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PERSPECTIVE

A network approach for managing ecosystem services and improving food and nutrition security on smallholder farms

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Abstract

1. Smallholder farmers are some of the poorest and most food insecure people on Earth. Their high nutritional and economic reliance on home-grown produce makes them particularly vulnerable to environmental stressors such as pollinator loss or climate change which threaten agricultural productivity. Improving smallholder agriculture in a way that is environmentally sustainable and resilient to climate change is a key challenge of the 21st century.
2. Ecological intensification, whereby ecosystem services are managed to increase agricultural productivity, is a promising solution for smallholders. However, smallholder farms are complex socio-ecological systems with a range of social, ecological and environmental factors interacting to influence ecosystem service provisioning. To truly understand the functioning of a smallholder farm and identify the most effective management options to support household food and nutrition security, a holistic, systems-based understanding is required.
3. In this paper, we propose a network approach to understand, visualise and model the complex interactions occurring among wild species, crops and people on smallholder farms. Specifically, we demonstrate how networks may be used to (a) identify wild species with a key role in supporting, delivering or increasing the resilience of an ecosystem service; (b) quantify the value of an ecosystem service in a way that is relevant to the food and nutrition security of smallholders; and (c) understand the social interactions that influence the management of shared ecosystem services.

4. Using a case study based on data from rural Nepal, we demonstrate how this framework can be used to connect wild plants, pollinators and crops to key nutrients consumed by humans. This allows us to quantify the nutritional value of an ecosystem service and identify the wild plants and pollinators involved in its provision, as well as providing a framework to predict the effects of environmental change on human nutrition.
5. Our framework identifies mechanistic links between ecosystem services and the nutrients consumed by smallholder farmers and highlights social factors that may influence the management of these services. Applying this framework to smallholder farms in a range of socio-ecological contexts may provide new, sustainable and equitable solutions to smallholder food and nutrition security.

KEYWORDS
ecosystem service, food security, Nepal, network, nutrition, pollination, smallholder farm, socio-ecological system

1 | INTRODUCTION

Smallholder farms are those operated by individual households, largely with their own labour and generally <2 ha in area (FAO, 2018). Smallholder farming supports over two billion people—83% of the world's agricultural population—making it the most common type of farming world-wide (Lowder et al., 2016; Steward et al., 2014). Almost all these farms are located in low- and middle-income countries and the families that run them are some of the poorest and most food insecure people on Earth; half of the world's undernourished people and the majority of people in absolute poverty live on smallholder farms (Wiggins & Keats, 2013).

Improving the food and nutritional security of smallholder farmers in a way that minimises negative environmental impacts is a core commitment of the United Nations Sustainable Development Goals (United Nations, 2015). Meeting this target will require interdisciplinary solutions, including an understanding of global food systems, local agroecosystems, human nutrition and socio-economic factors such as wealth, education, gender and ethnicity that determine farmers' access to knowledge, land, resources and markets. A wide range of socio-ecological systems approaches have been proposed to understand and manage agri-food systems (Partelow, 2018). These range from large-scale studies on topics such as food sovereignty, global sustainability and land use (e.g. Bengochea Paz et al., 2020; Oteros-Rozas et al., 2019), to smaller scale landscape-level studies which consider individual actors (e.g. farmers) and ecosystem components (e.g. species; e.g. Bretagnolle et al., 2018; Wittman et al., 2017). The former are more relevant to high-level policymakers and land-use planners, while the latter may be more useful to practitioners such as conservation and development organisations, outreach workers and even individual farmers. However, a common challenge in all of these frameworks is linking the biophysical components of the system (e.g. climate, ecosystems, species and crops) to the social components (e.g. individual farmers or institutions; Ostrom, 2009). One approach is to use the ecosystem services framework and link people to nature via the value they derive from ecosystem processes (Bohan, 2016). Valuing these services remains a challenge however as they are either vaguely defined (e.g. farmers benefit from the water regulation provided by native habitats), or quantified in a narrow economic sense (e.g. pollination is worth $x to crop production). Neither of these approaches provide useful metrics for a farmer trying to feed their family. To be relevant to smallholder farmers, a more tangible and mechanistic understanding of the ways in which the social and ecological components of a farm influence their food and nutrition security is required.

In this paper, we demonstrate how the application of the general network concept (Newman, 2003) to smallholder farms can provide a mechanistic, interdisciplinary perspective, helping us to quantify, visualise and model the varied contributions of social and ecological factors to smallholder food security. Networks are used in a wide range of disciplines to describe a complex system of interacting components (nodes) joined together by links or 'edges' and have been used extensively in the study of socio-ecological systems (e.g. Bodin & Tengö, 2012; Bohan, 2016; Dee et al., 2017). They provide a useful tool for studying the complex dynamics and emergent properties that arise from multiple interacting components, such as the wild species, crops, livestock and people on a smallholder farm.

In what follows, we first describe the many challenges facing smallholder farmers and the role that sustainable farming practices could play in overcoming these to improve food and nutrition security. We then outline a general, network-based framework which explores: (a) how an agroecological network approach can be used to identify and manage ecosystem services on smallholder farms; (b) how we can quantify these ecosystem services in a way that is relevant to the food and nutrition security of smallholder farmers; and (c) how a social network approach could be used to understand the interactions between farmers, and facilitate knowledge sharing and equitable, cooperative management of ecosystem services. We demonstrate the application of this framework through a case study in the remote Himalayan district of Jumla, Nepal where the food and nutrition security of many households is highly reliant on subsistence farming and the ecosystem services that support it (Appendix S1).

