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Spatial and Ecological Farmer Knowledge and Decision-Making about Ecosystem Services and Biodiversity

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Abstract: Amid climate change, biodiversity loss and food insecurity, there is the growing need to draw synergies between micro-scale environmental processes and practices, and macro-level ecosystem dynamics to facilitate conservation decision-making. Adopting this synergistic approach can improve crop yields and profitability more sustainably, enhance livelihoods and mitigate climate change. Using spatially explicit data generated through a public participatory geographic information system methodology (n = 37), complemented by spatial analysis, interviews (n = 68) and focus group discussions (n = 4), we explored the synergies between participatory farmer-to-farmer agroecology knowledge sharing, farm-level decisions and their links with macro-level prioritization of conservation strategies. We mapped farm conditions and ecosystem services (ES) of two village areas with varying knowledge systems about farming. Results of the farm-level analysis revealed variations in spatial perception among farmers, differences in understanding the dynamics of crop growth and varying priorities for extension services based on agroecological knowledge. The ES use pattern analysis revealed hotspots in the mapped ES indicators with similarities in both village areas. Despite the similarities in ES use, priorities for biodiversity conservation align with farmers' understanding of farm processes and practices. Farmers with training in agroecology prioritized strategies that are ecologically friendly while farmers with no agroecology training prioritized the use of strict regulations. Importantly, the results show that agroecology can potentially contribute to biodiversity conservation and food security, with climate change mitigation co-benefits. The findings generally contribute to debates on land sparing and land sharing conservation strategies and advance social learning theory as it pertains to acquiring agroecological knowledge for improved yield and a sustainable environment.

Keywords: agroecology; agroecosystems; climate change; ecosystem services; food security; public participatory GIS; Malawi

1. Introduction

Climate change, food insecurity and biodiversity loss have all being on the rise in the last decade [1,2]. Addressing these threats requires the active engagement of local communities to incorporate their views [3]. As a result, there have been calls to revise the models of participatory decision-making. This revision should involve the evolution of resource governance away from a top-down to a bottom-up approach to enable local communities to have a representative voice in the regulation of the risks they face [4–6]. Not only does a bottom-up approach to resource governance have a community empowerment effect [7], in the context of food security, bottom-up approaches account for the views of low-income smallholder farmers who are more vulnerable to the negative impacts of declining soil fertility, loss of wild edible foods, dwindling fish stocks and loss of freshwater sources—the consequence of (over) exploiting ecosystem services (ES) [8,9].

Rapid changes to socio-economic and ecological systems require the incorporation of traditional ecological knowledge (TEK) into resource governance to enable local farmers to adapt and become more resilient [10]. TEK, alternatively referred to as indigenous knowledge (IK), local knowledge (LK), and traditional knowledge (TK), from the socioecological systems perspective, is conceived as an evolving body of knowledge, practices and beliefs that develop over time from long-term observation and monitoring of the system functioning [11,12]. McCall and Dunn [13] argue that socio-economic and cultural factors, including an individual's production practices and knowledge base, are likely to (re)shape how ecosystem services are valued. This knowledge base will also shape the value placed on an ecosystem service (ES) and influences the priorities of conservation decisions, compliance or both, with those decisions [14]. Thus, farmers' understanding (and knowledge) of farm-level practices and processes are likely to influence priorities of seeking further knowledge (or information) to improve yields and prioritize biodiversity conservation strategies. However, most ES mapping studies [7,14,15] do not always link farmers' TEK and understanding of farm-level processes and practices with ES-use mapping, especially in resource-poor rural contexts. They have also generally not focused on smallholder agroecology farmers in the Global South. However, are there synergies between access to TEK/agroecological knowledge, farm-level practices and process and prioritization of biodiversity conservation in smallholder contexts?

This study draws on geospatial techniques, interviews and Focus Group Discussions (FGDs) with farmers to uncover smallholder farmers' knowledge of farm-level processes and practices to understand the spatial perception of farmers and farm-level decision-making about the on-field practices and the priorities for extension services. The study further examined farmers' use of ecosystem services at the community level, through participatory mapping, adapting the 2005 Millennium Ecosystems Assessment (MEA) as a guiding framework.

1.1. The Malawi Farmer-To-Farmer Agroecology (MAFFA) Intervention

The study compared agroecology practicing farmers who were involved in an agroecology intervention known as MAFFA with another group that did not practice agroecology from a different village area[1]. The MAFFA intervention was implemented from 2012 to 2017 in northern and central Malawi. It harnessed local resources and used horizontal knowledge sharing about agroecology to improve food security and nutrition [16]. Smallholder farmers were taught methods such as composting, manure application, crop residue incorporation into the soil, agroforestry, legume integration, crop rotation and crop diversification using farmer-to-farmer teaching. There were also trained Farmer Research Teams (FRTs) sharing new information and problem-solving procedures with farmers through demonstrations and farm visits.

Although many of these practices had been used in traditional Malawian agriculture, colonial and post-colonial governments have often promoted the use of synthetic fertilizers and pesticides and downplayed or denigrated these traditional agroecological practices [17,18]. The agroecological farmer-to-farmer training demonstrated the potential for such practices to ensure multipurpose benefits, including improved soil fertility, food security and more diverse diets while supporting biodiversity and its conservation. Therefore, we compared the participants of the MAFFA intervention in one village area to non-participants in a different village area to ascertain the influence of integrating TEK

[1] In the study context, a village area typically comprises several smaller villages with its catchment area.

with current knowledge on agroecosystems on farm-level decisions and prioritization of conservation strategies. This study considers the relevance of agroecological information at the micro and the macro scale for guiding farm-level decision-making and fostering sustainable agriculture and environmental resource use. We achieved this by examining spatial perception and farmers' understanding of farm-level practices and biodiversity conservation priorities across different knowledge systems.

1.2. Participatory Geographic Information Systems (PGIS) and Environmental Decision-Making

The use of geospatial techniques by local groups to facilitate decision-making regarding the management of natural resources has become more common [19–21]. This increasing use of geographic information systems (GIS) by local groups is because of the growing need for the direct involvement of local communities in democratically addressing problems that affect them most [3,22]. The adoption of a democratic, people-focused GIS for managing local resources has led to the development of public participatory GIS (PPGIS) or participatory GIS when conducted in the Global South. For purposes of this study, we will stick with the more broadly used term PPGIS though the study was conducted in a developing country.

PPGIS techniques, which capitalize on the knowledge of, experience with and perspectives toward contextual geospatial factors, allow for public participation in the resource management and governance by directly involving relevant stakeholders in the assessment of actual and perceived causes of environmental problems and the impacts of resource exploitation [23–25]. While PPGIS has been used as an approach to deal with the assessment of such broad-based community problems, its use for mapping place values [6,26,27] provides place-specific information and viable solutions to challenges associated with land use/land cover changes. As such, PPGIS can be an effective tool for identifying farm-level practices and processes such as crop health, crop growth patterns and effects of farm management practices. PPGIS can also assess place-specific abundance or scarcity of biodiversity, thereby creating an avenue for critically thinking about place-specific challenges, make effective decisions and find solutions to such problems. By applying PPGIS as a tool for identifying place-specific solutions to environmental challenges, this study explores the method's ability to empower individuals and local communities by providing them with the knowledge needed to operate spatial data collection devices and to carry out area measurements by themselves. This knowledge increases their capabilities to improve some farm decisions The community development and democratization role of PPGIS also help to identify relevant stakeholders such as government institutions and non-governmental organizations (NGOs) which increases their potential for finding timely solutions and ensuring accountability and transparency of institutions [28,29].

