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Elements of agroecological pest and disease management

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The development of large-scale monocropped agrisystems has facilitated increased problems with pests and diseases, perpetuating the reliance of farmers on synthetic pesticides. The economic success of synthetic inputs has, however, been achieved at a high cost to the environment through the loss of biodiversity, depletion of soil quality, greenhouse gas emissions, and disrupting the ecosystem services that can otherwise help mitigate losses caused by pests and diseases. Environmentally benign alternatives for pest and disease management are urgently needed and are now widely recognized as essential for sustainable food and agriculture. The Food and Agriculture Organization, for example, has published the 10 elements of agroecology as a framework for the transformation of agriculture. Agroecology combines ecological and social concepts and principles to develop sustainable food and agricultural systems by harnessing nature-based solutions that are tailored to farmers' needs. Plant-based biopesticides, for example, offer an alternative to synthetic pesticides that are less harmful to the environment and nonpersistent, yet effective at managing pests and have a long tradition of use among farmers so are more socially acceptable. Here, we provide a critical assessment of how nature-based approaches to pest and disease management comply with the 10 elements of agroecology and show how they integrate with other ecosystem services through farmer participatory research. We conclude that the adoption of nature-based solutions for pest management addresses all 10 elements of agroecology and provides an entry point to promote sustainable farming practices among farmers more widely.

Keywords: Agroecology, Botanical pesticides, Conservation biological control, Farmer research network, Sustainable agriculture

Introduction

The use of plants for pest control has a long tradition in most societies around the world and was one of the main interventions for managing agricultural crop pests before the development of synthetic pesticides (Gerwick and Sparks, 2014). Intensification of agriculture and adoption of large-scale monocropping practices, together with plant breeding focused on developing varieties with increased yield, can exacerbate pest and disease problems (Bommarco et al., 2011) and reduce biodiversity (Raven and Wagner, 2021). Pest outbreaks under intensive farming can be severe, and this has facilitated the elaboration and use of synthetic chemicals that are designed to quickly kill pests and persist in the environment to prevent pest reinvasion (Heong et al., 2015). Furthermore, pesticide use is often not beneficial in many farming systems (Pretty and Bharucha, 2015). During the mid-20th century, the use of persistent synthetic agrochemicals was considered to be highly efficient and cost-effective. However, environmental costs to health, biodiversity, and resilience were often ignored in cost–benefit assessments (D'Annolfo et al., 2017; Kanter et al., 2018). Although the safety of chemicals used to control arthropods, plant pathogens, and weeds have improved over recent decades (Seiber and Kleinschmidt, 2011), the economic benefits are at the cost of biodiversity loss (Zabel et al., 2019; Raven and Wagner, 2021). Further, synthetic pesticides continue to be a problem for human health particularly in low and middle income countries (LMICs) where exposure rates to a range of synthetic compounds are often well above established safety standards (Boedeker et al., 2020). The disruption of natural pest regulation by synthetic insecticides that kill parasitoids and predatory invertebrates is now well-understood in global agricultural contexts (Overton et al., 2021) and ironically can lead to the increased use of insecticides, further reducing biodiversity and habitat

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resilience (Cardoso et al., 2020) with economic impacts (Huang et al., 2018). We argue here that eliminating the use of synthetic pesticides must be a core objective to realizing agroecological food production to help support these natural processes. Our own work in which we focus on botanical pesticides provides an example of how this can be done. We use our data and show how botanical pesticides can be an entry point for smallholder farmers to engage with biorational concepts and adopt longer term agroecological pest and disease practices including intercropping, conservation biocontrol, ecological engineering, and enhancing biodiversity (Mkenda et al., 2019). While recognizing that these longer term practices are necessary, we highlight that botanical pesticides are more than simply an input substitution for smallholder farmers in LMICs (Isman, 2008). In fact, many smallholder farmers produce their own botanical pesticides from plants intentionally grown or collected from locally available resources (Grzywacz et al., 2014). Some of these locally used plant materials may be waste resources, for example, fruit seeds, or multiuse plants such as *Tephrosia vogelii* used to not only improve soil but also harvested for pest control. The on-farm inputs used by smallholder farmers for pest control can indeed be considered agroecological in nature as resources are local, with many ecologically supportive roles, for example, conservation biocontrol (nectar/pollen), support to soils (legume species), or recycling waste (citrus peel, seed wastes) (Rosset and Altieri, 1997). Plant-based pest control technologies can be as effective as synthetic insecticides while being far less harmful to beneficial insects (Tembo et al., 2018). Revitalizing and increasing the use of ecological pest and disease management technologies is occurring in many production systems around the world but needs wider adoption (Pretty et al., 2018). We provide evidence from farmer research networks (FRN) (Nelson et al., 2016) in Tanzania and Malawi in which plant extracts were used to manage crop pests. Our data show that this is economically viable and can help restore natural pest regulation as well as contribute to crop plant resilience and human health through the co-creation of knowledge that synergizes with new business development, a circular economy, and promotes responsible governance.

