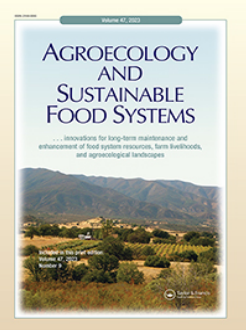

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ICT4Agroecology: a participatory research methodology for agroecological field research in Tanzania

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ABSTRACT

Agroecology has become increasingly popular but locally optimized agroecological production methods and information and communication technology (ICT) support tools are limited. This study was conducted at three different geographic locations across Tanzania; we co-developed an integrated participatory field research methodology consisting of two components, each supported by a specifically developed, complementary ICT tool, with maize and cassava as the two focal crops, to examine soil fertility and conservation (compost and mulching), increased biodiversity through intercropping (legumes), and organic pest control measures. Two specifically developed ICT tools, the AgroEco Research application (AER) and AgroEco Analysis application (AEA) were used for data gathering & storage and visualization & statistical analysis, respectively. Further, farmer-managed satellite experiments were performed to further test the research premises and validate their outcomes in the "real world" of smallholder farmers, which was supported by a smartphone application called "Ugunduzi" – enabling farmers to collect, store, and evaluate data generated at different stages of their research. Farmers were free to choose any type, number, and combination of the agroecological practices tested in the field research. This study serves as a methodology reference for a number of companion publications reporting on the findings of this project.

KEYWORDS

Agroecology; soil fertility; biological control; legume intercropping; information and communication technology applications

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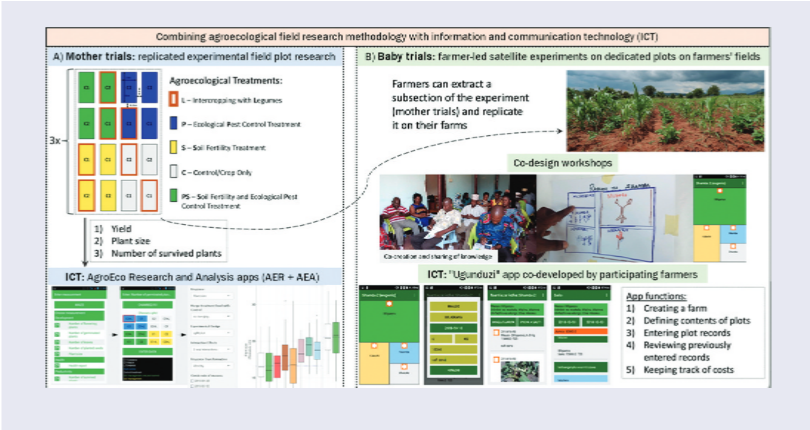

Introduction

Agroecology, the contextualized application of ecological principles to agriculture,[1] has gained traction worldwide in the recent decade. It has increasingly been adopted by farmers, organizations, and policy makers, who consider it to be a viable framework for transforming the current agro-food systems that have been widely recognized as unsustainable (De Schutter 2011; IAASTD International Assessment of Agricultural Knowledge Science and Technology for Development 2009; IPES-Food International Panel of Expets on Sustainable Food Systems 2018; Roman-Acalà 2018; Wezel et al. 2020). The UN Food and Agriculture Organization (FAO) describes agroecology along the "Ten Elements of Agroecology," which have been compiled based on the observations of Altieri (1995) and Gliessman (2014), with discussions held at FAO's multi-actor regional meetings (FAO 2018). The "Ten Elements of Agroecology" are interlinked, and are intended to serve as an analytical tool that "can help countries operationalize agroecology," and a guide for "policymakers, practitioners, and stakeholders in planning, managing, and evaluating agroecological transitions" (FAO 2018). Thus, agroecology entails the identification and application of the best locally adapted practices in food production. The knowledge, skills, and participation of farmers are considered indispensable (De Schutter 2011; FAO 2014). Major policy-making bodies, for example the European Common Agricultural Policy (EU Commission 2020), have recognized the importance of agroecology; in 2021, Tanzania initiated the drafting of a national organic agriculture strategy which broadly encompasses the key principles of agroecology.

Practically, agroecology relies on ecological principles to increase and maintain soil fertility and biodiversity and improve the biocontrol of pests (Nicholls, Altieri, and Vazquez 2017). Thus, agroecological practices can be categorized as soil fertility management using locally available means including organic fertilizers (animal or green manure, compost), increasing biodiversity through inter- and multi-cropping often with nitrogen-fixing legumes, or using herbal formulations for biological pest control only when absolutely necessary. However, depending on local and socio-economic conditions, the nature of practices differ in scale, time, and location. Unlike in high chemical-input industrial agriculture, no standard cultivation practice can be employed for agroecological production systems as local (standard) farmer's practices differ between regions depending on materials available and needed in the different environmental contexts. Constantine et al. (2021) surveyed and reported about common farmer's agroecological practices in Tanzania.

However, research in agroecological practices remains grossly underfunded (Biovision Foundation for Ecological Development, & IPES-Food 2020). Minimal investments have been made into on-site agroecological research to develop better adapted, local crop-specific sets of practices, and for developing technologies supporting agroecological farming systems, specifically digital technologies. While digital technologies can potentially be used to support agroecology, they require different conceptual approaches than in conventional farming (Waters-Bayer et al. 2015; Wettasinha et al. 2015; Hilbeck et al. 2022).

The use of Information and Communication Technologies (ICTs) is widely promoted in conventional, industrialized agriculture. Improvements in computing power and networking technologies facilitated further optimization of farm operations, from production to post-harvesting and marketing. The potential contribution of ICTs to agriculture in general was widely recognized for the first time in 2003, when the term e-agriculture was introduced at the World Summit on the Information Society (WSIS World Summit on the Information Society 2003). Originally, the aims of e-agriculture were stated as applying ICTs to dynamically disseminate accessible, up-to-date information relevant to agriculture, particularly in countries of the Global South, and to increase food production (WSIS World Summit on the Information Society 2003). More detailed potential contributions of ICTs to agriculture in such countries were identified in subsequent studies by non-governmental organizations (NGOs), ICT corporations, and researchers (Furuholt and Matotay 2011; Kirk et al. 2011). Alongside the original aims of e-agriculture, a general set of policy recommendations was formulated and progressively refined (Chapman, Slaymaker, and Young 2003; World Bank 2017). E-agriculture expanded rapidly, which culminated with its rebranding as ICT4Ag (ICT for agriculture), a term that came to be associated with the exploitation of business opportunities offered by the newly founded partnership of ICT corporations and agribusiness (Kalibata 2013). Consequently, the development and implementation of result-oriented ICT platforms that tended to uncritically amplify current unsustainable agro-food systems was largely favored (Rotz et al. 2019; Tisselli, 2016). Today, dominating digital packages for agriculture have emerged from agri-tech firms such as Monsanto, Bayer (e.g., Bayer, 2020), and agricultural machinery manufacturers such as John Deere or Claas, that are designed to improve the sustainability of industrialized forms of large-scale agriculture. In fact, industrialized processes and operations are a necessary precondition for many digital technology proposals which also presents an inherent barrier to the uptake and suitability of these corporate digital solution packages for farming systems that are not industrialized, small scale and require manual labor and artisanal skills and processes. Furthermore, these proposals also implicitly (rarely explicitly) acknowledge the destructive role of industrialized forms of agriculture, but only to the point where they have already developed and presented digital solution packages, without remediating or addressing the underlying causes and responsibilities (e.g., Walter et al., 2017). The Global South is largely considered to be an "untapped market" and as a lucrative business opportunity (Deloitte and Mastercard, 2017; GSMA, 2022a, 2022b – see Hilbeck et al. 2022 for further elaboration). The digital agriculture sector in Africa was estimated to bring in a revenue of 2.3 to 5.3 billion Euro in 2019 (Tsan et al., 2021). Consequently, the Global South – and Africa in particular – hosts a crowded and rapidly growing landscape of digital agricultural services and applications (Aker, Ghosh, and Burrell 2016; ITU and FAO, 2022). Hilbeck et al. (2022) have evaluated these for Tanzania and found that some of the available digital tools and applications may fulfil some elements of agroecology but only if applied within a larger agroecological strategy of transformation. For example, several organizations (e.g., Viamo Platform, Akilimo, TAHA Kilimo, LandPKS) have put significant effort into making their solution design and content farmer-centered and widely accessible, which aligns well with parts of the principles of agroecology but are otherwise designed to align with conventional agriculture (e.g. regarding required chemical inputs – Fertilizer Optimizer App, Akilimo). Hence, implementation toward agroecological goals would be collateral and coincidental at best. Hilbeck et al. (2022), therefore, argued that digital tools for use in agroecological systems need to be embedded in the principles of agroecology regarding their design already – which actually also applies to those destined for the Global North. Agroecology cannot be adopted piecemeal (see Alonso-Fradejas et al. 2020 on "junk agroecology"), but needs to be systemically embraced. As a contribution to resolving this problem, in this project, we aimed to develop, test and integrate different ICTs in a context-based way in support of farmer-centered transitions to agroecology.

