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# Farmers' biodiversity knowledge improves natural enemy conservation in agricultural ecosystems

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## ABSTRACT

*Context:* In the face of dual challenges of sustainable food production and biodiversity conservation, the knowledge gaps of farmers about biodiversity, pests, and their natural enemies can become a crucial barrier to adopting sustainable land management practices.
*Objective:* The study aimed to assess farmers' knowledge and understanding of crop pest and natural enemy diversity and their impacts, and whether the adoption of Climate-Smart or Conservation Agriculture (CSA here onwards) was associated with this knowledge.
*Methods:* We conducted questionnaire-based interviews and showed biodiversity images, including crop pests and beneficial insects, to understand farmers' knowledge of biodiversity on their farms. A comparison was drawn between farmers practising CSA and non-CSA farmers to understand the role of CSA in enhancing biodiversity knowledge.
*Results and conclusions:* Farmers facing greater yield losses were aware of pests, but they were less knowledgeable about their natural enemies, and they used fewer conservation management practices. CSA farmers, however, showed more biodiversity knowledge, especially of natural enemies, and they employed a wider range of CS management practices. Farmers' age, experience, education, and training were positively correlated with biodiversity knowledge, leading to better natural enemy conservation and pest management practices.
*Significance:* The findings underscore the need for biodiversity-focused capacity building in sustainable agricultural programs, targeting less knowledgeable farming groups. It emphasises the crucial role of farmers' knowledge in developing sustainable and biodiversity-friendly food production systems.
Africa, East Usambara Mountains, Food security, Biodiversity conservation, Invertebrates, Crop pests, Climate-Smart Agriculture, Farmer education.

## 1. Introduction

Agriculture is a significant contributor to global biodiversity loss, causing unprecedented declines in species diversity and subsequent reductions in ecosystem services (Zabel et al., 2019; Sánchez-Bayo and Wyckhuys 2019) and human well-being (Schröter et al., 2014). In particular, biodiversity loss within agricultural landscapes threatens the ecological integrity and resilience of food production systems (Holt et al., 2016a). With the projected increase in climate risks and human populations, addressing climate adaptation and enhancing food production are of immediate importance in ensuring future food security (Muluneh 2021), while at the same time conserving biodiversity. Increasing food production via expansion and intensification of modern agriculture may aggravate biodiversity losses (Lanz et al. 2018), while measures to safeguard biodiversity may reduce yield or increase the macro-economic cost of food production (Holt et al., 2016b). This amplifies the trade-offs between food production and biodiversity (Butsic et al., 2020). Consequently, it is imperative to identify opportunities that optimise synergies between food production practices, biodiversity conservation, and ecosystem service provision across agricultural landscapes and food production models (Norris 2008; Balmford et al. 2012; Lefcheck et al., 2015). Examining food production-biodiversity relationships in tropical agriculture systems, particularly in the Global South, is crucial, as existing knowledge primarily stems from temperate agricultural studies conducted in the Global North (Muenchow et al., 2018; Shackelford et al., 2013).

Tropical agriculture is typically undertaken in heterogeneous and biodiverse agricultural landscapes dominated by smallholder farming where farm sizes range from 1 to 10ha, and farmers cultivate a diverse range of food and cash crops for subsistence and local markets (Ricciardi et al., 2021a; Lowder et al. 2016). In addition, agricultural landscapes, in general, represent an essential focus for conservation progress, given

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that 40% of the Earth's land is under agricultural management (vs. 12% under protected status; (Rockström et al., 2017). These landscapes support biodiversity and offer opportunities for future biodiversity conservation by maintaining biodiversity and habitats that support biodiversity within agricultural landscapes (Wright, Lake, and Dolman 2012a; Ricciardi et al., 2021b). The future of these landscapes, and the biodiversity they sustain, however, depend primarily on sustainable agricultural transformation and land management pathways (Phalan et al., 2011; Wright, Lake, and Dolman 2012b), the conservation behaviour of land managers, including their knowledge and perception of biodiversity and associated ecosystem services and disservices (Crespin and Simonetti 2020; Wilhelm-Rechmann and Cowling 2011; Gurung 2003; Gladkikh et al., 2020), and livelihood choices and well-being outcomes (Waldron et al., 2012; R. E. Bennett et al., 2021; Muoni et al., 2019; Milheiras et al., 2022).

