CHAPTER ONE

Agroecological crop protection for sustainable agriculture

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Contents

Abstract

Crop losses from pests threaten global food security and safety. In the last six decades, pest control using chemical pesticides has resulted in important yield gains per unit area, worldwide. However, the long-term sustainability of chemical pest control has been increasingly thrown into doubt due to the negative impact on human health, biodiversity, and the environment. Consequently, there is an urgent need to improve the science of crop protection in order to tackle the five key challenges of 21st century agriculture holistically: (i) maintaining or improving agricultural productivity, (ii) producing healthy food, (iii) reducing the negative impacts of agriculture on ecosystem and human health, (iv) ensuring the economic viability of farms, and (v) adapting agriculture to climate change. Agroecological Crop Protection (ACP) can be a powerful approach to address these challenges, as we demonstrate in this paper. ACP is the application of the principles of agroecology to crop protection in order to promote virtuous and sustainable changes in agriculture and food systems. ACP combines multiple approaches and disciplines including ecology, agroecology, and Integrated Pest Management. It promotes a crop protection system compatible with healthy agricultural and food systems, agroecological principles and the "one health" approach. We predict that ACP will meet the challenge of pesticide-free agriculture in the future. In this paper, we will first present the scientific, agricultural and social components of ACP. We will then analyze the research approaches, questions, methods and tools needed to adopt ACP. Finally, we suggest key mechanisms to facilitate the transition to ACP, which will ultimately provide sustainable food, feed, and fuel in a context of major global change.

1. Introduction

Protection against pests (sensu *lato*, including animal pests, pathogens and weeds) is an essential component of agroecosystem management and prevents large scale yield losses (Oerke, 2006). Since the 1960s, pest control has relied on chemical pesticides which have led to numerous negative externalities, including unintended effects on human health (essentially from manipulation and application of plant protection products, and residues on food) and changes to biodiversity. Today, most humans are exposed to chemical pesticides, and a paradigm shift in crop protection is needed to reduce this exposure and the negative effects it causes.

Deguine et al. (2020) defined Agroecological Crop Protection (ACP) as the reduction of pest impacts through the reorganization of cropping practices and the improvement of agroecosystem sustainability by harnessing its ecological functions. This requires the optimization of interactions between plant, animal and microbial communities both below and above ground, within and around agroecosystems. In this paper, we present to the international community ACP as the application of agroecological principles to crop protection in order to foster positive and sustainable changes in agricultural food systems, with the ultimate objective of eliminating pesticides and solving the major agronomic, food, socio-economic, environmental and health challenges of the 21st century. ACP can be implemented in any physical, chemical and biological environment and any socio-economic context (Aubertot and Robin, 2013). The aim of ACP is to dismantle outdated practices (e.g., intensive agroecosystems in the global North and South) and to support agroecological transitions that are already underway (Côte et al., 2019; Hubert and Couvet, 2021).

Agroecological Crop Protection combines ecology, agroecology, Integrated Pest Management (IPM), Organic Farming (OF) and permaculture. Ecology is the guiding principle for crop protection (Altieri, 1980; Deguine et al., 2017; Kogan and Heinrichs, 2020; Nicholls and Altieri, 2004; Shennan et al., 2005; Stenberg, 2017; Thomas, 1999). The stimulation of ecological processes such as natural pest regulation through improved soil health and improved interactions between plant and animal communities, is a rich source of innovative crop protection models (Brévault and Clouvel, 2019). Second, ACP is part of agroecology, a practical alternative to conventional agriculture (Altieri, 1989; Dalgaard et al., 2003; Gliessman, 2016; Hubert and Couvet, 2021; Malézieux, 2017; Wezel et al., 2009, 2014). Wezel et al. (2009) defined agroecology as a set of (i) scientific, disciplinary and interdisciplinary fields, (ii) agronomic and landscape practices that are part of an orderly strategy for practical implementation in the field, and (iii) evolving and strengthened interactions between food system stakeholders. Third, ACP draws on the experiences of crop protection over the past half century under the aegis of IPM. Lessons learned from IPM should help ACP avoid similar pitfalls (Brévault and Bouyer, 2014; Deguine et al., 2021) and promote the transition of agricultural food systems toward zero chemical pest control. Fourth, ACP is also inspired by organic farming (Boisclair and Estevez, 2006; Francis, 2009; Lockeretz, 2007; Muneret et al., 2018; Simon et al., 2014; Zehnder et al., 2007), where chemical pesticides are banned, and stakeholders are unified across the food system. Fifth, ACP aims to redesign farming systems, from production objectives to cropping systems and pest management, as in permaculture (Ferguson and Lovell, 2014; Hirschfeld and Van Acker, 2021; Mollison, 2010; Mollison and Holmgren, 1978). This methodological development is in line with the most advanced level of the Efficiency, Substitution, Redesign framework for classifying transitions to sustainable agricultural systems (Hill and MacRae, 1996).