According to the FAO, agroecology recognizes the importance of farmers as innovators and highlights the need for combining local expertise and scientific knowledge.[2] We aimed to document and validate locally adapted agro-ecological practices together with local farmers and partners from government and non-governmental institutions, and to identify the best combination of agro-ecological practices for different locations. We established experimental research fields for systematically analyzing and comparing various agroecological practices at three locations in Tanzania, following standard scientific principles. In addition, the participating farmers managed and conducted satellite experiments on their own fields to further test them and validate the most promising agro-ecological practices identified using the systematic experimental research. This methodology was inspired by the "Mother and Baby Trial" method developed by Snapp (Snapp 2002; Snapp, DeDecker, and Davis 2019). The data generated throughout the formal and informal research processes were collected using ICT tools specifically developed for the chosen field research design, and the varying configurations of the farmers' fields. Significantly, the tool that supports the informal, farmer-driven research processes was co-designed with a group of smallholder farmers, as described below. We further developed an online application, which directly extracted and analyzed the data collected during experimental research. These ICT tools were developed by complying with key principles of open-source software, namely transparency and replicability (Open Source Initiative 2006). In summary, the research processes were aligned to Findable, Accessible, Interoperable, and Reusable (FAIR); Collective benefit, Authority to control, Responsibility, and Ethics (CARE); and Transparency, Responsive, User focus, Sustainability, and Technology (TRUST) principles. Thus, there was a fusion of principles from open science, open data, open source software, and agroecology (FAO 2018; Open Source Initiative 2006; Rotz et al. 2019).

The output from replicated experimental field research yielding real-time statistically evaluated outputs, complemented by farmer-led research in fields, is expected to provide robust results that can improve policy making for food security, improved livelihoods, and poverty alleviation. From our collective experience in the policy making, academic research and farmers field practice arenas, we know that different types of evidence are necessary to document the agroecological potential. For the academic research and science policy arenas, outcomes of formal research setups are necessary to serve as acceptable evidence that follow globally recognized research standards and its formalized evaluation procedures (statistical evaluations). However, our collective experience also informed us that, on the other hand, this is not appropriate evidence for farmer's decision-making processes on whether or not to accept new proposed farming methods. It is widely recognized – certainly in agroecologically minded circles – that farmer's need to be a partner in the development and research process. However, these communities work according to different principles and recognize different parameters which require different methodological approaches. Hence, in this paper, we, firstly, present the integrated participatory research methodology co-developed with partners from civil society, farmers, academics, and government institutions. In subsequent companion publications, we then report the results and outcomes of this integrated agroecology research project that focussed on cassava (Hilbeck et al. 2024a) and maize (Hilbeck et al. 2024b) as main crops. In these companion publications, we only offer a synopsis of the complex methodology applied and cross-reference for details to this paper. In yet further publications, the outcomes of farmer's participation, uptake and outcomes are presented – some are already published others are currently under review and will be cross-referenced here and in the companion publications.

Methodology and results

Integrated participatory research methodology

This research project consisted of two field research parts: A) replicated experimental field plot research at three research stations in Tanzania (mother trials), supported by the AgroEco Research (AER) app, a specifically developed research data collection tool; B) farmer-led satellite experiments on dedicated plots on farmer's fields (baby trials), supported by an ICT application co-developed by farmers called "Ugunduzi".[3]

Partners and study areas

The research was led by the Swiss Federal Institute of Technology (ETHZ) in collaboration with the Sokoine University of Agriculture in Tanzania (SUA). The overall field research was coordinated by SWISSAID Tanzania in collaboration with Sustainable Agriculture Tanzania (SAT) for the Morogoro (Vianzi, Mvomero) research site and with the Bagamoyo District Council for the Bagamoyo (Chambezi) research station. In addition, two complementary PhD projects were carried out by students registered at SUA to generate additional data on specific details of the field research and use of the ICT tools developed for this project. The first PhD project is titled "*Validation of Ugunduzi App in Enhancing Smallholder Farmers' Productivity through Farmer-Led Research of Agro-Ecological Practices in Tanzania*" with the main focus on usefulness of ICT for adopting agroecology and the participatory research approach through farmer-led research (a first publication has been published by Kihoma et al. (2021). The second PhD project is titled "*Agroecological practices for increased productivity of cassava-maize based systems: a case study of Mvomero and Masasi districts in Tanzania*" which focused on improving maize and cassava productivity in low altitude areas through application of two types of agro-ecological practices for soil fertility and pest management (a first publication has been published by Constantine et al. (2021)).

The agroecological field research was carried out in three different regions located in three different agroecological zones of Tanzania: Mumbaka in Masasi, Mtwara (the focal region of SWISSAID, a Swiss-based NGO); Vianzi, Mvomero (focal region of Sustainabel Agriculture Tanzania SAT, a Tanzanian NGO); and Chambezi in Bagamoyo, Pwani, where the farmer-led research and management model was implemented via collaboration with the Bagamoyo District Council (Local Governmental Authority).

Mumbaka village is located 10 km south of Masasi town (Mtwara Region), ~ 200 km inland on the semi-arid coastal lowland in the southern zone of Tanzania. Soils are characteristically deep, highly weathered, red sandy clay loam or sandy clay (Dondeyne et al. 2003). Mvomero is located in the much drier inland region, 20 km north of Morogoro town in the semi-arid Eastern zone. Soils vary with topography. Mountain areas are dominated by oxisols while valleys and low lands are characterized by alluvial soils. Grasslands and woodlands are dominated by sandy and clay soils (Hashim et al. 2018). Chambezi is situated in Bagamoyo district 50 km north of Dar es Salaam and has a humid coastal climate (Error: Reference source not found & Error: Reference source not found). Topography is characterized by plains covered by sparse vegetation with dominant soil types being sandy (60%) or sandy-loamy soils (30%) (Bagamoyo District Council 2018). All plots on all field stations were newly established on bushland that had not been under agricultural use before. Exact location of each research site is listed in Table 1 below.

More details on soil nutrient contents at the three research stations are presented in the companion papers on maize (Hilbeck et al. 2024b companion maize paper) and by Constantine et al. (2024).

Replicated experimental field plot research

Experimental design

The replicated experimental field plot research was conducted following a split-plot design, with two whole-plot factors varied on larger whole-plots, and one split-plot factor varied on smaller split-plots.

The whole-plot factors were:

1) ecological pest control (**P**; natural pest control remedies) and
2) soil fertility treatment (**S**; addition of organic material to the soil, i.e., compost and mulching).

The split-plot factor was intercropping with legumes (**L**; to increase biodiversity and soil nitrogen). Each of the three treatment factors was binary (either with or without treatment). In each of the three study areas, the experiments

Table 1. Coordinates of research areas.

Location	Latitude	Longitude	Altitude (meters above sea level)
Mumbaka	10°47′ 28.5″ South	038°53′ 35.9″ East	293
Vianzi	6°74′ 29.7″ South	37°55′ 01.4″ East	547
Chambezi	50 54″ South	350 57″ East	20

were conducted for two crops in parallel, maize (C1) and cassava (C2), replicated on three separate blocks of land (first block factor), and repeated across four seasons (second block factor). A randomized complete block (RCB) design was used at the whole-plot level, wherein every combination of whole-plot and split-plot factor levels occurred exactly once for each crop. Split-plots without application of any of the three treatments served as control plots. This design allowed testing of the main effects and interaction effects of three agroecological treatments individually and in two- and three-way combinations on kernel/tuber weights per plant and per plot (as proxies for yield) and other target variables like plant size and number of survived plants in two widely farmed crops.

As per the agroecological practices described previously (P, L, S), the treatment combinations were: **control** (no treatment), **PL**, **PS**, **SL**, and **PSL**.

One out of three blocks (replicates) per study area is represented in Figure 2. It comprised eight split-plots for each of the two crops, each with an area of 18 m^2 (6 m × 3 m), common size range of farmer's field beds.

After one season, the crops were rotated (C1 became C2 and vice versa) in every replicate block of land, but the treatments to split-plots were unchanged to prevent any carry-over effects.

In total, one study area comprised 48 split-plots (8 treatment combinations and control × 3 replications × 2 crops), yielding an experimental area of 864 m^2 (48 × 18 m^2) excluding footpaths and margins, or a total area of 1'196 m^2 (43.5 m × 27.5 m) including footpaths and margins (Figures 3 & 4)

Crops

Cassava (C1) variety Kiroba and maize (C2) variety TMV1 were used at all research locations. All seeds were sourced from Tanzania Agricultural Research Institute, Ilonga, Morogoro. The same varieties were used in all locations. However, other crops may be used in future research following the same experimental field design.

C1 - Cassava (*Manihot esculenta* Crantz) is a woody shrub from the Euphorbiaceae family. The plant is extensively cultivated in the tropical and subtropical regions for its edible roots and leaves. The crop provides the staple food for an estimated 800 million people in the world (Howeler, Lutaladio, and Thomas 2013), and is valuable owing to its high energy yield per hectare and low input requirements.

We chose cassava because it is an important crop for food security. Moreover, cassava is an integral part of most cropping systems in Tanzania, highlighting the importance of the crop to small-scale farmers and marginal regions (Kapinga et al. 2005). Furthermore, the Ministry of Agriculture has defined Cassava as a focus crop for the Mtwara/Masasi region.

Cassava can perform well on nutrient-poor soils and under semi-arid climate, as long as the soil is reasonably well drained (sensitive to water logging). The crop is highly tolerant to stress conditions, especially water stress. Therefore, cassava is often grown on poor soils in drought-prone areas.

C2- Maize (*Zea mays* L.) was selected because it is the most important cereal crop in Sub-Saharan Africa and is the staple food for 50% of its population. It is an essential source of carbohydrates, protein, iron, vitamin B, and minerals (Biovision 2018). The land area under maize cultivation is growing and expected to continue growing in the future. However, yields are low and sustainable solutions to increase the production are highly needed (Constantine et al. 2021; Shiferaw et al. 2011).

Cropping cycles and seasonal timeline

Because the research aimed to reflect the farmers' practice as closely as possible, cultivation occurred during the rainy season and the crops were primarily rain-fed. The cropping cycles for each research location and year of the project are shown in Figure 5 below. These cycles varied due to changing weather conditions (e.g., start of the rainy season, floods). Planning the cropping cycle involved a level of uncertainty, because the rainfall patterns in Tanzania have become increasingly unpredictable due to climate change. We overcame these challenges via flexible planting times and some irrigation when crops were at risk of failure.

