agroecological practices: compost application, mulching, intercropping, and biological pest control either alone or in combination. Two custom-built ICT tools – AgroEco Research (AER) and AgroEco Analysis (AEA) application – supported the field research. AER and AEA integration allowed secure data storage and real-time automated visualization and statistical analyses without programming. At no field station did legume intercropping or biological pest control increase cassava yields. The Chambezi field station had the highest yields even under untreated control conditions and only here, soil fertility amendments further increased root weights. Intercropping with cowpea legumes, alone or in combination with other practices, had no significant effect on cassava plant size or survival at the Mumbaka and Vianzi field sites and even negatively affected one or both parameters. Organic pest control had no effect on any target variable, except for plant size at Chambezi. Therefore, labor-intensive and expensive pest control practices may not be worth the investment at least when virus-resistant cassava varieties like Kiroba are used.

KEYWORDS
Agroecology; information and communication technology; soil fertility; biological control; legume intercropping; interaction effects

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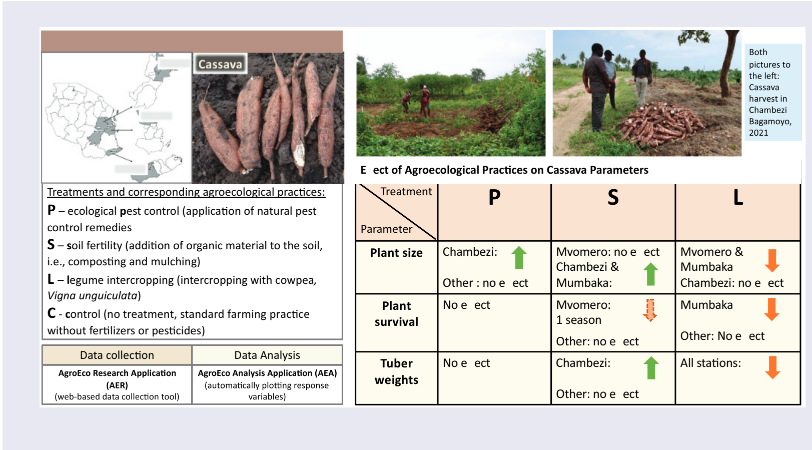

Introduction

Tanzanian agriculture is characterized by small-scale subsistence farming with surplus produce sold at local markets or in the proximity of the farm (e.g., at roadside sale points). Moreover, the Tanzanian agricultural sector exhibits low productivity. The conventional approach to boosting productivity has been to rely on expensive and often hazardous external inputs (pesticides). This approach had limited success and resulted in the contamination of vast areas with harmful pesticide residues that pose serious threats to human health and the environment (Kapeleka et al. 2020; Ndengerio-Ndossi and Cram 2005; Ngowi et al. 2007). Therefore, the Tanzanian government is aware of the need to explore strategies for increasing crop productivity using agroecological methods without the use of toxic chemicals. Against this backdrop, agroecological production methods have gained prominence in recent years, with the United Nations Food and Agricultural Organization (FAO) and other multinational stakeholders supporting their implementation.

Agroecological practices and production systems are the "*application of ecological sciences to the study, design, and management of sustainable agroecosystems*" (Altieri 1995; Gliessman 2007). This systematic approach to agriculture and food production integrates various disciplines (Wezel et al. 2014). However, agroecological practices are also "*knowledge-intensive, based on techniques that are not delivered top-down but developed on the basis of farmers knowledge and experimentation*" (De Schutter 2011). Several organizations are advocating agroecological farming practices in Tanzania, including non-governmental organizations such as Sustainable Agriculture Tanzania (SAT), the Tanzania Organic Agriculture Movement (TOAM)and SWISSAID Tanzania. These organizations also include universities like the Sokoine University of Agriculture (SUA), a leading training, research, and development center for agroecology. Although these organizations provide training and actively develop locally adapted agroecological farming practices in collaboration with farmers, the evaluation and scientific documentation of their impact remain inadequate.

Research-based projects providing robust scientific assessments of the various promoted agroecological farming practices are still limited and largely address individual practices independently (e.g., testing the impacts of organic fertilizers or biocontrol measures or intercropping on their own) (Adjei-Nsiah et al. 2007; Howeler, Lutaladio, and Thomas 2013; Pinto-Zevallos, Pareja, and Ambrogi 2016). However, farmers generally apply multiple cultivation practices concurrently, frequently in an ad-hoc fashion, as a response to seasonal challenges. Research on the evaluation of agroecological farming practice combinations is called for (Pinto-Zevallos, Pareja, and Ambrogi 2016), but it remains rare. We are not aware of peer-reviewed scientific publications that evaluated the main impacts and interaction effects of multiple commonly used agroecological farming practices for cassava (or other crops) in Eastern Africa. With this research project, we aimed to contribute novel research findings to assist in closing this recognized knowledge gap, as well as propose a research methodology for assessing sets of various agroecological practices.

This study is the outcome of a 5-year Agroecology Research and Advocacy project implemented in three agroecological zones in Tanzania. The experiments were conducted on cassava and maize, a second staple crop. The primary goal of this project was to scientifically validate the effectiveness of selected agroecological practices (applied individually or in combination) so that they could be advocated and recommended to smallholder farmers, farmer training institutions, policymakers, and the general public with robust evidence and scientific confidence. The evaluated agroecological practices fell into three categories of common agroecological methods: soil fertility and conservation measures (composting and mulching); increasing biodiversity through intercropping (e.g., cassava with cowpea legumes); and biological pest control measures (using ash or botanicals such as neem, chili, garlic, and aloe extracts) (Bezner Kerr et al. 2021; Constantine et al. 2021; Himmelstein et al. 2017; Paracchini et al. 2020). The research design allowed for a single, double, or triple assessment of practices at each location.

Another goal was to use the readily available technologies on mobile phones to ensure that the integration of Information Communication Technology (ICT) tools contributed to context-based and farmer-centered agroecological transitions. Therefore, our field research effort was supported by a custom-built ICT tool for data collection and storage, the AgroEco Research (AER) application. Furthermore, and to the best of our knowledge, for the first time, the data recorded by the AER application was automatically read by another custom-built ICT tool, the AgroEco Analysis (AEA) application. This tool retrieves data directly from the AER website, enabling instant (real-time) data visualization, statistical analyses, and data export. Details on the overall methodologies applied and the materials used are provided in a separate companion paper published alongside this paper in the same journal volume (Hilbeck et al. 2024a methodology companion paper). Here, we report on the findings for cassava, while the outcomes for maize are presented in another companion publication alongside this paper in the same journal volume (Hilbeck et al., 2024b maize companion paper).

Cassava is a commonly cultivated staple crop in Tanzania that is resistant to various environmental challenges, such as droughts, nutrient-deficient soils, pests, and diseases. Therefore, cassava has been promoted as a crop with relevance for food security (e.g., an insurance crop) to buffer against the effects of adverse meteorological conditions such as protracted droughts (Burns et al. 2010; El-Sharkawy 2014). In addition to cassava roots that are ground into flour and used to make porridge (ugali), snacks, or biscuits, cassava leaves are traditionally consumed as leafy vegetables (i.e., kisamvu) that provide protein, minerals, and vitamins for human nutrition. However, cassava storage root productivity in Tanzania is low, with an average annual yield ranging from 3.5 to 8.5 t/ha (FAO 2013; United Republic of Tanzania 2021) commonly assigned to infertile soils without external inputs. The Tanzania Ministry of Agriculture has devised a National Cassava Development Strategy (NCDS) for 2020–2030. According to this strategy, the Tanzanian government intends to triple the current cassava production by 2030, from 8.2 million tons (2018/2019) to 24 million tons by 2030.