While numerous studies have deployed PPGIS and employed several ways of participation [30–35], what defines "public" and "participation", especially as they pertain to resource-poor settings, remains unclear [36]. According to Schlossberg and Shuford [29], p. 19, "participation" can be explained in at least two ways: "as specific activities that individuals engage in or in the broader purposes that participation is supposed to achieve." They further define "public" in two ways: "as actual people organized in some type of grouping (e.g., decision-makers) or in terms of methods for identifying and selecting such people" (p. 20). Aggens [37], p. 186 makes the point that in public participation, "there is no single 'public', but different levels of the public based on differing levels of interest and ability", while participation can range from citizen control through delegation, partnership, placation, consultation, informing therapy to manipulation [38]. In this study, "public" refers to the farmers who were trained to use Global Navigation Satellite System (GNSS) devices and participation involves using GNSS devices to geolocate various phenomena or creating polygons on maps to identify areas of ES use.

1.3. Knowledge Flows, Farm-Level Decisions and Prioritization of Biodiversity Conservation Strategies

A better understanding of farmers' knowledge and processes of learning is a critical goal in the drive towards more sustainable agricultural practices [39]. As such, a growing body of research has sought to discover the nature and complexities of farmers' knowledge as they relate to how they understand their farm environments [40]. Social learning theory has been applied to examine how such acquired knowledge can bring lasting transformative change in the management of resources [40–42]. Additionally, Riley [43] points out that there is the possibility of knowledge conflicts when (rural) farmers become exposed to conservation-focused environmental knowledge. Due to increasing concerns about climate change, food insecurity and the need for sustainable use of environmental resources, recent attention has moved beyond a focus on the individual farmer knowledge toward more collective forms of environmental management and farmer-to-farmer knowledge relations. Even though individual farmer knowledge is key to understanding farm-level, agri-environmental processes, McKenzie et al. [44] argue that farmers do not operate in isolation, but that the activities and actions of farmers transcend their farm boundaries to affect other farmers and other actors in the environment. As such, the individual farmer's knowledge is insufficient to achieve environmental objectives. Furthermore, the broader structures in place (e.g., subsidies and social norms) influence individual farm management decisions. However, one cannot begin to talk about the collective without progressing from the individual. Therefore, it is imperative to look at the individual (farm-level) knowledge and farmers' understanding of the broader ecosystem synergistically to ensure effective farm-level and conservation decision-making.

While several studies have recognized the importance of fostering more landscape-scale interaction between farmers and the need to encourage farmers to learn from, and take into consideration, the knowledge of other farmers in their locality [45–47]. Stock et al. [48], p. 412 note the need to pay "greater attention to the micro/macro relationships between actors at and across different scales". By examining farm-level practices and processes and linking them with the wider spatial patterns of ES use, we focus attention not only on the micro but also the interaction with the macro-level agri-environmental processes that (re)shape farm-level decision-making and prioritization of conservation strategies across groups with different knowledge flows about sustainable agriculture and the environment.

Based on the foregoing premise, this paper makes two overarching arguments: that even though smallholder farmers are knowledgeable in many respects as it pertains to their farming practices and processes, changing environmental conditions such as climate change/variability, biodiversity loss and food insecurity calls for new and dynamic ways of understanding the processes and conditions on the farm, and; secondly, that there is the need for heightened effort to disseminate sustainable agricultural (agroecological) knowledge from government and non-governmental sources through knowledge co-production and sharing to foster environmental sustainability.

2. Materials and Methods

2.1. Study Area Description

The study was conducted in the Mzimba district in northern Malawi (Figure 1). Mzimba district is the largest in Malawi, with a total land area of 10,430 km^2. According to the 2018 population census, the district has 936,250 (51.2% are female) residents [49]. Soils in the district are moderately fertile, generally of medium to light texture, mostly sandy-loam and loamy, with moderate to good drainage, making them suitable for growing most staple foods including cereals, legumes, roots and tubers [50]. The climate type in the district is semi-humid, characterized by average monthly maximum temperatures ranging from 27 °C to 33 °C, the hottest month being November. During the winter months, temperatures usually range from 0 °C to 10 °C, with June and July being the coldest months. The unimodal rainfall pattern in the area starts in November/December and ends in May, with an annual range from 650 to 1300 mm [51].

Economically, residents in the Mzimba district earn their livelihood usually through various activities including informal labor (called ganyu), petty trade, fish sales, food crop sales, cash crop sales and sale of forestry products [49]. Maize production is regarded as essential to the general welfare of the population and is, therefore, a significant socio-political factor in government agricultural policy [52,53]. Many farmers intercrop maize with pumpkins, legumes such as soybeans, groundnuts, beans, or cowpea and sometimes with finger millet [17,54,55]. Dimba gardens (during the dry season) in dambos (shallow wetlands) significantly contribute to household food security and income for those who have access to dambos [52]. As in other parts of the country, agriculture in the district is highly dependent on the unimodal rainfall pattern, increasing the likelihood of seasonal food insecurity, while the use of forest products for fuelwood, tobacco curing and burnt bricks production makes deforestation a major environmental challenge [56].

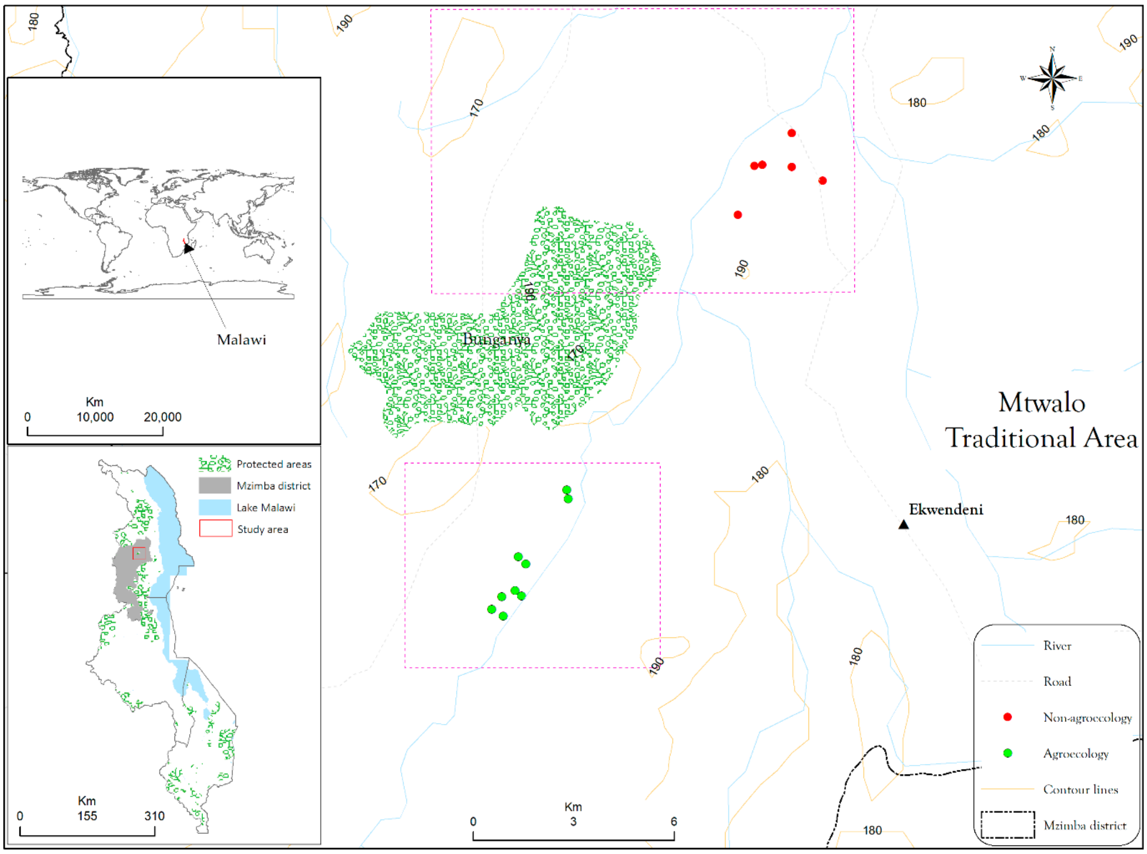

Figure 1. Location of study areas. Dotted pink rectangles represent areas demarcated by participants for ecosystem service use mapping.