Biodiversity can be perceived as benign or harmful depending on the socio-economic circumstances, cultural preferences, and educational backgrounds of farmers (Martín-López et al., 2012; N. J. Bennett 2016). For example, an increase in biodiversity, which is mainly an upsurge in the number and activity of invertebrate pests on high biomass, improved-variety crops (Bigger and Marvier 1998; Kansiime et al., 2019), may be perceived as additional pest pressure incurred by farmers due to their adoption of the improved variety crops (Kansiime et al., 2019). Such a perception, which does not capture the total responses of biodiversity, could inhibit the uptake of sustainable technologies and trigger harmful mitigation measures, such as the excess use of pesticides (Heong and Escalada 1999; Ntow et al., 2006), which reduce pests as well as a broad range of non-target invertebrate species and functional groups (Wyckhuys et al., 2019). In contrast, knowledge and experience obtained through training programs, farmer-field schools, access to extension services and education, farming experience, and interactions with other farmers, can lead to a better understanding and appreciation of biodiversity and associated benefits (Jacobson et al., 2003; Morgan-brown et al., 2010), which may help in promoting conservation behaviours in agroecosystems and in the broader agricultural landscape (Wyckhuys et al., 2019; Morgan-brown et al., 2010; Ratto et al., 2022). Therefore, there is a need to understand what underpins differences in biodiversity knowledge and understanding of ecosystem services among farmers representing a range of farming characteristics and agronomic backgrounds.

Agriculture interventions, such as climate smart agriculture (CSA), aim to improve climate adaptation and food security by implementing sustainable and climate-resilient land management strategies (Lipper et al., 2018). Understanding biodiversity and its relationship with new technologies and management practices is essential to maintain and optimise biodiversity and food production in CSA landscapes (Meijer et al., 2015) and reduce CSA-biodiversity trade-offs (Tripathi et al., 2022). Most research about evaluating the ecological implications of agri-environment schemes has focussed on impacts on biodiversity and implicit links between biodiversity and ecosystem services via functional traits of species or taxonomic groups (Bengtsson et al. 2005; Letourneau and Goldstein 2001; Swanepoel et al. 2018; Shackelford et al., 2013). No study has yet evaluated CSA or related agri-environment schemes to understand the links between farm management, biodiversity knowledge and understandings or perceptions of ecosystem services and disservices. To address this gap, we examined farmers' knowledge of pests and natural enemies and the biological control services that natural enemies provide in smallholder farming landscapes. We specifically explored (i) farmers' knowledge of natural enemies and associated crop pests, (ii) farmers' assessment and understanding of the impact of pests and the importance of natural enemies in controlling pests, and (iii) the use of management practices to reduce pest pressures and maintain natural enemies in crop fields.

## 2. Methods

The study was conducted in July 2020 in the East Usambara Mountains (EUM) in Tanzania (Fig. 1). EUM habitats primarily comprise evergreen rainforests intermixed with maize-cassava-spice dominated agroecosystems. They are characterised by a bi-modal rainfall pattern, with March to July *(Masika)* being the primary cropping season and October to December (*Vuli*), a short cropping season (Sallu et al. 2018). Agriculture in the region is predominantly small-scale (amidst few large-scale tea plantations), with most farmers holding less than 1ha of land and growing a diverse range of cash crops, such as clove, cinnamon, cardamom and bananas, and food crops, such as maize, beans, and cassava. These crops are often intercropped and integrated with livestock, mainly dairy cattle and chickens (Tripathi et al., 2021). In the region, management practices primarily focus on traditional methods, including the use of local crop varieties, slash-and-burn techniques, and brief fallow periods. Often, these practices incorporate extensive tillage and the application of pesticides, all aimed at increasing crop productivity. However, such methods tend to neglect the potential negative impacts on the local environment, biological pest control agents, and biodiversity. Moreover, the frequent occurrence of flash floods and extreme climate conditions further threatens the sustainability of agricultural production in the area (Sophia and Emmanuel 2017).

From 2015 to 2019, the European Union-funded Global Climate Change Alliance Plus programme (EU GCCA+) spearheaded the 'Integrated Approaches for Climate Change Adaptation in the East Usambara Mountains' initiative. This effort was a component of the broader Integrated Approaches for Climate Change Adaptation Project (Ongawa 2019); Table 1). The project focused on promoting climate-smart agriculture (CSA) practices among farmers to increase their resilience to climate variability, enhance productivity, and improve climate risk mitigation. Key activities included setting up Farmer Field Schools (FFS) and delivering extensive training and capacity-building in CSA methods to the participating farmers who volunteered to implement CSA in their fields. These practices encompassed adopting improved crop varieties, utilising increased inter-row spacing of 75–100 cm, implementing trenches with live mulches (mulches, here on), and integrating diverse agroforestry systems alongside maize, cassava and beans. Our main objective was to select both CSA and non-CSA farmers in the landscape to compare their understanding of pests and natural enemies, their selection of management practices to enhance biological control and minimise pest risks, and their perception of primary factors driving crop yield losses in their fields.