In our study, we investigated the effects of agroecological soil fertility practices (consisting of compost applications, mulching and inter-cropping with cowpea legumes), common local ecological pest control and its various combinations on cassava storage root weight, plant size and plant survival. We posed the following four questions: 1) Do traditional soil fertility management measures consisting of local ingredients and mulching affect cassava root weight, plant size, and plant survival?; 2) What effect does inter-cropping with cowpea legumes have on cassava root weight, plant size, and plant survival?; 3) Does common ecological pest control utilizing local substances and applied as necessary have a quantifiable impact on cassava toot weight, plant size, and plant survival?; and 4) How do these practices function in conjunction with one another?

Materials and methods

Description of study sites

We conducted multi-year (2018–2021) field plot studies at three field stations in three agroecological zones in Tanzania: Chambezi field station (Bagamoyo District, north-east coastal region), Vianzi field station (Morogoro District, 200 km inland from Dar es Salaam), and Mumbaka field station (Masasi District, southern region bordering Mozambique) in

Tanzania. Chambezi site is situated on the coastal plains dominated by sandy and sandy-loamy soils with humid coastal climate (Bagamoyo district council, 2018). Vianzi site is located on much drier, semi-arid land in the northern part of the Morogoro region, dominated by oxisols (Hashim et al. 2018). Lastly, Mumbaka site is situated in the southern zone of Tanzania on semi-arid coastal lowlands with characteristically deep, highly weathered, sandy clay and sandy clay loam soils (Dondeyne et al. 2003). All plots on all field stations were newly established on bushland that had not been under previous agricultural use.

This publication is one of a triple set of companion publications all published simultaneously in the same journal volume. One of the triple publications is exclusively dedicated to the detailed description of the materials and methods used and the ICT tools specifically developed for this integrated research project (Hilbeck et al. 2024a, methodology companion paper). Therefore, we provide here only a summary overview of the methods that were utilized.

Design and layout of field plot research

At each field site, the complete field research setup comprised 48 plots of 18 m^2 (6 m × 3 m) each. We used a full factorial design in which each treatment was administered separately or in combination with other treatments, and control plots where none of the treatments under investigation were applied were used for comparison. Treatments were replicated three times at each field site, resulting in three distinct experimental areas per site, each consisting of 16 neighboring experimental plots. Cassava was cultivated on eight plots per replicate area (24 plots in total), while the remaining half of the plots were set aside for cassava experimentation, which we report elsewhere. We evaluated three agroecological practices: 1) single crop versus intercrop system, 2) ecological pest control versus no ecological pest control, and 3) soil fertility amendment versus no soil fertility amendment. The treatments and corresponding sets of agroecological practices were abbreviated as follows:

- **P** – ecological pest control (application of natural pest control remedies)
- **S** – soil fertility (addition of organic material to the soil, i.e., compost application and mulching)
- **L** – legume intercropping (intercropping cassava with cowpea, V*igna unguiculata*)
- **C** – control (no treatment, standard farming practice without fertilizers or pesticides)

Season and replicate area (Rep) were included as block factors. The factorial design enabled the assessment of both main effects (i.e., the effect of a single treatment factor on the response variable) and potential interaction effects. Given that pest control and soil fertility amendment were more difficult to adjust across plots than legume intercropping, we utilized a split-plot design in which pest control and soil amendment were varied across larger areas than during intercropping. Specifically, one-quarter of each replicate area was treated with P, one-quarter with S, one-quarter with P and S, and one-quarter with neither P nor S. Within each quarter, legume intercropping was applied to half of the plots.

Local drought and flooding events

Unpredictable weather events occurred at all three field sites. In 2019 and 2021, field experiments in Mumbaka and Vianzi were affected by a lack of precipitation, leading to localized droughts. In addition to these drought spells, flooding was a major issue in the low coastal region of Chambezi during the beginning of the rainy seasons of 2018 and 2020. The floods destroyed nearly all planted cassava cuttings during germination (e.g., via rot), necessitating the cultivation of replacement crops in both years. This was possible with cassava but not with maize (see companion methodology paper) since the saturated soils contained sufficient moisture to sustain cassava through its most susceptible early planting phase, after which it becomes highly drought-tolerant.

Response variables

We analyzed three distinct response variables (also known as dependent variables or outcome variables).

Plant size per plot and treatment

Cassava plant size was assessed at the time of harvest. The plant height was measured from the soil surface to the top of the leaf canopy.

Weight of cassava storage roots per plot and treatment

Cassava yield was recorded as the total weight of fresh roots (in kg) per plot (18 m^2) and converted to tons per hectare (t/ha).

Number of surviving cassava plants per plot and treatment

The number of surviving cassava plants (from an initial population of 10 plants) per plot was recorded on the day of harvest. This allowed for the evaluation of whether differences in plant survival were random, systematic, and associated with any of the treatments (individual or in combination) or related to other reasons.

Data collection

Data were collected using a custom-built tool, the AER application, the details of which are discussed in a supplementary methodology paper (Hilbeck et al. 2024a methodology companion paper). In summary, the AER application[1] is a mobile and web-based data collection tool that enables researchers to record data pertaining to the aforementioned parameters. The application ensured the standardization and comparability of data across all geographical locations and seasons in which the methodology was replicated. The data collected by the application were stored in a centralized online database, allowing for real-time querying and analysis as well as ensuring the safe storage of data via daily backups. Field station work using the AER application was supervised either directly by scientists or by field staff and farmers who were instructed and trained by scientists. At these field stations, scientists or staff used the AER application to record the agricultural inputs applied to the fields, such as seeds or manure; the activities associated with fieldwork, such as planting or harvesting; and the various parameters used to monitor the development, health, and performance of crops. The process of recording all of the different materials, events, and measurements involved in this methodology could be performed using a smartphone or a computer, owing to the various tools offered by the AER application.

Data analyses

The data recorded using the AER application were automatically read by another custom-built ICT tool known as the AEA application, the details of which are discussed in a supplementary methodology paper (Hilbeck et al. 2024a methodology companion paper). In summary, the AEA application[2] reads the response variables, field sites, replication areas, experiment dates, and treatment factors from the AER application website and automatically plots the response variables as a function of treatment factors, their combinations, and time. A single response variable from a single crop and field site can be analyzed at a time, and all or only a subset of seasons (e.g., eliminating seasons with crop failure because of flooding) can be selected for analysis. Once the data subset has been selected, the main and interaction effects of treatments on the response variable are automatically assessed using analysis of variance (ANOVA) and considering the split-plot experimental design. The replicated area is always included as a block factor, but the season is only included as a block factor if the user specifies season end dates. Dedicated residual analysis plots can be examined for potentially influential single measurements or model assumption violations. First-aid transformations on the response variables (none applied by default) and interaction terms (all main and two-way interaction effects by default) can be included to improve model fit. In addition, the AEA application enables the download of raw and aggregated data (e.g., means per plot) in a format that is suitable for further analyses. The data were analyzed separately for each field station (Chambezi, Mumbaka, and Vianzi). We refrained from conducting a single common analysis with the field site as an additional block factor because there were too many uncontrolled differences between field stations as a result of different climatic conditions, soil types, and sowing and harvesting schedule

Results

In this section, we present the research outcomes for each measured parameter at each station separately and conclude by comparing these outcomes across all stations.

Mumbaka field station

Plant size

When analyzing legume intercropping (L) and soil amendments (S) as main factors across all seasons, both significantly affected plant growth (S main factor, $p = 0.074$; L main factor, $p = 0.0044$), but in opposite directions (Figure 1a). While cassava plants remained significantly smaller when intercropped with cowpea legumes than in the untreated control, they tended to grow taller in soil-amended plots (Figure 1a). In contrast, pest control, as the main factor, had no measurable impact on the final cassava plant size.