2.2. Data Collection and Analysis

A mixed-method design that combines both qualitative and quantitative approaches was adopted in this study. The methods used include PPGIS interviews and focus group discussions (FGDs). In all, 68 randomly selected smallholder farmers spread across 15 villages in two village areas were selected to participate in the study. The selected farmers were from Edundu (35 farmers—23 women and 12 men—from 9 villages) and Thimalala (33 farmers—22 women and 11 men—from 6 villages). Active agroecology-practicing farmers are contained in a database from a 2019 survey to identify farmers who continued to practice agroecology after the MAFFA intervention concluded in 2017 [57]. Names of the beneficiary farmers were identified from the database and taken to Edundu. The research team then visited every third house from the last farmer identified.

The MAFFA intervention was implemented based on several criteria including forest density of the area (high, medium, low), level of food insecurity and socio-economic status of the people. The same sampling criteria were used to select the non-MAFFA village area to ensure that the participants share similar characteristics. To ensure that the two village areas were reasonably apart, we used buffer analysis—we made three buffer areas from Edundu at 5 km, 10 km, 15 km and >15 km distances using ArcMap. Using ESRI base maps, we assessed the forest density in each buffer to see if they had similar characteristics as the MAFFA village. We then identified the village areas within each buffer and conducted a baseline survey to examine the socio-economic characteristics of a randomly sampled group in each village area. Those villages that shared similar socio-economic characteristics were considered as candidates. To ensure that there was no contamination (in terms of adoption of methods used in the MAFFA villages due to knowledge diffusion) we selected the village area that had similar characteristics but was farthest from Edundu. We settled on Thimalala because it met all the criteria and the village area was also accessible by road (~18 km by motorable road). It was also cut off from Edundu by a river/valley and hills, thus limiting interaction between the two villages. To identify the farmers to participate in the study, the research team contacted the village chief to seek permission to work in the village area. The team then randomly went to every third house in all directions (houses are sparsely distributed), to identify household members willing to participate in the study after we explained the study objectives.

The research assistants were trained on ethical compliance and the research protocols were explained to them. This was to enable them to explain the research purpose to the farmers in the local Tumbuka language. Ethical approval for the research was granted by the Western University Non-Medical Research Ethics Board (NMREB# 113568). All farmers were trained to use a Garmin eTrex Vista HCx GNSS device to collect the spatial data. The research activities were conducted during the rainy season from December 2019 to the end of February 2020.

2.3. PPGIS Training and Mapping

2.3.1. Mapping of Farm-Level Processes and Practices

The farm-level data collection process was in four interlinked phases (see Figure 2 for the timeline of the various phases). In Phase 1 each farmer geolocated their farm, recorded crop conditions and geolocated the spot of insect infestation on the farm. This activity was to improve the visual experiences and spatial perception of the farmers [58] and create critical spatial awareness of the farm environment. According to Hatfield [59], spatial perception is the ability to be critically aware of your relationships with the environment around you and with yourself. In Phase 2, each farmer mapped the spatial extent of their farm after they had given a rough estimate of the area of the farm by "eyeballing" it. Each farmer carefully walked around the farm and recorded a coordinate after every few steps. These data were compared with the estimates given by the farmers for comparison, to determine the accuracy of farmers' estimates. Being aware of the accuracy of one's estimates is useful as it could help farmers' decisions regarding the quantity of seed to acquire for planting or the quantity of manure to apply per unit area. Phase 3 involved one-on-one interviews with farmers using a predesigned datasheet. The farmers were required to check information regarding conditions on their farms (e.g., insect infestations and soil conditions), record a coordinate and briefly describe certain farm processes and practices such as the treatment of insect infestation, manure application and weed management practices which were recorded by the research assistants. These descriptions were examined by the research team and compared to standard farm conditions to validate the farmers' observations. The farmers also described their preferences and priorities for extension services. Phase 4, described in detail in the next section, involved ES use mapping and focus group discussions on biodiversity conservation prioritization.

Three types of data were collected during these activities: textual data based on one-on-one interviews and field notes from the researchers' observations; spatial data comprising geographic coordinates (gpx format) of the central location of farms, the spatial extent of the farms, the location of farm/crop conditions; and quantitative data derived from the analysis of attribute table of farmers' and coordinates estimation of farm sizes. The textual data were analyzed thematically through descriptive coding techniques that assign a word or short phrase to summarize the main contents [60]. The gpx files from the GNSS devices were exported into ArcMap 10.7 to generate polygons of the various farmlands. The estimates of the farmers and other matching textual data were also entered in the attribute tables of the spatial data and mapped (see Figure 3). The Root Mean Square Errors (RMSEs) between the automatic tracking of the GNSS device and the farmer's coordinates were computed to measure the degree of accuracy of the two measurements. All the RMSE values for the polygons averaged about ±1.1 m, which is smaller than the error of the GNSS device (±2 m), and generally within the acceptable margin of error for georeferencing ground control points [61]. The attribute tables of the spatial data were exported to STATA (v16) and simple linear regression analysis was conducted to check for correlation between the two measurements for the two groups. Furthermore, a nonparametric Mann–Whitney U test [62] was conducted to test for differences between the GNSS estimates and farmers' estimates of farm areas at a 95% confidence level. The Mann–Whitney test was chosen because the data did not meet the normality criteria required for a parametric test [63].

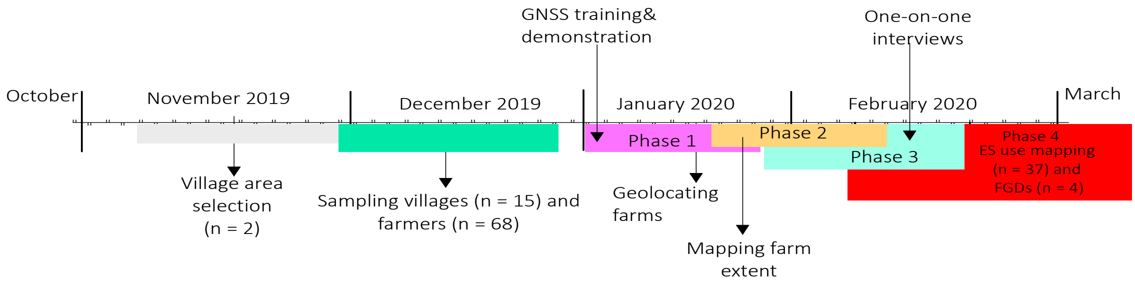

Figure 2. Timeline of research activities undertaken during the study.

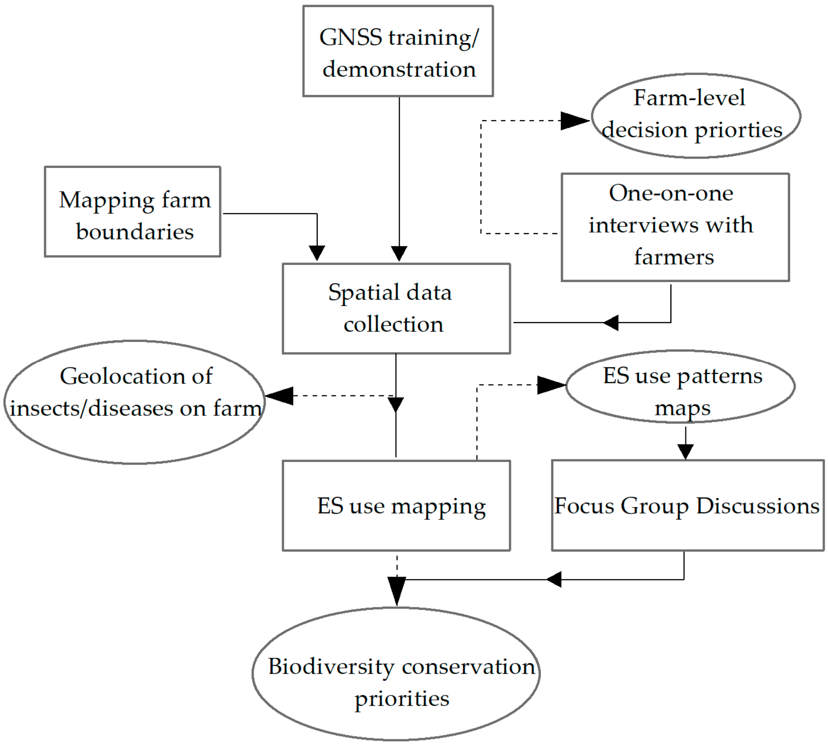

Figure 3. Flow chart of the research process. Dotted arrows to ovals represent outcomes of activities. Rectangles are activities engaged in while solid lines represent inputs to activities/next activity.