Treatments

Notably, the focus of this project was not on testing the particular composition of specific inputs nor their amounts or other characteristics (e.g., chemical analysis of nutrient contents). Our prime aim was to replicate, as closely as possible, the actual practice of farmers, who use variable, locally available inputs in differing amounts and compositions. The key points raised for this field research were:

- whether the amendment of (any) organic matter – regardless of type, source, or composition – increase soil fertility and lead to measurable impacts on plant yield and growth,
- whether the application of biological pest control based on different ingredients impact plant yield and growth,
- whether increasing biodiversity via intercropping with a nitrogen-fixing legume, such as cowpeas, lead to a measurable impact on yield and health of the main crop over monocropping of maize or cassava.

The effects of various amounts and types of soil amendments (i.e., increasing amounts of manure vs compost), and increasing concentrations of specific biological pest control substances (i.e., neem seed vs neem leaves) were studied in the complementary PhD research at SUA on the same field stations. The outcomes of this complementary research will be reported in separate publications.

Ecological pest control – P. Local ecological pest control remedies, including solid or liquid plant-based mixtures or other available substances, were used (neem, chili, garlic, *Aloe vera*, and wood ash) that comply with the organic farming norms according to IFOAM (International Federation of Organic Agriculture Movements 2014). To control fall armyworm (FAW; *Spodoptera frugiperda*) infestation in Mumbaka field, we ground neem leaves (3 kg), hot chili (0.5 kg), and garlic (0.25 kg), mixed with water (20 L), soaked overnight (24 h), and filtered and sprayed to the affected plants. In Vianzi, four leaves of *Aloe vera* were added in the aforementioned neem-based mixture and the same procedures applied. At all stations, we applied a tablespoon of ash on the whorl of each maize plant.

Ecological pest control was carried out only on P plots (P, PL, PS, PSL) and was based on the occurrence and intensity of pest infestation, for example, FAW infestation. Most pest control mixtures were rarely targeted to control a specific pest/disease; however, early detection is often critical for successful control, especially for FAW (Van den Berg, Du Plessis, and Erasmus 2020). Thus, researchers and other field staff were encouraged to monitor pest infestation and health of crops.

Soil fertility management – S. The set of agroecological practices within the S treatment was only applied on S-Plots (S, SL, PS, PSL). These practices included composting and mulching and occasionally, in addition, as top dressing of plants during the cropping cycle.

Composting. Compost was produced in pits or heaps, and prepared by watering the pit or space for the heap first, and subsequently adding layers of ash, dried grass and harvest residues, fresh legumes, fresh manure, and/or soil. The procedure was repeated several layers until the filled pit or heap was covered with dried grass to maintain the moisture. The compost was turned every three weeks to prevent anaerobic conditions and extreme heating. To prevent loss of nutrients and/or quality, the mature compost was stored under shade, thereby also preventing excessive water infiltration during the rainy season. Covering the heap with a plastic tarpaulin and securing the ends with heavy stones on the ground was recommended. Similar measures were taken when storing animal manure.

Mulching. Mulching was done using mature grasses and, if available, leguminous plants were collected and cut finely into approximately 20 cm pieces. The cut grasses and legumes were then applied as a thin layer of mulch over the plots. Mulch application retains nutrients and moisture in the soil, prevents erosion, and suppresses weed germination.

Top-dressing. To provide additional nutrients in a readily available form to the plants during critical points in the cultivation period, top dressing was applied in 2018, 2019, and 2020 in Mumbaka, but not in Vianzi, Mvomero and Chambezi. Top-dressing, also called tea manure, was applied as a liquid fertilizer prepared from manure whose components varied according to the availability of input material and plant requirements. For preparation, a permeable bag was filled with one part of fresh animal manure and soaked in a large bucket filled with three parts of water. The bag then stayed for ~3 weeks in the water, which was occasionally stirred to improve the seeping process.

Legume intercropping – L. Cowpeas (V*igna unguiculata* (L.) Walp.) are annual legumes, and they were chosen as they are widely used by local farmers and readily available, and are well-adapted to different agroecological zones in Tanzania (Matusso, Mugwe, and Mucheru-Muna 2014). The plant is well-adapted to heat and drought and can grow under low-fertility conditions (Ehlers and Hall 1997). Intercropping is defined as the "cultivation of two or more crops in the same space at the same time" (Matusso, Mugwe, and Mucheru-Muna 2014) and is advantageous in terms of nutrition, biodiversity, and productivity. These include risk minimization, support of a balanced nutrition, improved soil fertility, soil conservation, weed control, radiation use efficiency, and decreased spread of diseases or pests (Matusso, Mugwe, and Mucheru-Muna 2014).

Cultivation of cereals and legumes (such as cowpea) in the same space is practiced in Sub-Saharan Africa, especially in East Africa, where the combination of maize and cowpeas is common (Jensen et al. 2003). In addition to the aforementioned benefits of intercropping, combining maize and cowpeas has further advantages, such as the use of different nitrogen sources in the soil, which decreases the competition between both plants. Moreover, cowpea acts as a fertilizer due to its nitrogen-fixing capabilities. Residual nitrogen transfer in subsequent cropping cycles can increase maize yield up to 66% after 2 years of intercropping, in contrast to monocropping (Matusso, Mugwe, and Mucheru-Muna 2014). Furthermore, Jensen et al. (2003) obtained 7% higher maize yields in inter-cropped systems compared to mono-cropped maize, due to a direct nutrient transfer from the cowpea. However, the same study showed that under fertilized conditions, maize yield was lower in intercropped systems compared to mono-cropped systems. This might be due to greater competition between the crops resulting in higher cowpea yield. The yields of both crops are important for most farmers who practice inter-cropping and, therefore, this effect is not necessarily detrimental. In this study, cowpea legumes were solely utilized as fertilizer and therefore, no data related to cowpea were recorded. In all field trials, the same non-crawling cowpea variety Tumaini from TARI, Ilonga was planted.

Field preparation. All field plots at all stations were established on land that had not been under agricultural cultivation before but had instead been covered by natural vegetation. The vegetation was removed and the designated research plots were plowed to a depth of 50 cm to loosen the soil and render it workable. Seedbed preparation included raking the soil to a fine seed bed texture (Figure 6).

Soil amendments (compost and mulch). Compost was mixed into the soil on the plots designated to receive soil treatments (S-plots). A total of 180 kg compost (10 buckets, each with 18 kg compost) was applied, broadcasted, and mixed into the soil within the plot in all S-plots. Subsequently, mulch was applied on all S-plots after germination of the main crops and legumes to prevent germination suppression. The soil surface was covered with a layer of fine-cut mature grass. The layer was supposed to cover the soil surface completely (Figure 7).

Crop planting

As per farmers' practice, two maize seeds were sown per seed hole at a depth of approximately 5 cm. One plant per hole was left after thinning at 21 days after emergence. During the growth and development of the maize plants starting from germination, all the agronomic and plant management practices were performed accordingly.

Cassava was planted via vegetative propagation using stem cuttings. The stems were recycled from harvested plants or organized from other sources (such as Chambezi). The cassava stems were cut with a sharp knife diagonally to the direction of growth into 20–25 cm sticks (see Figure 8 below). The sticks were planted in a lopsided manner (to promote vertical and not horizontal root development), whereby 1/3 of the planted stick was above the ground and 2/3 below, with the leaf scars looking upside-down.

C1 - cassava plots. Cassava sticks were equidistant, regardless of whether the plots were intercropped with legumes or not Figure 9 & Figure 10). The seedbed preparation on these plots involved digging holes according to the scheme below, with the planting position of each cassava stick clearly visible.

In Mumbaka and Vianzi, two cowpea seeds were sown at a depth of about 5 cm per hole. In Chambezi, three to four cowpea seeds were sown and later thinned to two germinated plants per hole. The layout of the cassava planting scheme is depicted in Figure 9 and those of cassava sticks intercropped with cowpeas in Figure 10.

C2 – maize plots. Without cowpea legumes, maize was sown according to a 30 cm x 60 cm scheme (Figure 11, below) with 17–20 plants per row. When maize was intercropped with legumes (L), a 45 cm x 60 cm sowing scheme applied with 10–13 maize plants in one row (Figure 12, below). This led to plants number per plot ranging between 190–200 in mono-cropped plots or 120–130 when plots were intercropped.

In Mumbaka and Vianzi, two cowpea seeds were sown at a depth of about 5 cm per hole. In Chambezi, three to four cowpea seeds were sown and later thinned to two germinated plants per hole. The legumes were planted up to 3 weeks after the maize plants germinated to prevent overgrowth. The planting scheme of maize intercropped with cowpeas is shown in Figure 12 below.

Crop husbandry

Thinning, gap filling, and transplanting were performed, in addition to general crop husbandry activities such as weeding. Additional seeds or sticks were only planted up to 2 weeks after sowing or planting, respectively. Cassava plants were not pruned (except during the first season in Vianzi). Neither were leaves, which are used as food, harvested during the growing period.

As the aim of the research project was to simulate farmer field conditions as closely as possible, irrigation was minimal. Irrigation was only carried out when the plants showed symptoms of severe water deficiency and, in those cases, it was done only on plots with the same crop. In 2018, irrigation was carried out once in Vianzi and twice in Mumbaka. In 2019, no irrigation was done. In 2020, irrigation was carried out twice in Vianzi. Therefore, all the plots with both crops were irrigated at some point over the years, except in Vianzi in 2021, where irrigation was done to prolong the irregular, short rainy season and simulate a regular rainy season.

Measurements

The following parameters were measured for both crops:

1) Yield as proxy for productivity measured as weight (kg/per plot) of roots (cassava) or kernels (maize) was recorded. Yield was measured using formal standard scientific (metric) means of quantification on the field station research. In the case of farmers' satellite experiments, or "Baby trials," traditional means of measurement (either using bags or buckets) were used to record yield data and subsequently converted to kg to perform joint evaluations.

