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Understanding the pathways from biodiversity to agro-ecological outcomes: A new, interactive approach

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ABSTRACT

The adoption of agro-ecological practices in agricultural systems worldwide can contribute to increased food production without compromising future food security, especially under the current biodiversity loss and climate change scenarios. Despite the increase in publications on agro-ecological research and practices during the last 35 years, a weak link between that knowledge and changed farmer practices has led to few examples of agro-ecological protocols and effective delivery systems to agriculturalists. In an attempt to reduce this gap, we synthesised the main concepts related to biodiversity and its functions by creating a web-based interactive spiral (www.biodiversityfunction.com). This tool explains and describes a pathway for achieving agro-ecological outcomes, starting from the basic principle of biodiversity and its functions to enhanced biodiversity on farms. Within this pathway, 11 key steps are identified and sequentially presented on a web platform through which key players (farmers, farmer networks, policy makers, scientists and other stakeholders) can navigate and learn. Because in many areas of the world the necessary knowledge needed for achieving the adoption of particular agro-ecological techniques is not available, the spiral approach can provide the necessary conceptual steps needed for obtaining and understanding such knowledge by navigating through the interactive pathway. This novel approach aims to improve our understanding of the sequence from the concept of biodiversity to harnessing its power to improve prospects for 'sustainable intensification' of agricultural systems worldwide.

1. Introduction

Agriculture has been called the largest ecological experiment on earth (Porter et al., 2009; Sandhu et al., 2015). Recent estimates suggest that the world will need 25–70 % more food by 2050 (Hunter et al., 2017) but available suitable land area is unlikely to increase by any significant amount (Godfray et al., 2010; Sandhu et al., 2015). Better education and skills training in developing countries can play an important role in improving yields *in situ* (Seufert et al., 2012), alleviating to some extent the need for more land, but such training must not neglect the socio-economic and environmental problems that have arisen after 'The Green Revolution' (Gaud, 1968; Tilman, 1999). Currently, the possibly oxymoronic idea of 'Sustainable Intensification' (SI) is being advocated (Godfray et al., 2010; Pywell et al., 2015; Pretty et al., 2018). SI can be defined as 'a process or system where agricultural yields are increased without adverse environmental impact and

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without the conversion of additional agricultural land' (Pretty and Bharucha, 2014; Pretty et al., 2018). This needs to be given practical meaning through appropriate research, policy and farmer-training approaches (Holt-Giménez, 2008; Altieri and Toledo, 2011; Khan et al., 2014; Pretty and Bharucha, 2014; Murage et al., 2015; Wyckhuys et al., 2018; Pretty et al., 2018; Shields et al., 2019; González-Chang et al., 2019) using locally-adapted, environmentally-sound technologies. Deploying agro-ecological principles and practices can optimize interactions between plants, animals, humans and the environment to achieve sustainable and fair agricultural and food systems in terms of yield increases (Pywell et al., 2015; Kleijn et al., 2019) and food distribution (FAO, 2017). Unfortunately, a substantial proportion of produced food is wasted and this loss has been recently estimated to be 44 % of harvested crop dry matter before humans can eat it (Alexander et al., 2017), which is far from a fair food system. Therefore, a better food distribution system and access to it, a reduction in food waste, alongside in-farm yield increases are crucial to fulfil humankind's future food needs.

In this context, a global increase in agricultural outputs since the 1960s occurred through 'The Green Revolution'; however, it resulted in high environmental and social costs. Such a simplified conventional agricultural system has continually, but only linearly, increased crop yields at high environmental costs (Tilman, 1999). However, this linear yield response to increasing water and agro-chemical inputs has not persisted (Ray et al., 2012; Roser and Ritchie, 2018). Compounding this, conventional agriculture has delivered major negative externalities which impact severely on functional biodiversity (Gurr et al., 2017), human health (Barański et al., 2014) and the environment (Steffen et al., 2015; Bernhardt et al., 2017). These impacts, derived largely from land-use intensification, have led to over-exploitation of natural resources and environmental degradation, so this activity is not an ethical option for the future security of food and humans worldwide. It is generally agreed that there is an urgent need to enhance social, human and natural capital to boost ecosystem services (ES) in global food systems (European Commission, 2012; IPES-Food, 2016). In this sense, ecologists have contended that biodiversity can provide the ecosystem goods, functions and services needed to effect change and avoid further reliance on synthetic inputs and degradation of the natural resource base (Simpson et al., 2011; Khan et al., 2014; Wezel et al., 2014; Gurr et al., 2016; Reganold and Wachter, 2016; Garibaldi et al., 2017; Gurr et al., 2017; Lichtenberg et al., 2017; Dainese et al., 2019), while also increasing human well-being (Roberts et al., 2015).