2.3.2. Ecosystem Service Use Mapping and Focus Groups

The ES mapping was conducted by integrating PPGIS with focus group discussions FDGs. Integrating PPGIS with FGDs is efficient for capturing group perspectives while collecting policy-relevant spatial data for community development. Locally relevant ES indicators that fit within three ES categories in the Millennium Ecosystem Assessment (MEA) [64]: provisioning services, regulating services and cultural services, were used to guide the mapping process. The decision on which ES to use was reached after an initial remote sensing classification of the area to identify the major land use/cover categories. A random forest classification algorithm was used with a PlanetScope image (3-m spatial resolution) for 22 February 2020. Ground truth/reference data were collected using GNSS devices while other samples were identified using high resolution ESRI base maps. The classification was based on 7 land use/cover categories (water bodies, shrublands, forests, farmlands, settlements, roads and bare land). Accuracy was assessed using the overall, producer and user accuracies [65]. The results were printed on large maps for use in assisting with ES selection. Services in the provisioning category are the products obtained from ecosystems including food, water, timber, fiber and genetic resources; regulating service are the benefits obtained from the regulation of ecosystem processes such as soil conservation, water purification and disease regulation; whereas cultural services are the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences including cultural diversity, knowledge systems, educational value and social relations [64]. Provisioning ES was chosen because chronic food insecurity and rapid deforestation are major challenges facing smallholder farmers in the study area. On the other hand, cultural services were chosen because of the diversity in knowledge systems in the two village areas due to the exposure to the intervention and the strong social relations that exist among households in both study areas. The PPGIS interviews were based on a modification of the MEA ES indicators. For instance, recreation and ecotourism in the cultural services category were excluded because local tourism is not a priority for people in the area, while dimba gardening was included because it is a common practice in the area.

To facilitate the mapping process, a topographic map of the study area was created from high resolution PlanetScope data (3 m) and shapefiles of roads and other landscape features. The extent of the areas to be mapped were determined in consultation with village leaders and agreed on by all farmers. The topographic maps, as well as natural color and false color composite maps of the satellite image, were printed on A3 sheets and laminated at a scale of 1:500,000. Farmers were given markers to draw polygons on the maps to indicate locations of ES they use regularly. Given the topography of the study areas (hilly, with valleys) and drawing on the experiences of similar studies in other places [7,14,66], farmers were allowed to use hand-drawn polygons to mark the areas of ES use rather than points. The description of the various landscape features and colors on the topographic and satellite maps were explained to the farmers to make it easy for them to identify and draw the polygons. The polygons were drawn based on a questionnaire, designed using the 9 ES indicators, to obtain spatial information of "current ES use"—defined as the past 10 years which covers the MAFFA intervention period. Participants indicated how they use the services at the drawn locations, and these were recorded in predesigned datasheets.

In total, 37 farmers (18 in the Edundu area and 19 in the Thimalala area) took part in the ES mapping activities. The mapping process was stopped in favor of more detailed discussions on biodiversity conservation when the mapping exercise began producing the same patterns, meaning the use patterns were similar across households and the same hotspots patterns were emerging. Thus, continuing mapping would only produce similar patterns of "hot" and "cold" spots as what was already recorded. The farmers drew 768 polygons in total (Edundu = 389; Thimalala = 379). The map sheets were georeferenced and digitized in ArcMap and joined with the corresponding farm data in a geodatabase. The polygons were analyzed to identify areas of overlap and the number of ES uses they overlap with (areas of multiple uses), using the polygon neighbor tool in ArcGIS. Density maps were generated to show "heat maps" or hotspots of ES use in both village areas.

To elicit views on the priorities of strategies for biodiversity, FGDs (n = 4) divided by gender (two in each village area) were conducted. The discussions were conducted in the local language and moderated by the researcher and two assistants. FDGs lasted between 45 and 90 min. Based on experiences of farmer-recorded information in other studies [67,68] and our desire to encourage active participation, a group leader was chosen during each discussion to document the main points discussed.

Even though this prolonged the discussions, it allowed the farmers to simplify their views rather than making winding statements that do not capture any specific concern. The notes of the farmers were compared with the notes taken by the research assistants to ensure the consistency and reliability of the findings and later categorized according to the ES indicators.

3. Results

3.1. Knowing the Farm: Spatial Perception, Farm Processes and Practices

Table 1 presents the socio-demographic characteristics of the participants in participatory activities. Participants were of varying age groups, educational levels and cultivated diverse crops. The educational level was fairly uniform across both groups of farmers. Intercropping, which is an effective agroecology method, was more common in Edundu while monocropping was more common among participants in Thimalala. Nine different types of crops were planted in Edundu compared to the eight in Thimalala.

Table 1. Characteristics of the study sample.

Variable	Edundu Area			Thimalala Area		
Education						
No Education	1	-	1	-	-	-
Primary	21	9	30	14	8	22
Secondary	1	3	4	7	4	11
Crop cultivated (rainy season farms n = 11)						
Beans	5	2	7	2	-	2
Bambara beans	1	1	2	-	3	3
Cassava	1	-	1	2	2	4
Groundnut	5	4	9	5	2	7
Maize	13	5	18	6	3	9
Pigeon peas	1	1	2	-	1	1
Pumpkin	1	1	2	-	-	-
Soya	4	2	6	5	2	7
Sweet potato	-	1	1	-	1	1
Tomato	-	1	1	-	-	-
Finger millet	-	-	-	1	-	-
Cropping system						
Monocropping	10	3	13	16	10	26
Intercropping	12	10	22	5	2	7

Figure 4 shows the extent of the fields measured by the farmers using the GNSS devices. The different colors represent different crops or combinations of crops (intercropped farms). Farms were generally distributed across the two village areas as seen in the inset maps.

In general, the estimates of the farm sizes by the farmers in the two village areas appear similar to the GNSS measurements (Figure 5). Table 2 shows that there was a significant correlation between the two estimates for the Edundu group (Pearson/multiple $R = 0.77$, $p < 0.0001$, $\alpha < 0.05$). In Thimalala, the regression coefficients show no significant correlation (Pearson/multiple $R = 0.02$, $p < 0.93$, $\alpha < 0.05$).