Ten elements of agroecology and ecological pest and disease management

Awareness about the benefits of sustainable pest management methods in farming is growing among consumers, farmers, and policy makers, who advocate more environmentally sustainable practices and the adoption of agroecological farming (Nicholls and Altieri, 2018; Mdee et al., 2019; Wezel et al., 2020). The evidence base that agroecological methods of crop production can be economically and environmentally sustainable continues to grow but requires effective incentivization (Piñeiro et al., 2020). The United Nations Food and Agriculture Organization (FAO) has led international coordination to help countries transition to sustainable food and agricultural systems and has published a set of principles consisting of 10 elements (diversity, co-creation and sharing of knowledge, synergies, efficiency, recycling, resilience, human and social values, culture and food traditions, responsible governance, and circular economy) to guide the world's transition to agroecological intensification of food production (FAO, 2018). These elements cluster around key environmental, ecological, and social paradigms and have seen the restructuring and growth of social capital in farming communities leading to increased productivity of agricultural and land management systems (Hatt et al., 2016). This has empowered those who were previously excluded but requires policy support at regional scale to optimize the societal benefits (Pretty et al., 2020).

Compared to some crop limiting parameters, the damage and yield losses from pests and diseases are often visually apparent making it easier to engage stakeholders in approaches to address the problem (Stevenson et al., 2017). We argue that the social drivers of sustainable pest control can be relatively easy to harness, acting as an entry point to transition farming systems to adopt agroecological concepts. Across all regions and cultures, the use of botanical pesticides remains a concept that people can identify with (Stevenson et al., 2020). Awareness about the use of natural products as medicines, herbal remedies, as well as for pest control is often customary, in both advanced economies and among LMICs (Balick and Cox, 2020). Some of the earliest agricultural pest control products commercially manufactured were based on extracts from plants containing rotenone (*Derris* and *Lonchocarpus* spp.) or pyrethrum (*Tanacetum cinerariifolium*) (Isman, 2006). Current organic farm production continues to frequently rely on natural pyrethrum production as well and neem products extracted from *Azadirachta indica*, products that are sold widely and at scale in North America, Europe, China, and India (Isman, 2020). The market for such botanically based products remains small but is growing in many emerging markets where consumers are demanding organic produce, as well as among home gardeners (Isman, 2015). Constraints to new botanical product development are substantial and relate to patent laws, product registration requirements, and undeveloped local value chains (Sola et al., 2014). Traditions in many LMICs involve the use of plants in ethnoveterinary uses, medical treatments, and for crop protection, where often the products are not produced at scale and where knowledge is handed down the generations for local use in rural communities (Dougoud et al., 2019). In these situations, botanical products are typically sold at community level as home remedies from traditional healers or farmer to farmer. Particularly in the Tropics, there have been many local plant species identified as possessing pest control properties, many of which have had some level of scientific investigation and confirmation of bioactivity through controlled trials; however, critical data (e.g., bioactive phytochemical constituents) are frequently missing, reducing its value (Isman and Grieneisen, 2013). Unfortunately, there is evidence that this traditional ethnobotanical knowledge is being eroded and lost in many communities (Wyckhuys et al., 2019), arguably due to the commercial promotion of synthetic pesticides and modern pharmaceuticals, which are perceived to be more effective and