Different terms have been proposed to describe, study and promote ES in sustainable agricultural systems worldwide, such as agroecology, organic agriculture, regenerative agriculture, ecological intensification and sustainable intensification, among many others. Interestingly, all of them share the principle of enhancing on-farm functional biodiversity to reduce the reliance on synthetic inputs (Wezel et al., 2014; Altieri et al., 2015; Reganold and Wachter, 2016; Dumont et al., 2018; LaCanne and Lundgren, 2018; Pretty et al., 2018; Kleijn et al., 2019). These approaches are intended to lead to a consensus of how much biodiversity, where it is located and what type, among other key questions that are needed to effect enhanced ES. In parallel, many national and international agencies have recognised the high importance of improving ES in global agriculture. These include the Food and Agriculture Organisation (FAO, http://www.fao.org/ecosystem-services-biodiversity/en/) (Accessed November 25, 2019), the United Nations Environment Programme (UNEP, http://web.unep.org/evaluation/keywords/ecosystem-services) (Accessed November 25, 2019) and the United Nations Development Programme (UNDP, http://www.undp.org/content/undp/en/home/ourwork/global-policy-centres/sustainable_landmanagement/bes_net.html) (Accessed November 25, 2019), among many others.

Recently, the European Directorate has determined that ES will play a major role in future EU agriculture policy and has fully committed itself to enhancing ES as part of its Biodiversity Strategy 2020 (European Commission, 2012). Other recent policy publications include the work of De Schutter (De Schutter and Vanloqueren, 2011) who suggest strongly that if biodiversity-based, agro-ecological protocols and principles were embedded in global food production, the latter could double in one decade. However, future global population growth will come mostly from developing countries (Godfray et al., 2010; Reganold and Wachter, 2016) and this represents particular food security and environmental challenges.

There is a major global impediment, however, to developing these ideas and policies into real outcomes in the global process of food production. It is true that there is a plethora of agricultural enhancement schemes (AES) worldwide (Kleijn and Sutherland, 2003; Batáry et al., 2015; Hammers et al., 2016) but how effective these are has often been questioned (Pe'er et al., 2019). They may generate ecosystem disservices (EDS (Zhang et al., 2007; Gillespie and Wratten, 2017)), if applied in agricultural systems or in contexts that were not initially included in the development of ES-enhancing protocols (ie Tscharntke et al., 2016; Karp et al., 2018). A lack of understanding of how these schemes interact with the local social and ecological conditions can reduce or remove their previously-designed, agro-ecological benefits, without having a significant enhancement of functional biodiversity on farms, so the major challenges to food production outlined above largely remain. Nevertheless, several examples in the scientific literature can be found reporting successful biodiversity-based, agro-ecological outcomes in East Africa (Khan et al., 2014), South and South-East Asia (Pretty and Bharucha, 2015; Gurr et al., 2016; Ketelaar et al., 2018), Oceania (Scarratt et al., 2008), Central (Holt-Giménez, 2008; Bunch, 2012) and South America (Altieri and Toledo, 2011; Nicholls and Altieri, 2018). One common pattern arising from these successful cases is the inclusion of key 'actors' (farmers, policy makers, scientists and other stakeholders) during the development of agro-ecological advances, using participatory dynamics to create social networks that promote sharing, co-creation and spreading of knowledge (Garibaldi et al., 2017; Cacho et al., 2018; Pretty et al., 2018). Farmer field schools in Asia (Ketelaar et al., 2018) and Africa (Khan et al., 2014), and other farmer-to-farmer practices in Central and South America (Holt-Giménez, 2008) are good examples. This highlights the importance of communicating science outside the sometimes closed scientific environment. Therefore, we propose here an interactive, web-based pathway for uniting these efforts in a way that maximises outcomes at the farm as well as at the research and policy level. This framework takes biodiversity as the starting point and moves through a series of steps, in which different concepts are highlighted, illustrated and explained in a connected sequence, as a pathway to the development of real agro-ecological outcomes. The pathway developed here is not a decision-support system of the type developed by Mann et al., 1986 and Rose et al., 2016 but rather an interactive device which explains clearly the pathway from the concept of biodiversity to agro-ecological outcomes. End users are likely to include farmer networks, and field schools, policy makers, high-school and university teachers and some individual farmers. It will be most effective when used by networks of farmers, scientists and when other stakeholders work together (Warner, 2007).