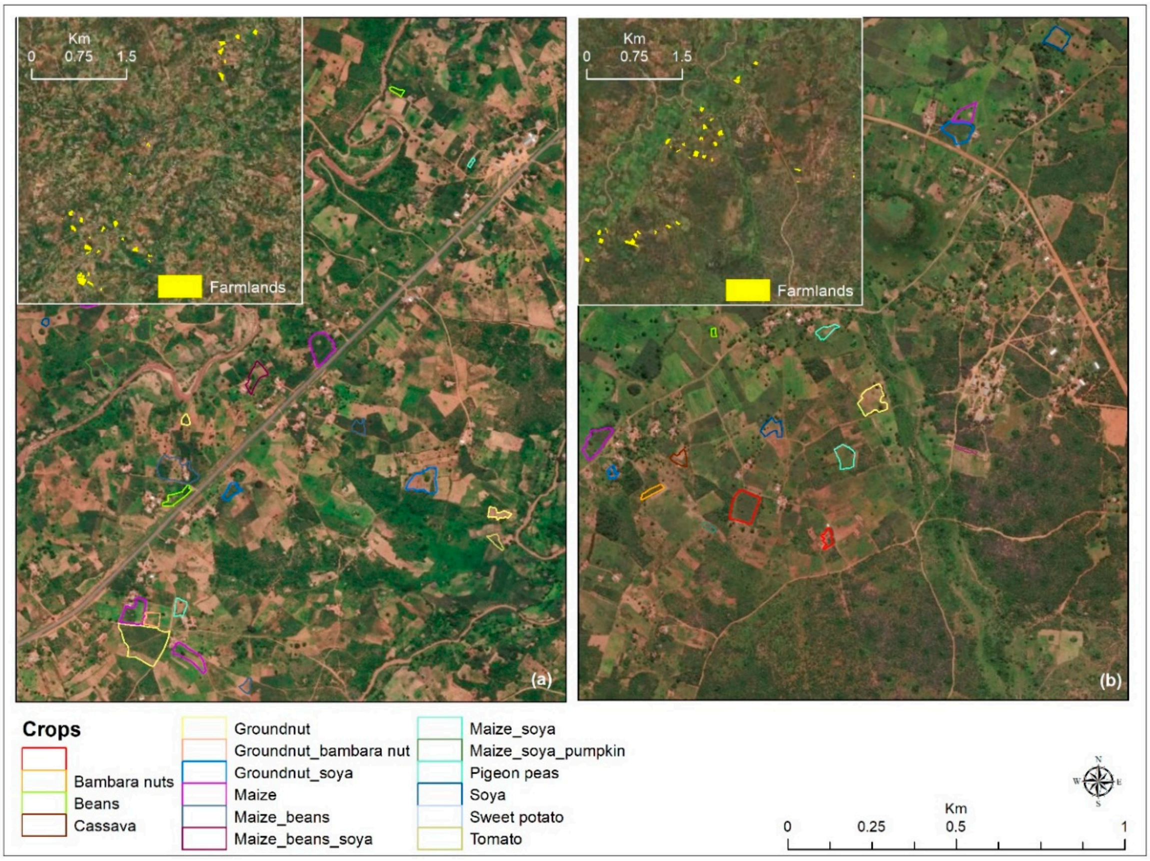

Figure 4. Extents of farms surveyed by farmers in (**a**) Edundu and (**b**) Thimalala. The inset map shows all the mapped farms. The base map is obtained from ESRI ArcMap v10.71. Inset maps represent entire areas covered during fieldwork.

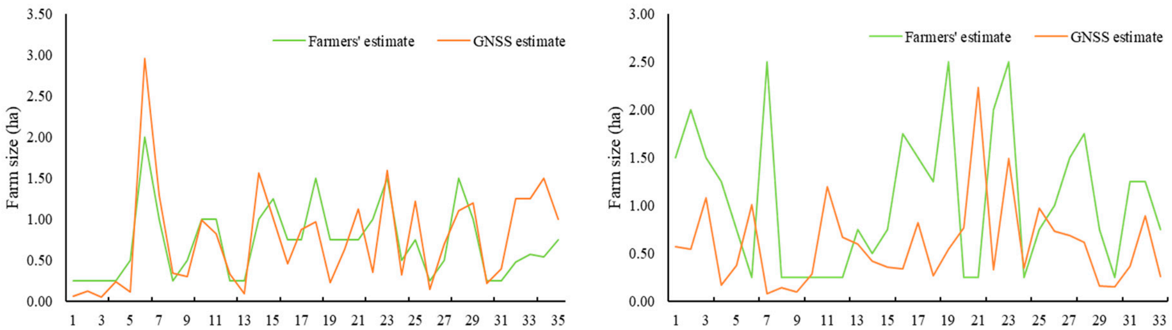

Figure 5. Comparison of farmers' estimates of farmlands with results of PPGIS mapping.

Table 2. Regression statistics of the relationship between farmers' estimates and GNSS measurements of the two groups.

Statistic	Edundu	Thimalala
Multiple R	0.77	0.02
R Square	0.59	0.0003
Adjusted R Square	0.57	−0.03
p-Value	<0.0001 ***	0.93
Standard Error	0.29	0.75
Observations	35	33

*** Significant at $\alpha < 0.05$.

Table 3 further shows that the agroecology-practicing farmers in Edundu have a better perception of the area as there was no significant difference in the areas they estimated compared with the areas measured with the GNSS device ($U = 604.5$, n1 = n2 = 35, $p < 0.925$). Farm areas estimated by farmers in Thimalala were significantly different (larger than) measurement of the same fields using a GNSS device ($U = 350$, n1 = n2 = 33, $p < 0.012$). These results further confirm the observations in Figure 5 and Table 2 and indicate that farmers who did not practice agroecology overestimated their farms.

Table 3. Non-parametric test of statistical significance for GNSS and farmer estimates of farm sizes.

Category	Farm Area Estimation Method	Number of Farms	Mean Rank	Sum of Ranks	Null Hypothesis	Mann–Whitney U	Asymptotic. (2-Tailed)	Decision
Agroecology	Farmers	35	35.73	1250.5	Agroecology farmers' estimates of farm area are the same as GNSS estimate	604.5	0.925	Retain the null hypothesis.
	GNSS	35	35.27	1234.5				
	Total	70						
Non-Agroecology	Farmers'	33	39.39	1300	Non-agroecology farmers' estimates of farm area are the same as GNSS estimate	350	0.012 ***	Reject the null hypothesis
	GNSS	33	27.61	911				
	Total	66						

*** Significant at $\alpha < 0.05$.

3.2. *Mapping Farm-Level Practices and Processes*

Table 4 shows farmer's observations on some processes and practices on their farms. There were notable variations of farmers' reports on insect infestation, treatment methods and plant conditions. For instance, 28.57% of farmers in the Edundu area reportedly used organic materials from *Tephrosia*, *Dahlia* and neem (*Azadirachta indica*) to produce insecticides for treating the insects whereas chemical treatment methods were more common in Thimalala. Table 4 shows farmers' observations of conditions in the fields and the remedial actions taken. Whereas most responses of the farmers in both areas accurately indicated that their crops were healthy, those in Thimalala also accurately identified and mapped stressed crops (due to disease infection or poor nutrition), water-stressed spots on the farm and discoloration of some crops (Figure 6). The research team crosschecked these observations for accuracy.

Table 4. Description of farm conditions based on farmers' observation ($n = 37$ farmers).

Description of Crop Condition	Edundu		Thimalala	
Insect Identification and Treatment	**Response**	**% Total**	**Response**	**% Total**
No infestation	6	10.71	12	30.00
Infested	29	51.79	23	57.50
Organic treatment	16	28.57	0	-
Chemical treatment	5	8.93	5	12.50
Total	56	100	40	100
Plant Condition				
Healthy	32	86.49	26	54.17
Water-stressed	-	-	1	2.08
Discoloration	-	-	2	4.17
Stressed (due to insects)	2	5.41	16	33.33
Stunted	3	8.11	3	6.25
Total	37	100.00	48	100.00

Note: Farmers were allowed to name and identify more than one insect on the farm and locate them using the GNSS device.

Figure 6. Discoloration of crops as observed by some farmers. Farmers expressed that such discolorations are due to the deficiency in some nutrients and such deficiencies could potentially affect yield.

Table 5 shows that even though there were similarities and variations in farmers' knowledge and understanding of the functions of common insects, there were variations in the accuracy in naming and describing the role of those insects on their farms and surrounding ecosystems. The farmers in the Edundu area were more accurate in naming and identifying the function of the insects, and some were able to describe the life cycle of the worms better than their counterparts in Thimalala. For instance, while 12 farmers in Thimalala named fall armyworms, only 5 of the responses were accurate as the rest could not identify them in the field or when shown to them, with the majority of them mistaking the worms for a different kind of worm or assumed that all worms function the same way. Other respondents in Thimalala did also not fully understand some of the ecosystem services provided by some insects such as bees; they thought bees were good for their honey or were destructive (they sting people). Responses with question marks mean farmers named those insects but could not identify them in the field. Figure 7 shows examples of insects identified and named by some of the farmers in Edundu.