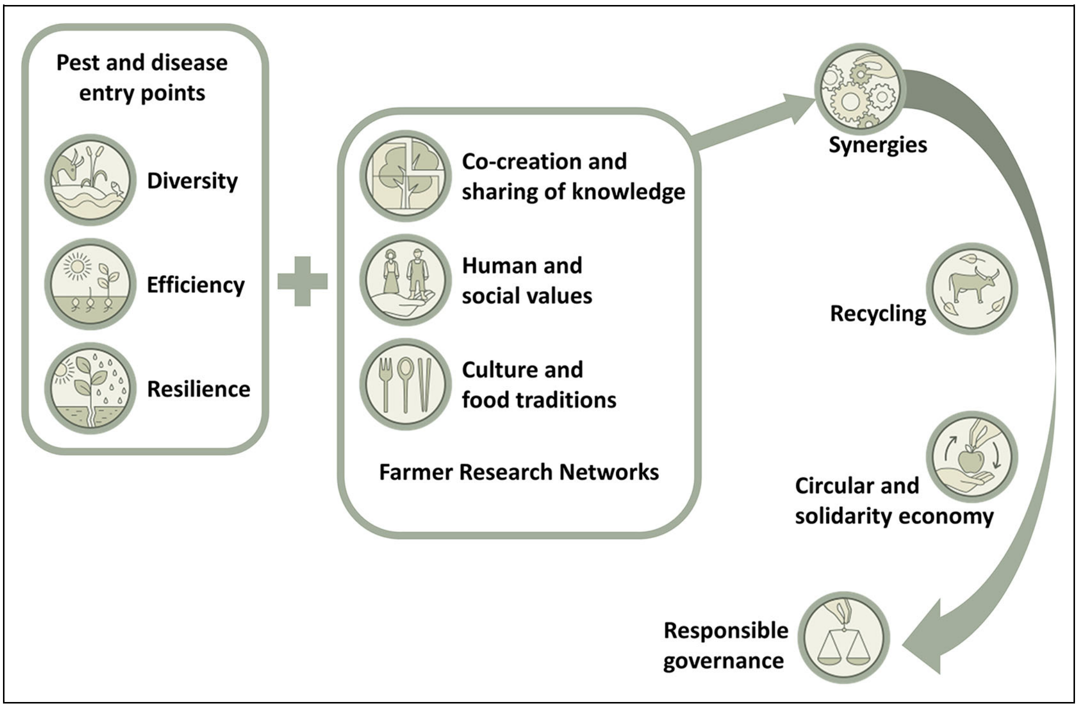

Figure 1. The 10 elements of agroecology described by the Food and Agriculture Organization (2018) with emphasis on how they can act as a framework facilitated by ecological pest and disease management to help realize more environmentally and socially sustainable crop protection and a transition to agroecological farming practices. DOI: https://doi.org/10.1525/elementa.2021.00099.f1

"modern," leading to younger community members being less likely to use botanicals compared to older farmers (Mkindi et al., 2021). Knowledge about ecosystem services and the role of beneficial invertebrates to help regulate pests and pollinators to optimize yields also appears to be limited (Elisante et al., 2019; Mkenda et al., 2020; Tarakini et al., 2020). Other studies have highlighted that some farmers may perceive all insects to be detrimental (Palis, 1998), while others generally do not consider biodiversity issues in their farm management (Busse et al., 2021). The need to preserve and strengthen traditional knowledge for sustainable pest control has never been greater, and we propose the 10 elements of agroecology can be used as a framework to facilitate ecological pest and disease management (**Figure 1**). We argue below that pest and disease management is a socially relevant entry point that enables wider agroecological principles to be appreciated and adopted.

Three of the FAO agroecology elements particularly embrace the social dynamics of pest and disease control: culture and food traditions, human and social values, and co-creation and sharing of knowledge. Culture and food traditions are central to shaping society, where modern food systems can lead to a disconnection between food habits and culture. Cultural practices, traditional foods and practices highlight the global diversity of foods and knowledge. We would argue that global industrial agriculture is propped up by synthetic agrochemicals leading to the erosion of cultural food traditions and where traditional pest and disease practices are being eroded through global supply chains promoting synthetic pesticides. Agroecological practices combining modern science and traditional knowledge can support natural pest regulation through crop rotation, intercropping, field margin plant diversity, and the use of botanical pesticides (Mkenda et al., 2019; Ouyang et al., 2020; Mwani et al., 2021), and these approaches are often compatible with each other (Ndakidemi et al., 2021) and often follow existing traditional crop production practices making them easier to adopt (Wezel et al., 2009). Human and social values relate to pest and disease management through the need for agroecology to be based on agricultural production that is knowledge intensive, environmentally friendly, socially responsible, innovative, and which depends on skilled labor. Agroecology aims to protect and improve rural livelihoods, equity, and social well-being where often pest and disease issues are experienced at a community level and where community action can help reduce pest and disease problems through coordinated actions at group level (Kansanga et al., 2020). Co-creation and sharing of knowledge has underpinned pest and disease management practices for centuries (Abate et al., 2000; Morales, 2002). Ethnobotanical surveys on the uses of plants, particularly for medicines but also as pesticides, in different cultural landscapes have sometimes been criticized for exploiting traditional practices for commercial benefits without recourse to the indigenous knowledge holder. In response, the United Nations Convention on Biological Diversity drafted legally binding legislation committing countries signed up to the agreement to share benefits equitably. This culminated in the Nagoya Protocol on Access and Benefit Sharing, which has been ratified by 132 countries

(Convention on Biological Diversity Secretariat, 2011). The Protocol provides a legal framework for sharing knowledge and genetic resources that may lead to, for example, new pest control products, with a view to preventing the exploitation of indigenous knowledge without financial recompense. Co-creation and sharing of knowledge in the context of pests and diseases is also relevant with respect to the revitalization of traditional knowledge and scientifically building agroecological farming systems. This element is particularly important between farmers and scientists who must work together to optimize the use of botanical pesticides and manage landscapes to optimize natural pest regulation to increase the abundance of predators and parasitoids while reducing the abundance of pest species through ecological engineering (Bliss, 2017; Charatsari et al., 2020).