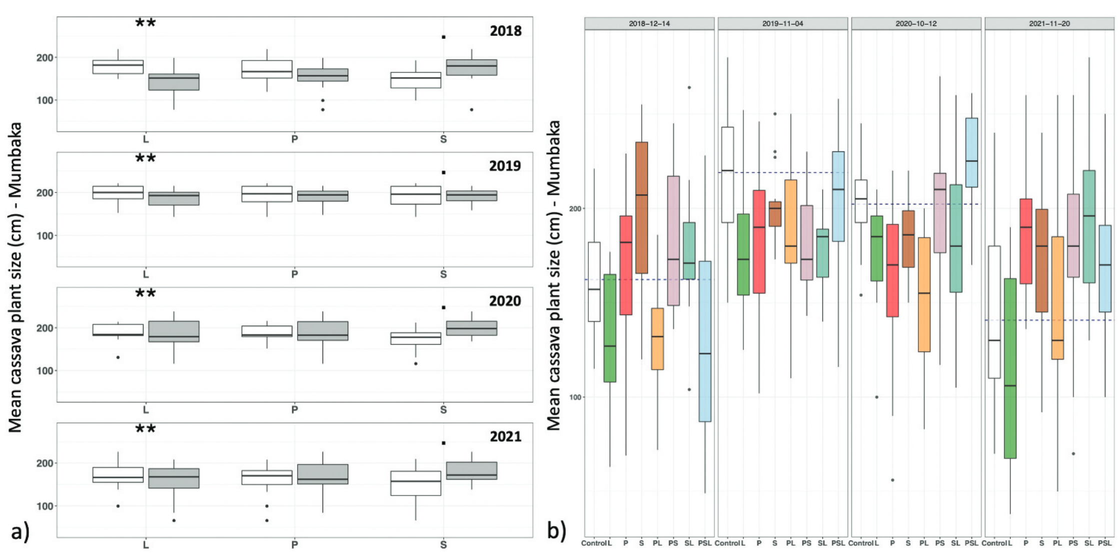

Figure 1. Mean cassava plant sizes at the Mumbaka field station: a) factor or plot displaying mean plant sizes (all data pooled across all seasons) for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean plant sizes at the time of harvest for the main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

When analyzing all treatments for all seasons individually or in combinations, cassava plants were frequently, on average, smaller in plots intercropped with cowpea legumes than in untreated control plots; however, because of the high variability of the data, this was not statistically significant in the individual treatments (Figure 1b). In 2020, the PSL plots featured some of the tallest cassava plants (up to 250 cm). In addition, independent of treatment, final plant sizes differed significantly between seasons ($p < 0.0001$), although the differences between years appeared minimal and variability was high (Figure 1b). In seasons 1 and 4, the smallest plants were recorded in legume intercropped plots, ranging from as little as 50 cm to approximately 200 cm, whereas in all other plots, including the untreated control, cassava plant sizes always exceeded 100 cm and could reach 200 cm in plots that had received soil amendments. In seasons 2 and 3, cassava plant sizes were on average greater than those recorded in the other seasons (>150 cm). The tallest plants were recorded in 2019 in the untreated control plots, with most plants exceeding 200 cm in height.

Plant survival

Cassava plant survival was significantly lower in plots intercropped with cowpea legumes (L main effect, $p = 0.005$). Cowpea legumes had an adverse effect on the survival of cassava plants at least during the first season because of their competitive effect (overgrowth) during the early stages of cassava plant development during season 1. Consequently, cowpea plants were pruned or thinned on some plots to prevent further overgrowth of cassava plants. In subsequent seasons, cowpea densities were reduced, and they were sown with a two-week delay after cassava planting, but they still exerted a rather adverse effect. Nevertheless, even when analyzing cassava plant survival without the first-year data (2018), cowpea legume intercropping tended to have a detrimental impact on cassava survival, albeit at a lower level of significance (L main factor, $p = 0.09$; Figure 2), partly because of the large variability of the data in season 4. Furthermore, the number of surviving plants did not vary between seasons, ranging between 4 and 5 plants in most plots, with the exception of the PSL plots in 2018 and the L and SL plots in 2021. In turn, this indicated that slightly more than half of the cassava plants were lost each season. There were no differences between replications.

Harvested storage root weights

Consistent with the results above, it was not surprising that harvested cassava storage root weights were consistently lower in plots where cassava was intercropped with cowpea legumes (L). This resulted in a highly significant L main factor effect (Figure 3a) ($p < 0.001$). However, in the means comparison analysis, significant effects on cassava root weights from cowpea intercropping were primarily observed during seasons 1–3 (PL, $p = 0.079$; SL, $p =$

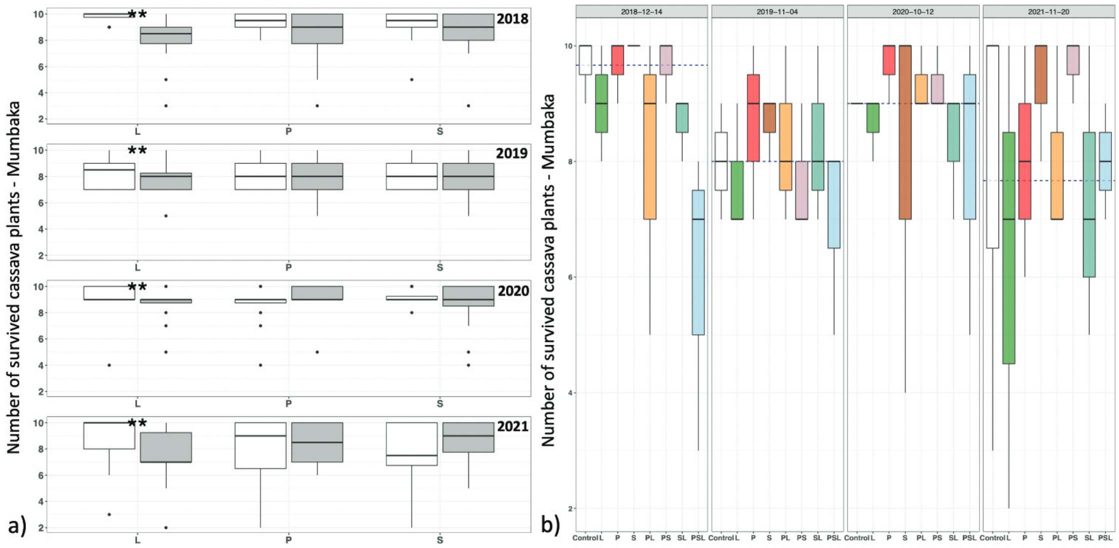

Figure 2. Mean values for the number of surviving cassava plants at the Mumbaka field station: a) factor plot displaying all data pooled across all seasons for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean values for the number of surviving cassava plants at the time of harvest for the main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

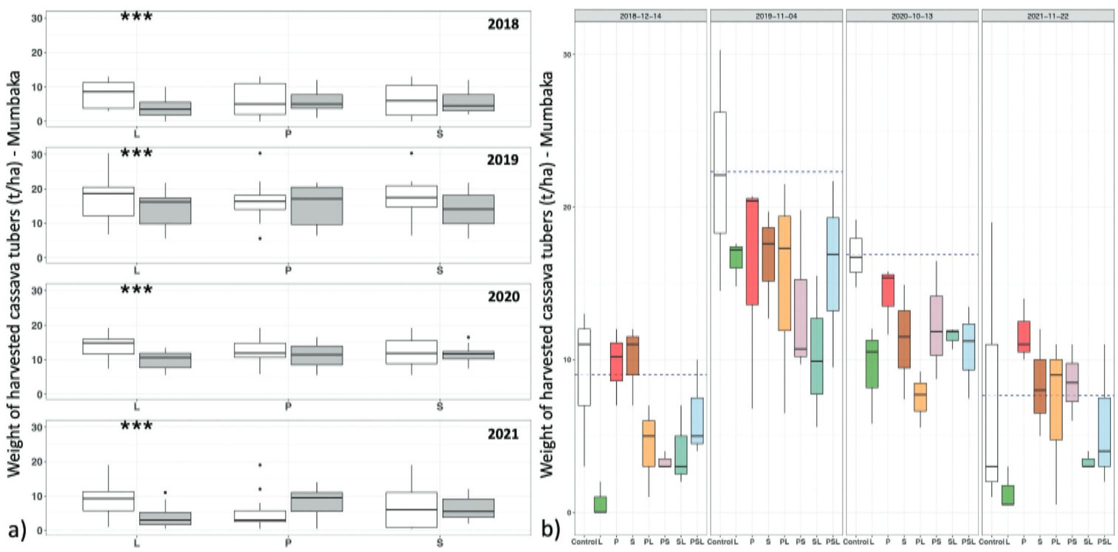

Figure 3. Mean harvested cassava storage root weights (t/ha) at the Mumbaka field station for each year: a) factor plot displaying mean weights when analyzing all data collected during the season pooled for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean weights for all main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