Agroecological Crop Protection requires a substantial shift away from conventional crop protection. ACP is not simply a case of understanding and managing biotic stresses or biotic × abiotic stress interactions (Rickerl and Francis, 2004; Wezel et al., 2020), rather, it requires multidimensional thinking (Francis et al., 2003). ACP must be set in a wider context, including its goals (i.e., plant protection in a sustainable food system) and its different interactions (soil–plant–human–animal health, crop health–harvest quality, crop health and its economic and social standards, etc.). More globally, ACP consistently meets most of the United Nations' 17 sustainable development goals (UN, 2021). We emphasize that a sustainable alternative to the current model of intensive agriculture is made possible by designing agroecology-based plant protection solutions which promote sustainable food systems. Here, we present the scientific foundations and principles of ACP, how to facilitate ACP implementation, and research required to further enhance its efficacy and large-scale deployment.

2. Agroecological crop protection as an ambitious scientific field

Relying on ecological processes within diversified agroecosystems is challenging and requires a paradigm shift toward an integrative approach far beyond the intensive agriculture model (Meynard et al., 2012; Simon et al., 2017). Research goes beyond the monocrop field—the usual area of study of agronomists—to consider the whole agroecosystem at supra-field level (including field margins and landscape), as well as the different layers, functions and temporal dimensions of the agrosystem's interactions (Aguilera et al., 2020; Garland et al., 2021). Moving from mono-disciplinary to multi-disciplinary and system-based approaches, as well as linking research and practical applications, help lead the crop protection sector away from a product-based approach to a chain-based approach at a regional scale, and encourage a question-driven rather than a research driven approach (Lamichhane et al., 2019). This section briefly presents the key pillars of ACP and how to facilitate the transition from the conventional crop protection systems to ACP and the key issues related to its implementation.

2.1 Prevention, biodiversity conservation and soil health: The three pillars of ACP

Developing preventive approaches to pest management in agroecosystems is the priority research area in ACP. New agroecological strategies, based on plant genetic resources and cropping practices (Section 3), are required to reduce pest infestations or the risks of build-up of pest populations.

Natural pest regulation is a complex ecosystem service (ES) that is generally positively associated with a high level of richness or diversity of natural enemy communities. Optimizing plant–animal–microbial interactions promotes the healthy ecological functioning of agroecosystems, therefore making them less vulnerable (Beillouin et al., 2021; Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Dainese et al., 2019; Eisenhauer et al., 2012; Lemanceau et al., 2015; Molina and Pugliese, 2022; Quijas et al., 2010; Ratnadass et al., 2012; Tamburini et al., 2020; Veres et al., 2013). Promoting a high level of abundance and diversity of pest natural enemies (conservation biological control) has long been recognized as a nature-based strategy with which to regulate pest populations (Anjos et al., 2022; Duru et al., 2015; Ferron and Deguine, 2005; Gurr et al., 2004; Landis et al., 2000; Lichtenberg et al., 2017; Nicholls and Altieri, 2004; Ratnadass et al., 2012, 2021; Simon et al., 2014; Zehnder et al., 2007). This requires an intimate knowledge of their life cycle as well as better resource management.