The central ecological features of pest and disease management particularly relate to 3 of the FAO elements: diversity, efficiency, and resilience. These factors underpin the potential development of insects and pathogens to levels where their damage to crops surpasses the threshold of economic injury, and where their pest status becomes evident (Higley and Pedigo, 1993). Biodiversity in crop protection is important within the cropping area and supported through crop rotation, intercropping and push-pull strategies that ensure mixed crop plant species are grown alongside each other (Dainese et al., 2019; Brooker et al., 2021) as well as diversity in habitats immediately adjacent to cropping areas, such as field margins, other nearby cropping areas, and diversity at wider landscape levels (Mkenda et al., 2019). While on the one hand evidence supports the notion that increased plant diversity can lead to reduced pest and disease pressures, this is not universally the case where global analyses have shown that the relationship between landscape composition and natural pest regulation is not always beneficial (Karp et al., 2018). Mixed cropping can reduce the abundance of insects and diseases that spread by creating barriers of different plants that particular pests/pathogens are not able to exploit (Hooks and Fereres, 2006; Parolin et al., 2012; Dada et al., 2020). Thus, reducing the practice of monocropping could have significant positive impacts on pest and disease management. Monocropping can be made more sustainable through practices of planting flower margins or flower strips in crops that provide food and harborage for predators and parasitoids which can augment their populations at key times for when their prey species become abundant (Hatt et al., 2017; Albrecht et al., 2020). Maintaining field margin plants, increasing the plant diversity of field margins, and even engineering field margins by planting particular plant species with beneficial properties have all been shown to be effective strategies in facilitating natural enemies of crop pests (Gurr et al., 2016). Ensuring plant diversity at these different agricultural landscape scales is usually a good practice for ensuring higher insect diversity that leads to improved natural pest regulation that facilitates lower pest numbers and higher natural enemy abundance. Other ecosystem services such as improved pollination are also facilitated by ensuring good plant diversity within and around cropping areas (Arnold et al., 2021; Raderschall et al., 2021), and diversity can often assist with improving soil fertility (McDaniel et al., 2014; Tian et al., 2019; Saleem et al., 2020). Thus, diversity helps enable the elements of efficiency and resilience. Resilient habitats are usually diverse habitats. Resilience to pests and diseases is often a factor of soil fertility, access to nutrients and water where vigorous, healthy plants are able to employ their natural defenses against attack or increase compensatory growth mechanisms post attack (Blundell et al., 2020), meaning that there are overlaps and synergies with approaches such as conservation agriculture (Fanadzo et al., 2018). The use of botanical extracts can also help facilitate natural plant defenses through the stimulation of endogenous defenses as well as acting as foliar fertilizers that strengthen plant resilience (Mkindi et al., 2020). The agroecological element of resilience is also relevant for farmers and communities when people can use locally available renewable resources for pest and disease management. In most LMICs, agrochemical inputs are imported and sometimes even subsidized by local governments (Tambo et al., 2020). These products can create import reliance and distortion of local pest and disease management services, such as the use of locally available pesticidal plant products. The development and strengthening of local value chains for botanicals or businesses rearing biological control agents (Grzywacz et al., 2014; Sola et al., 2014) can lead to increased socioeconomic resilience in pest management practices, reducing the need for synthetic pesticide imports (Coulibaly et al., 2002; Isman, 2015). The element of efficiency further highlights the link between diversity and resilience to challenges and constraints. The use of pesticidal plants and natural pest regulation help to reduce the need for other external resources. For example, not only can the use of botanical pesticides act as foliar fertilizers (Mkindi et al., 2020), but several plant species are used to improve soil fertility in other ways. Research on the legume *T. vogelii* has demonstrated that it not only can be used as a highly effective pest control option but also to help improve soil fertility through its ability to fix nitrogen and its deep roots that help bring minerals closer to the surface to be accessed by crop plants (Mafongoya and Kuntashula, 2005; Belmain et al., 2012). Other pesticidal plants such as *Tithonia diversifolia* are often used as green mulches or cover crops (Jama et al., 2000; Desaeger and Rao, 2001). Multiple uses of plant species used for pest control highlights the multifunctional potential of some noncrop plant species, that is, pyrethrum and other pesticidal plants, in agricultural systems that could even provide new crops, building on experiences of pyrethrum production to cultivate plants such as *Tephrosia vogelli* for pest control products (Mkindi et al., 2017).