0.044; and PSL, $p = 0.003$) (Figure 3b Seasons 1–3). When data from the final season (2021) were included, no significant differences in mean weights were detected in the means separation analysis, but the highly significant overall L main factor effect remained at $p < 0.001$. The observed decrease in cassava root weights in plots intercropped with cowpea legumes was at least in part due to fewer surviving plants in these plots (see above), thereby contributing to plot yield. None of the other treatments, including pest control and soil amendments, had statistically significant effects on harvested cassava root weights, which were often lower or at best comparable to the control (Figure 3b).

Regardless of treatments, harvested root weights significantly differed between seasons ($p < 0.0001$). The highest mean root weights were recorded in the untreated control plots during seasons 2 (2019) and 3 (2020), ranging between 22 and 17 t/ha. The root weights of all other treated plots were significantly lower than those of the control plots. In seasons 1 (2018) and 4 (2021), the mean root weight levels were overall less than half of those recorded in seasons 2 and 3, with most mean weight values ranging at or below 10 t/ha (Figure 3b).

Chambezi field station

In two of the four field seasons, cassava crops had to be re-planted due to the destruction of seedlings caused by severe flooding (see discussion in methods section).

Plant size

When analyzing treatments (L, S, and P) as main factors, soil amendments (S) had only a moderate effect on plant growth (S main effect, $p = 0.086$; Figure 4a). In general, cassava plants in plots that received compost and mulching grew slightly taller than those in the untreated control plots. Interestingly, pest control as a main factor significantly affected final plant size (P main effect, $p = 0.0419$; Figure 4a). However, when analyzing the effect of treatments individually or in combination, except for the combined treatment of soil amendment and pest control (PS, $p = 0.0756$), none appeared to significantly affect cassava plant sizes, although cassava plants grown on plots that had received soil amendments (S, PS, SL, and PSL) tended to be somewhat taller on average than in the control, particularly in the last two seasons (Figure 4b). This lack of statistical significance is likely attributable to the large variability in cassava plant sizes. However, there were highly significant differences in plant sizes between seasons (season, $p < 0.0001$). While in seasons 1 (2019) and 3 (2021), mean plant sizes mostly ranged between 200 and 250 cm, they grew on average half a meter taller in season 2 (2020), with many plants growing well over 3 m in height (Figure 4b). In season 4 (2022), cassava plants cultivated on plots without soil amendments remained shorter than 200 cm, whereas most cassava plants cultivated on plots with soil amendments averaged 200 cm or taller (Figure 4b).

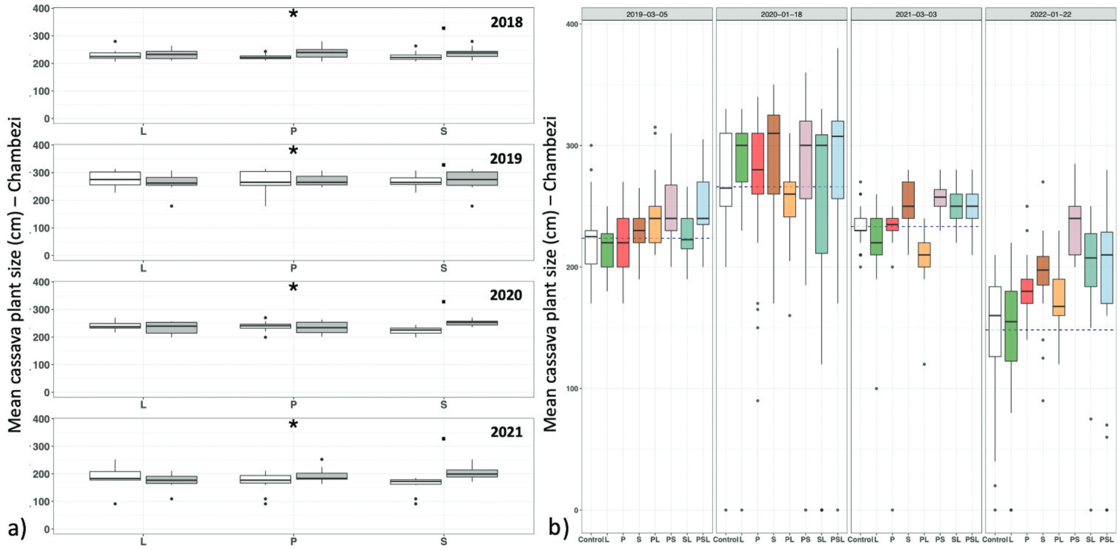

Figure 4. Mean cassava plant sizes at the Chambezi field station: a) factor plot displaying mean plant sizes (all data pooled across all seasons) for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean plant sizes at the time of harvest for the main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

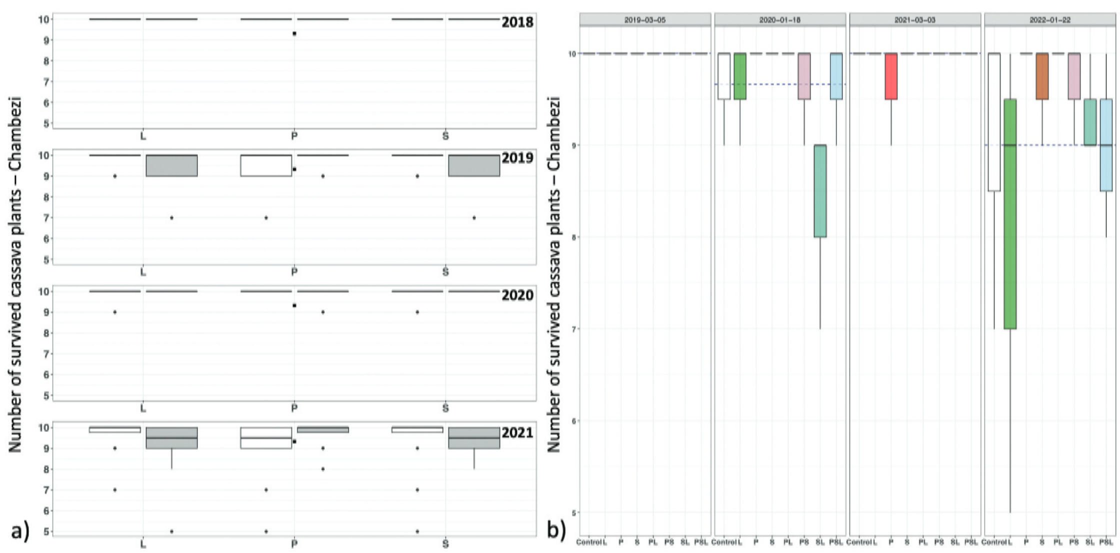

Figure 5. Mean values for the number of surviving cassava plants at the Chambezi field station: a) factor plot displaying all data pooled across all seasons for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean values for the number of surviving cassava plants at the time of harvest for the main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

Plant survival

At the Chambezi field station, cassava plant survival was high throughout all seasons (Figure 5). It was only in seasons 2 and 4 that a few (1–2, rarely more) cassava plants did not survive, resulting in a significant seasonal effect (season, p = 0.003), which was possibly still attributable to the saturated soils as a result of the floods in both years. However, there were no significant differences in the statistical analyses between any of the treatments and the controls, and it appeared that plots were randomly affected. Consequently, the demise of the plants in these two seasons could not be attributed to any of the treatments applied.