2 | THE CHALLENGES FACED BY SMALLHOLDER FARMERS

Although access to markets and global food systems is increasing across most of the world, many smallholders are still highly reliant on their own agricultural produce for their food and nutrition security (FAO, 2018). With insecure land tenure and limited access to markets and credit services, their ability to invest and adapt to novel stressors is often limited (Land Inequality Initiative, 2020). Undernutrition and micronutrient deficiencies are common in smallholder farming households and the physiological, social and economic impacts of these are serious and lasting (IFAD, 2013). The improvement in smallholder agriculture through raising productivity, increasing production diversity and closing yield gaps (the difference between a crop's actual yield and its maximum potential yield) is therefore crucial for improving global food and nutrition security and public health (Carletto et al., 2015; FAO, IFAD, UNICEF, WFP and WHO, 2021; Kadiyala et al., 2014). However, intensification through conventional industrial means, such as increasing chemical or technological inputs, may not be environmentally sustainable or affordable for resource-constrained farmers.

With less access to chemical inputs, advanced technologies and global markets, smallholder farmers are more dependent on the services provided by local ecosystems such as pollination, biological pest control and nutrient cycling. They also derive an important component of their nutritional intake from wild-foraged foods (Rasolofoson et al., 2018). Thus, in contrast to much of the world's globalised population (e.g. Silva et al., 2021), smallholders remain closely linked to, and highly dependent upon, their local ecosystem (Figure 1). This makes them particularly vulnerable to ecological degradation and climate change, both of which can reduce the provisioning of ecosystem services, thereby reducing agricultural productivity and their food and nutrition security (FAO, IFAD, UNICEF, WFP and WHO, 2021; Harvey et al., 2014). Thus, as farmers in higher income countries are able to afford the advanced technologies (e.g. climate-optimised seeds, sophisticated agrochemicals, soil monitoring and precision application of inputs) necessary to adapt or cope with growing environmental constraints on agriculture; poorer smallholder farmers are not similarly equipped. Instead, without the capability to confront the effects of environmental pressures, smallholder farmers bear a disproportionately large share of the

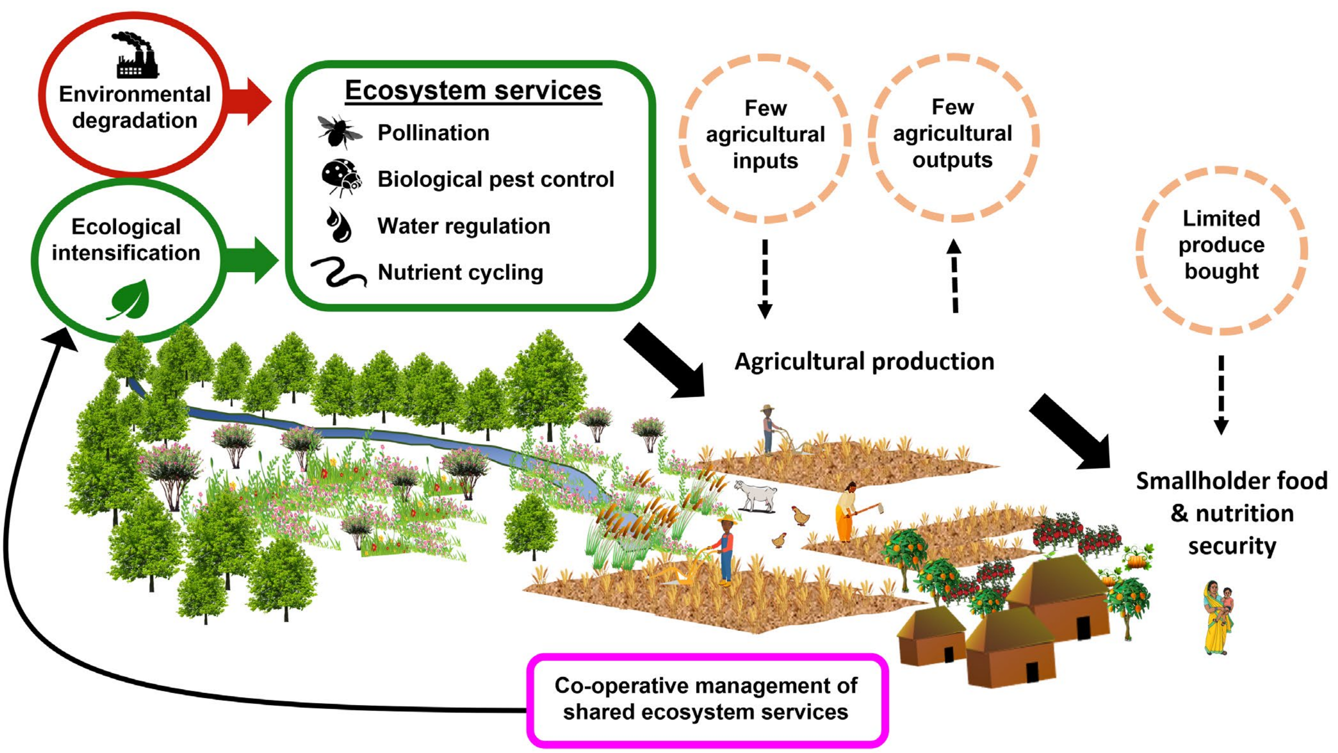

FIGURE 1 Smallholder farming landscape showing the role of ecosystem services in supporting agricultural production and food and nutrition security. Limited market access means there are fewer purchased inputs or sales (dashed arrows) than in commercial agriculture. Thus, reliance on ecosystem services and local agricultural production is high. Environmental degradation threatens the provisioning of ecosystem services (red arrow) and smallholder food security, but farmers can also manage the agroecosystem to enhance ecosystem services (green arrow) and increase their food and nutrition security

environmental, economic and health costs from the degradation of the global natural environment (Myers et al., 2013).