There are 4 further agroecology elements identified by the FAO: synergies, recycling, circular and solidarity economy, and responsible governance. Their relevance to pest and disease management has been partly discussed in the relations with other elements. Synergies in the use of botanical pesticides and soil fertility (Tian et al., 2019; Saleem et al., 2020), plant resilience (Blundell et al., 2020), and natural pest regulation (Mkenda et al., 2019; Ndakidemi et al., 2021) highlight that ecological pest and disease management can support multifunction ecosystem services. Encouraging biodiverse landscapes within crop fields and their surroundings can synergize with other uses such as the provision of livestock fodder, wild food plants, local medicines, pesticidal plants, and pollination services (Harrison et al., 2014; Duru et al., 2015; Englund et al., 2017). The use of botanicals helps to reduce the need for external synthetic inputs, recycling sustainable plant resources for pest and disease management as well as supporting nutrient recycling when botanicals are used as foliar fertilizers, mulches, and intercrops (Nyende and Delve, 2004; Mkindi et al., 2020). The element of recycling local pest control products increases the autonomy of producers and reduces their vulnerability to synthetic imports. A circular and solidarity economy aims to reconnect producers and consumers in ways that prioritize local markets and supports local economic development by creating virtuous cycles. Local organic food has been shown to be an important entry point to create local farmer markets (Curtis et al., 2020), and, similarly, research with smallholder farmers in Africa has shown they also value producing food that they consider to be safer for their families to consume by using botanical pesticides instead of synthetic products (Mkindi et al., 2021). The final agroecology element, responsible governance, is arguably the area where ecological pest and disease management needs the most assistance. Synthetic pesticides are typically produced by large multinational companies as their development and registration requires huge resources. They also have considerable influence and interest in maintaining their monopoly of food production systems. There is a perception at policy level that such inputs are essential, and this can lead to subsidies that distort pesticide use (Tambo et al., 2020; Aubert and Enjolras, 2021). Rigorous efficacy and safety tests are required for the registration of pesticides. Such regulation is essential when many of these chemicals are designed to be toxic to animals and persist in the environment. However, the use of botanical pesticides may also come with risks since some plant compounds are toxic, but typically, these are present in plant material at concentrations lower than levels likely to lead to acute toxicity (Belmain et al., 2012; Isman, 2020). Furthermore, plant chemicals are typically much less persistent often due to them being ultraviolet labile reducing longer term effects and may need to be applied more frequently but are potentially less environmentally harmful especially to nontarget insects (Tembo et al., 2018; Kilani-Morakchi et al., 2021). Rapid photodegradation of plant compounds reduces likely exposure of toxic levels of compounds to consumers.

Despite the reduced risks associated with botanical versus synthetic pesticides, regulatory and product registration requirements are typically the same scale, and such high costs make this unaffordable for comparatively small-scale plant pesticide products (Isman, 2008). Some countries have recognized this stifles innovation of safer pest control products and have created different regulatory pathways to help reduce the cost of evaluating the safety and efficacy of new botanical pesticide products. For example, China, Brazil, and India have relaxed regulations to support the plant pesticide sector (Isman, 2020). However, improved governance of the pest control sector is clearly needed in more countries to reduce reliance on synthetics and instead develop sustainable plant-based pest control products that encourage communities to protect their health while supporting local commercial opportunities.

Governance of land tenure, both crop and noncrop habitats, can significantly impact on how landscapes are managed to promote biodiversity that facilitates natural pest regulation, which can disconnect farmers and communities from the land they cultivate and discourage investment in land improvement through planting trees or adding organic matter to soil on land that does not belong to them. Our interpretation of the relationships among the FAO 10 elements of agroecology (**Figure 1**) aims to show how synergies between the social and natural elements can influence the development of responsible governance of the pest and disease management sector. We argue below that innovations in FRN may enhance grassroots engagement with policy makers to help bring about improved governance frameworks and policies.