2. Trends in the number of scientific publications on agro-ecologically managed systems

Recent years have seen a rapidly-increasing rate of publications concerning aspects of SI and related agro-ecological ideas. These include meta-analyses which attempt to quantify biodiversity losses and their causes and also try to identify patterns in the complexities of biodiversity/ecosystem function relationships (Sala et al., 2000; Cardinale et al., 2012; Hooper et al., 2012; Lefcheck et al., 2015; Gurr et al., 2017; O'Connor et al., 2017; Perović et al., 2018; Dainese et al., 2019). To establish the magnitude of this database, and trends within it, the scientific literature related to agro-ecological principles and

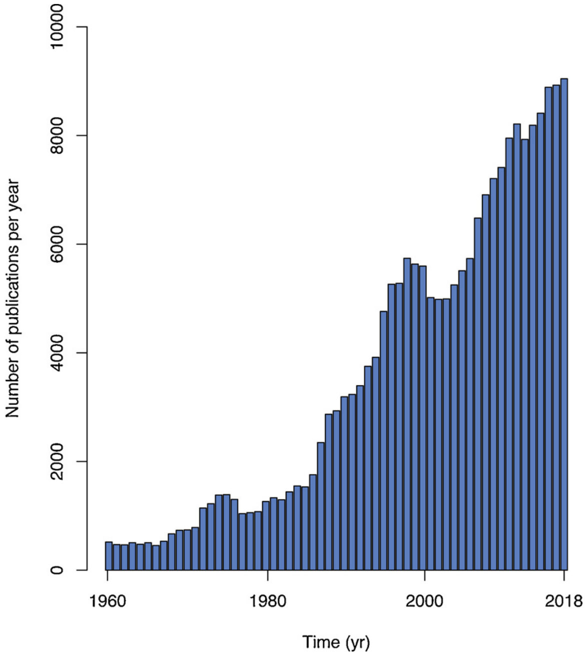

Fig. 1. Increase in the rate of publications per year related to agro-ecological farming practices from 1960 until 2018. Publications were found using the ISI Web of Science search engine (Accessed July 16, 2019, using a Lincoln University account) based on the keywords used by (Kremen and Miles, 2012) and (Gómez et al., 2013).

practices was searched using all databases available within the ISI Web of Science search engine (Accessed July 16, 2019, using a Lincoln University account). We acknowledge that not all scientific articles available on the topic can be retrieved from using only this database, but due to its coverage of the topics investigated here, an indicative trend of publications through recent years can be obtained. From 1960–2018 the number of articles published every year was recorded, using the keywords found in Kremen and Miles, 2012 and Gómez et al., 2013, because they provided a comprehensive literature review in agroecologically-related topics. These keywords were grouped as follows: “ecoagriculture” OR “sustainable agriculture” OR “agroecology” OR “agroecological” OR “organic farming” OR “organic agriculture” OR “poly-culture” OR “diversified farming system” OR “traditional farming systems” OR “intercropping” OR “crop diversity” OR “multicropping” OR “agrobiodiversity” OR “hedgerow” OR “insectary strip” OR “cover cropping” OR “crop rotation” OR “no-till agriculture” OR “agroforestry” OR “alley cropping” OR “livestock integration” OR “compost” OR “green manure”. Overall, 211,624 documents were found over the search period, with the numbers increasing rapidly since 1985 (Fig. 1). Although this increase in such publications matches the worldwide trend in all scientific publications (Fischer et al., 2012), it does not necessarily constitute an increase in the adoption of those agro-ecological advances by growers (Kleijn et al., 2019). A recent study shows that 29 % of farms worldwide, that occupy 9% of the global agricultural area, have crossed a ‘redesign threshold’ in terms of practicing forms of SI that include agro-ecological approaches (Pretty et al., 2018). This redesign implies changes in agricultural practices towards: i) integrated pest management strategies, ii) conservation agriculture, iii) integrated crop and functional biodiversity, iv) mixed pasture-forage-crop systems, v) trees in agricultural systems, vi) irrigation water management, and vii) intensive small and patch systems (Pretty et al., 2018). Unfortunately, around 90 % of agriculture land is still under a non-sustainable monoculture approach and this is dominated by the largest farming enterprises (Reganold and Wachter, 2016; Pretty et al., 2018; Kleijn et al., 2019). Key impediments to this lack of uptake of biodiversity-based schemes is likely to include the interactions between local social dynamics, economics and access to markets, the current political environment, inexpensive agro-chemicals and availability of appropriate applied agro-ecological knowledge (Cacho et al., 2018; Pretty et al., 2018; González-Chang et al., 2019; Shields et al., 2019). Also, when agro-ecological information is presented in peer-reviewed articles, definitions and explanations of concepts such as ‘service providing units’ (SPU) (Luck et al., 2009) and ‘ecosystem service providers’ (ESP) (Kremen, 2005) are explained in a language appropriate to stakeholders such as scientists and policy makers, so do not directly necessarily help facilitate enhanced functional biodiversity on farms (Kleijn et al., 2019). Therefore, it is important to translate the vast amount of scientific knowledge generated from basic and applied sciences into efforts that maximise agro-ecological outcomes at the farm level, so end-users can be widely benefited from current advances in theoretical ecological knowledge, and their associated sub-disciplines.