3 | SUSTAINABLE SOLUTIONS FOR SMALLHOLDER FARMERS

Fortunately, some of the environmental degradation threatening smallholders can be reversed, at least on a local level, by managing the ecosystem to increase its provisioning of ecosystem services. This is known as 'ecological intensification', a knowledge-intensive process which improves agricultural system performance, efficiency and farmers' livelihoods through optimal management of nature's ecological functions and biodiversity (Bommarco et al., 2013; FAO, 2011). It may also help farmers adapt to climate change—a process known as ecosystem-based adaptation (Vignola et al., 2015). Ecological intensification is becoming increasingly popular across the world (Pretty, 2018). It is particularly effective in smallholder farming systems due to the small scale at which management occurs, the extensive local knowledge of many smallholder farmers and because the principal input is information and experience, rather than material resources (Garibaldi et al., 2016). However, there are several challenges in applying this approach to smallholder farms. First, ecological intensification requires an understanding of the organisms providing ecosystem services and how they interact with crops, livestock and each other. This information on the ecology of smallholder farming systems is grossly under-represented in the literature (Steward et al., 2014). Although ecological knowledge among smallholder farmers is often extensive (e.g. Smith et al., 2017), it is seldom formalised in a way that allows coordinated management in the face of novel environmental stressors such as climate change. Second, measuring the value of ecosystem services on a smallholder farm is more difficult than in industrialised agriculture. Unlike industrialised agriculture, the goal in smallholder farming is not always to maximise profit, but instead to ensure household food and nutrition security by maintaining access to a diverse and stable supply of energy and nutrients through the year. Finally, in contrast to large, commercial farms, smallholder farms are clustered tightly together with complex social dynamics within and among farming households that affect agricultural productivity (Agarwal & Bina, 1994; Rocheleau & Edmunds, 1997; Udry, 1996). These clusters of neighbouring farms (and plots within farms) rely upon shared ecosystem services which must be collectively managed, requiring equitable social cooperation.

In the following sections, we explore solutions to these three challenges (lack of predictive ecological knowledge, difficulty in valuing ecosystem services and the need for social cooperation), proposing a network approach to understand, visualise and model the complex interactions among wild species, crops and people on smallholder farms. Importantly, we do not imply that the application of this framework would depend upon a detailed understanding of all interacting components on *each* farm. What we suggest is clear identification of the different types of interactions occurring on a smallholder farm (e.g. crop–pollinator, crop–farmer and farmer–farmer), and a better understanding of how different types of networks (e.g. social and ecological) are linked on a farm (Figure 2). Characterising these socio-ecological networks will provide a new understanding of the functioning of smallholder farms and how management solutions can affect their functioning to improve ecosystem services such as pollination and pest management. Previous studies at the social–agricultural interface have, for example, proposed the use of networks to manage and assess ecosystem services (Bohan, 2016; Dee et al., 2017) and developed socio-ecological frameworks to understand the role of social factors in influencing ecosystem service delivery (e.g. Rüdisser et al., 2020). Our study builds upon this work by explicitly linking ecosystem services to the food and nutrition security of smallholder farmers and demonstrating its application through a case study in rural Nepal.

4 | USING AN AGROECOLOGICAL NETWORK TO IDENTIFY AND MANAGE ECOSYSTEM SERVICES

A high proportion of the crops grown on smallholder farms benefit from the ecosystem services provided by wild species (Steward et al., 2014). For example, the yields of many nutritionally important fruit, vegetable and pulse crops are highly dependent on animal pollinators (Eilers et al., 2011; Klein et al., 2007). Pollinators may also increase the yield and quality of various cash crops such as coffee, cocoa, cotton and apples which provide income and livelihoods for some smallholder farmers (Stein et al., 2017). Meanwhile, various species that predate, parasitise or deter crop pests (natural pest enemies) such as parasitoid wasps, ladybirds and various plants are known to increase crop yields and reduce the need for pesticides on smallholder farms (Pretty & Bharucha, 2015). Smallholder farms may also suffer 'ecosystem disservices' such as crop herbivory or weeds which compete with crops for water and nutrients, lowering yields (Zhang et al., 2007).