Harvested storage root weights

In the Chambezi field trials, soil amendments significantly increased harvested storage root weights when pooled across all seasons and other treatments (S main factor, $p < 0.001$), whereas legume intercropping significantly decreased root weights (L main factor, $p = 0.021$) (Figure 6a).

The highest storage root weight levels were recorded in the first season (2019), with maximum mean weights for plots receiving only soil amendments (S) ranging around 130 t/ha and those receiving all treatments (PSL) even slightly higher (Figure 6b). In addition, mean root weights in the untreated control plots ranged around 110 t/ha during the first season. However, in the subsequent seasons, overall root weights declined because of two very wet seasons (2020 and 2022) and one relatively dry season (2021), with mean root weight levels dropping to half or below those of season 1. Yields ranged between 40 and 100 t/ha in season 2 and were less than those in seasons 3 and 4 (2021 and 2022). This resulted in a highly significant seasonal effect (season, p < 0.001, Figure 6b). Nevertheless, despite the variable weather

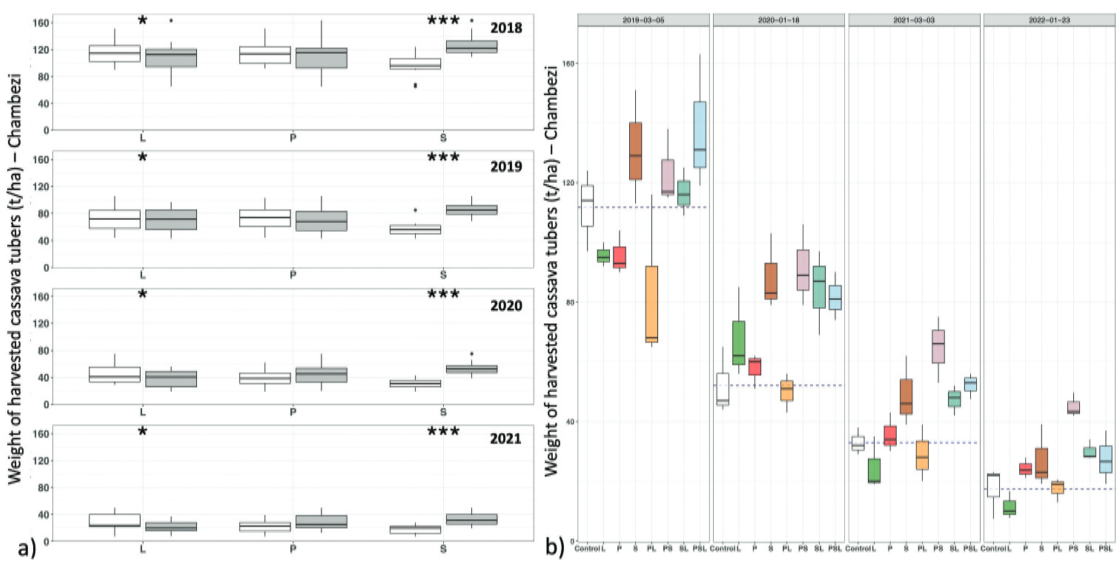

Figure 6. Mean harvested cassava storage root weights (t/ha) at the Chambezi field station for each year: a) factor plot displaying mean weights when analyzing all data collected during the season pooled for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean weights for all main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

conditions, the mean harvested root weights on plots with soil amendments were typically greater than those on plots without soil amendments, except during season 4. In season 4, root weights dropped below 40 t/ha, and the differences in mean root weights between soil treatments and controls narrowed, except for those plants on plots that had received both soil amendments and pest control (PS). Therefore, none of the individual treatments were statistically significant when comparing the mean root weights of each season to the controls. The lowest root weights were primarily recorded on plots intercropped with cowpea legumes and without soil amendments. Pest control measures had no discernible effect in any year. The harvested root weight levels in pest control-only plots (P) were either equal to or lower than those in untreated control plots.

Vianzi field station

Plant size

Cassava plant size data were only recorded from 2019 onwards at this station, resulting in a total of three field trial seasons for this parameter. Cowpea legume intercropping (L) as the main factor significantly affected plant growth (L main factor, $p = 0.004$; Figure 7a). In fact, cassava plants were smaller on average when intercropped with cowpea legumes than those in the untreated control (Figure 7b). However, there were no significant differences between individual treatments in the control group (Figure 7b). Additionally, overall plant sizes differed significantly between seasons across all treatments and the control ($p < 0.0001$) (Figure 7b). In 2019 and 2020, the average plant size was slightly higher than 150 cm, and it remained slightly below that during the dry season of 2021.

Plant survival

The number of surviving cassava plants was mostly high, ranging between 7 and 10 plants per plot. Interestingly, the survival of cassava plants was significantly lower in plots that received soil amendments (compost and mulching), leading to a significant S main factor effect ($p = 0.0163$, Figure 8a) and replication effect ($p < 0.001$). However, this result was exclusively a result of the 2019 season. When excluding the 2019 season from the analysis, neither the soil nor the replication effects remained significant (S effect, $p = 0.68763$; Rep, $p = 0.05885$).

Harvested storage root weights

Cassava storage root weights at the Vianzi field station varied significantly between seasons ($p < 0.0001$), with the highest yields recorded in season 1 (2018). The highest mean root weight levels in season 1 (2018) ranged between

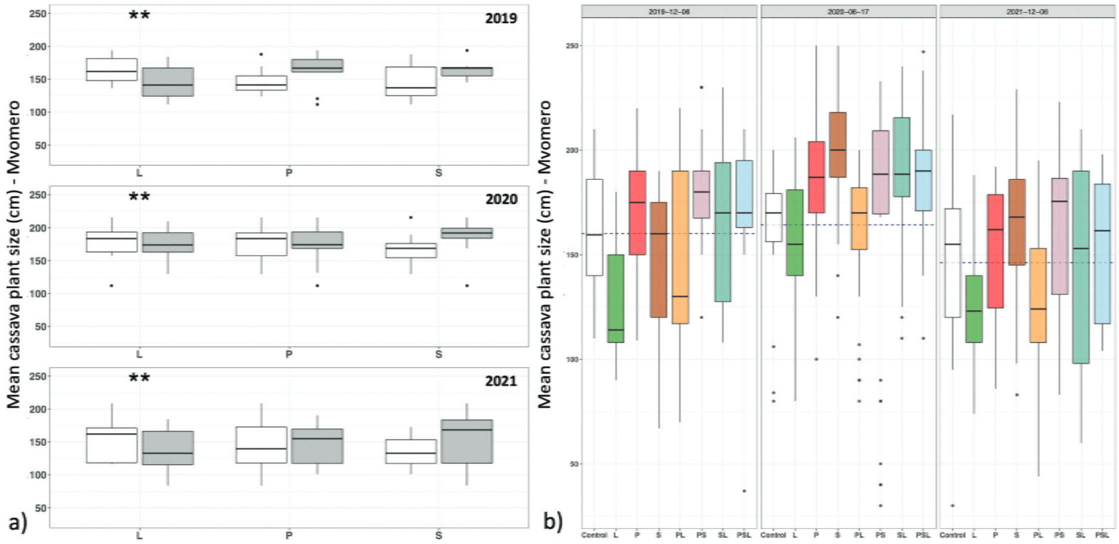

Figure 7. Mean cassava plant sizes at the Vianzi field station: a) factor plot displaying mean plant sizes (all data pooled across all seasons) for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean plant sizes at the time of harvest for the main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