3. Creation of the interactive spiral approach

Exploring the challenges of enhancing biodiversity to promote agro-ecological outcomes in farming systems always requires a dialogue between different scientific disciplines, such as sociology, ecology, agronomy and economics. Because of the wide dialogue required, a group-based methodology can contribute to promoting consensus among participants when working on complex topics (Mukherjee et al., 2015). In the current work, the creative process behind the interactive spiral approach was driven by the combination of a Delphi approach (Mukherjee et al., 2015), the nominal group concept (Carney et al., 1996) and brainstorming techniques (Yang et al., 2017). A facilitator (S.D. Wratten) called meetings to discuss the construction of an initial conceptual framework. That person guided the discussion (Carney et al., 1996) and each of the individuals in the group (5 PhD students) expressed opinions which were then discussed (Cantrill et al., 1996; Yang et al., 2017). After two hours, a recorder (M. G.-Chang) captured the main agreements or disagreements reached during the meeting (Carney et al., 1996; Mukherjee et al., 2015). Then, specific tasks were assigned to each participant, such as reviewing, proposing or clarifying a concept that might be used in the spiral approach, based on the above discussions (Cantrill et al., 1996). A subsequent meeting took place and the results from those allocated tasks were presented to the facilitator to promote discussion among all participants of the group. Meetings continued until an iterative consensus was reached on the theoretical framework and on the conceptual steps involved in the spiral pathway, which was at that stage starting to be developed (Cantrill et al., 1996; Mukherjee et al., 2015). This iterative process was carried out during six meetings, in which the participants remained the same. Once the framework was completed, it was sent to specialists around the world for their feedback (all the co-authors of this paper without a New Zealand affiliation). The interactive spiral content was then reviewed again and expressed tangibly as an interactive web page using the content-management system WordPress © before its final on-line publication (www.biodiversityfunction.com). While creating this spiral approach, we became aware that although the annual production rate of publications in agro-ecology is increasing markedly (Section 2), most do not, and perhaps many were not intended to effect change at the farm level. In this context, the creation of an interactive web-based tool, as the one presented here, can help at reducing the knowledge gap between scientists and the public regarding a pathway to enhance functional biodiversity in farms.

4. Applying the spiral approach to produce successful agro-ecological outcomes

4.1. The rationale behind exploring the spiral approach

The spiral approach dynamically illustrates the pathway from the concept of ‘Biodiversity’ to ‘Agro-ecological outcomes’. It has been