Maize cobs from the harvested area (18 m^2) were air-dried and shelled. The maize grains were air-dried and weighed using a weighing balance. For cassava, at harvest, the fresh weight of cassava roots per plot (6 m × 3 m) were recorded in metric kilograms per plot.

2) Plant size (cm) was used as indicator for plant development. The size of each plant was measured using a measuring tape and recording the length of the stem from the plant basis/soil surface to the tip of the top leaf (Maize) or to the top branch (Cassava). Maize plant size was measured at the flowering/ tasseling stage (roughly 8 weeks after planting) because the vegetative growing stage of the plant was finished and no subsequent significant changes in plant size occur anymore.

3) Numbers of survived plants was measured once at harvest, as indicator for plant survival over the season.

The measurements were recorded either directly using the AER mobile application (see below), or first recorded on paper and subsequently entered via the application's web interface.

Soil sampling and analyses

Composite soil samples were collected on each plot at a depth of 0–15 cm in three sampling missions. The first soil sampling was carried out directly after plot preparation of the first year and before any treatment. This constituted the baseline for future comparisons. Subsequently, two further sampling missions were carried out on the same plots in 2-year intervals, in 2019 and 2021.

Soil samples were air-dried and a 500 g sub-sample was sieved to 2 mm and analyzed to determine soil texture, total nitrogen (N), soil organic carbon (SOC), soil pH, available phosphorus (P). Particle size distribution was determined using Bouyoucos hydrometer method after dispersing soil with calgon (Gee and Bauder 1986). The soil pH was measured both in water and $CaCl_2$ at a ratio of 1:2.5 soil-water or soil: $CaCl_2$ (McLean 1983). SOC was determined using the Walkley and Black method (Nelson and Sommers 1996). Total N was determined using Kjeldahl method (Bremner 1996) while available P was extracted using Bray and Kurtz-1 (Kuo 1996). Following extraction, available P was determined via the phosphomolybdate-ascorbic acid procedure using a spectrophotometer (Okalebo, Gathua, and Woomer 2002).

Newly developed ICT support tools

A key component of this project was the specifically developed set of ICT tools to support a) a standard research setup on field stations (AER AgroEco Research application) and its statistical evaluation (AERs companion application AEA – see below) and b) farmer-led research on farmer's own farms (Ugunduzi application). A unique feature of the formal field station research method are the two interconnected applications for guided field data collection (AER) feeding automatically into the connected statistical evaluation application using shiny R application (AEA). This allows to generate statistically evaluated outcomes almost in real time as field data is collected and submitted. Hence, to make this component unique feature available to others (all published under open-source license and freely accessible) and amendable for purpose (code can be adjusted and made fit for slightly different experimental designs, collected parameters, etc.), we offer a detailed description of its features below.

AgroEco Research (AER) application. The AER application was developed to support the aforementioned research process by gathering the data generated throughout it. Because the application was used by researchers in all three locations, it allowed for the uniformization of research practices across different fields and periods, as well as the aggregation of data generated in different locations and at different times in a centralized database. The AER application was designed specifically for the research configuration presented in this text, yet it remains flexible enough to support other configurations (i.e., different crops, field layouts, or agroecological methods) that may be used in future research.

The AER application was developed using a set of menu-driven mobile and web applications that could be used to directly enter data in the fields or at local offices. The AER application has three levels of usage. Administrators of the application can configure all the research parameters, including crops, agroecological treatments, or the layouts of plots and fields, using a set of low-level software tools that can be considered a back-office application. Data gatherers can use the AER application to enter data related to different activities such as field preparation, treatment, or irrigation of the plots, and also standardized measurements such as yields, plant sizes or number of surviving plants, as well as other parameters related to plant development and crop productivity. Finally, users who wish to consult, filter, and analyze the data can use the sections of the AER application that were specifically developed for this purpose[4]. The main navigation diagram of the AER mobile application, along with selected screenshots, are shown in Figure 13 below.

Technically, the AER application was implemented using standard web components. The centralized database is supported by the MySQL database service, and is hosted in a commercial server managed by the implementers of this research. The mobile component of the AER application was developed using Java for the Android operating system, and was mainly used by data gatherers in Mumbaka, Vianzi, and Chambezi, who were supplied with a smartphone for the purpose. The data from the research fields could also be entered using a web application, implemented using a combination of PHP, JavaScript, HTML, and CSS languages. Finally, because the AER application was developed and published under an open-source license, it can be made available to other researchers who wish to implement a similar methodology.[5]

AgroEco Analysis (AEA) - visualization and statistical analyses connected to AER-based data recording. The AgroEco Analysis (AEA) application is an interactive R Shiny app[6] available online (https://ict4agroecology.shinyapps.io/analysis/). It accesses the measurements entered via the AER application (i.e., the AER research data) in real time, allowing for a coupling of data collection via AER with data visualization and statistical analysis via AEA. As an R Shiny app, it is written entirely using the R programming language (R Code Team 2021), and interaction on the web is enabled through the Shiny package (Chang et al. 2021). The visualizations and statistical analyses provided by the AEA app can be achieved without the need for programming skills, although app users should be familiar with box plots, and basic statistical knowledge is required to correctly interpret the ANOVA results.

The AEA user interface (UI) has a simple (few key options) and effective (multiple tabs with visualizations or statistical output) design. The four key options can be set by switching choices in the app's sidebar: 1) study site (Location, single choice), 2) crop (Subject, single choice), 3) target variable (Response, single choice), and 4) considered time frame (multiple-choice selection of dates and seasons). Further options affect the analysis of variance (ANOVA) carried out on the specified data subset and include the choice of experimental design (split-plot by default), level of interactions analyzed (two-way interactions by default), and transformation of the response variable for improved model fitting (no transformation by default). After choosing a particular set of options, users must hit the "Submit" button, resulting in updates to the output provided as various tabs in the main panel of the app.

An important block factor is the season, which starts with the planting of maize seeds or cassava sticks and ends with harvest of the same plants. Data collection spanned several seasons, which must be defined accordingly for visualization and statistical testing; however, the start and end dates of seasons differ between crops and study areas. Therefore, after selecting a different Location and/or Subject via the UI, the first click on the "Submit" button will result in an updated multiple choice for the considered dates and time frame, with calendar years as the suggested boundaries between different seasons. The appropriate ends of each season (corresponding to the dates of harvest and largest average plant size) must be recorded, and the "Submit" button must be hit again such that the seasons are visualized and analyzed correctly.

The visualization conducted by AEA consists of box plots made using the *ggplot2* package (Wickham 2016). Users interested in visualizing the response variable separately for each of the eight split-plots can activate the "Boxplot I" tab. Here, one box plot represents the repeated measurements of a single chosen target variable in response to a particular treatment applied singly or in combination with other treatments (i.e., split-plot). Eight box plots representing the eight split-plots are arranged in a panel for each date on which measurements were taken. Once the end date of each season (last date of a year by default) in the considered time frame (all dates by default) has been set and submitted by the user, the box plots are rearranged such that each row of panels represents a single season, with consecutive dates appearing as consecutive panels. The control split-plot is displayed as the first box plot in each panel, and a horizontal dashed line represents the mean value of the response variable in the control split-plot. Star annotations above each box indicate whether a specific treatment or treatment interaction effect was found to be statistically significant at the 10% (.), 5% (*), 1% (**), or 0.1% (***) level, respectively. These percentages reflect the significance level, or the probability of wrongly rejecting the null hypothesis of there being no difference to the control.

Users interested in visualizing the overall differences between the three treatment main factors can activate the "Boxplot II" tab. Here, shaded box plots represent the combined measurements of all split-plots where a specific treatment (L, P, or S) was applied, regardless of the measurement date within a season, and other treatments applied simultaneously. Shaded box plots can be compared to open box plots, which represent split-plots where a specific treatment was not applied, although other treatments may have been administered. Given that season effects often explain a substantial amount of variance, these comparisons are shown separately for each season. Star annotations above each pair of box plots indicate whether a significant difference is observed in a global *F* test.

While the interpretation of most target variables is intuitive in the units of measurement, agroecologists are typically interested in comparing yield in tonnes per hectare. Therefore, a checkbox appears whenever a target variable measuring yield is selected, allowing for the conversion of kg/plot to tonnes/ha. The conversion depends on the number of planted seeds per unit area, which is set in accordance with the experiment to 10 per split-plot (18 m^2) for cassava and to 200 (mono-cropped) or 130 (inter-cropped) per split-plot for maize.

The R output of statistical tests can be obtained by activating the "ANOVA" tab. Here, the model formula, as interpreted by R, is shown together with the ANOVA table and confidence intervals for the treatment effect sizes relative to the control. The default split-plot ANOVA is presented in the form of a linear mixed-effects model as implemented in R's *lmerTest* package (Kuznetsova, Brockhoff, and Christensen 2017). The model formula is automatically constructed based on user input and takes the following components into account: 1) season effect (if multiple seasons are considered), 2) block effect of three replicate plots of land (Rep), 3) main and interaction effects of each of the three treatment factors, the whole-plot error term for soil treatment (1 | Rep:S), whole-plot error term for pest control (1 | Rep:P), and split-plot error (residual standard deviation sigma), which is only shown as a confidence interval. The ANOVA table lists the sum of squares (i.e., the variance between levels of each block or treatment factor), mean squares (i.e., the sum of squares divided by the numerator degrees of freedom), and F test statistic (i.e., the variance between treatments divided by the residual variance within treatments) and corresponding p-values (i.e., the probability of obtaining a test statistic that is at least as extreme, assuming the null hypothesis of no effect is true). A 95% confidence interval for the effect size of each treatment factor level is shown below the ANOVA table. Intervals that include zero are typically not significant.