We conducted 82 face-to-face questionnaires and picture-based surveys involving local farmers (Table 1). Questionnaire surveys were

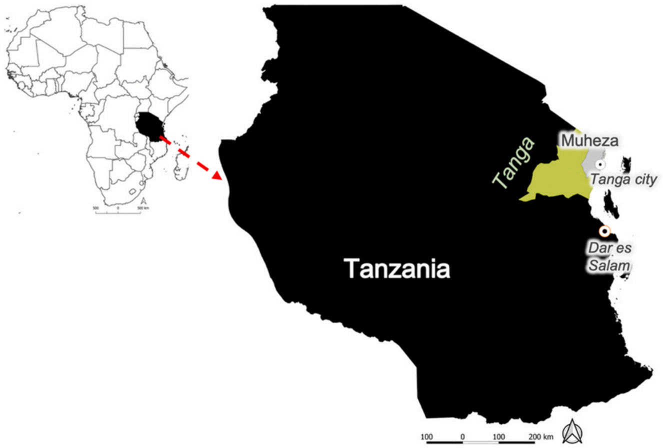

**Fig. 1.** Study area In Tanzania showing Muheza District in the Tanga region where the 82 farmer interviews took place in villages in the East Usambara Mountains during July 2020.

**Table 1**
Basic demographic and farming profile of farmers in the study.

| Parameters | Mean (±SE) | Range |
|---|---|---|
| *Age* | 52.7 (±1.5) years | 30–86 years |
| *Farming experience* | 28.5 (±1.5) years | 4–60 years |
| *Age of the field currently used* | 14.3 (±1) years | 4–50 years |
| *Farm size* | 0.8 (±0.1) ha | 0.2–6 ha |
| *Crops* | 2.4 (±0.14) crop species | 1 (n = 23) −5 (n = 10) crop species |
| *Gender* | Women:24, Men:58 | |
| *Commonly cultivated crops (number of fields)* | Maize (n = 64), Cassava (42), Beans (26), Cloves (17), Banana (14), Cardamom (7) | |
| *Management practices* | Climate Smart (CSA) – (41) Improved variety crops, Inter-row spacing (75–100 cm), Trenches with live mulches (mulches, hereon) and Agroforestry.<br>Conventional (non-CSA) - (41) Local variety maize, intercropped with beans or cassava, compost and manure.<br>**Number of farms under each of the practices:** Agroforestry (28), Improved variety crops (40), Manure (40), Mulching (9), Inter-row spacing (56), Spice (47), Intercropping (65), Trenches (23) | |
| *Times cultivated* | Single season – 37, two seasons - 45 | |
| *Education* | Primary (8), Secondary (64), College (1), no formal education (9) | |

carried out in the local language (*Swahili)* by a trained team of two: a research assistant from Sokoine University of Agriculture (SUA) and a local agriculture extension officer. The farmers were randomly shortlisted from a stratified pool of 150 farmers, of which 50% used one or more CSA technologies in their fields (Tripathi et al., 2022). Background information on farmers' socioeconomic profiles and farm characteristics was recorded for all farms by local agriculture extension officers. The socio-economic variables were age, gender, level of education, and farming experience. The farm characteristic variables comprised size and age of the farm, and the implementation of CSA or non-CSA traditional practices, such as improved or local variety crops, mulching, crop row spacing, agroforestry, the application of manure as fertiliser, spice plantation, and with-in field crop diversity (Tripathi et al., 2022).

**Pest and natural enemy knowledge:** Farmers were asked to identify and distinguish between the different crop pests and natural enemies they knew using local names (local ID) and based on descriptions and pictures (Descriptive ID) from field guides. We used the guide of common crop pests in East Africa, published by (ASHC 2019). For natural enemies, we compiled images of 28 commonly found natural enemies in the region.

**Management practices:** To investigate whether knowledge of management practices either reduced pests or increased natural enemies, we asked farmers to report and describe the management practices they used to reduce pests or increase natural enemies for each species they mentioned in the questionnaire.

**Impact and importance:** To understand the perceived impact of pests and the significance of natural enemies, we asked farmers to rate the species they mentioned on a scale from low (1) to high (6) influence – thus, they identified both influential crop pests and influential natural enemies. They were also asked to identify the crops affected by these pests and the pests targeted by natural enemies, along with the months these species were most active. This rating helped determine the perception of whether a particular pest significantly affected crops, or if a natural enemy played a crucial role in mitigating pest pressures. Additionally, noting the months of occurrence provided insights into the prevalence of the described species. Importantly, farmers were not pre-informed about which species were classified as pests or natural enemies.

**Yield losses:** We also asked farmers to estimate yield losses in 2020 due to pests by giving them a total of 50 beans and asking them to choose the number of beans they allocated to pest-driven yield loss if 50 beans represented their total expected yield. We converted this number in to %.

**Data analysis:** In our study, we used key metrics to understand the diversity and impact of pest and natural enemy species as described by farmers:

(i) Species Richness: This represents the total number of species farmers mentioned. It gives us an idea of how much the farmers know about different species.
(ii) **Dissimilarity**: This is a pairwise dissimilarity relative to the mean of other farmers and measures how varied the species mentioned by farmers are in composition. The unit ranges from 0 to 1; a higher number means more variation in what different farmers reported. This was estimated using mean values of a pairwise Simpson's dissimilarity index (Baselga 2010).
(iii) **Pest impact ($I_P$) and natural enemy importance ($I_N$)**: We averaged the impact and importance ratings given by farmers for each species to calculate these measures at the farm level.
(iv) **Management Richness**: This counts the different management practices farmers mentioned to control pests or improve biocontrol, helping us understand the variety and choice of management strategies they use.