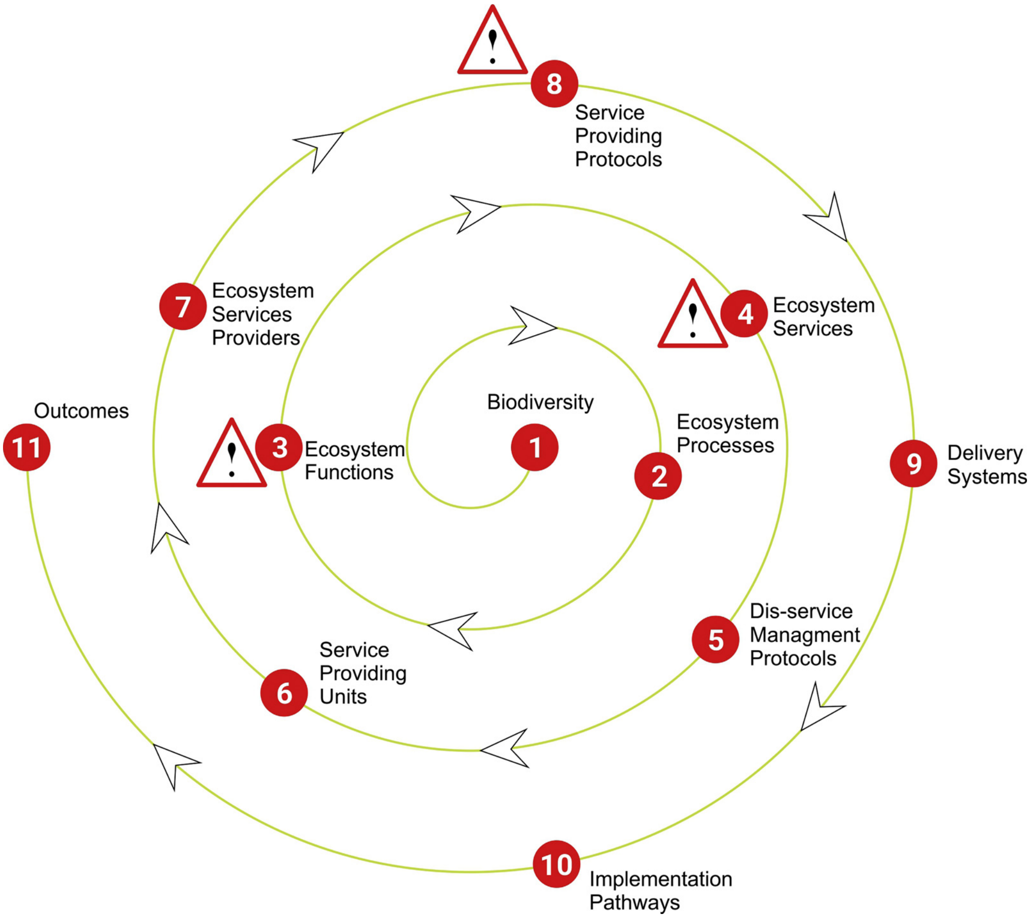

Fig. 2. 'The interactive spiral approach' illustrates the theoretical pathway from the concept of biodiversity to agro-ecological outcomes. Some potential problems associated with following these steps are represented by 'warning' triangles.

designed with 11 sequential steps as follows: 1) Biodiversity, 2) Ecosystem processes, 3) Ecosystem functions, 4) Ecosystem services, 5) Dis-service management protocols, 6) Service providing units, 7) Ecosystem service providers, 8) Service providing protocols, 9) Delivery systems, 10) Implementation pathways, and 11) Agro-ecological outcomes (Fig. 2). A brief description for each of these steps can be found in Box 1. By clicking one of the icons that appear on the spiral image in this website (www.biodiversityfunction.com), any internet user will have access to its content, where each icon represents one of the 11 steps identified. The spatial arrangement of the concepts in the spiral pathway is based in a sequence of scientific events that should occur to provide enough knowledge needed before moving towards the practical application of the next step. For example, it is not recommended to have a service providing protocol (step 7) based on biodiversity if the ecosystem processes (step 2) associated with it are unknown, as ecosystem dis-services can occur (step 4). The push-pull system in East Africa will be now used as an example to illustrate the usefulness of the spiral approach at identifying locally available knowledge to produce successful agro-ecological outcomes. Push-pull systems have been created to control the maize stem borer *Chilo partellus* Swinhoe and the weed root parasite *Striga hermonthica* (Del.) Benth. and *Striga asiatica* L., by using *Desmodium* spp., Molasses grass *Melinis minutiflora* P. Beauv and Napier grass *Pennisetum purpureum* Schumach (Khan et al., 2014). In this example, available scientific knowledge covers several of the spiral steps, such as knowing local grass and pest species (B; step 1), identifying the grass species that could be used for pest and weed control (EF; step 2), assessing plant semiochemicals that attract or repel the pest and/or the allelopathy involved in weed regulation (EP; step 3), valuing pest reduction and crop yield increases (ES; step 4), identifying the contribution of each of the grass species involved in pest and weed control (SPU; step 6), creating a mix of plant species that synergistically promote pest and weed control (ESP; step 7), having a clear protocol to establish the selected plant species that farmers can easily adopt (SPP, step 8), use of radio broadcasts and printed material to disseminate the SPP (DS, step 9), spread of SPP between farmers using horizontal and participatory dynamics (IP, step 10). As illustrated above, the knowledge available to inform those spiral steps has led to the outcome that by 2014, more than 68,000 farmers have adopted this technology in East Africa (Khan et al., 2014). Therefore, in this manuscript, agro-ecological outcomes are biodiversity-based protocols that enhance socio-economic and/or socio-ecological outcomes that ultimately promote farmers' wellbeing. Speculatively speaking, if socio-ecological issues arise after the creation of an SPP, end-users can come back to previous spiral steps, such as to ecosystem dis-service management protocols (step 5). This exercise of unravelling the available knowledge that covers the spiral steps can be useful at identifying research and/or policy gaps that impede advancing into the next spiral step.