The "Results (Global)" tab displays the most important values of the ANOVA table (i.e., the p-values and test results for each treatment factor or interaction), while the "Results (Specific)" tab displays the estimated effect size of each treatment level along with their 95% confidence intervals and test results. Estimated effect sizes above zero can be interpreted as leading to an increase in the response variable (positive effect), while estimated effect sizes below zero lead to a decrease in the response variable (negative effect) if the treatment is applied (S1, P1, L1, etc.) compared to the situation where the treatment is not applied. The effect sizes must be interpreted in the same unit as the target variable, or in the same unit as the transformed target variable in case of a selected transformation.

The "Residuals" tab shows the model residuals, which represent the deviation of the actual measurements from the values fitted by the ANOVA model. These plots must be evaluated before making strong conclusions based on the test results, because they indicate whether the model assumptions are met. Briefly, the residuals should have a constant variance (residuals vs. fitted values form a uniform band rather than an opening or closing funnel for larger fitted values) and follow a normal distribution (standardized residuals vs. theoretical quantiles lie close to the straight dotted line in the Normal Q-Q plot). Further, we assume that the measurements are independent of each other. If one or multiple of these assumptions are grossly violated, as indicated by the residual analysis, the test results and any conclusions drawn from them may be invalid.

The remaining tabs are useful to inspect 1) the raw data in a wide format ("Data (Raw)" tab), 2) aggregated data summarized across repeated measures per split-plot in a wide format ("Data (Means)" tab), and 3) aggregated data in a long format ("Data (ANOVA)" tab), which represents the input for ANOVA.

The current implementation of the AEA app allows for joint visualization and statistical analysis of measurements taken at one study site, for one crop and one target variable at a time. Comparisons across study sites and crops are possible after carrying out separate comparable analyses and downloading the respective graphs, data subsets, and statistical results using the download buttons, which can be found at the bottom of each tab.

An important feature of the AEA app is its direct connection to the AER research data, which is represented as comma-separated text. A fast download of the complete AER research data is achieved using the *data.*

table package (Dowle, Srinivasan, and Short 2019). To minimize data traffic, we designed the AEA application to access the complete AER research data only once at start-up rather than each time a new subset of the data (e.g., a different crop or measurements from a different study area) is analyzed. Furthermore, we designed the app to omit time-consuming, repetitive calculations. The time-consuming reshaping of the complete raw data to a table in long format is performed only if new data has been entered through the AER application. This is determined by comparison of the current AER research data to a regularly updated local copy of that database, which is already reshaped to an appropriate format. The source code of the AEA application is available at the following open-source repository: https://github.com/scrameri/AgroecoAnalysis.

Satellite experiments on farmer's field plots (baby trials) supported by the "ugunduzi" app. Farmer-led research resonates with the agroecological principle of co-creation and sharing of knowledge (FAO 2018; Waters-Bayer et al. 2015; Wettasinha et al. 2015), which encourages engagement in participatory processes where the dialogue between various situated (e.g., local or indigenous) and scientific knowledge systems can lead to context-specific innovations. During visits to the formal research field station trials, the participating farmers were introduced to the "Mother and baby trial" research methodology and the agroecological practices that were being tested. The group of farmers who took part in the co-design of the Ugunduzi application was selected based on their interest and experience on doing research and record keeping in their farming activities.

The "Mother and baby trial" approach is a systematic trial design used in farmer-led participatory research. It comprises a mother trial (i.e., formal field station experiments) from which farmers can extract a subsection of the experiment and replicate it on their farms (Snapp 2002). These farmer-managed satellite experiments were used to validate the findings from the field station research in the "real world" of the farmers' fields, and also to train farmers in their own experimentation. Per field station location, 15 farmers participated in this joint research effort. Their rough locations are indicated in Figure 1 above (black triangles) and an example of a farmer's satellite research field compared to a formal field research plot (mother trial) is shown below (Figures 14 and 15).

The farmer-led research was supported by a smartphone application called "Ugunduzi," an ICT tool co-designed together with the participating farmers specifically for collecting data derived from their on-farm experiments and sharing their findings with peers. Ugunduzi comprises a smartphone app supported by an online database that aims to assist smallholder farmers in their record keeping and self-driven research tasks. The platform was developed by following the participatory principles of farmer-led research, and the

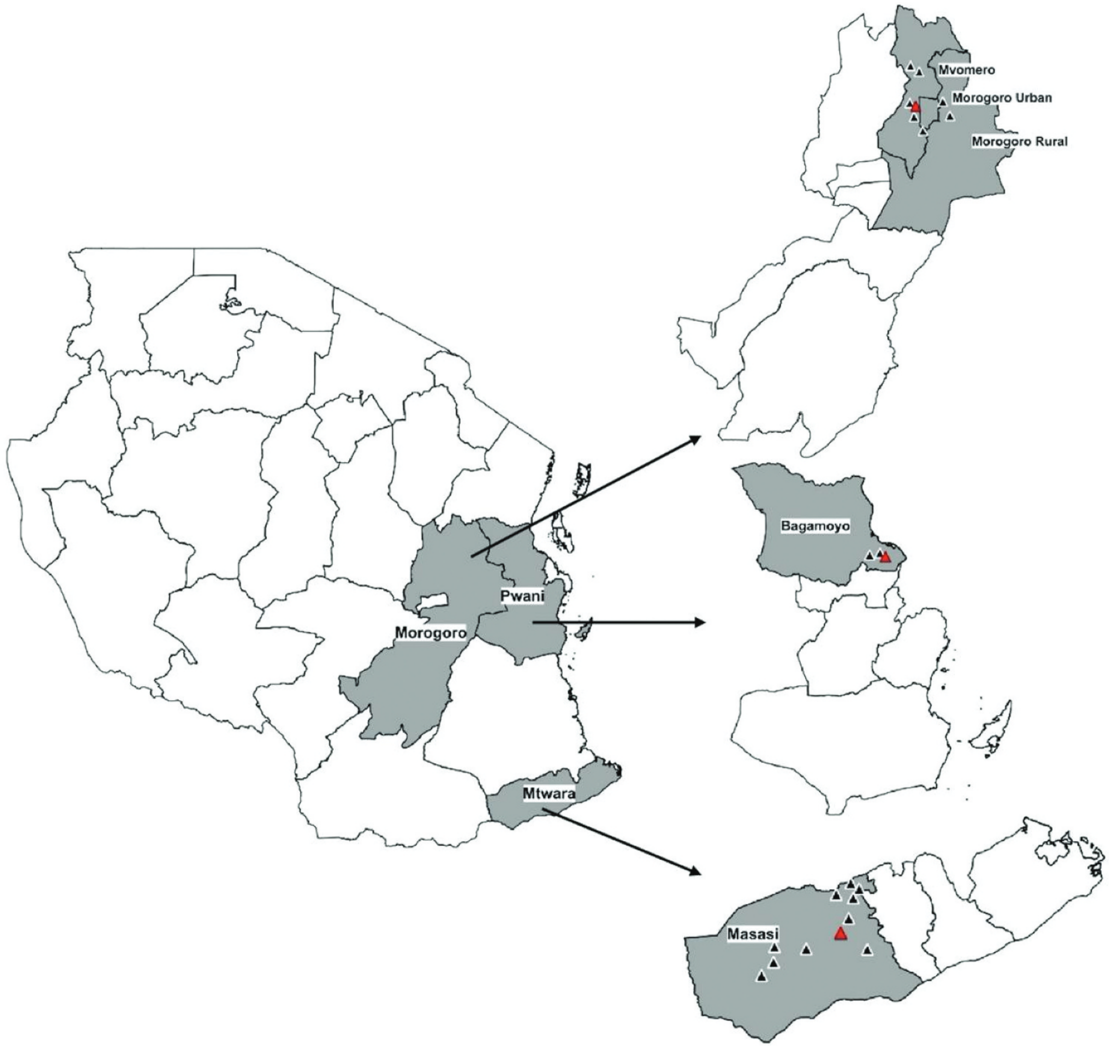

Figure 1. Location of scientific research fields (red triangles) and farmer's research fields (black triangles).

social principles of agroecology, particularly co-creation and sharing of knowledge. These farmer-centered principles were applied in a guided process that engaged a group of farmers in the co-design of the Ugunduzi smartphone application. This process is described in detail in Tisselli (2022).

The main challenge during the co-design and development of Ugunduzi was to strike a balance between the farmers' own understanding of research, based on practical problem-solving approaches, and the more systematic scientific method. We conveyed to farmers the notion that performing research according to scientific methods, such as establishing a test plot to compare the performance of crops and specific agroecological treatments to a control, i.e., common (no treatment) farmer's practice, may yield a greater degree of certainty than unsystematic, ad-hoc problem-solving attempts.