The species providing these ecosystem services and disservices do not exist in isolation; they are dependent upon a whole suite of other species in the ecosystem. For example, crop pollinators are highly dependent on the nectar and pollen from wild flowering plants to sustain them throughout the year, especially outside crop flowering time (Timberlake et al., 2019). Managing a farm to increase ecosystem service provisioning requires farmers to understand and balance both these direct (e.g. crop–pollinator) and indirect (e.g. crop–pollinator–wild plant) associations with the crop, though these may not always be obvious. For example, a weed may compete with a crop plant for nutrients but also provide resources for pollinators or predators of crop pests (Figure 3). If the benefits from increased pollination or pest control outweigh the cost of nutrient loss, then it is beneficial to farmers to preserve the weed. A network approach can capture both direct and indirect contributions to ecosystem service provisioning (Dee et al., 2017), enabling us to make more effective management decisions. While early work on identifying net

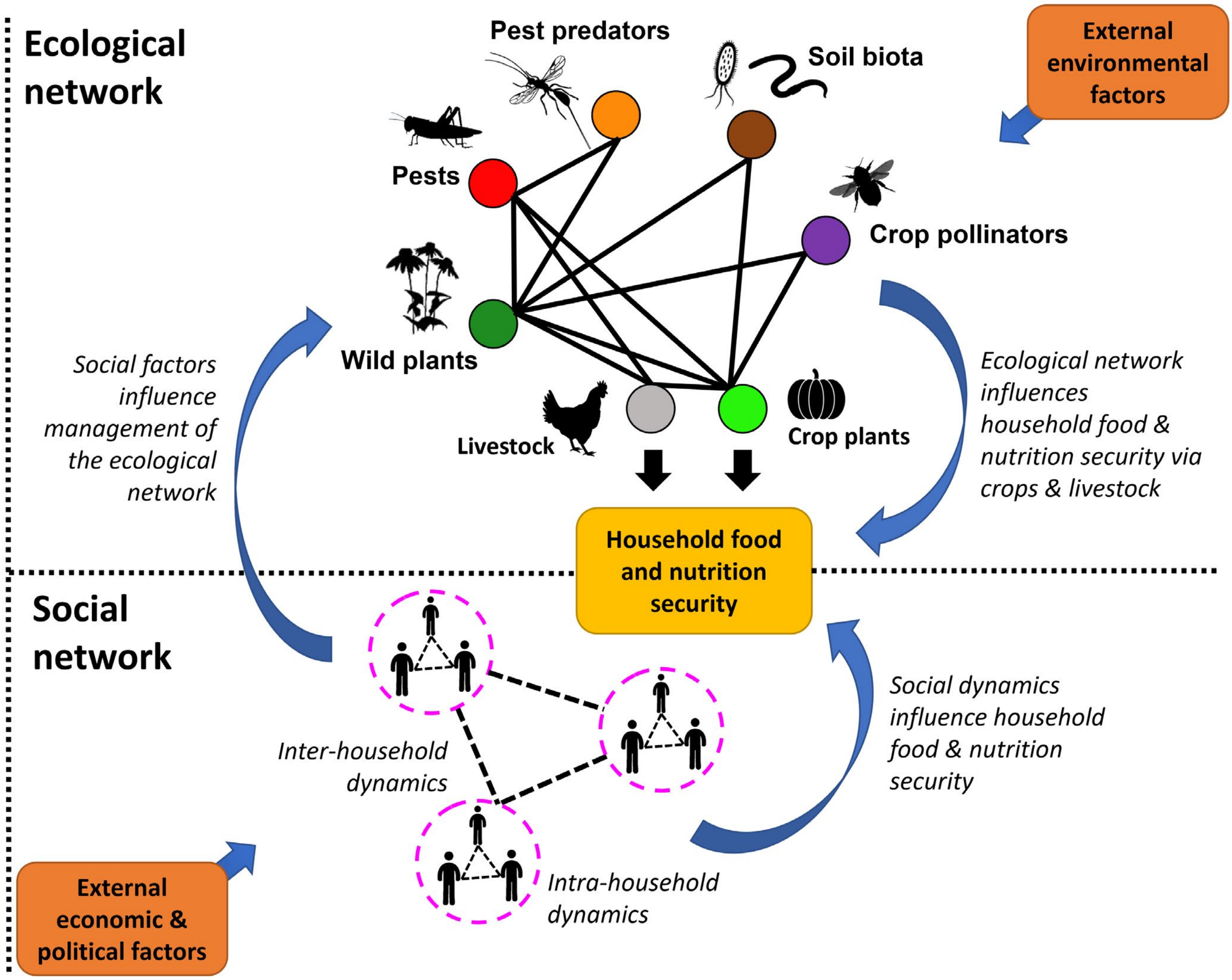

FIGURE 2 Schematic diagram of a smallholder farming system, represented as a socio-ecological network. Interactions between the ecological components of the network (full black lines) give rise to ecosystem services (e.g. pollination) and disservices (e.g. crop herbivory) which influence crop and livestock production and thus household nutrition. Social interactions between and among households (dashed black lines) are important in influencing the spread of knowledge and levels of cooperation and equity in the management of shared ecological resources. External environmental factors such as climate change and pollution can impact the ecological network while external socio-economic and political factors such as market access, education and food prices can influence social dynamics; both may in turn impact food security

effects (including those of direct and indirect interactions) has focused on networks with a single type of interaction, we propose that weighing up the true costs and benefits of different wild organisms will be most useful if different types of interactions (e.g. competition, herbivory and pollination) are considered collectively (Figure 3), as in Windsor et al. (2021).

Analysing the structure of ecological networks provides a powerful way to understand the complexity of ecosystems, and a modelling framework to make predictions about how changes in species composition and/or interactions may influence ecosystem functioning and stability (Tylianakis et al., 2010). For example, ecological networks can be used to identify species with particularly strong effects on the rest of the network, which could make good targets for management interventions (Cagua et al., 2019).