To analyse relationships between these aspects and to understand how they are influenced by factors such as socio-economic status and farm characteristics, we used the following statistical models:

- **Linear Additive Regression Models**: We modelled – *richness and dissimilarity,* $I_P$, $I_N$ and *Management, Yield losses (%)* as functions of socio-economic profile and farm characteristics using linear additive models. We used stepwise backward variable selection, where variables in different combinations were tested, and the best-fit model (based on the lowest AIC values) was automatically selected.
- **Generalized Linear Models with a Poisson Distribution**: We utilised this approach to model richness, given richness data consisted of counts.
- **Variable Inflation Factors (VIF)**: To ensure reliability of our results, we checked for variables that might distort our models (those with a VIF greater than 4 were removed) (Akinwande et al. 2015).

Data analysis was performed using R software version 4.0.3.

## 3. Results

**Yield losses:** Farmers reported a mean crop yield loss ("loss" hereafter) of 45% (±6.8 as Standard Deviation) and considered crop pests (mean 15.5 ± 2.5% of reported yield loss) to be a significant production constraint (Table 2). Yield loss was estimated to be higher for farms at high altitudes, but lower for farms with mulching, educated farmers, and higher crop richness (Table 2). Gender was not selected in the most parsimonious model. However, gender and education were correlated with men being more educated than women ($r = 0.68$, $\rho < 0.5$). On testing the relationship between gender and reported yield losses separately, we found that women reported significantly higher losses than

**Table 2**
Reported yield losses (%) and its relationship with agronomic and socio-economic variables.

| Predictors | Overall yield loss (%) | Yield loss (%) attributed to pests |
|---|---|---|
| Intercept | 44.6 (6.8) | 15.5 (2.5) |
| Altitude | 0.03 (0.006) ** | 0.02 (0.007) * |
| Mulching | −21.14 (5.3) ** | −14.1 (6.9) * |
| Education | −1.5 (0.8) * | −1.5 (0.8) |
| Crop richness | −5 (1.4) ** | −4 (1.5) * |
| Spice | | −4 (1.8) * |
| Adj. $R^2$ | **0.33** | **0.21** |

men (9.4 ± 4.2, $p < 0.02$, $R^2 = 0.07$). Farmers' age or agricultural experience had no significant effect in reporting yield losses.

**Pest and natural enemy knowledge:** Farmers were knowledgeable about a wide variety of pests and natural enemies as they collectively reported 38 pests and 26 major natural enemies species. Nearly all farmers mentioned at least one pest and natural enemy, and some mentioned up to eight. Most farmers used Descriptive ID rather than specific names when naming a pest or natural enemy. As a result, while they pointed out more species from the illustrated guides (3–4 species more than the descriptive ID), they could only provide local names for a small number of them. Most of those local names were generic and used for multiple species and growth stages of the invertebrates mentioned.

Stalk borers (62%; *Busseola fusca*) among the pests, and black ant and spiders (53%) among the natural enemies, were most frequently mentioned (Table 3). Interestingly, the most commonly mentioned species were not regarded as the most impactful, as fall armyworm (*Spodoptera frugiperda*) was considered the most harmful pest (3.41 AI), but only 29% frequency, while safari ant (*Dorylus* spp.*)* was considered the most effective natural enemy. Ants, in general, were given higher ratings in natural enemy effectiveness. About 8–10 farmers also mentioned baboons, field mice, mole rats, and red-billed quelea (*Quelea quelea*) as pests.

The knowledge of pests and natural enemies was higher among farmers who practised CSA, who cultivated a greater number of crop species, and where cultivation was done for both seasons in a year (Table 4 a). This indicated that CSA and farming experience correlated with greater biodiversity knowledge since natural enemy knowledge was positively associated with participation in CSA. The composition of reported pests and natural enemy species (i.e., knowledge dissimilarity) varied among farmers with respect to their background and management practices. Specifically, the size of the farm, the variety of crops cultivated, the frequency of cultivation, and mulching were associated with greater knowledge dissimilarity (Table 4b).

**Table 4**
Results of generalized linear models (Poisson) and linear models showing the determinants of variation in the number (richness) and composition (dissimilarity) of pests and natural enemies reported by farmers. Climate Smart Agriculture (CSA) fields included: Improved variety crops, Inter-row spacing (75–100 cm), Trenches with mulches and Agroforestry.