The final prototype of the Ugunduzi app provides a simple and flexible interface (Figure 16 below) for record-keeping that allows

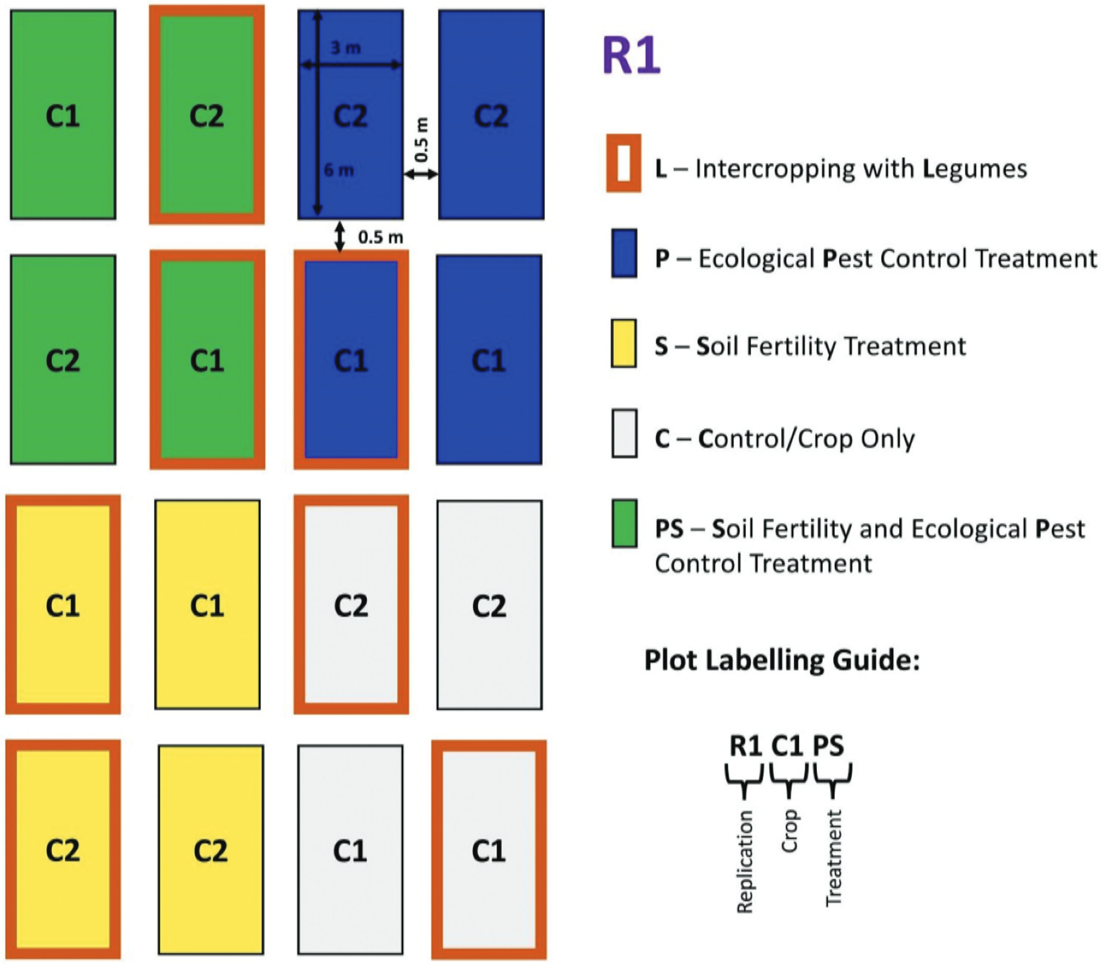

Figure 2. Experimental layout of one field replication (R1) following a split-plot design with randomized complete block (RCB) design applied at the whole-plot level. Maize (C1) and cassava (C2) were the crops used. Color codes indicate treatment applied.

farmers to keep track of the interactions between their crops and the agroecological treatments applied to them, and the related monetary costs and benefits.

The main functions performed by the Ugunduzi app are[7]:

- **Creating and editing a farm**: starting from an empty space, plots can be added, moved and resized. Plots may be placed on the screen as a grid of up to 16 variably sized rectangles. Existing farms may be subsequently edited according to changes made by farmers.
- **Defining the contents of plots**: each plot could contain one or two (intercropped) crops, and one or two agroecological treatments, namely pest control and soil management, or none.
- **Entering plot records**: two types of records could be entered at the plot level: qualitative, consisting of a combination of a picture and voice recording, or quantitative. Quantitative records were based on the different kinds

Figure 3. Complete layout of field research design including three in-field replications.

Figure 4. Image of research plots on vianzi (mvomero) field station.

of activities, processes, and transactions identified by farmers during the workshops (for example land preparation, planting, or the cost of seeds).

- **Reviewing previously entered records**: records for a specific plot or for the entire farm could be viewed chronologically.
- **Keeping track of costs**: recording financial transactions and breaking down costs and benefits per crop, treatment, and other farm activities.

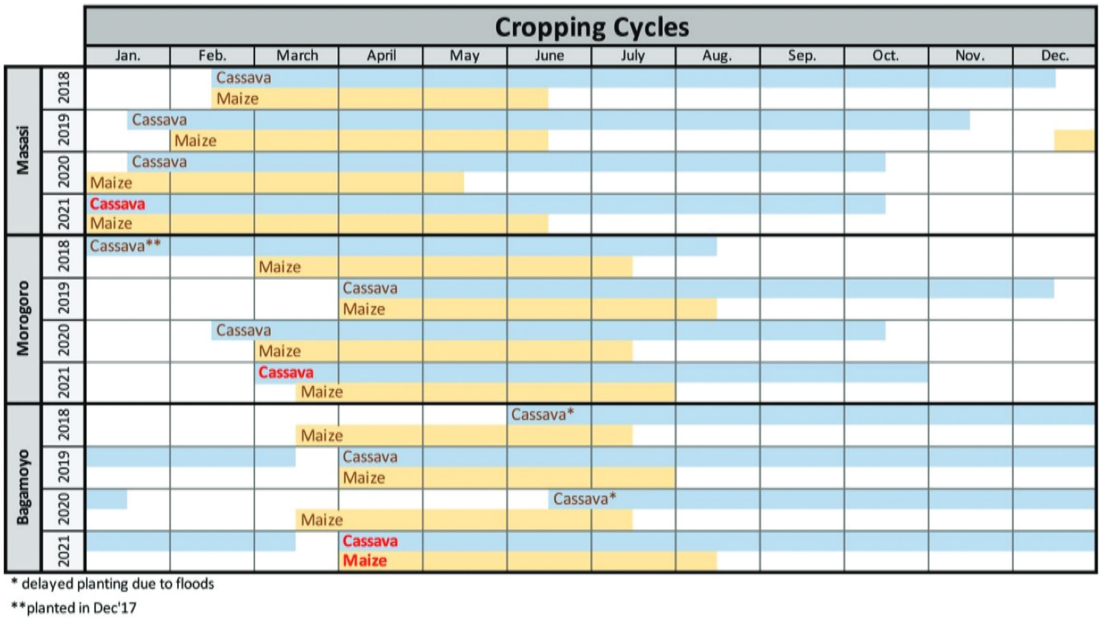

Figure 5. Cropping cycles with location and year.

Figure 6. Field preparation work. In the background, natural vegetation on plots prior to cultivation is visible.

The co-design workshops that led to the development and testing of these functions were planned and executed as a series of incremental steps, which were guided by participatory principles and grounded on specific techniques of Soft Systems Methodology (SSM) (Checkland 1989) and design thinking (Figure 17 below).

This approach attempted to differ from the conventional, top-down technology transfer models in agriculture, which often minimize active farmer participation in research processes, and tend to consider farmers as recipients of technological innovation, rather than co-designers (Martin and Sherington 1997; Vanclay and

Figure 7. Mulched S-plot.

Figure 8. Cassava cutting preparation.

Lawrence 1994). By integrating farmers as co-designers, it is expected that they may not only claim ownership of the Ugunduzi app, but also of the practices of on-farm record keeping and self-led research. Based on their experience with the applied and tested agroecological practices in the "Mother trials," either during visits or while helping with the research on-station, farmers who participated in the co-design and testing of the Ugunduzi app could choose which and how many of the agroecological practices they would like to "test" on their own farms, where and in how many plots. These farmers were asked to record their experiments using the Ugunduzi app by entering data related to their chosen plot configuration, tested crops and treatment combinations, activities related to their trial and outcomes, both in terms of yields and costs. By helping farmers to reflect upon their research activities and past outcomes, the app hopes to encourage optimization and innovation, while fostering a research-based practice. Ugunduzi is currently in its pilot phase, and is being tested against the real-life scenarios of the farms of the participating farmers. The actual levels of acceptance, usability,

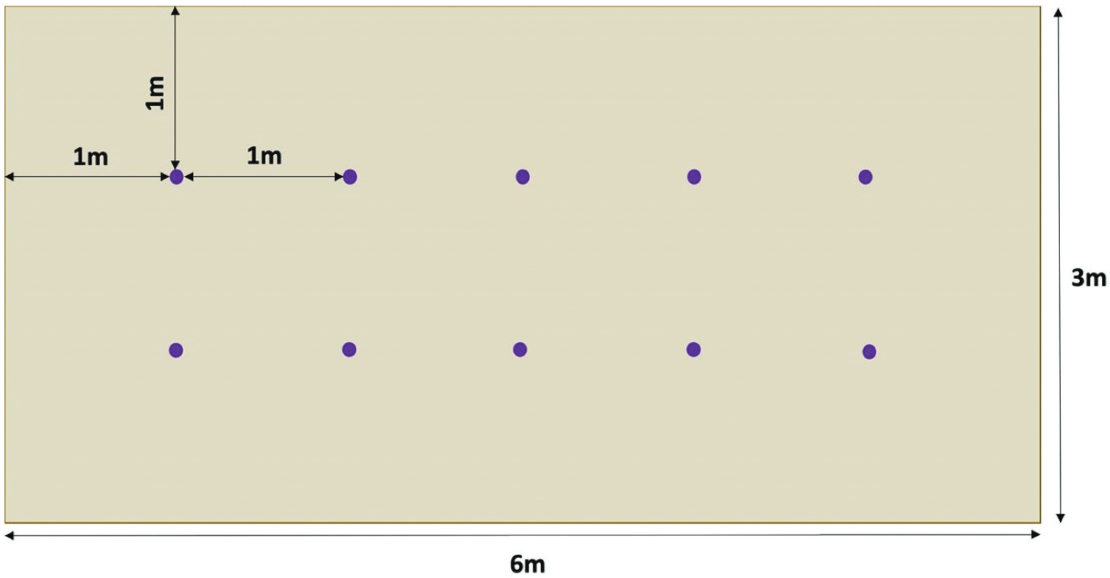

Figure 9. Planting scheme for cassava only in field station research plots.