A network perspective can also inform us about the vulnerability of an ecosystem service to various stressors such as species loss, ecological degradation, invasion or environmental change, and identify management actions to mitigate the effects of these drivers on the ecosystem service (e.g. Keyes et al., 2021; Memmott et al., 2010). Depending on network structure, the effects of stressors can be amplified or attenuated within the network, with important implications for ecosystem service provisioning (Morrison et al., 2020; Tylianakis et al., 2010). For example, the loss of important nodes in a network can result in secondary species losses (Solé & Montoya, 2001). An ecosystem service is particularly vulnerable when a single node is providing the service with no redundancy (Petchey et al., 2008), or when a node providing the ecosystem service is dependent on a small number of resources, for example a pollinator which is reliant

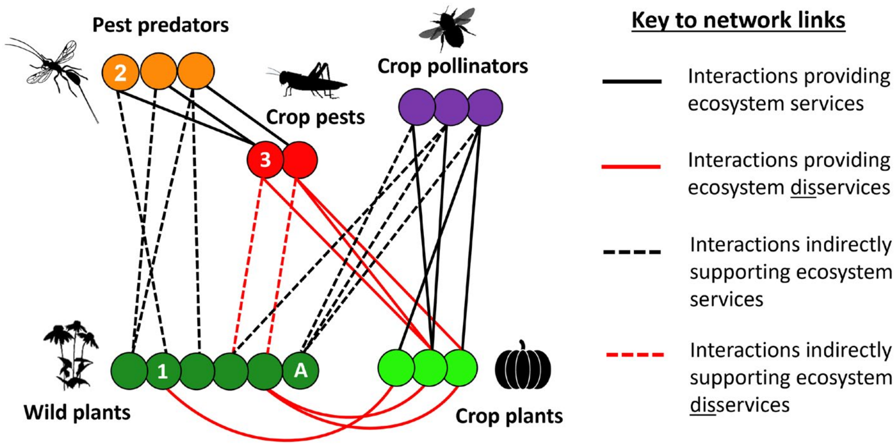

FIGURE 3 A network-based depiction of the ecological interactions giving rise to ecosystem services and disservices that influence crop production on a smallholder farm. Ecological interactions which directly result in an ecosystem service or disservice are shown as full lines (black and red respectively) while interactions which indirectly contribute to the provisioning of an ecosystem service or disservice are shown as dashed lines. This demonstrates the complex and often unexpected effects that wild plant and animal species may have on crop production. For example, plant species 1 (a weed) competes with crop plants for nutrients (direct negative effect on crop production) but also supports populations of pest predator 2 which reduces populations of pest species 3 and therefore indirectly supports crop production. Completely suppressing this weed may therefore not be the most effective management strategy. In contrast, plant species A has no direct interaction with crop plants but nevertheless supports crop production via its beneficial effect on crop pollinators

on just a few key plant species for food. In contrast, higher redundancy lowers the vulnerability of service provision.

5 | QUANTIFYING THE VALUE OF ECOSYSTEM SERVICES TO SMALLHOLDERS

To manage the provisioning of an ecosystem service effectively, it is important to be able to quantify it in a way that reflects its true value to the beneficiary (Olander et al., 2018). In industrialised agriculture, ecosystem services might be valued as the increase in total yield or economic value generated by the service. However, this may not be the most appropriate metric for a smallholder farm, where most produce is not sold, and the primary aim is to feed the family. In these systems, it is the nutritional value of the food produced, the energetic and financial costs of labour and other inputs, and the stability of food supply through the year which are most important (Jones, 2017; Kadiyala et al., 2014). Using a network approach, it is possible to quantify the nutritional rather than the monetary output of the farm by linking crops (or livestock) with the nutrients they provide (Box 1).

Although humans exert considerable influence over the ecosystems in which they live, it is difficult to incorporate them as functional components of an ecological network. Nodes in an ecological network are often connected based on their feeding (trophic) relationships with one another (i.e. who eats who), but the food supply of most humans is now so globalised that their trophic interactions with locally occurring species are negligible. Indeed, the few food webs which do include humans tend to refer to pre-historic hunter-gatherers (e.g. Dunne et al., 2016) rather than industrialised populations. However, given that many smallholder farmers obtain much of their nutritional intake directly from their farm (Figure 1), trophic links between farmers and their crops and livestock can easily be added to the set of networks connecting crops, livestock and wild species (Figure 2). As we are more interested in the nutritional value of these trophic interactions, rather than their occurrence per se, it may be more valuable to frame these links as connections between crops (or livestock) and essential nutrients, which the humans consume. If links are weighted by the sum of nutrients provided by each crop (from food composition tables), such a framework highlights the origin of each nutrient in the diet and provides an overview of how different crops complement each other to nourish smallholder farmers (Box 1).

If data are also available on the dietary intake of smallholder families (e.g. from dietary recall surveys), the intake of different nutrients can be calculated and compared with estimated nutritional requirements to determine their probability of dietary adequacy at the population level (Institute of Medicine (US), 2000). Given the known health implications of specific dietary inadequacies (Murray et al., 2020), it is possible to go one step further and predict the human health consequences of losing an ecosystem service. For example, loss of pollination services is predicted to increase rates of non-communicable and nutrition-related diseases as a result of reduced intake of pollinator-dependent, micronutrient-rich healthy foods such as fruits, vegetables and nuts (Smith et al., 2015). Alternatively, the human health benefits of restoring an ecosystem service could be modelled using this type of network approach. Thus, adding crop-nutrient links to a network which maps the ecosystem services and disservices that affect crops means we can visualise how wild species such as