***(a) GLM Poisson* models for the number of pests and natural enemies reported by farmers**

| Predictors | Pest | Natural enemies |
|---|---|---|
| *Intercept* | *0.6 (0.18)* | *0.52 (0.2)* |
| Crop richness | 0.13 (0.04) ** | 0.1 (0.04) * |
| Climate smart fields | | 0.27 (0.12) * |
| Times cultivated (2019-20) | 0.27 (0.1) * | 0.26 (0.1) * |
| Mulching | | 0.3 (0.18) |
| ***Adj. $R^2$*** | ***0.38*** | ***0.46*** |

***(b) Linear models for dissimilarity in the composition of pests and natural enemies reported***

| Predictors | Pest | Natural enemies |
|---|---|---|
| *Intercept* | *0.36 (0.05)* | *0.33 (0.07)* |
| Gender (men-0, women −1) | −0.08 (0.03) * | |
| Education | 0.03 (0.01) * | |
| Farm size (ha) | | 0.06 (0.02) ** |
| Local variety | 0.04(0.1) * | 0.05 (0.02) * |
| Improved variety | 0.05(0.01) ** | 0.06 (0.02) ** |
| Local and Improved mix | 0.14(0.03) ** | 0.09 (0.04) * |
| Times cultivated (2019-20) | 0.1 (0.02) ** | 0.09 (0.03) * |
| Mulching | 0.3(0.06) ** | 0.18 (0.06) ** |
| Agroforestry | −0.05 (0.02) * | |
| ***Adj. $R^2$*** | ***0.4*** | ***0.39*** |

There was a significant positive association between pest richness and pest-driven yield losses (0.004 ± 0.001, $p < 0.01$, $R^2 = 0.15$), as farmers who experienced higher yield losses due to pests also reported greater diversity of pests and natural enemies (Fig. 2b). However, the mean dissimilarity of pest and natural enemy species reported by farmers reduced yield losses (Fig. 2d), indicating that farmers who experienced greater yield losses often mentioned similar types of pests and natural enemy species.

Furthermore, farmers in maize and cassava fields reported a significantly greater diversity of pests and natural enemies (Fig. 2a). In

**Table 3**
Crop pests and natural enemies as reported by the farmers. Frequency is the number of farmers who reported the pest or natural enemy species. Assigned impact indicates the impact category (low 1 to high 6) assigned by the farmers. The respondents described the species affected i.e., the crops species affected by pests or the target pest species of natural enemies. They also reported the respective management practices to reduce pest damage and increase natural enemy populations. Species mentioned above a frequency of 15 are shown in the table below and a full list is provided in the SI.

| Name | Frequency | Assigned impact | | Crop or pest species affected | Management |
|---|---|---|---|---|---|
| | | mean | SD | | |
| *Crop pests* | | | | | |
| Stalk borer | 51 | 2.75 | 1.04 | Beans, Maize | Wood ash, Sand, Clearing, Chemical |
| African bush grasshopper | 32 | 3.38 | 1.04 | Banana, Beans, Cassava, Cloves, Groundnut, Maize, Sugarcane | Chemical, Intercrop, Trap-Kill |
| Fall armyworm | 29 | 3.41 | 0.78 | Beans, Cassava, Maize | Wood ash, Sand, Plant extract, Chemical |
| Caterpillar | 25 | 3.20 | 0.87 | Beans, Cassava, Coffee, Maize, Sugarcane | Wood ash, Sand, Clearing, Chemical, Weeding |
| Field mice | 22 | 2.73 | 0.94 | Beans, Cassava, Cloves, Maize, Sugarcane | Plant extract, Chemical, Clearing, Trap-Kill, Weeding |
| Elegant Grasshopper | 15 | 2.07 | 0.26 | Cassava, Maize | Chemical, Trap-Kill |
| Banana weevil | 14 | 2.57 | 0.85 | Banana, Maize | Clearing |
| *Natural enemies* | | | | | |
| Black ant | 44 | 2.64 | 1.06 | Cassava mealybug, Caterpillar, Fall army worm, Grasshoppers, Insect eggs, Stalk borer | Intercrop, Mulching, Weeding |
| Spiders | 44 | 1.93 | 1.23 | Cassava mealybug, Caterpillar, Fall army worm, Grasshoppers, Insect eggs, Stalk borer | Clearing, Habitat, Intercrop, no insecticides, Tree, Weeding |
| Safari ant | 39 | 3.49 | 1.55 | Cassava mealybug, Caterpillar, Fall army worm, Grasshoppers, Insect eggs, Stalk borer | Intercrop, Moist soil, Monocrop, Terracing, Tree, Weeding |
| Nightshade ladybird | 38 | 2.26 | 1.08 | Caterpillar, Fall army worm, Insect eggs, small insects, Stalk borer | Intercrop, Weeding |
| Black-brown ground beetle | 28 | 1.82 | 0.67 | Caterpillar, Pupae, Small flies, small insects | Intercrop, Manure, Monocrop, Mulching, Terracing, Weeding |
| Wasp | 23 | 1.74 | 1.01 | Caterpillar, Thrips | Clearing, Intercrop, Tree, Weeding |
| Small black ant | 18 | 2.61 | 1.61 | Bean bruchid, Caterpillar, Fall army worm, Insect eggs, Milkweed grasshopper, Stalk borer | Clearing, Intercrop, Mulching, Weeding |