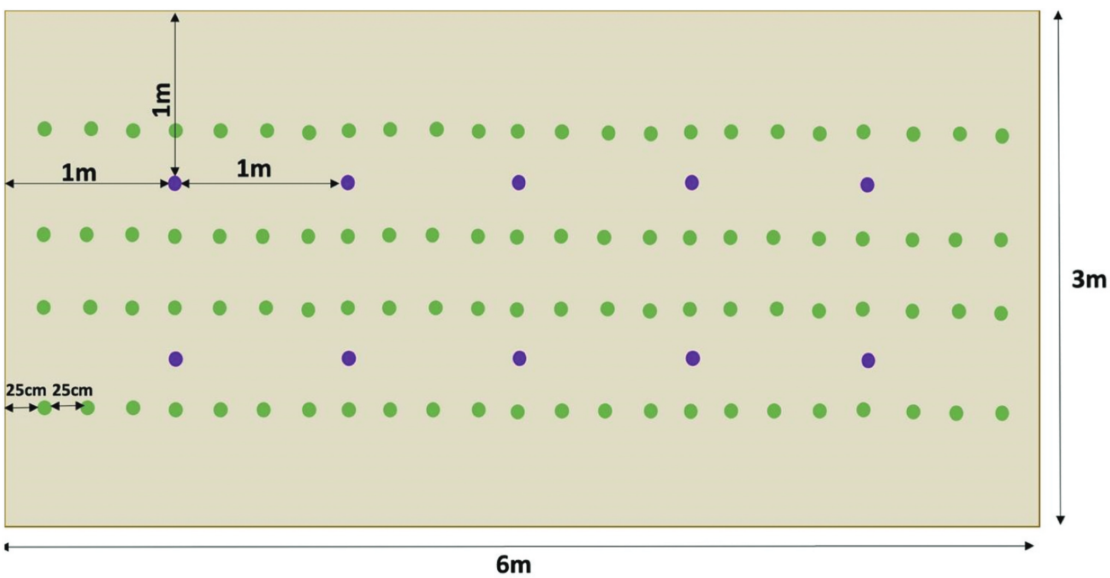

Figure 10. Sowing scheme for cassava plots (C1) intercropped with legumes (L; cowpeas) in field station research plots. Violet and green dots are cassava sticks and legume seeds, respectively.

and usefulness of Ugunduzi are presently being monitored and evaluated at SUA, with partial results already indicating that participating farmers intend to continue using Ugunduzi, since it has contributed to increase their knowledge agroecological practices (Kihoma et al. 2023)

The Ugunduzi app was programmed using Java for Android smartphones, and is supported by an online database server (MySQL) and a set of server-side support scripts written using open-source web standards.[8]

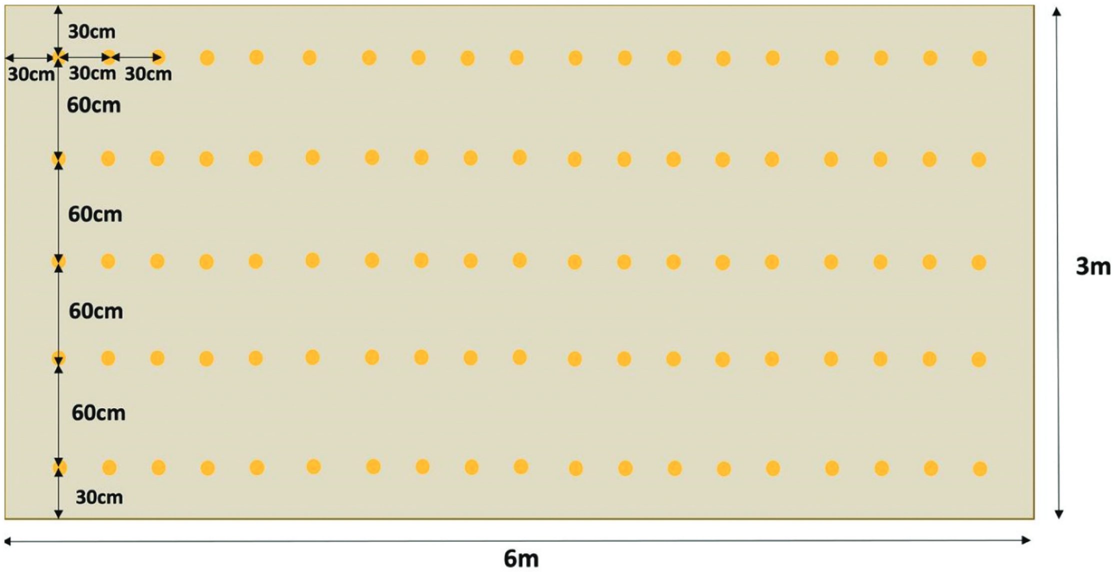

Figure 11. Sowing scheme for maize only plots (C2) – without legumes.

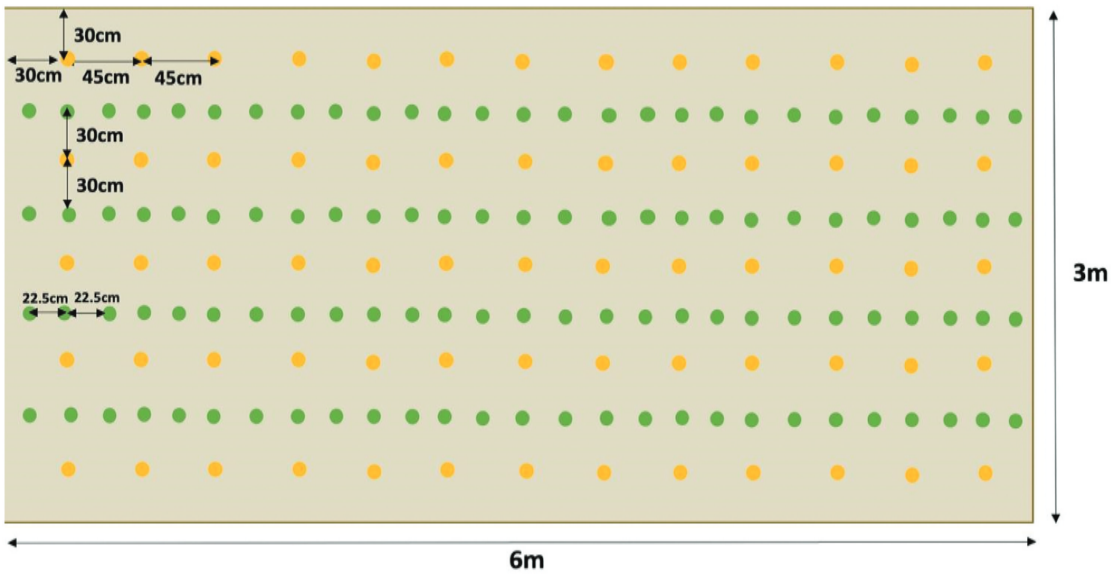

Figure 12. Sowing scheme of maize (C2) plots intercropped with legumes (L; cowpeas). Yellow and green dots are maize seeds and legume seeds, respectively.

Discussion and conclusions

This integrated participatory research methodology was developed with the understanding that transition to agroecology requires active participation from the farming community at all levels, including research, practices, and socio-economic aspects. It aims at supporting advocacy for agroecology transitioning by generating data that is robust, significant, and reliable, and that can, therefore, be communicated to farmers, policy makers, and other stakeholders. To achieve this, we chose a method of research practice that benefits from two complementary approaches. One approach consists of