As the spiral is explored, it can be used to promote discussions that enrich the educational process, such as the one promoted when navigating the spiral tool during an international conservation biological control workshop held in China (Beijing) and Vietnam (Hanoi) during September 2017 (https://www.iobc-wprs.org/IOBC-Global_Newsletter_102_December-2017.html#TrainingCourseReport) (Accessed March 10, 2020), and one held at Lincoln University, New Zealand, during November 2018 (https://mailchi.mp/e0008e6576cd/wnjebda2lk#TrainingCourses) (Accessed November 25, 2019). It can also raise awareness among users that not all biodiversity interventions may have

Box 1
Key concepts in the interactive spiral approach.

Biodiversity (B) is the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (Convention on Biological Diversity, 2007) https://www.cbd.int/ibd/2007/ (Accessed November 25, 2019).

Ecosystem processes (EP) are changes in the flows of energy and matter in an ecosystem, resulting from the interactions among organisms and with their physico-chemical environment. Examples of these processes include photosynthesis, plant nutrient uptake, microbial respiration, nitrification, denitrification, nitrogen fixation, plant transpiration, etc.

Ecosystem functions (EF) are internal functions of ecosystems such as recycling of organic matter, pollination, biomass production, etc., resulting from the interactions between the abiotic and biotic components (vegetation, water, soil, atmosphere and organisms) that transfer energy and matter within and across ecosystems. Thus, EP drive EF.

Ecosystem dis-functions (EDF). When EFs are damaged or destroyed, the outcome is referred to as an ecosystem dis-function (EDF). While EF results in a positive feedback which supports biodiversity, biomass and response capacity, EDF generate a negative feedback.

Ecosystem services (ES) comprise goods and services that have value to humans and which are derived from EF.

Ecosystem dis-services (EDS) are the negative impacts from nature that lead to a decrease in human well-being.

Dis-service management protocols (DMP) are protocols designed to overcome potential EDS arising from enhancing biodiversity.

Service providing units (SPU). A SPU is the smallest unit (such as a population or a community) at the desired scale that directly provides ES.

Ecosystem service providers (ESP). An ESP is a species, a food web, habitat or system that facilitates and supports the provision of ES. Can be delivered by multiple SPUs.

Service providing protocols (SPP) are practical advice on how to translate ES into action. It is a ‘recipe’ for farmers and other decision makers to put functional biodiversity into practice to deliver enhanced ES.

Payment for ecosystem services (PES). An approach to encouraging the uptake of ES in farms is through PES to private landowners. In this approach, those that benefit from the provision of ES make payments to those that supply them, thereby maintaining those ES.

Delivery systems (DS). A delivery system in an agro-ecological context is scientifically and farmer based agro-ecological methods assembled in a format that is easily accessed by end users, such as scientists, farmers, policy makers and the public.

Implementation pathways (IP) are strategies that help in the uptake of a SPP through different DS. It usually involves some form of participatory social strategy such as farmer to farmer (‘Campesino a Campesino’) which often includes the involvement of ‘farmer teachers’.