FRN, pest management, and agroecological transitions

Agroecological farming is acknowledged to be knowledge intensive requiring considerable awareness in many different domains (Pereira et al., 2018). To implement agroecological principles, it has been argued that helping farmers to adapt to agroecology can require stronger collective problem-solving through strengthened knowledge extension programs that enable collaborative learning processes between researchers, farmers, and other relevant stakeholders (Méndez et al., 2013). Several approaches aimed at facilitating this kind of engagement have been attempted over recent decades, most notably farmer field schools (van den Berg et al., 2020). More recently, the concept of FRN has been proposed to increase farmer agency in the research process, particularly to carry out agroecological research at large scale with many farmers across different contexts that empower farmers to evaluate and adapt agroecological practices to their local values and traditions (Nelson et al., 2016). Important elements of FRNs are as follows: (1) farmers co-create the research agenda, (2) farmers are engaged throughout the experimental process, (3) farmers strengthen their capacity to acquire and seek knowledge, and (4) networks are community inclusive (Richardson et al., 2021). Our recent research has shown that FRNs can be an effective way to engage with pest and disease issues experienced by smallholder farming communities in Tanzania and Malawi. In both countries, FRNs were initiated by university researchers who contacted farmers in target regions to explain objectives and principles of engagement. Interested farmers volunteered to be involved and were encouraged to establish small groups with other nearby farmers. As pest and disease management is a clear priority for all farmers,

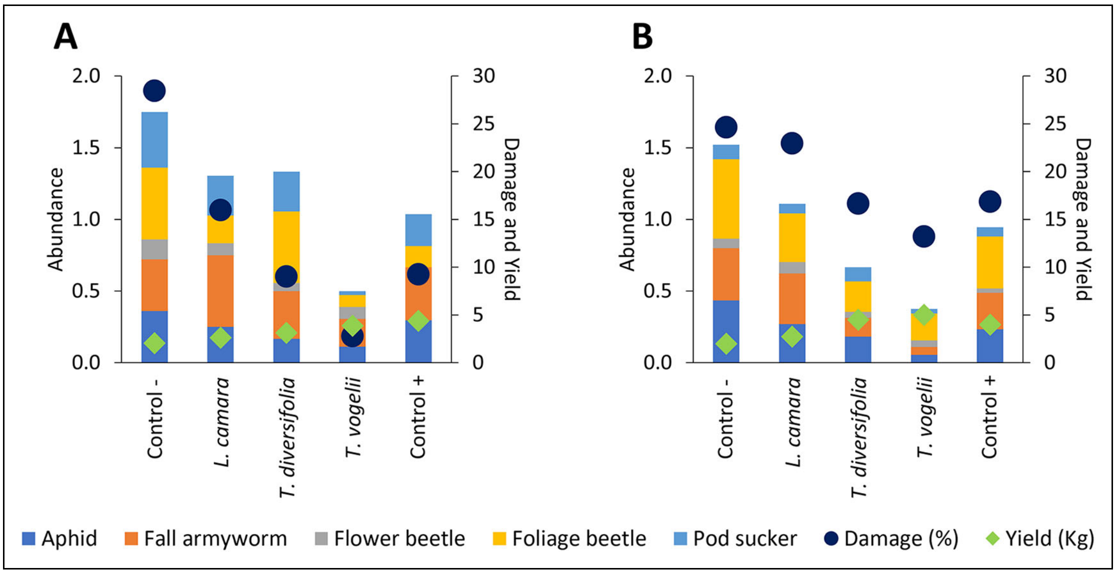

Figure 2. Farmer-led data collection to evaluate the impact of three commonly used pesticidal plants (*Lantana camara, Tithonia diversifolia*, and *Tephrosia vogelii*) on common bean (*Phaseolus vulgaris*) grown as intercrop with maize (*Zea mays*) by farmers in the Kilimanjaro region, Tanzania. Research was carried out by a farmer research network with 100 farmers, with (A) a commonly managed researcher-led demonstration plot at a central community location and (B) farmer-led replicated plots on their own land. Damage is scored using quartile percentages, yield is per square meter, and insect abundance is the mean weekly number per plant. The positive control involves spraying a synthetic pesticide, Karate (lambda-cyhalothrin) as recommended, negative control plots are untreated, and botanical plots sprayed with a 10% w/v water extract. All other cropping and management practices were standardized. DOI: https://doi.org/10.1525/elementa.2021.00099.f2

we argue that it provides a widely supported entry point to develop more environmentally sustainable crop production, particularly by first showing farmers that pesticidal plant products can be just as effective as synthetic pesticides in protecting their crops, without the expense of buying commercial products as well as without the safety and health issues that farmers can experience when using synthetics (Mkindi et al., 2021).