Figure 7. Farmers in the agroecology site showing some insects they named and identified on their farms. Being able to correctly identify such insects is seen by the farmers as the first step to seeking the appropriate treatment.

Table 5. List of insects identified as most important in farming activities during farm-level PPGIS activities (Edundu = 35 participants, Thimalala = 33 participants). Farmers named (in local language), identified and geolocated the insect on their farms using GNSS devices and their findings were corroborated by the research team.

Edundu Area				Thimalala Area			
Insect	**Function**	**No. of Responses**	**% of Total**	**Insect**	**Function**	**No. of Responses**	**% of Total**
Fall armyworms	Destructive	19(19)	28.36	Fall armyworms	Destructive	12(5)	29.26
Stem borers	Destructive	17(17)	25.37	Stemborer	Destructive	7(4)	17.07
Flea beetles	Destructive	9(9)	13.43	Flea beetles	Destructive	7(7)	17.07
Butterflies	Pollination	2(2)	2.99	Butterflies	None	1(1)	2.44
Bees	Pollination	5(5)	7.46	Bees	Food/harmful	3(3)	7.32
Grasshopper	Destructive	8(8)	11.94	Grasshopper	Destructive	5(5)	12.20
Black millipede	Destructive	2(1)	2.99	Black millipede	Destructive	1(?)	2.44
Rats	Destructive	2(2)	2.99	Rats	Destructive	1(1)	2.44
Termites	Destructive	2(1)	2.99	White worms	Destructive	2(?)	4.88
Blister beetles	Destructive	1(1)	1.48	Green worms	Destructive	2(?)	4.88
Total		67	100			41	100

Note: number in parenthesis represent respondents who accurately identified insects. Furthermore, farmers were allowed to mention more than one function for the insects named. Responses with question marks mean farmers named those insects but could not identify them in the field.

3.3. Knowledge of and Priorities for Extension Services

Being aware of and seeking services of agricultural extension officers can be a useful resource in identifying challenges on the farm and making decisions regarding farming practices. Farmers in both locations were asked if they knew the name of their Extension Planning Area (EPA), Agricultural Extension Development Coordinator (AEDC) and if they had ever received any services from them. Although all the farmers knew of the name of their EPA, only three farmers from both village areas knew the name of their extension officer. Those who knew the AEDC reportedly had at least one meeting with them in the past season to discuss issues about their farms (Table 6). Each farmer prioritized and ranked the services from most important to least important that they would need from the extension officer (Table 6). Farmers in the Edundu area ranked the provision of improved seeds as the topmost priority whereas those in the Thimalala area prioritize fertilizers. While farmers in the Edundu area also highly prioritize research, information and technology/innovation sharing by extension officers, their counterparts in Thimalala highly prioritized education/information about on-farm practices, provision of agrochemicals and food aid. Other noteworthy differences include high priority for information on tree planting and the creation of market avenues for the sale of farm produce by farmers in the Edundu area. On the other hand, farmers in Thimalala did not prioritize research and innovation/technology sharing which is highly relevant for increasing yield.

3.4. Ecosystem Service Use Patterns

Table 7 shows the ES indicators, categories and the number of participants using them as delineated on the maps. The food category (food crops and wild edible food) was the most mapped while the cultural service category was the least in the agroecology village area. In the non-agroecology area, food crops and hunting/trapping wild animals for food were the most mapped categories while natural medicine and scientific/educational landscapes were the least mapped. These mapping orders reflect the importance placed on the ecosystems in the area as a whole.

Table 8 shows the ES indicators, the number of unique overlapping polygons indicating multiple uses, and the total area of overlap (in ha). Most provisioning services that serve as common-pool resources had high numbers of overlapping polygons, whereas others such as food and dimba/dry season gardening have lower numbers of overlapping polygons because farmers delineated individual farmlands. The variation in the total area of overlap for the two village areas is likely because Edundu had a smaller mapping extent than Thimalala.

Table 6. Access to and ranking of extension service needs based on relevance (number of responses = 156). Information was gathered through face-to-face interviews with each farmer on the field during the PPGIS activities. Each farmer listed their priorities which were then collated and ranked according to the village area.

Edundu Area			**Thimalala Area**		
Access to extension officer(s)	Respondents		Respondents		
Yes	3		3		
Services acquired	Training on vegetable growing skills Crop caring Different advice agricultural practices		Demonstration at field office Application of manure to MH33 Information on farming different crop types		
Ranking of extension service needs by farmers					
Service	**Response**	**% of Total**	**Service**	**Response**	**% of Total**
Provision of improved seed	18	21.69	Provision of free fertilizers	23	31.51
Education/information on farm practices	12	14.46	Education/information on farm practices	16	21.92
Training on manure/pesticide preparation	10	12.05	Provision of free Seed	13	17.81
Information on new farming methods	9	10.84	Provision of agro-chemicals	6	8.22
Provision of fertilizers	8	9.64	Food aid	5	6.85
Research, innovation/technology sharing	8	9.64	Training on manure/pesticide preparation	3	4.11
Market information	7	8.43	Information on new farming methods	3	4.11
Provision of agro-chemicals	6	7.23	Problem identification	2	2.74
Pest and disease management training	3	3.61	Market information	2	2.74
Information on tree planting	2	2.41	Pest and disease management training	0	0
Food aid	0	0	Research, innovation/technology sharing	0	0
Total responses	83	100		73	100

Note: MH33 is Malawi Hybrid 33—a maize variety introduced by the National Seed Company of Malawi. There were 68 respondents in total, but farmers were permitted to give more than one response.

Table 7. Ecosystem service indicators and the total number of polygons drawn across knowledge groups.

		Edundu Area			**Thimalala Area**		
Ecosystem Service Indicator	**ES Category**	**No. of Participants**	**Total Polygon**	**Mean Area (ha)**	**No. of Participants**	**Total Polygon**	**Mean Area (ha)**
Hunting/trapping wildlife	Provisioning	11	23	10.64	17	30	25.15
Wild edible plants (for food)	Provisioning	18	76	2.55	15	34	9.43
Wood (fuelwood and charcoal)	Provisioning	16	82	1.33	13	96	6.44
Natural medicines	Provisioning	3	9	2.25	2	12	9.83
Dimba/dry season farming	Provisioning	11	34	0.92	12	37	1.62
Food (food crops)	Provisioning	18	103	3.21	19	112	4.99
Aesthetic landscapes	Cultural	2	5	15.50	6	22	10.95
Scientific/educational landscapes	Cultural	1	4	14.35	2	9	31.72
Erosion regulation	Regulating	13	53	0.34	11	27	4.75

Table 8. Multiple-use ecosystem services in the village areas.

	Edundu Area		Thimalala Area	
Ecosystem Service	**No. of Overlapping ES**	**Total Area of Overlap (ha)**	**No. of Overlapping ES**	**Total Area of Overlap (ha)**
Hunting/wildlife trapping	4	66.13	7	240.58
Wild edible plants (for food)	6	41.97	6	96.27
Wood (fuelwood and charcoal)	6	25.44	6	137.16
Natural medicines	4	9.37	6	33.90
Dimba/dry season farming	2	0.22	2	2.58
Food (food crops)	2	0.17	4	3.60
Aesthetic landscape	4	33.87	5	154.02
Scientific/educational landscapes	3	1.14	7	210.81
Erosion prevention	7	0.92	5	12.17

Figure 8 represents the areas of multiple uses (hotspots) of ES in the village areas categorized as high, medium and low. In both the Edundu and Thimalala areas, hotspots (areas of frequent and multiple uses) of ES use are found in forest patches which farmers indicated as being exploited for multiple purposes including natural medicines, wild edible plants for food, fuelwood and aesthetic purposes. The largest ES hotspots were 66.13 ha and 137.16 ha in Edundu and Thimalala, respectively.