Agro-ecological outcomes (AO). As illustrated and explained in this manuscript, the aim of the spiral approach is to show the pathway from the concept of functional biodiversity in agriculture to achieve real agro-ecological changes that enhance environmental health and human well-being, at different spatial and temporal scales.

positive outcomes (Zhang et al., 2007; Tscharntke et al., 2016; Gillespie and Wratten, 2017; Karp et al., 2018), as illustrated by the warning triangles at points on the spiral pathway. As an example, one key step in the pathway is the development of locally-based, agro-ecological protocols for farmers and farm advisors that can be summarised as ‘service providing protocols’ (SPP) (Gurr et al., 2017). Because SPP can be used inappropriately, such as in a crop/pest system for which they were not designed, warning triangles are provided in the spiral at such ‘risk’ areas. Each of these includes a discussion of the importance of the possible impact of farming practices, research programmes or policy guidelines in terms of producing ecosystem dis-functions (triangle at step 3) and ecosystem dis-services (triangle at step 4). Managing these dis-services is explored in step 5 although this is a relatively new research area. Another challenge points to the fact that the likelihood of a payment by governments or the private sector for ecosystem services (PES, triangle at step 7) needs to be considered, where applicable.

4.2. The spiral approach, its relevance, scaling up and future challenges

Despite the increase in agro-ecological research in the last 35 years, its adoption by farmers has been slow. In terms of arable land area available, ‘conventional’, high input agriculture remains as the dominant agricultural system worldwide. The spiral approach presented here aims at facilitating the adoption of a range of available agro-ecological protocols which do exist (see Scarratt et al., 2008; Kremen and Miles, 2012; Khan et al., 2014; Wezel et al., 2014; Altieri et al., 2015; Gurr et al., 2016; González-Chang et al., 2019, among many others), by suggesting the use of horizontal and participatory community-based methods within local farmer groups (step 10 in the spiral) (Holt-Giménez, 2008; Altieri and Toledo, 2011; Bunch, 2012; Khan et al., 2014; Garibaldi et al., 2017; Wyckhuys et al., 2018; Pretty et al., 2018; González-Chang et al., 2019; Shields et al., 2019). This community-based form of governing the dissemination of agro-ecological protocols could hugely benefit when interacting with other forms of governance that use market tools and “hierarchical” governmental regulations (Vatn, 2015). In this sense, a hybrid system that combines these three forms of governance (Muradian and Rival, 2012) could boost knowledge uptake by farmers, further enhancing the adoption of agro-ecological techniques worldwide. In terms of governing natural resources, the spiral approach can contribute to different decision-making support models, such as hierarchical decision trees, by creating locally adapted SPPs that can be used as inputs to model the outputs of certain ES under different scenarios, as suggested for forest (Seely et al., 2004) and river management (Gurnell et al., 2016). Recently, it has been proposed that a well-being based economy should drive the governance over ES instead of the current consumerist mainstream economic thinking (Coscieme et al., 2019; Costanza, 2020). Considering the key role of biodiversity in human well-being, the spiral approach presented here could help in sustaining this new kind of economy, by creating SPPs that can directly enhance aspects of human well-being. However, in many cases the necessary knowledge needed for achieving the adoption of particular agro-ecological techniques is not available. In these cases, the spiral approach can provide the necessary conceptual steps needed for creating such knowledge by navigating through the interactive pathway. Through an explicit understanding of the nature and connectedness of the steps arising from the biodiversity concept, it is likely that evidence-based and practicable changes to agricultural systems will increase. It is important to realise that the spiral pathway presented here is unidirectional, which to some extent is a simplification of the ecological dynamics that take place in nature. Positive and negative feedbacks are also likely to occur when adding biodiversity to farms. For example, once an SPP is established it is likely that other ecosystem services, not originally consciously deployed, will operate. One such example is the deployment of flowering buckwheat or phacelia in vines to enhance nectar and pollen production for predatory and parasitic insects. This may also provide sugars and amino acids to bees, especially in a floristically-depauperate environment (Filipiak et al., 2017). The latter can improve honeybee fitness, leading to higher honey production and enhanced financial benefits for the viticulturalists themselves and for local bee-keepers through the development of a new ES. This is an example of a new ES arising from a positive feedback loop. This process can change a food web's structure and its dynamics. This type of ES enhancement can occur between many or a few steps in the spiral pathway (eg ES, EF, Biodiversity, SPP, etc.). Also, potentially negative feedbacks can appear, creating new and unexpected EDS. An example is the use of added floral nectar by pests, such as vespid wasps which sting and bite humans as a result. Plant pests may also benefit (Tscharntke et al., 2016). The commonly used alyssum plant when established in lettuce in California, attracted flea beetles (Coleoptera: Chrysomelidae) which are brassica feeders. This could have had consequences for successive crops (Gillespie and Wratten, 2017). These feedback loops are also present in human societies, affecting human behaviour in complex ways (Liu et al., 2007). Although the spiral tool presented here follows a logical sequence of steps, when these are applied to real problems, complex interactions between humans and farming systems are likely to appear. These interconnected social-ecological systems (SES) could impact on the likelihood of successful implementation pathways (step 10) that lead to agro-ecological outcomes (step 11) (Liu et al., 2007; Reyers et al., 2013). Thus, these interactions can have positive or negative feedback impacts at each of the spiral steps, influencing the development and application of these in farms at local, landscape and regional scales. Therefore, end-users of the spiral approach have to realise that interactions between the steps are not necessarily in one direction only, allowing stakeholders to understand the interactions between earlier and later steps in the spiral approach, when needed (i.e., feedback loops). Because socio-ecological conditions vary in space and time between farms worldwide, the spiral should be used as a flexible theoretical framework to guide research and/or political actions, and not as a strict 'protocol' that can easily produce agro-ecological outcomes from using biodiversity in farms.