Our experience has shown that FRNs can be used to collect reliable field data that is comparable to what researchers are able to collect. The reliability of farmer-collected data can be confirmed by operating farmer-managed trials and researcher-managed trials alongside each other in the same locality using the same protocols (**Figure 2**). To do this, farmers are trained in how to make optimized botanical extracts, which includes standard procedures for the cultivation and harvesting of pesticidal plants, drying and processing of plant materials, and the preparation of extracts and their application. This can be done through small training workshops or the use of short training videos viewed on smartphones (Bello-Bravo et al., 2011; Maredia et al., 2018; Belmain et al., 2018). Through group discussion, farmers and researchers must come to an understanding on how the trial should proceed, which parameters and treatments to use, and what data should be collected to provide evidence that the different treatments have different effects. Evaluating different botanical pesticide extracts to protect common bean crops using an FRN has shown that there can be slight differences in data collected, but that it very often follows the same trend as data collected by research teams (**Figure 2**). This trial indicated that the crop damage assessments carried out by farmers were generally higher than the damage recorded by researchers. Despite this, the crop yields recorded by farmers and researchers across treatments were very similar. This highlights that smallholder farmers can be competent researchers when they receive the right support and training to understand basic principles of replication, using standard protocols and the need for comparative data, for example, positive and negative control treatments.

As an example of how an FRN can be used to explore principles of agroecology, farmers in central Malawi carried out simple evaluations to assess the number of key pest and beneficial arthropod species found on their bean crops when sprayed with a conventional synthetic pesticide, Karate (lambda-cyhalothrin), compared to using a botanical pesticide (*T. vogelii*; **Figure 3**). This study was able to show farmers that the synthetic killed all kinds of insects, including beneficial species, while the botanical did not kill nearly as many pests or beneficials (**Figure 3A**). Despite the higher numbers of pests on the botanically treated bean crops, the yield of the beans was very similar between the synthetic and botanical treatments (**Figure 3B**). This discovery by the farmers was used to discuss how botanicals may not always kill insects quickly but lead to a cessation of feeding or repellence, as well as greater awareness about how plants can usually compensate for some level of insect damage. Further, farmer awareness was increased about beneficial species and how not killing them in high numbers could contribute to pest control. These discussions led to wider FRN community awareness

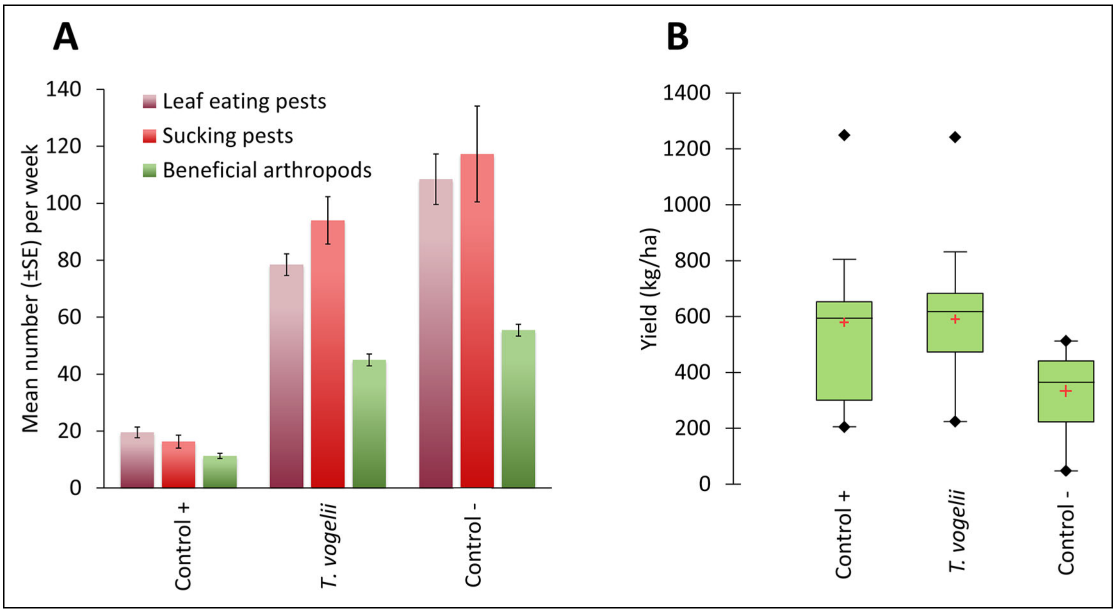

Figure 3. Farmer-led data collection to evaluate the impact of a commonly used pesticidal plant, *Tephrosia vogelii*, on common bean (*Phaseolus vulgaris*) grown as a monocrop. Research was carried out by a farmer research network in Malawi with 200 farmers, who (A) measured the abundance of key arthropod groups per field plot per week and (B) measured the bean yield at harvest. The positive control involves spraying a synthetic pesticide, Karate (lambda-cyhalothrin) as recommended, negative control plots are untreated, and botanical plots spray a 10% w/v water extract of *T. vogelii*. All other cropping and management practices were standardized. DOI: https://doi.org/10.1525/elementa.2021.00099.f3

about the importance of biodiversity in pest management and the ecosystem services related to providing sustainable and healthy food and safe food production without harming the environment (Mkindi et al., 2021).