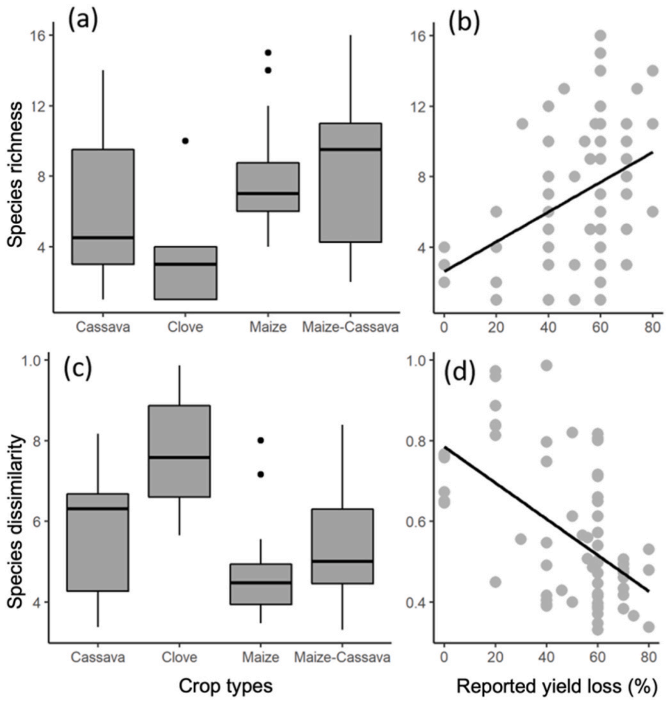

**Fig. 2.** Relationship between pest and natural-enemy knowledge richness (top panel) and dissimilarity (bottom panel) with crop type (left panel) and yield loss (right panel). Richness was higher in Maize-Cassava intercrop, followed by maize, and lowest in clove farms. Also, clove farms had the most distinct pest-natural enemy community identified by the respondents. Yield loss was positively associated with richness and negatively related to dissimilarity in the farmer-mentioned species composition.

contrast, farmers in clove plantations reported highly dissimilar sets of pest and natural enemy communities (Fig. 2c). When analysed separately, natural enemy richness did not show a significant correlation with yield loss, as the number of natural enemies mentioned had no significant association with the crop yield losses reported by farmers.

**Management practices:** Pest and natural enemy richness (species recognised by the farmers) was positively associated with management richness, i.e., farmers who reported a higher number of pest and natural enemies (i.e., overall biodiversity knowledge) also practised a greater number of management methods ($0.13 \pm 0.03$, $p < 0.001$, $R^2 = 0.15$). Management richness was also higher in CSA fields and fields belonging to more educated (secondary levels) and experienced farmers (30 ± 2 years). Interestingly, there was a negative association between reported yield losses and management richness, i.e., farmers who reported the highest yield losses used just one CSA management method or they did not practice CSA.

The number of pest management methods used by farmers ranged from 0 to 4. Common pest management methods included sprinkling wood ash ($n = 23$), removal of weeds (22), using sand to cover infected or pest-affected plants (13), chemical control ($n = 10$), removal of affected plants (10) and trapping and killing of pests (9). Other methods involved clearing, early planting, gap filling, and using plant extracts, especially of *Tephrosia and Azadirachta* species. Most farmers relied either on traditional pest management practices (65%) or did nothing (23%). In this context, “traditional pest management practices” refer to the use of locally available resources, knowledge, and methods to control pests. These practices included using botanical or biological controls, such as homemade plant-based pesticides or traps, crop rotation, or intercropping to minimise pest populations. Also, approximately 23% of the farmers did not take any action to manage pests or natural enemies, possibly due to a lack of knowledge, resources, or perceived necessity. About 25% of farmers described using practices to support natural enemies and suppress pests, such as maintaining intercrops with beans and vegetables, maintaining soil moisture through compost and mulches, intercropping with trees, and managing vegetation patches and non-crop habitats. These farmers also linked natural enemies, such as ground beetles, ichneumon wasps, ladybird beetles, and braconid wasps, among others, that targeted pests. Most farmers only mentioned common pests such as fall armyworm, milkweed grasshopper, red locust, and stalk borers as target pests, the most commonly associated pests with commonly grown crops (maize and beans) in the region. A majority of farmers (70%) described broad groups or growth stages, such as moths, caterpillars, larvae and eggs, rather than naming specific target pests.