The spiral approach presented here could impact the environment at different scales. At the farm level, improvement in ecosystem functions based on functional agricultural biodiversity can help deliver lower input costs and provide potential savings for farmers (LaCanne and Lundgren, 2018; Scarratt et al., 2008; Khan et al., 2014; Gurr et al., 2016; Dainese et al., 2019). At the landscape scale, an improvement in ecosystem structure and its functions can help to reduce agro-chemical pollution (Gurr et al., 2016; Dainese et al., 2019), reducing pesticide-related human health effects, thereby contributing to better health outcomes for farm workers, their families and the surrounded population. At the regional level, sufficient and nutritious food can lead to better health and well-being of all consumers. Feeding a constantly, growing population in the future with nutritious food, which needs to be available and accessible to all segments of society and does not harm human health and the environment, requires the redesign of agricultural and food systems (Gliessman, 2018; Pretty et al., 2018). It is important to note that other approaches aiming at enhancing agro-ecological outcomes for sustainable intensification currently exist (Garibaldi et al., 2017, 2019; Nicholls and Altieri, 2018; Kleijn et al., 2019), assessing the ecological, social and economic performance of farming systems (Garibaldi et al., 2017), understanding pathways to promote its adoption through policy interventions (Garibaldi et al., 2019), aiming at reducing the gap between science and agro-ecological practices by understanding socio-economic farmers´ impediments to its adoption (Kleijn et al., 2019), and using agro-ecological "lighthouses" that spread agro-ecological principles out to the community (Nicholls and Altieri, 2018). To the best of our knowledge, so far no other framework tries to understand the pathway from the concept of biodiversity to agro-ecological outcomes, tangibly expressing this through a web-based interactive tool. In this context, the spiral approach can hugely contribute at the existing proposed frameworks by creating appropriate locally-adapted SPP that can fill knowledge gaps that are crucial to promote the dissemination of biodiversity-based farming systems worldwide.

5. Concluding remarks

The spiral tool presented here contributes to the creation, adaptation, adoption and dissemination of biodiversity-based farm interventions by illustrating an ideal pathway to achieve agro-ecological outcomes. Through understanding the interactions, connectedness and feedback loops between the steps presented in the spiral pathway, a paradigm shift from the current conventional agriculture approach can be created. However, this agricultural transformation needs a shift from the current narrow focus of improving only yields, to one that also appreciates social and environmental outcomes and improves well-being of all people involved in agriculture and food systems (TEEB, 2015; Coscieme et al., 2019; Costanza, 2020). Further engagement with key decision makers in farming communities, agribusinesses and governments will help its uptake by practitioners in regional, national and global agricultural and food policies.

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Data availability statement

The data supporting Fig. 1 of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

Declaration of Competing Interest

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

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