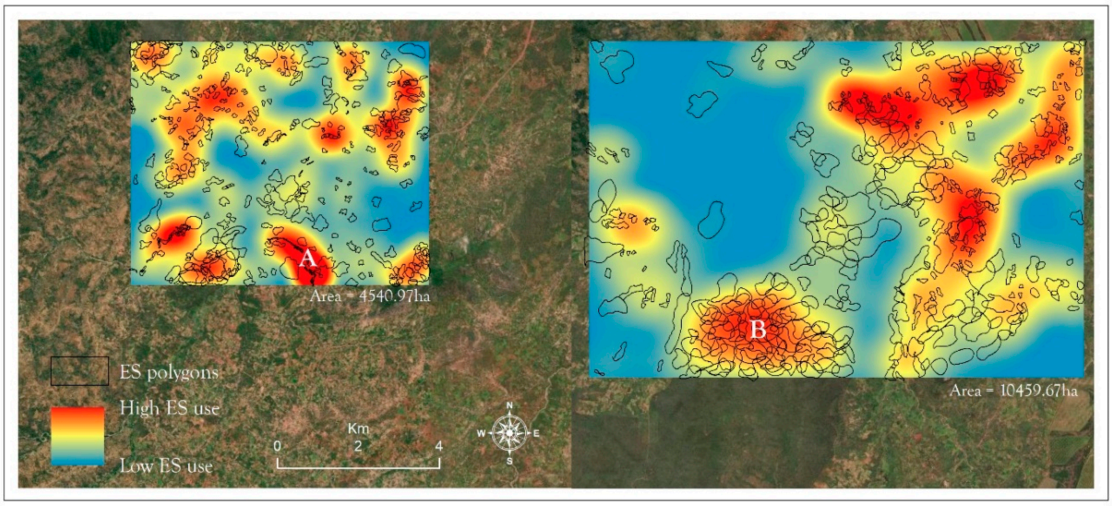

Figure 8. Patterns of ES use in Edundu (left) and Thimalala (right) with digitized polygons. Dark red areas indicate hotspots of ES use. The base map is from ESRI ArcGIS online base maps.

The ES hotspot in the southern part of the Thimalala area coincides with a forest reserve (labeled B), whereas the hotspot in the southern part of Edundu coincides with a valley area (labeled A). In both village areas, food crops and dimba gardening ES areas show medium to low hotspots because farmers mostly drew polygons around individual farms that were visible on the satellite images (also see Table 7).

3.5. Conservation Priorities across Knowledge Groups

Despite more similarities than differences in the patterns of ES in both village areas, the results of the FGDs showed marked variations in the prioritization of conservation strategies. In comparing the farmers' and researchers' notes, the prioritized strategies as shown on Figure 9 were based on the literature [69–71]: (i) maintain intact ecosystems, (ii) reverse declining ecosystems, (iii) recover depleted ecosystems and (iv) control emerging threats. There were variations in the prioritization of conservation strategies. Farmers in Edundu mainly prioritized strategies that favor the maintenance of intact landscapes or reverse declining ecosystem stocks while those in Thimalala prioritized strategies that will recover depleted ecosystems through regulatory measures.

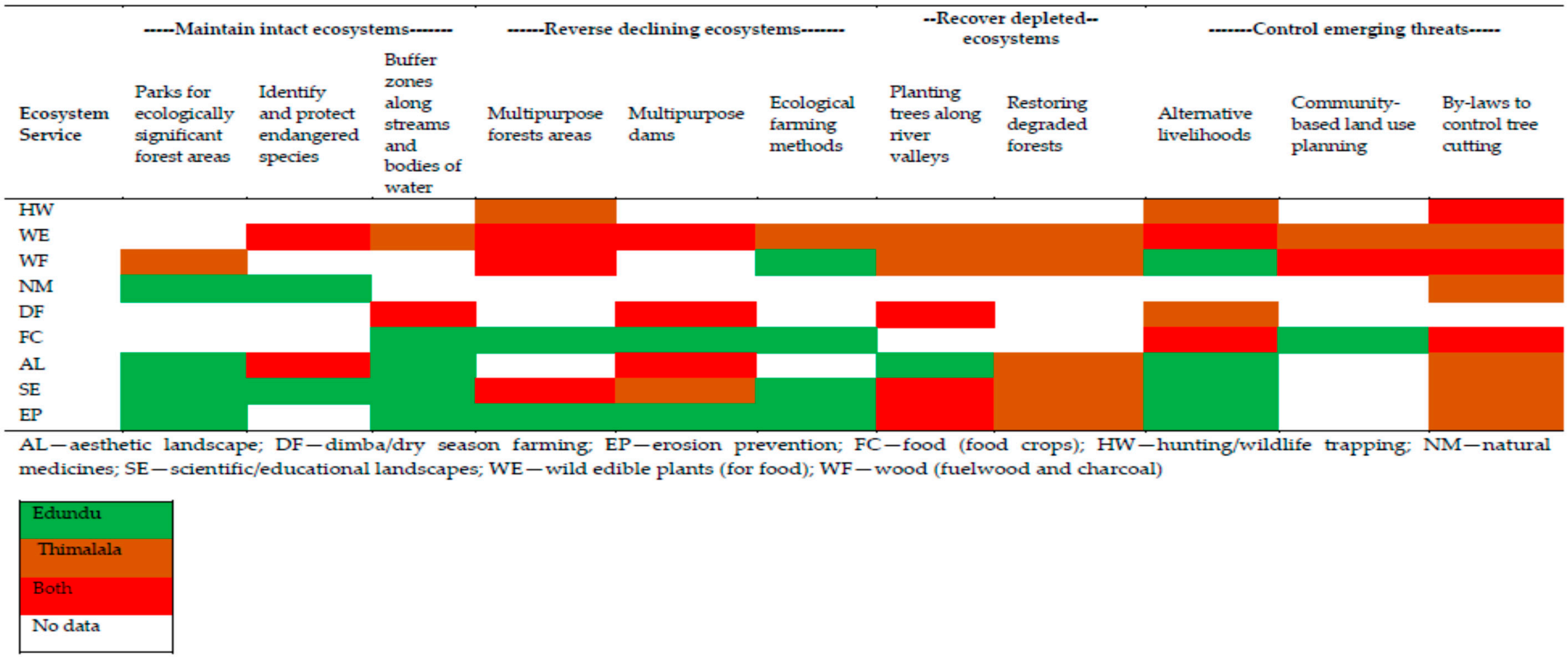

Figure 9. Prioritization of biodiversity conservation strategies based on ES mapping activities with farmers.

4. Discussion

This participatory mapping study revealed two main findings. First, the flow of knowledge about agroecology farming methods enhances the understanding of farm-level processes and practices. Farmers who participated in a participatory farmer-to-farmer agroecology intervention were more conscious of farm-level conditions such as the health of crops, soil conditions and the functioning of insects on their farms (see Table 5). Agroecology farmers were also more adept with practices such as biological insect control. Rusch, Bommarco, and Ekbom [72] made similar observations in India where they studied how agroecological knowledge can be used to enhance crop protection and insect pest management using biological control. Furthermore, participating farmers prioritized agricultural extension services that would provide more ecologically sound farming information, training on manure and biological pest management, information on new farming methods and sharing of research findings with them to boost productivity while non-agroecology farmers prioritized free fertilizers, education on farming methods, food aid and provision of free seeds (see Table 6). Recent studies by Micha et al. [73] and Bezner Kerr et al. [74] concluded that ecological farming (agroecology) is complex but influenced by cognitive beliefs and knowledge within stakeholder groups. For instance, though three farmers each from both communities reported that they had interacted with extension officers in the last and current growing season (see Table 6), farmers practicing agroecology had better knowledge of insects and so could easily contain them due to the greater understanding of the farm. The knowledge was likely acquired from educational programs where these insects are exhibited, and sample photos are given to lead farmers in the communities to use for educating other farmers. Overall, these observations are generally consistent with those in previous studies that examined the efficacy of participatory farmer-to-farmer knowledge sharing for promoting sustainable agriculture [16,75–78]. Studies by Thomas et al. [39] and Mills et al. [79] have also found that collaborative ways of passing on knowledge and advisory messages to farmers aid in decision-making at the farm-level including decisions on when and how to access help from extension officers for improved crop productivity.