**Pest impact and natural enemy importance:** The $I_P$ and $I_N$ (impact of pests and natural enemies, respectively) were positively correlated, suggesting that most farmers who understood pest impacts also realised the effectiveness of natural enemies. Farmers reporting a higher yield loss attributed greater importance to natural enemies ($0.02 \pm 0.008$, $p < 0.01$, $R^2 = 0.18$), meaning they felt the greater yield loss was because there weren’t enough NEs. During our interactions, we also observed that these farmers wanted to learn more about interventions and management practices that increase natural enemies. Also, $I_N$ was positively correlated with educational background of farmers ($0.1 \pm 0.05$, $p < 0.05$, R2 = 0.18). In comparison, $I_P$ had a relatively weaker yet positive association with yield loss ($0.01 \pm 0.005$, $p < 0.01$, R2 = 0.08) and no significant relationship with education.

## 4. Discussion

This study revealed interactions and feedback associations between participation in sustainable agriculture or climate-adaptation programs like CSA, farmers’ biodiversity knowledge, uptake of sustainable management practices, lower yield losses, and biodiversity conservation in agricultural landscapes. Farmers who adopted CSA practices cultivated their fields for both seasons in a year and had greater in-field crop diversity. They knew more about biodiversity and its value than non-CSA and single-season mono-crop farmers. We also found a positive association between biodiversity knowledge and the number of management practices farmers used. Pest damage emerged as a major constraint to crop production. Farmers with greater knowledge of pests and their natural enemies attributed higher yield losses to a scarcity of natural enemies. Consequently, they implemented more strategies for pest management and conservation of natural enemies and reported lower yield losses.

While the primary focus of the EU GCCA + programme was on crop diversification and production, as well as reduced greenhouse gas emissions, our study revealed that farmers who participated in the programme also used a range of pest management and natural enemy conservation strategies. These strategies included intercropping, using pest-resistant crop varieties, applying biopesticides, and conserving non-crop habitat for natural enemies. Notably, these practices were not necessarily exclusive to pest and natural enemy management, but were synergistic with the broader CSA objectives. For example, using live mulches and compost to maintain soil moisture, a common CSA practice, also provided additional benefits for pest and natural enemy management. Mulching helps suppress weed growth, which can harbour pests, while compost can improve soil health and promote the presence of beneficial soil organisms that help control pests (Brown and Thomas, 2004). In this way, adopting CSA practices can have positive spillover effects on pest and natural enemy management, even if the EU GCCA + programme did not specifically target these aspects (Tripathi et al., 2022).

We also found a positive association between CSA, biodiversity-ecosystem service knowledge, and the use of management practices for the conservation of natural enemies for biocontrol of pests in our study sites. The CSA programme in the East Usambara Mountains (EUM) provided a platform for capacity building and training via farmer field schools, facilitating frequent communication with extension officers and enabling networking and interaction with other farmers (Ongawa 2019; Gaworek-Michalczenia et al., 2022). These interactions may have helped CSA farmers improve their knowledge and understanding of biodiversity, given studies elsewhere have indicated that training and education are linked to positive conservation and pest management behaviours (Price 2001; Kross et al., 2018). Farmers with greater knowledge of natural enemies also deployed diverse management practices to ensure the maintenance of natural enemies and related ecosystem services in their fields. This validates findings from other studies exploring the links between knowledge and farmer actions (Kross et al., 2018). In contrast, farmers with poorer knowledge of biodiversity and natural enemies also used fewer management practices and reported more significant yield losses due to pests. If synthetic pesticides are not used, improving knowledge and promoting CSA practices that support biodiversity would help farmers better manage pests through natural enemy conservation and related ecosystem services, ultimately reducing yield losses. These findings suggest that knowledge of biodiversity is crucial for recognising its benefits and adopting strategies to conserve biodiversity in agricultural systems. Importantly, our results highlight the potential role of farmer participation in sustainable agriculture and land management programmes, in addition to education and farming experience, towards improving biodiversity knowledge. This improved knowledge can help biodiversity conservation by enabling practices that support biodiversity without compromising food production.

Our results revealed that the perceived importance of natural enemies, i.e., biological control, was high for farmers with extreme yield losses. In other words, farmers who experienced more significant yield losses knew about or could identify fewer natural enemies, yet they regarded those natural enemies as most important for providing biocontrol. However, it is essential to note that when natural enemies effectively control pests, their contribution may go unnoticed as there are fewer pests and less crop damage (Martínez-Sastre et al., 2020; Tscharntke et al., 2016). There may also be a time delay between an increase in pest numbers and the corresponding increase in natural enemies, which might affect the perception of their value. Our results also suggested that the perceived importance of natural enemies may be influenced by their commonness and abundance rather than their value in controlling crop pests (Callaghan et al., 2021); more common natural enemies may be regarded as most effective (e.g., ants and beetles in this study), even if they are not effective at controlling common pests. On the other hand, farmers may overlook more efficient pest predators (e.g., parasitic wasps) as they are often smaller in size, look similar, and are not easily noticed by farmers (Callaghan et al., 2021). Parasitic wasps are among the most diverse and abundant insects, but certain species within the group might be less common or less visible.