BOX 1 Case study from Jumla District, Nepal

Jumla is a remote mountain district (altitude 900–4,000 m) in the Karnali province of western Nepal (Figure 4). As a result of its social, economic and physical isolation, the region has high rates of food insecurity, low household income and a heavy reliance on subsistence agriculture (Government of Nepal & United Nations Children's Fund, 2019). A wide range of crops are grown, including many pollinator-dependent species such as apples, beans, pumpkins and buckwheat which comprise an important part of people's diets. Farming households are clustered into small villages, adjacent to closely spaced fields meaning ecosystem services are shared between multiple households and must be managed collectively. Collaborative farming structures are common, including reciprocal labour sharing, farmer cooperatives and shared use of natural resources such as water and grazing land. Pollination is another shared natural resource that could be collectively managed by farmers to improve agricultural productivity and food and nutrition security. However, with limited awareness by farmers of the importance of pollination services, and very little information on the species involved and how they interact with important crops and wild plants, it is not clear how this service would be most effectively managed.

Using a plant–pollinator dataset from seven farms in Jumla and a household food consumption dataset from rural Nepal (Harris-Fry et al., 2018), in combination with a food composition table (Harris-Fry et al., 2016), we demonstrate how a network approach can be used to link wild plants, pollinators and crops, with human-consumed micronutrients (Figure 5). This allows us to identify the crops providing key micronutrients to smallholder farmers, the insects that visit these crops and the wild plant species that support these pollinators. Given that the plant–pollinator network only includes a subset of crops grown in this region (ones that were flowering at the time of survey), and the food consumption data are disaggregated at the food group level (e.g. green leafy vegetables, pulses etc.) rather than the individual crop level, this network should not be seen as a full representation of reality. Instead, it serves to demonstrate how—with a more detailed dataset—this approach could be applied to quantify the nutritional value of an ecosystem service and identify the wild species involved in its provision (see Appendix S1 for more details).

plants, pollinators or pests influence the health and nutrition of the farming household. We can also identify nutrients that may be particularly vulnerable to the loss or disruption of an ecosystem service, for example vitamin A and folate which are derived to a larger extent from pollinator-dependent crops (Eilers et al., 2011; Smith et al., 2015).

A network approach allows us to identify management actions which are likely to increase people's supply and adequacy of specific nutrients or make the supply more resilient to disruption. For example, we could identify groups of wild plants which support many crop pollinators or pest predators while hosting few pest species and vice versa. While rural farmers are likely to possess much of this knowledge already, the ability to predict the effect of specific management scenarios on household nutrition and adapt management practices in the face of novel environmental stressors, such as climate change, may still be useful. Instead of taking a general 'rule of thumb' approach to ecological intensification, this approach can also be used to identify more targeted, labour-saving and site-specific management interventions. These may help reduce the burden of drudgery that is often associated with agroecological development projects (Halbrendt et al., 2014; Jewitt, 2000). Moreover, the ability to draw mechanistic, visual links between wild species, crops and human-consumed nutrients provides a powerful tool for informing and promoting agri-environmental policy and development work, as well as serving as a useful education tool (Pocock et al., 2016).

6 | A SOCIAL NETWORK APPROACH FOR FACILITATING COOPERATIVE MANAGEMENT

The small size and close spatial clustering of smallholder farms means that ecosystem services are shared between multiple farms and cannot be managed by a single farming household in isolation (Figure 1). The agricultural productivity and food and nutrition security of each individual farming household is therefore influenced by the management practices of neighbouring farmers. For example, excessive pesticide application by one farmer may reduce populations of natural pest enemies and pollinators on neighbouring farms, diminishing their ecosystem services. Cooperation between smallholder farmers is therefore crucial but is dependent upon a range of complex social factors operating within and between households (Udry, 1996). Factors such as land ownership status, wealth, education, gender, class and ethnicity may all influence a farmer's access to knowledge and resources, their power to make decisions (Holmelin, 2019) and motivation to invest in, or change agroecological practices (Place, 2009). For example, in many patriarchal rural communities, women face difficulties in obtaining, articulating and acting upon their agroecological knowledge (Jewitt, 2000). Therefore, central to the success of any sustainable farming initiative is an understanding of the local social context and existing power structures that influence farmer decisions, knowledge sharing and cooperation.

Cooperative farming systems are common and highly developed among smallholder farming communities. For instance, many smallholders engage in reciprocal labour sharing arrangements, cooperative irrigation and livestock grazing agreements, and may belong to groups such as community forest user groups or farmer cooperatives

FIGURE 4 Map and pictures of the case study site in Jumla, Nepal

(Bizikova et al., 2020). These existing social structures and connections between smallholders can be thought of as part of their 'social capital'—a term used to describe the social bonds, trust and reciprocity between and among actors and institutions (Coleman, 1988). High social capital facilitates cooperation by lowering the costs of working together, accelerating the spread of new ideas and reducing the chances of individuals engaging in 'selfish' actions with negative outcomes, such as resource degradation (Pretty & Smith, 2004). For smallholder farmers, it is an important determinant of their ability to learn, apply new sustainable farming practices and adapt to global pressures such as climate change and ecological degradation (Pretty et al., 2020). For example, increased social connectedness through farmer cooperatives, household communication networks and technology learning groups have been shown to enhance the adoption of new technologies, increase household income and improve environmental outcomes for smallholder farmers (Bizikova et al., 2020; Ma & Abdulai, 2016; Wu & Pretty, 2004).