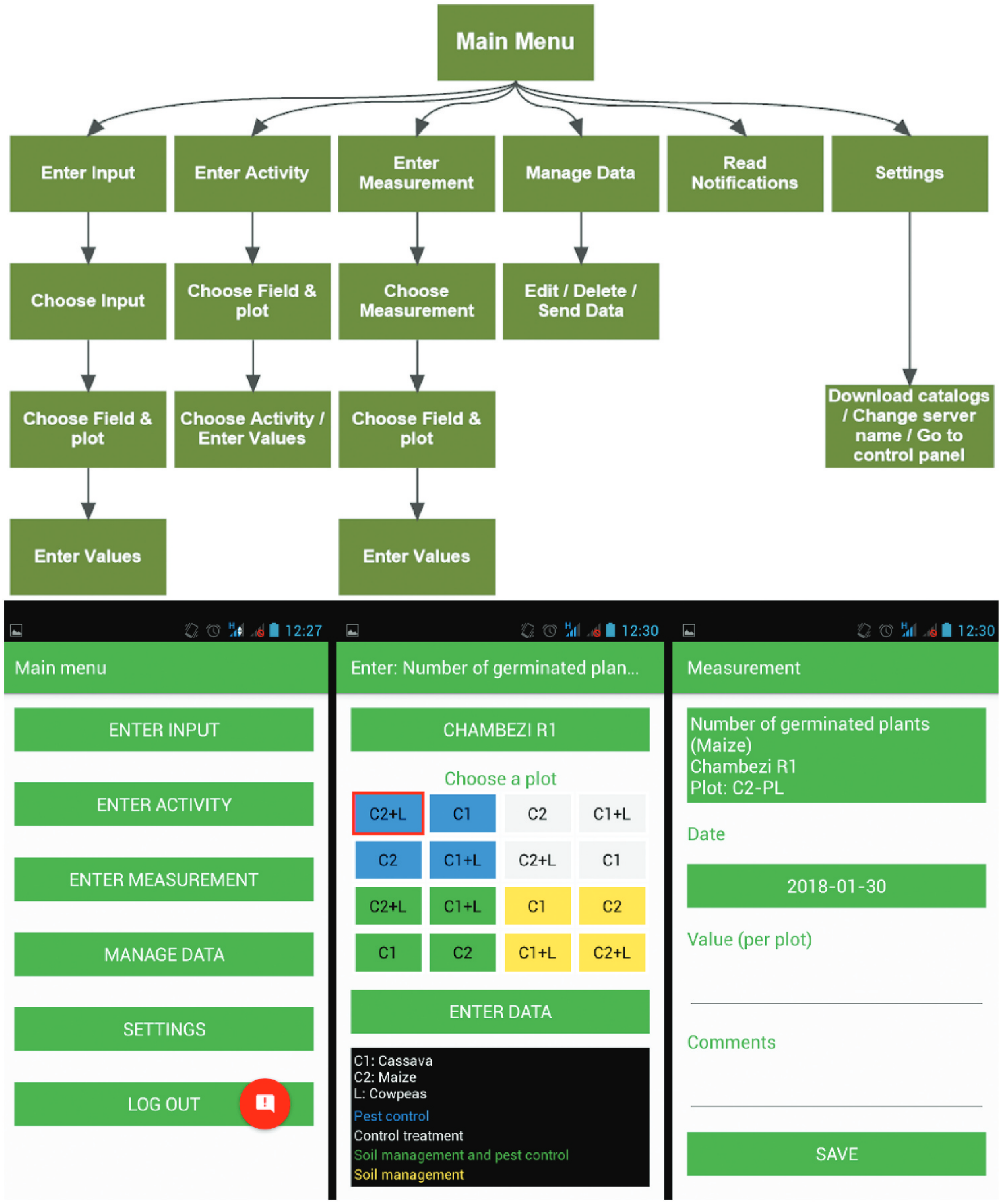

Figure 13. Main navigation diagram and screenshots of the AER mobile application.

experimentation with high degrees of control and reproducibility, generating data that can be evaluated using statistical tools to deliver robust publishable findings that can be communicated to farmers and policy makers alike. However, this type of research has little flexibility to include tacit knowledge, non-numerical observations, and experiments on other crops planted at other scales or locations, using different combinations of agroecological practices. To account for this, farmers' research on their own farms was included. They had larger degrees of freedom regarding types of crops, combinations of

Figure 14. Formal research field in Chambezi, Bagamoyo. Compost and mulch were applied to the far-left maize plot, while no soil amendments were applied to the other two.

Figure 15. Research fields of an Ugunduzi farmer. Soil and pest management was performed on the left plot, while the right plot is the conventional (untreated) control.

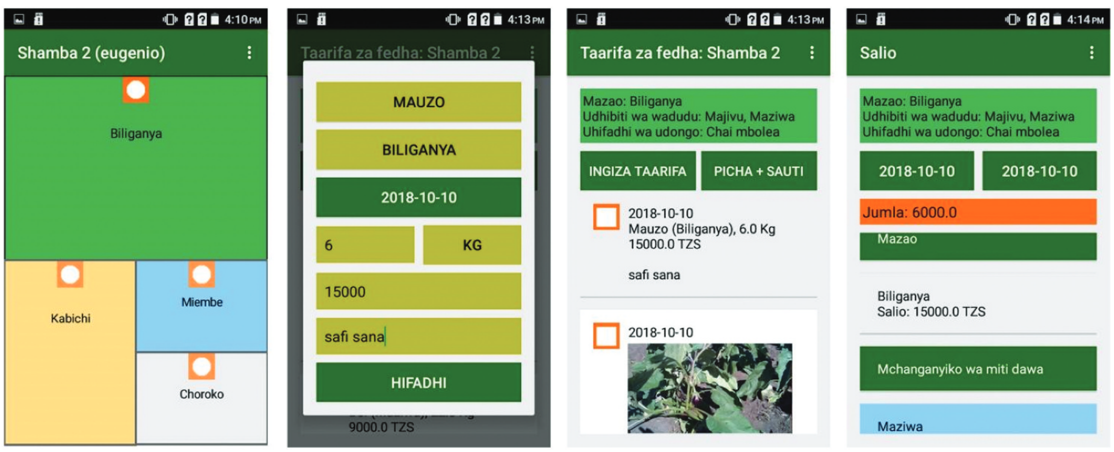

Figure 16. Screenshots of the Ugunduzi app: designing the farm and entering records for the selected plot.

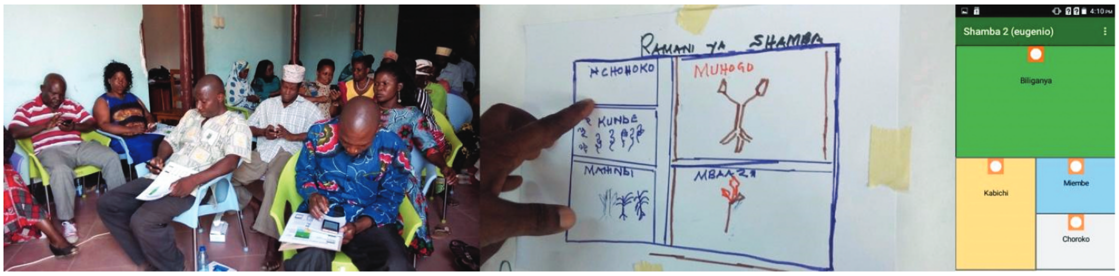

Figure 17. Farmers at workshop, drawing their farms which are then copied to screen.

practices, plot sizes, and comparators. They recorded their findings using the Ugunduzi app, which still gave the collected data the necessary structure, allowing it to be qualitatively and semi-quantitatively evaluated. Furthermore, these data are well-preserved and remain available to farmers for years. This integrated approach is, to our knowledge, unique.

The developed ICT applications are farmer- and farming-centered support tools rather than change driving technology tools. Farmers were active partners in the design and development of the Ugunduzi application, which attempts to embody the social principles of agroecology, namely, the co-creation and sharing of knowledge (FAO 2018). For many of the participating farmers, this tool became part of their operation and allowed them to monitor the impact of the practices and focus on the most efficient practice (Kihoma et al. 2023). The sustainability aspect was expected to be incorporated from the initial stage of design to development of ICT tools; therefore, the farmers and other stakeholders could continue using those tools after the end of project funding. A separate companion research project specifically evaluated whether this expectation was met and what outcomes it yielded. The results of this sister project will be reported in separate publications.

Record-keeping and data-gathering using mobile phone-based applications is highly advantageous. Both data collection applications (AER and Ugunduzi) allow for standardization and centralization of the collected data, although they have different scopes and data structures. Data collected through the Ugunduzi app is mainly intended as a record-keeping tool for farmers, while data collected through the AER app provides the basis for visualization and statistical analyses conducted by researchers using the AEA app. A requirement for researchers is that they know the experimental design, are able to interpret box plots and output of statistical software, and evaluate the results from different perspectives to answer various research questions (hypotheses) using formal statistical tests. Contrarily, no programming skills are required to use the AEA application, which overcomes a hurdle that is often encountered by researchers confronted with large and complex data sets. To the best of our knowledge, such a coupling of collection, visualization, and analysis of agroecological data with modular and interconnected online applications and platforms developed under open-source principles has not been used previously. Despite the different target groups, such connections and integrations of tools can potentially foster interactions between farmers, practical agroecologists, professional statisticians, and other actors in platform innovation, and could also contribute toward bridging the gap between informal experiments and replicated experimental field plot research.

Data from the Ugunduzi app has been collected by farmers and is visible to farmers and accredited researchers alike, but are stored separately from the AER research data. For farmers, their collected data and information are reliably documented and stored long-term. The data are backed up daily and will not be lost even if the mobile device is stolen, broken, or lost, wherein such instances are not uncommon in farmer's community lives. However, the data from both the AER app and the Ugunduzi app could eventually coalesce in the form of concurrent evaluations and comparisons for accredited users only.

Most importantly, the Ugunduzi farmers offered their observations and reflections regarding their own findings, substantially adding to the creation of knowledge emerging from the formal scientific field station experiments (Tisselli 2022; Kihoma et al. 2021, 2023). Thus, farmers progressed out of their role as consultants offering external information, and became researchers themselves, referring to themselves as such; this methodology was rare (Sachet et al. (2021) presents an in-depth discussion on these roles). We can confirm that it had a mobilizing effect on the participating farmers who stated that information and interconnection were lost when their phones went missing (due to various reasons) or under unreliable coverage. Furthermore, the conclusions by Sachet et al. (2021) show that this co-construction of knowledge fostered agroecological transition as it empowered farmers. At the time of writing, many farmers had explained that others are now also engaging in comparative research themselves or observed the effects of certain practices on the participating farmer's fields and began to apply them on their farms as well (Kihoma et al. 2023). We will report in sister publications the results of our research and refer to this paper for methodological details. Additionally, farmers' adoption, benefits, and challenges of the ICT tools will be explained in depth in further focussed publications currently under preparation.

Notes

1. https://www.wto.org/english/thewto_e/minist_e/mc10_e/agroecologyppmc10_e.pdf
2. http://www.fao.org/agroecology/knowledge/science/en/
3. "Discovery" in Kiswahili.
4. The user's manual of the AER application can be consulted for further detail at http://sautiyawakulima.net/agresearch/app/agroeco_manual.pdf (Accessed 16.12.2021)
5. The source code of the AER application is available at the following open-source repository: https://github.com/ojovoz/AgroecoResearch (Accessed 16.12.2021)

6. Shiny is an open-source package that provides a web framework for building applications using the well-known statistical software R.
7. The user's manual of the Ugunduzi app can be accessed at http://sautiyawakulima.net/ugunduzi/download/ugunduzi_en.pdf
8. The source code of Ugunduzi is available at https://github.com/ojovoz/ugunduzi

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Data availability statement

Software codes are already available online under GNU General Public License – links provided in text.

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