Similarly, understanding pest impact by farmers may also have an observational bias due to the ubiquity and activity of pest species, especially on common crops such as maize and cassava, as more visibly destructive pests might be regarded as most impactful. Past experience of pest outbreaks might also influence farmers' perception of pest impacts (Phophi et al., 2020). For example, the fall armyworm was regarded as more impactful pest in lowland areas as these farmers experienced frequent fall armyworm outbreaks (De Groote et al., 2020). The respondents considered grasshoppers, a widely occurring pest, more destructive. Understanding pest and natural enemies and their varying impacts will have implications for evaluating biodiversity costs and benefits and the corresponding management of biodiversity and ecosystem services and disservices in the region.

Our study highlighted that farmers' understanding of biodiversity varied based on age, education, gender, years of experience, and exposure to capacity-building initiatives and educational outreach. Specifically, older and more educated farmers often exhibited a broader understanding of pest management and biodiversity conservation due to accumulated knowledge, experience, and more frequent participation in educational programmes. Conversely, young, less experienced farmers might be less knowledgeable and more prone to misconceptions about the impacts and benefits of biodiversity, underscoring the need for targeted educational interventions. This requires expanding capacity-building initiatives to focus more on biodiversity, especially among young and less experienced farmers. Meanwhile, further research is warranted to investigate the interplay between age, education, and other socio-economic factors and their collective impact on pest management practices and biodiversity knowledge.

There is a long history of conservation intervention and agri-environment programmes in the EUM (Reyes 2014; Hall et al. 2011). Due to these past interventions, most farmers in the region would be expected to have some prior training and knowledge about biodiversity and associated ecosystem services. Despite this, we found a significant difference between CSA and non-CSA farmers. CSA farmers had a better understanding of pests, natural enemies, and the management practices that affected them. It is important to note that although CSA is not typically promoted for its potential biodiversity benefits, the positive impacts on biodiversity observed in this study demonstrate the potential for synergies between CSA and biodiversity conservation. However, not all CSA interventions have such positive results on biodiversity or biodiversity knowledge as CSA effects vary based on the local-scale context and management practices under consideration (Tripathi et al., 2022). For example, CSA in the neighbouring West Usambara Mountains (WUM) involved chemical inputs to manage pests (Mtashobya 2017), and farmers in the WUM were more reliant on chemical inputs than CSA farmers in the EUM. Hence, they may need more knowledge and appreciation of biodiversity and biocontrol by natural enemies (Bonhof et al., 2001; Kross et al., 2018). Another layer of complexity comes from potential selection bias within CSA programmes. Recent studies (Smith et al., 2021; Gaworek-Michalczenia et al., 2022) on CSA in the EUM suggest that these programmes may inadvertently favour wealthier, better-educated, or more well-connected farmers. Hence, the enhanced knowledge levels observed among CSA farmers in our study may be a function of this bias. Further research is needed to address this issue, ensuring that CSA benefits reach a more diverse range of farmers and contribute to broader biodiversity conservation goals.

## 5. Conclusion

Human actions and behaviour drive biodiversity loss in agricultural landscapes, but with better knowledge and appreciation of biodiversity, the conservation outcomes of farm management practices can be improved. Our study suggests that sustainable land management programs, such as biodiversity-friendly CSA practices, can potentially deliver benefits to biodiversity by promoting technologies with a positive association with biodiversity-food production synergies.

Based on farmer perspectives, we show that farmers' age, education, training, and participation in agri-environmental schemes like biodiversity-focused CSA potentially improve natural enemy conservation and biocontrol in agricultural ecosystems. However, avoiding CSA practices that heavily rely on pesticides is essential, as they may negatively impact biodiversity.

The understanding developed from our study suggests that more effort is needed to ensure inclusivity in training provision, including young and new farmers, those less knowledgeable in the study area, and non-CSA farmers who may not typically access training. Additionally, it is important to include strong foci on biodiversity and the ecological dimension of agriculture during the training of farmers and extension officers. This will allow the achievement of greater conservation benefits and the development of integrated biodiversity-friendly and climate-smart food production systems in the future.

## CRediT authorship contribution statement

**Hemant G. Tripathi:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Resources, Supervision. **Harriet E. Smith:** Conceptualization, Methodology. **Susannah M. Sallu:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Suzan D. Machera:** Data curation, Methodology. **Mosha Florence:** Data curation, Investigation, Methodology. **Manzil Maburuki:** Data curation, Investigation, Methodology. **Sixbert Maurice:** Conceptualization, Supervision, Writing – review & editing. **William E. Kunin:** Funding acquisition, Supervision, Writing – review & editing. **Steven M. Sait:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2024.106777.

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