Like ecological networks, social networks provide an effective tool for analysing and visualising complex interactions and have helped explain a wide range of phenomena in the social sciences (Borgatti et al., 2009). For example, the structure of a social network can be used to evaluate social capital and identify 'structural holes' which may be limiting the spread of new ideas and information to certain groups (Burt, 2000). In the context of smallholder farming, this network approach could be used to evaluate the interactions among different groups of farmers, extension workers and other relevant actors (Figure 6). It can also contribute to identifying key channels for spreading knowledge, bridging social gaps and reaching isolated or disenfranchised groups (e.g. Kadiyala et al., 2016). This will be key to achieving inclusive, equitable and sustainable improvements in health and welfare outcomes.

The most comprehensive understanding of smallholder farms is likely to come from examining the social and ecological dimensions together, considering them as a single interconnected and interdependent socio-ecological system (Figure 2). Multilayer networks are a new frontier in the study of socio-ecological systems, providing a valuable tool for merging networks consisting of multiple different interaction types (Bohan, 2016; Hutchinson et al., 2018; Pilosof et al., 2017). Understanding the structure of these socio-ecological networks allows us to measure and model their resilience to stressors, such as environmental or social change, and identify features that provide important adaptive capacity, for example, 'closed, socio-ecological triangles' which arise when two actors collaborate in the management of a shared resource (Barnes et al., 2017). It may also allow us to identify keystone species (Cagua et al., 2019) or keystone actors who are in a position to influence outcomes in socio-ecological systems (Österblom et al., 2015). Our framework offers a new way of applying the multi-layer network approach, using human nutrient consumption as a 'cross-level currency' to link the social and ecological networks. Studying the combined contributions of social and ecological factors to human nutrition is likely to reveal more sustainable and equitable solutions to smallholder food and nutrition security, in line with the United Nations Sustainable Development Goals (United Nations, 2015).

7 | LIMITATIONS

Our study has two main limitations. First, though we have presented smallholder farmers as highly dependent on their own agricultural production for their food and nutrition security, we acknowledge that total subsistence agriculture is now rare and most smallholders (including those in our Nepali field sites) buy and sell at least a small proportion of what they eat and grow. Nevertheless, our framework remains useful as it can easily be adapted to include the contribution of ecosystem services to income rather than nutrition and, likewise, the contribution of purchased rather than home-grown foods to nutrient intake. Second, while we were able to demonstrate a practical application of the ecological component of this framework (linking the ecological network to human-consumed nutrients), the social component remains purely conceptual for now, though could feasibly be incorporated if the relevant data were available.

8 | CONCLUSION

Smallholder farms are diverse and complex systems consisting of a range of interacting social, ecological and environmental