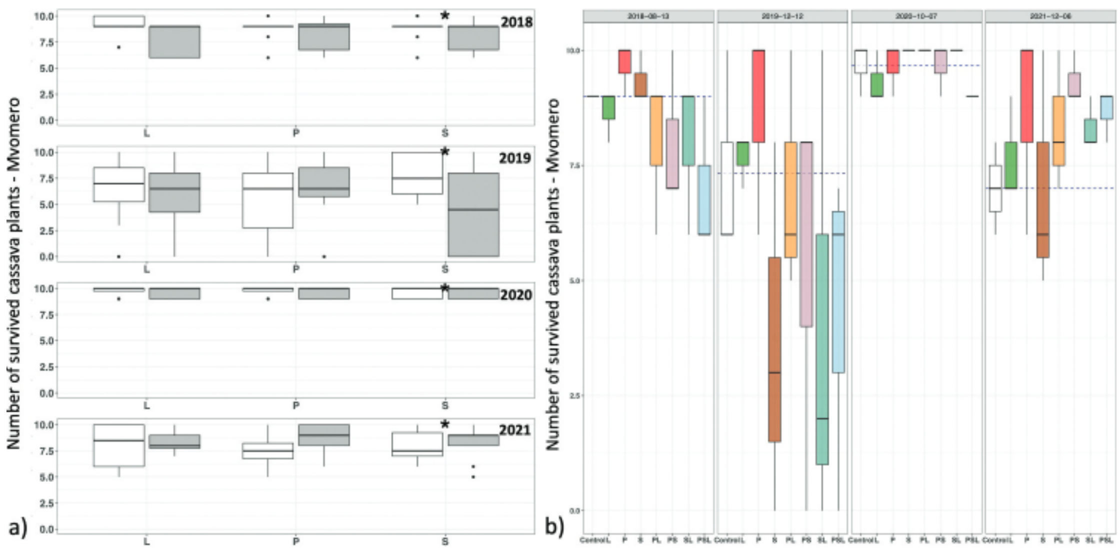

Figure 8. Mean values for the number of surviving cassava plants at the Vianzi field station: a) factor plot displaying all data pooled across all seasons for the main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean values for the number of surviving cassava plants at the time of harvest for the main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

18 and 28 t/ha. However, when excluding season 1, root weight levels were significantly lower (3–15 t/ha) but fairly similar across years, with no remaining significant seasonal effects ($p = 0.195482$).

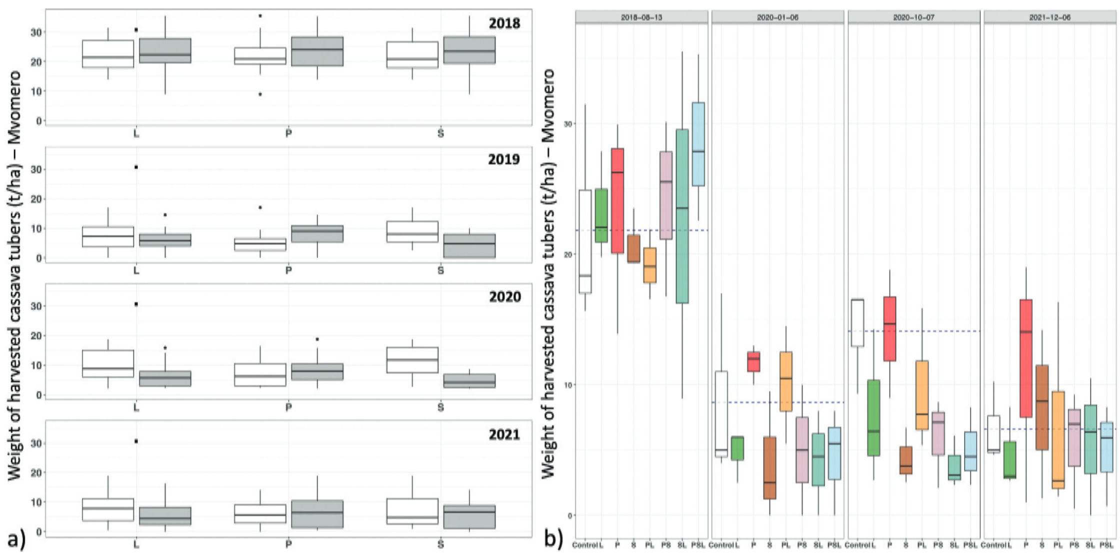

Figure 9. Mean harvested cassava storage root weights (t/ha) at the Vianzi field station for each year: a) factor plot displaying mean weights when evaluating all data collected during the season pooled for main treatments only (L, P, and S; grey boxes) versus the control (white boxes); b) mean weights for all main treatments (L, P, and S) and their combinations (PL, PS, SL, and PSL) versus the control. S = soil amendments; *P* = pest control; and L = legume intercropping (cowpeas). '***' 0.001; '**' 0.01; '*' 0.05; and '.' 0.1.

Conversely, harvested root weights were either unaffected by the main treatments (i.e., pest control and soil treatments) or marginally negatively affected, resulting in a near-significant effect of cowpea legume intercropping (L) as the main factor ($p = 0.07$) (Figure 9a). The low root weight levels recorded in the 2019 season were largely attributable to the low number of surviving cassava plants in that season, but not in the other two seasons. However, when excluding the data of the first season from the means comparison analysis, root weights on plots with soil amendments appeared to be significantly lower than those on the control plots (for seasons 2–4 only: S, $p = 0.049$; PS, $p = 0.034$; SL, $p = 0.039$; and PSL, $p = 0.039$). Although the effect of soil amendments was strongest in season 2, which is reflected in the decreased survival (Figure 9b), it was also evident in season 3 (Figure 9b).

Across all field stations

The final plant sizes and weights of harvested storage roots differed significantly between seasons owing to the unpredictable and adverse weather events (droughts, floods, or both) that occurred at various times and in different forms at all field stations. While the impacts of the various treatments fluctuated between locations, they were largely consistent within locations.

The tallest cassava plants were recorded at the Chambezi field station, with the majority of plants reaching heights of 2 to 3 m. At the Mumbaka field station, the final plant sizes ranged between 1.5 and 2.5 m. In contrast, the cassava plants remained the shortest at the Vianzi field station, with the majority of plants reaching final plant sizes of only 1 to 2 m in height. Interestingly, the impact of cowpea legume intercropping on cassava plant size had either no effect (i.e., Chambezi field station) or an adverse effect (i.e., Mumbaka and Vianzi field stations). Soil amendments occasionally had a minor positive effect on final plant size at the Chambezi and Mumbaka field stations, but not at the Vianzi field station, whereas pest control only had a significant overall impact on cassava plant size at the Chambezi field station.

Plant survival was affected by different treatments at different locations. At the Mumbaka station, it was legume intercropping that reduced cassava plant survival, but at the Vianzi field station, it was surprisingly soil amendments. None of the treatments affected cassava plant survival at the Chambezi field station, where survival rates were nearly always 100%. The lowest survival rates were recorded at the Mumbaka field station, with less than half of the plants surviving, whereas at the Vianzi field station, more than half of the plants survived; however, this was still less than at the Chambezi field station.

The Chambezi field station produced the highest storage root weight levels by a significant margin, occasionally outnumbering those at other field stations by more than a factor of 10. The lowest root weight levels rarely fell below 20 t/ha at the Chambezi field station, whereas they rarely exceeded 20 t/ha at the Vianzi and Mumbaka field stations. The lowest root weights per plot were recorded at the Mumbaka field station. However, this was attributable to the fact that there were few surviving cassava plants per plot. When correcting all root weights by the number of surviving cassava plants that contributed to these yield proxies, the per-plant root weight levels for the Mumbaka and Vianzi field stations were comparable or even slightly higher at the Mumbaka field station (Figure 10a-c). The per-plant cassava root weights at the Chambezi field station were exceptional, with the lowest recorded yield levels equaling the highest recorded yields at the other field stations (4 kg/plant) (Figure 10b below).