Secondly, the study found that farmers who adopt agroecology also understand the synergies between micro-level farming processes/practices and the larger ecosystem and tend to prioritize ecologically sound conservation strategies such as establishing parks for ecologically significant forest areas, protecting endangered species, practicing agroecological farming methods, sustainable land management methods and alternative livelihoods (see Figure 7). These would sustain the services derived from ecosystems for future use. This finding is consistent with those of other studies that have examined the role of agroecology in ensuring sustainable biodiversity management [79–81]. The finding demonstrates the potential of participatory agroecology farmer-to-farmer knowledge sharing for improving farm-level decision-making, sustainable land use planning and context-specific biodiversity conservation strategies. There were also nuances in the patterns of mapping ES use that showed that the practices of agroecology farmers likely conserved biodiversity than non-agroecology farmers. For instance, while six overlapping polygons were mapped for fuelwood ES use, the total land area in the agroecology area was 25.44 ha, the area of overlap was about 137.16 ha for the non-agroecology area (see Table 8). The observation means that fuelwood harvesting was more prominent in the Thimalala area than the Edundu area likely because of the positive environmental behaviors acquired from learning about ecological farming methods. Thus, the knowledge differences may have influenced the choices of livelihoods and the implications that may have on biodiversity conservation. In one study, Schneiderhan-Opel and Bogner [82] observed that there was a positive relationship between knowledge and preservation and the appreciation of nature but a negative relationship between knowledge and environmental utilization.

Meanwhile, the priorities of the non-agroecology farmers for stricter controls on the use of ES to conserve biodiversity (Figure 9) have also been proven successful in conserving common-pool resources such as forests and water bodies in some contexts [83,84]. However, given that implementation of such regulations in the Global South tend to lead to conflict between implementing authorities and livelihoods of local people [85], such regulations are likely not to achieve the desired impact of conserving biodiversity. The conservation priorities of the farmers in both study areas reflect debates on "land sparing" and "land sharing" conservation strategies [86–88]. Our study demonstrated the importance of understanding how the transmission of agroecology knowledge occurs and indicates that a horizontal approach, rather than a top-down model, as well as pragmatic engagement of local farmers, can affect farm-level and biodiversity decision priorities. Of particular importance is farmers' heightened sense of spatial perception as observed in the differences between estimating farm sizes (see Figure 5) and understanding of the roles played by other members of the ecosystem, such as butterflies and bees, gained through the transmission of agroecological knowledge Understanding what happens on the farm and its neighboring ecosystems shapes farmer decisions about a wide range of farming practices. For instance, through heightened spatial perception about the farm area, it is possible, in such resource-poor settings, to optimize the application of farm inputs such as manure and biological pesticides to maximize yield without the use of equipment that degrade the environment. The agroecology farmers more accurately estimated farm areas because they have been engaged in the measurement and weighing activities when applying organic farming inputs. As such, they were able to better perceive space. On the other hand, farmers in Thimalala have not had any experiences with consciously measuring and weighing quantities which likely explains why their field measurements did not correlate with the GNSS measurement (see Figure 5 and Table 2). Zhao, Ren and Wen [89] also found that variations in education significantly affected the spatial perception of people to identify and select urban forests in China.

The study further revealed that agroecology-practicing farmers prioritize conservation strategies that favor the maintenance of intact landscapes or reverse the current trends of degradation of ecosystems. The prioritization of such approaches by farmers with knowledge on agroecology can be explained by the concept of amplification of agroecology [90]. The amplification of agroecology beyond the farm-level due to the wide range of sustainable production methods learned to create what Nicholls and Altieri [91] describe as "agroecological lighthouses from which principles radiate out to local communities, helping them to build the basis of an agricultural strategy that promotes efficiency, diversity, synergy, and resiliency" (p. 1). Given that the level of education across the two groups of farmers is similar, it is likely that the knowledge learned from the FRTs and through horizontal farmer-to-farmer learning has created "agroecological lighthouses" whose knowledge is being shared in the form of prioritizing environmentally sustainable conservation strategies. Prioritization of ecologically-friendly conservation strategies by the farmers conforms with arguments for methods that favor the maximization of ES use while reducing the risk of extinction of ecosystem members that provide these essential services [92].

Using participatory geospatial methods to explore the synergies between knowledge flows and agroecology broadens our understanding of how environmental sustainability can be achieved from a bottom-up approach through active engagement with and among farmers to inform sustainable land use and conservation decisions [93]. Identifying ES use through participatory mapping would help to identify important locations of ES use in communities [94] so that targeted conservation strategies can be designed [95]. Thus, participants were empowered with the careful application of geospatial technology combined with agroecological knowledge to identify local avenues of fostering sustainable production and democratic governance of local ecosystems. By understanding how agroecological knowledge can translate into decision priorities for sustainable biodiversity conservation, this study contributes to social learning theory by connecting participatory farmer-to-farmer knowledge sharing with the effects of such knowledge on the broader ecosystem service use using geospatial tools. With recent changes to the agricultural extension landscape in Malawi and Sub-Saharan Africa (SSA) in general, and the gendered nature of access to extension services in the Global South [96,97], participatory farmer-to-farmer learning is a viable alternative to ensuring equitable access to farming information.

A limitation of participatory methods, including PPGIS, is that results from their processes are not inevitably considered technically accurate in "scientific" standards [98]. Rather, data generated from PPGIS are viewed as constituting the early, exploratory and hypothesis-generating stages of scientific projects [99]. However, in resource-poor settings where spatial data on ES use patterns are scant or not available at all, the type of analyses conducted in this paper provides relevant data for making policy decisions on improving decision-making about crop production and biodiversity conservation. For instance, in delineating ES use areas, farmers revealed that local forest reserves are being exploited for other purposes, such as fuelwood, despite their reserve status. However, in interpreting hotspots of ES use, care must be taken to not conclude that such hotspots are necessarily places of a high volume of continuous activity. Rather, the results provide information on pin-point locations where there are higher risks of degradation due to multiple users and uses.

5. Conclusions

As climate change gathers pace and those at risk of food insecurity increases [1], biodiversity and ecosystem services have declined rapidly [2], while the demand for multiple ecosystem services increases. This combination necessitates a growing need to integrate both micro-level knowledge about farm conditions and macro-scale knowledge about ecosystem services in a way that decision-makers at all levels—individual, community and governmental levels—can use. Individual and local perceptions can be represented on maps that can more easily channel the local understanding to external decision-makers, which exemplifies the bottom-up approaches to decision-making. We found it to be true that farmers' agroecological knowledge at the farm-level amplified that knowledge into more consciousness about the environment, thus creating "lighthouses" that amplify agroecological knowledge for transformative biodiversity conservation. By these findings, the study adds to the growing use of participatory spatial methods for quantifying and mapping farmers' voices and ES use. We conclude that understanding the synergies between farm-level and macro-scale biodiversity could potentially contribute to the attainment of Sustainable Development Goals (SDGs) 2 (zero hunger) and 12 (ensure sustainable consumption and production patterns). Most importantly, the results suggest that educating more smallholder farmers on agroecological methods, through effective participatory approaches, could improve biodiversity conservation with food security and climate change mitigation co-benefits.

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