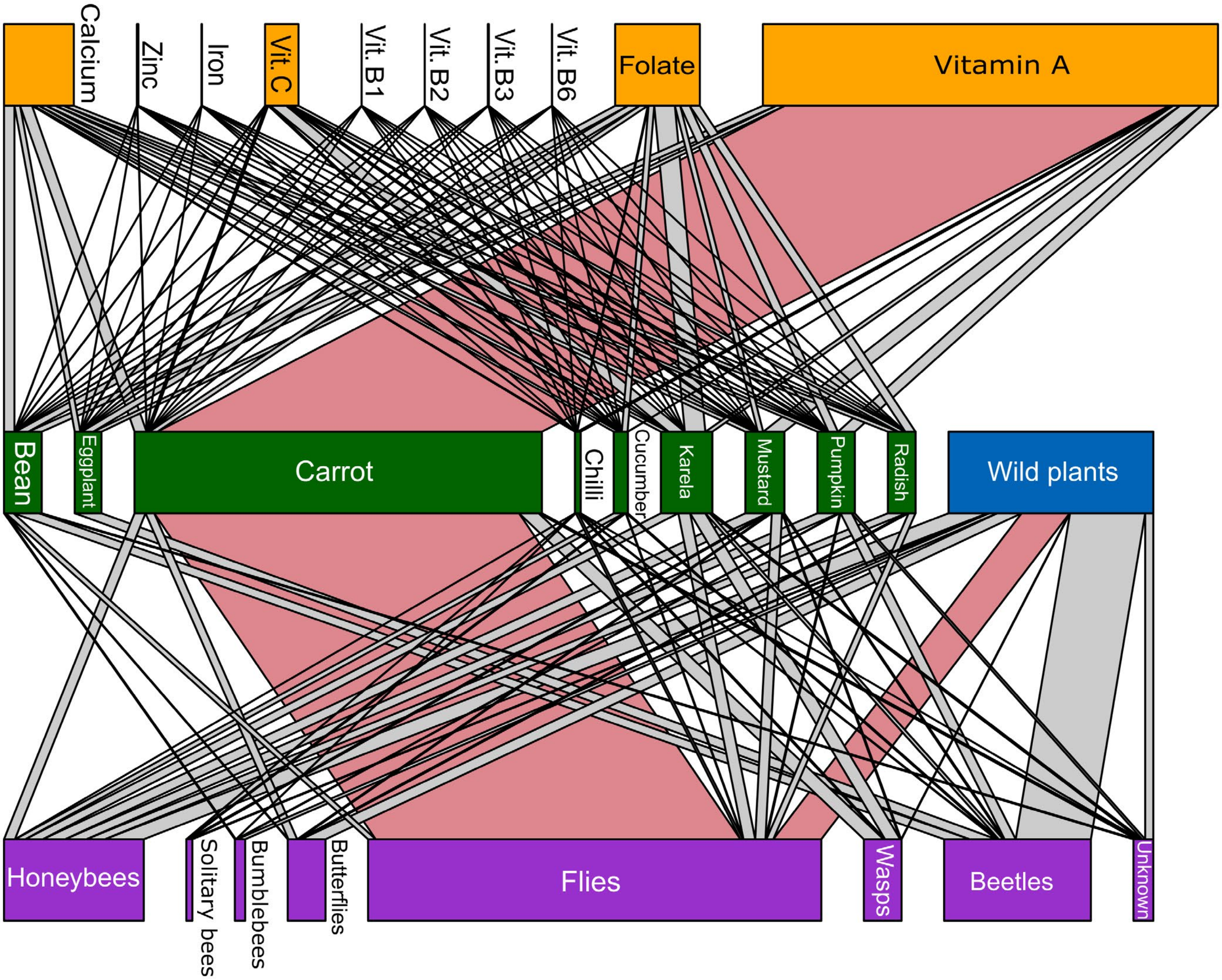

FIGURE 5 Plant–pollinator–nutrient network showing which pollinator groups (purple boxes) are visiting the flowers of common Jumla crops (green boxes) and wild plants (blue box) and how these crops contribute to the supply of key dietary micronutrients (yellow boxes). The width of the yellow boxes represents the mean quantity of micronutrient consumed per day; the green box width represents the contribution of each crop to total nutrient supply and the purple box width is the number of visitations by each pollinator group. Highlighted in pink is an example of one key pathway in the network: carrots provide smallholders with an important source of dietary vitamin A; carrot flowers are almost exclusively visited by flies which ensure the production of seeds for cultivation the following year; flies also rely upon resources from certain wild plant species which could be targets of intervention to support pollination services and thus indirectly support the production of vitamin A

components. The precise way in which these different components interact can have an important influence on agricultural productivity, the provision of ecosystem services, levels of co-operation between people and the resilience of the whole system to stressors such as climate change. We have shown how a network approach can help us to understand, visualise and model these complex interactions and presented a conceptual framework for linking the social and ecological components of a farm via the contribution of ecosystem services to smallholder food and nutrition security. Applying this holistic, network-based approach to the study of smallholder farms, building upon existing local knowledge and social structures, could help provide more sustainable, adaptable and equitable solutions to smallholder food and nutrition security. This will become increasingly important as smallholders adapt to novel pressures such as climate change and globalisation.

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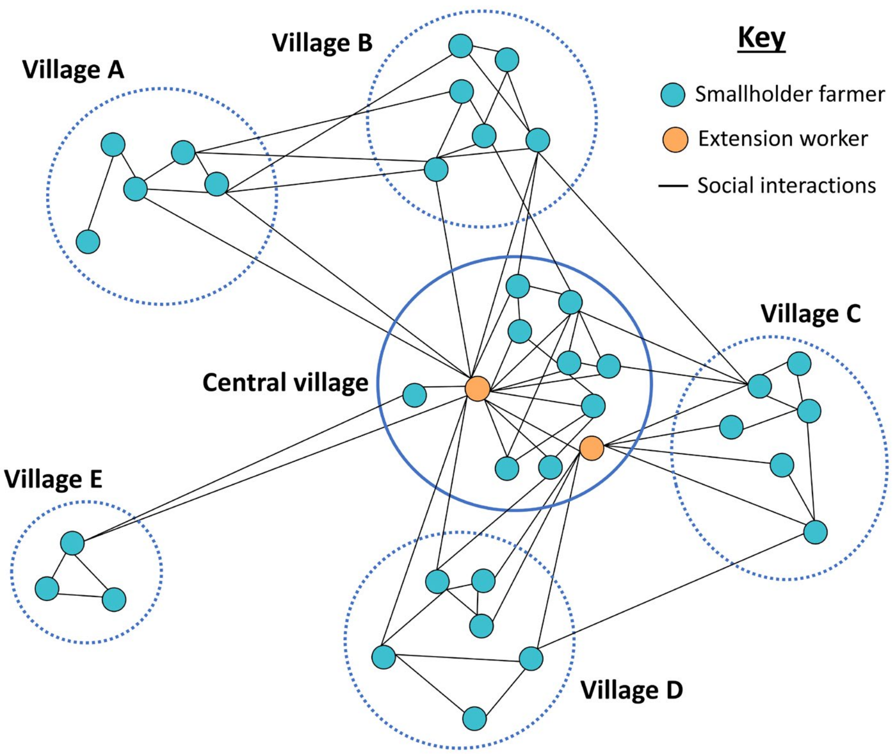

FIGURE 6 Schematic diagram of a social network showing the interactions among individual farmers (blue) and agricultural extension workers (orange). Farms are clustered around five satellite villages (blue dotted rings) and one central village (full blue ring), corresponding to the scale at which ecosystem services need to be collectively managed. Extension workers increase the social capital of the system by acting as 'brokers' or 'bridges' between villages, closing 'structural holes' by spreading key information and resources between farmers. The structure of the network may be used to identify isolated individuals or modules (e.g. village E), as well as keystone actors with a high influence on the network (e.g. extension workers or village leaders) and important social structures which enhance social capital and the spread of knowledge (e.g. farmer collectives or women's groups)

CONFLICT OF INTEREST

The authors have no conflict of interest to declare that are relevant to the content of this article.

AUTHORS' CONTRIBUTIONS

T.P.T., J.M. and A.R.C. conceived the ideas; T.P.T. and A.R.C. analysed the data; T.P.T. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The small pilot dataset used in this study is available in Table S1.

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