However, the difference in measured cassava storage root weights between the best performing (soil) treatment and the untreated control was predominantly smaller than a factor of two. Except for one parameter at one field station (i.e., cassava plant size at the Chambezi field station), pest control did not have a measurable impact on cassava plant size, the number of surviving plants, or harvested root weights at any field station or during any year. There was never a statistically significant replication effect confirming that at all field stations, soil, and other environmental (seasonal) conditions were uniformly applied to all plots and did not confound treatments.

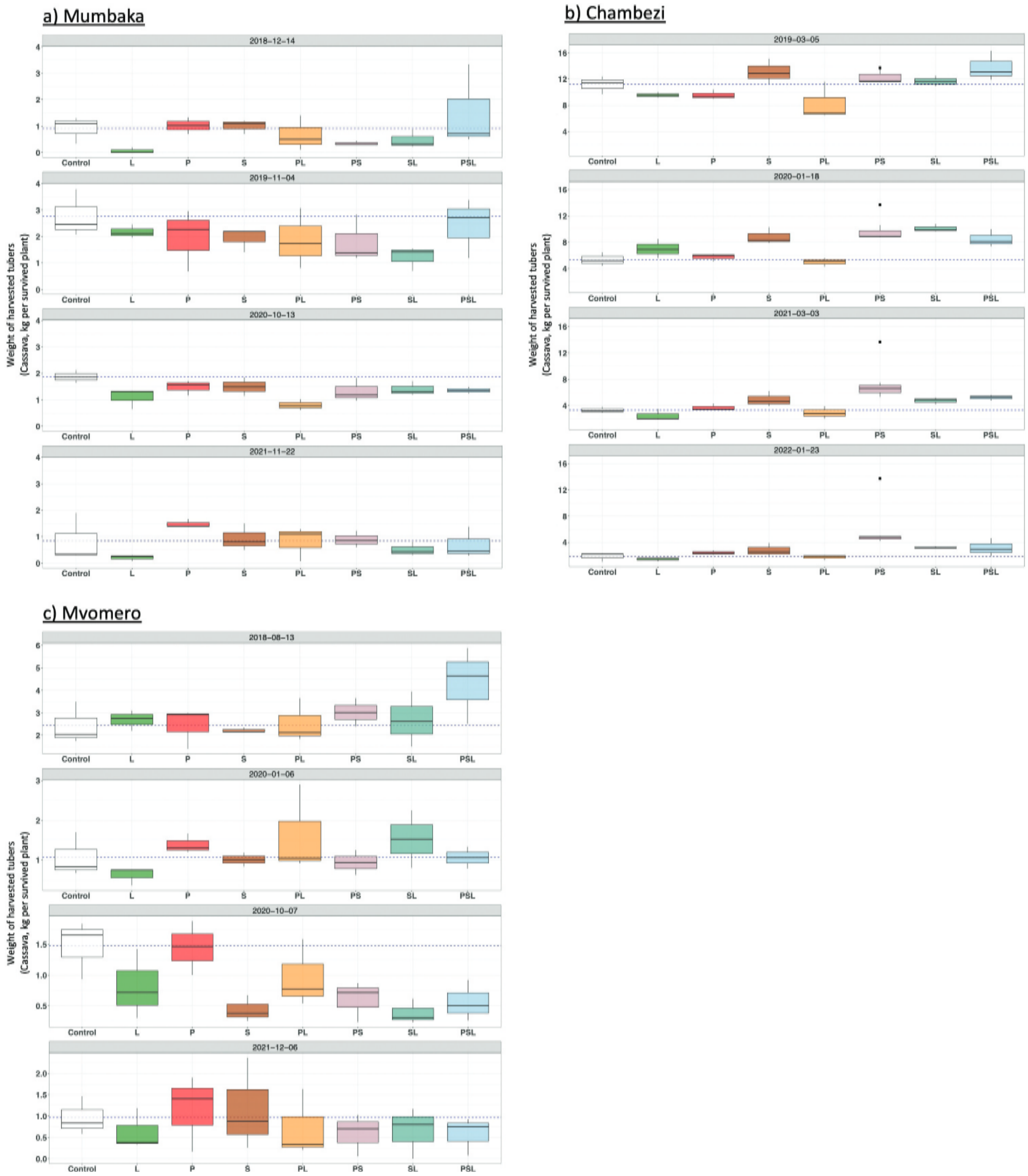

Figure 10. Comparison of per-plant cassava storage root weight levels per plot and treatment at all field stations: a) Mumbaka, b) Chambezi, and c) Vianzi.

Discussion

Our findings confirmed that the Kiroba cassava variety employed in our trials was best adapted to the environmental conditions of the lower Tanzanian coastal regions, such as Bagamoyo, where the majority of cassava cultivation takes place. Despite sharing a number of similar environmental conditions as the Mumbaka field station, the yield from the Kiroba cultivar used at all stations yielded exceedingly more at the Chambezi field station. In Mumbaka, the soils are primarily sandy and nutrient-deficient, and the climate is often hot and dry. However, cassava is sensitive to lack of water during its early germination and establishment phases (Bakayoko et al. 2009; Baker, Fukai, and Wilson 1989; Pardales and Esquisel 1996). Water could have been more of a limiting factor during this susceptible early germination phase at the Mumbaka and Vianzi field stations than at the Chambezi field station, which was far more prone to flooding. The mean yields at Chambezi were extraordinary, particularly in the first field trial season of 2018, when yield levels of 120 t/ha or higher were recorded for some plots that had received soil amendments, while yields in control plots peaked at approximately 100 t/ha. Although subsequent seasons in Chambezi experienced lower yields, these levels were still considerably higher than the average national yield levels of 3.5 to 8.5 t/ha (FAO 2013; United Republic of Tanzania 2021)[3]. In the literature, yields of 40–54 t/ha were reported from in-situ trials on farms in the west African nations of Togo and Nigeria (Eke-Okoro and Njoku 2012; Ezui 2017). In addition, Fermont et al. (2007) reported yields ranging from 14 to 59 t/ha in Uganda and western Kenya. According to Burns et al. (2010), yields of 90 t/ha recorded in Colombia under ideal conditions show that the yield potential of cassava has not yet been fully realized in most of the cassava-producing regions of the world. The yields achieved in Chambezi during at least one season strongly corroborate this notion also for an African country.

While plant survival was high at the Chambezi and Vianzi field stations, the Mumbaka field station stood out, losing approximately half of its cassava plant production each year across all treatments. One explanation for this phenomenon was the recurring termite invasions from neighboring grasslands during the early season. Evidently, the organic pest control measures applied were incapable of preventing the termites from destroying the young cassava plants. One hypothesis was that the woody cassava sticks provided appealing food for termites in that region during that specific time of the year. Although termite attacks were occasionally observed at the Vianzi field station, they did not have the same impact on plant survival as they did at the Mumbaka field station. No termite attacks were reported at the Chambezi field station, and surviving cassava plants were typically in good health. Although we occasionally observed various herbivores feeding on cassava plants, except for the termites during the early season in Mumbaka, none exerted a limiting impact on the growth or survival of the cassava plants. This could also explain why most pest control measures had no discernible impact on plant size or yield. Moreover, two factors could have contributed to that. First, cassava plants produce various plant compounds (mainly cyanogenic glycosides) that serve as an important defense mechanism against pests (Burns et al. 2010). However, mites (e.g., the cassava green mite), cassava mealybugs, and whiteflies are capable of withstanding the toxic effects of these plant compounds. Whiteflies are also known as vectors for severe cassava virus diseases. The Kiroba variety we used in our trials demonstrated sustained resistance to the cassava brown streak and mosaic viruses. We observed very few or no virusinfected cassava plants. Second, in a 2-year field experiment in Cameroon, Fondong, Thresh, and Zok (2002) found that intercropping cassava with maize and cowpeas reduced the adult whitefly population by 50% and the subsequent incidence of cassava mosaic disease by 20%. Hence, it was plausible that the field experiments have additionally benefited from the presence of both cowpeas and maize in neighboring plots.