Discussion

Agroecological transitioning toward sustainable agriculture and food systems has been highlighted as an important paradigm that requires entry points to enable positive economic, environmental, and social change (Barrios et al., 2020). We have provided evidence that FRNs investigating local use of botanical pesticides can act as such an entry point through applying our visual narrative (**Figure 1**) to enable farmer awareness and initiate a process of behavioral change that can move beyond the simple use of botanical pesticides to more complex and context-specific practices related to natural pest regulation. Further, our examples of farmer-centered research open up this nexus to explore other important issues in ecological pest and disease management, such as conservation biocontrol, maintain/increase biodiversity of flora and fauna and other underpinning ecosystem services such as soil health and fertility, and landscape/territory management as has been substantiated in other parts of the world (McCune and Sánchez, 2019; Rossi, 2020). Co-learning and sharing of knowledge has been repeatedly evidenced as a key concept to promote discourse, experimentation, and learning to enable agroecological transitions (Kangmennaang et al., 2017; Anderson et al., 2019). Increasing application of ecological pest and disease management has also been shown to support farmer engagement in changing policies and regulations and supporting responsible governance for pest and disease control (van der Ploeg, 2021; Sampson et al., 2021). Although there are many potential entry points to facilitating agroecological transitions (Barrios et al., 2020), we would argue the immediacy and crisis of managing pest problems experienced by smallholder farmers can garner farmer support, particularly through the use of local plant resources with pesticidal properties that can more safely and sustainably replace the use of synthetic pesticides. This can often be done without sacrificing crop yield while enabling cultural traditions of pest management and promoting circular economies, recycling, and crop resilience. Botanical pesticides, particularly when grown or harvested locally to make simple extracts, can open conversations with smallholder farmers around sustainable agriculture and open the door to agroecological transitions.

Plant-based pesticides are typically produced and harvested locally and thus have the additional benefit of a reduced carbon footprint compared with synthetics as they require no manufacture and no transport. Their use is also agroecological in nature, although the context of use is important. In the case of smallholder farmers, the use of local plant materials collected under different growing conditions has an impact on phytochemical content and efficacy. Therefore, contextual variability must be established based on what plant species are growing in different localities, local extraction and application technology, and for different crop/pest species. Entry points to engage with farmers over complex issues such as conservation biocontrol are needed. However, the highly contextual and variable nature of conservation biocontrol means that results are not always promising or quickly apparent, leading to potential demotivation of farmers and loss of trust. In our experience researching these challenges alongside smallholder farmers in eastern Africa, we believe it is important to help farmers with their immediate problems to gain trust to tackle longer term more challenging issues that require significant farmer investment. FRNs are a powerful research and development tool we have used to facilitate the co-creation of knowledge, connect producers, amplify innovations, and support grassroots processes that advance horizontal dialogue with institutions and decisions makers. Our work with smallholder farmers in eastern Africa shows that botanical pesticides can be an appropriate and supportive entry point to leverage agroecological transitions based on contextual resources, both social and ecological in nature.

Conclusions

The degree of compatibility of synthetic pesticides with agroecology is limited (Lefèvre et al., 2020; Deguine et al., 2021); however, more ecological pest and disease approaches are available that strongly align with the 10 principles of agroecology described by the FAO. Transitioning farmers to more sustainable pest and disease management is possible and can be done without significantly increasing financial costs, ensuring profitable cost–benefits. The motivations for farmers to adopt ecological pest and disease management can be high, and transitioning can be highly successful if farmers are provided with adequate support and increased agency through enabling frameworks such as FRN. We believe that ecological pest and disease management can act as an entry point to farmers considering other agroecological production issues such as soil fertility and climate mitigation that will be essential as the world aims to produce more food under more sustainable conditions.

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Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author contributions

Contributed to conception and design: SRB, YT, AGM, SEJA, PCS.

Contributed to acquisition of data: YT, AGM.

Contributed to analysis and interpretation of data: SRB.

Drafted and/or revised the article: SRB, YT, AGM, SEJA, PCS.

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