The recurring adverse effects of cowpea legume intercropping were somewhat surprising, although they appeared to be consistent with other recent scientific studies. For example, Silva et al. (2016) observed in a cassava-legume intercropping field experiment in Brazil that their cassava cultivar showed greater productivity when cultivated in a monocrop system with good weed control than when intercropped with green beans, pigeon peas, or maize. In a South African field experiment, Legodi and Ogola (2020) showed that intercropping cassava with cowpeas and chickpeas could decrease yields by 40% and 26%, respectively. This effect lessened as the sowing of legumes was delayed following the planting of cassava sticks. In addition, Pypers et al. (2011) found that intercropping cassava with legumes increased soil fertility; however, this effect could be negated if the legume variety had high biomass productivity that exerted a competitive effect. In our field experiments, we delayed the sowing of cowpeas by two weeks. However, on various occasions, cowpea plants still had to be pruned to reduce their overgrowth and impact on cassava sticks. The cassava sprouting and subsequent growth periods are slow during its early development, which constitutes the most vulnerable stage of its life cycle. It is in this early period of establishment and growth that cassava plants are susceptible to competition for water and nutrients as well as pest attacks (e.g., termite attacks). However, intercropping can increase the productivity of both cassava and legumes with a good system design. In Nigeria, Makinde et al. (2007) observed cassava yield increases of 10–23%, but only after two years of cassava-soybean intercropping.

In our field trials, we observed that adding soil amendments such as compost or mulch further increased yields under the already favorable conditions of the Chambezi field station. However, in sub-optimal environments, soil fertility amending practices of compost application, mulching, or intercropping cassava with nitrogen-fixing legumes did not appear to be sufficient to overcome the limited potential of sub-optimally adapted cassava varieties. Even at the Chambezi field station, the increase in storage root weights gained by adding soil fertility amendments was modest and typically less than half the yield gains obtained for maize in parallel trials (Hilbeck et al. 2024b maize companion paper).

In terms of the limitations of the study, the following needs to be kept in mind. The cassava variety (Kiroba) was used at all field stations. Similarly, the same cowpea variety (Tumaini) was used for legume intercropping at all field stations. However, we would like to emphasize that despite the fact that also the preparation method, the ratio of compost to mulch, and the volume and timing of application of the soil amendment were all standardized across field stations, the compositions of the soil amendments differed between (but not within) field sites as a result of the different local organic resources available to the farmers (Hilbeck et al. 2024a methodology companion paper for details). Similarly, biological pest control was performed with comparable rigor across field sites, but the components (i.e., ash, chili, aloe vera, garlic, and neem) differed depending on what was typically used in the region. Therefore, conclusions regarding the utility of these treatments should be interpreted in light of their local applicability. For additional information on the applied treatments, including the components and preparation methods of inputs (compost, mulching, and pest control), we refer the readers to a supplementary methodology paper (Hilbeck et al. 2024a methodology companion paper).

Conclusions

Our methodology for evaluating sets of various agroecological practices yielded robust and reproducible outcomes that can be used to make evidence-based recommendations to local farmers and to guide future research.

We conclude that the Kiroba cassava variety can deliver high yields with minimal additional support, but only when cultivated in the lowland coastal regions of Tanzania, where this cultivar was bred and appeared to be best adapted. Therefore, we recommend that in-situ breeding of varieties may be the most prudent way forward to develop better-adapted, high-yielding varieties for the other locations in Tanzania where cassava is cultivated.

Legume intercropping did not improve cassava yields in our experiments. However, it may have a more long-term contextual effect on soil properties and cassava yields than a 4-year field experiment could capture. In addition, legume intercropping provides additional nutritious crops that can complement starch-based cassava food products. Further research is required to establish the optimal combinations of cassava varieties, planting times, and potential legume intercrop species in a regional context.

When cassava varieties with stable resistance to common virus infections, such as the Kiroba variety, are utilized, our findings further support the notion that labor-intensive and expensive agroecological pest control practices produce too few tangible benefits to justify the time and economic resources invested. Instead, we advise investigating the potential benefits of a diversified production system, which may help to balance pest-predator relationships.

The AEA application was designed for automated and rapid graphical and statistical analyses of large agroecological field experimental data sets collected in a rigorous and structured manner based on a given experimental design (split-plot). The coupling of data collection, and statistical analysis including data visualization enabled us to draw conclusions and make practical recommendations from the collected data without the need for specific programming expertise. However, basic statistical knowledge is required to conduct meaningful analyses and interpret the results correctly.

The AEA application was developed alongside a separately designed data gathering and storage application, the AER application, on the basis of a specific experiment. Nevertheless, the general concept of coupling two ICT tools to complete the workflow, from conceptualization and execution of experiments and data acquisition by local researchers and farmers to graphic and statistical analyses, could be applicable to other study fields and experimental settings. Both the AEA and AER applications are based on open-source software and were designed in such a way that key aspects (e.g., link to input data, choice of experimental design, and names of response and treatment variables) could be adapted to other experimental settings. This might necessitate some or many adjustments to the underlying code, depending on how much the new experiment would conceptually differ from the present one. During application development, we tried to avoid "hard coding" (i.e., the embedding of data or code that is not generally valid but specific to the present experiment) as much as possible. Therefore, in the case of the AEA application, some or the majority of the core component may be reused for the analysis of other similar experiments, provided that the global application parameters, such as the link to the database or the names of treatment and response variables, are properly defined in the provided parameter file. Correspondingly, the AER application is composed of standard web components: an online database and a set of scripts that can be readily installed on any common web server and customized to match the needs of unique experimental setups. The definition of the parameters of the experiment can be managed by a back-office system, which includes functions such as field configuration or the specification of crops, treatments, and measurement variables.

Notes

1. The user's manual of the AER application is available at: http://sautiyawakulima.net/agresearch/app/agroeco_manual.pdf. The source code of the application is available at https://github.com/ojovoz/AgroecoResearch
2. The AEA application is available at https://ict4agroecology.shinyapps.io/analysis/. The source code for the AEA application is available at https://github.com/scrameri/AgroecoAnalysis
3. Tanzanian national average yield in 2018 was 5.71 t/ha; https://ourworldindata.org/grapher/cassava-yields

Acknowledgments

We wish to thank the many farmers and station staff for their endless dedication to managing the field trials over the years, diligently and with greatest care applying the various treatments and recording their activities and observations: the farmers of the Chambezi Sauti ya wakulima group: Abdala Jumanne Pazi, Nuru Mohamedi, Rehema Maganga, Renalda Msaki are farmers in Chambezi village, Kilomo Ward in Bagamoyo district council; for the SAT field station, Vianzi, the staff include (late) Jackson Palangyo, Athumani Lungu, Frank Mwara and also SAT co-director Alex Wostry. For Swissaid Mumbaka field station, this includes Nuru Andrew. We further want to thank the fantastic support from several ETH students joining the teams in Tanzania for their internships: Milena Wiget, Mirjam Schleiffer, Rahel Brühlmann, Nicolas Dörig, Samira Amos. Moreover, we thank Anna Ingwersen, ETH student assistant, for her great help in compiling, organizing, formatting the many references, figures and tables in preparation for submission of this series of manuscripts. Also, we would like to thank Sokoine University of Agriculture for hosting our PhD students. This project was truly a joint effort.

Disclosure statement

No potential conflict of interest was reported by the author (s).

Funding

This research work was funded by SWISSAID (Berne, Switzerland) under 'Research and Advocacy for Agroecology' Project and co-funded by the Swiss Development Cooperation (SDC) and the Swiss Federal Department of Foreign Affairs, the Liechtenstein Development Service (LED) and France Embassy in Tanzania.

Data availability statement

The link to the online data has been submitted with this manuscript. The software codes are already available online under creative commons license – links provided in text.

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