Soil health plays a crucial role in ACP on many levels. By ensuring good ecological functioning and providing sustainable ES, healthy soils play a key role in plant growth, development and overall plant health. Soil health also promotes biological regulation pathways which impact pest development (Kibblewhite et al., 2008; Sahu et al., 2019): quantifying this biological pest control links the concept of soil health to that of plant health (Janvier et al., 2007; Kulagowski, 2021). Mainly driven by soil biota, soil functionality and vitality are key components of soil health, (Janzen et al., 2021). Links with soil physico-chemical properties need to be integratively addressed (Kibblewhite et al., 2008; Vogel et al., 2018).

2.2 Socio-technical systems as catalyzers in the transition to agroecological crop protection

Agroecological transition including ACP needs to be conceptualized, managed and governed at multiple organizational levels (Duru et al., 2015; Meynard et al., 2017), among which landscape or territory levels have recently emerged as key (Landis, 2017; Vialatte et al., 2019). Multiple stakeholders (farmers, technicians, input suppliers, market actors, policy makers) have different ES preferences and potential conflicts of interest (Ratnadass et al., 2021), hence hindering change within socio-technical systems (Vialatte et al., 2019, 2022). These systems regulate crop and pest management strategies at all levels, and should be thoroughly studied in the ACP scaling-up process (Geels, 2011). In designing ACP strategies, interactions and routines between local stakeholders do matter. Choices should be made explicitly and negotiated jointly with all stakeholders (Barnaud and Antona, 2014), while keeping in mind that farmers are interdependent on ecological functions and services (Barnaud et al., 2018). For example, hedgerow management around a given field might provide ES (pest regulation, soil erosion control), beneficial to both the owner of the field and neighboring farms. ACP encourages farmers not only to change their own individual practices but also to do so collectively at the landscape level.

To assist in this change, agronomists have suggested connecting production systems and agricultural landscapes using synergy between agriculture and livestock farming (Moraine et al., 2016). One major challenge is to identify lock-ins and levers of collaborative landscape management, for an agroecological transition which is adapted to each individual territory. Lock-ins may be technical, economic, social, political, regulatory or industrial (Meynard et al., 2018). For instance, most current agri-environmental schemes in Europe involve contracts with individual landowners; collective contracts and incentives would be required for landscape-level management (Prager et al., 2012). Furthermore, public and private farm advisory services often have a narrow scope, excluding landscape-level processes when focusing on a small range of crops. Addressing environmental issues at local and larger scales is essential for the successful implementation of ACP (Dhiab et al., 2020).

2.3 Challenges facing the implementation of ACP: Relationships between stakeholders, nature and spatio-temporal scales

ACP implementation requires four key components: (i) The production or mobilization of practical tools from different disciplines and the empirical knowledge of farmers and advisors; (ii) A reassessment of the (often hierarchical) relationships between actors from different sectors (farmers, service providers, technicians, scientists, retailers, consumers and the public); (iii) The incorporation of different time frames, different agricultural activities and different ecological processes into decision-making; (iv) The consideration of different organizational levels, from basic (e.g., plant, field, farm) to landscape, and their connections (e.g., introducing ecological infrastructure into or around a field).

Agroecological research seeks to understand the ecological interactions between trophic levels and to apply them to managed agroecosystems. Its three main steps, which may overlap, are: observation of nature, implementation of process-based experimentation, and participatory re-design of cropping systems (enhancing natural processes). Malézieux (2012) defined "nature" as wild or barely managed systems; here and in the following sections, we extend this definition to "natural" aspects of agroecosystems. Agroecosystem designs which mimic natural processes should, however, only be utilized if they originate from different knowledge sources, i.e., disciplinary and experience-based sciences, via an interactive, participatory scheme with the complementarity of researchers, technicians and farmers (Le Gal et al., 2011).

Working with nature (rather than attempting to constrain it) is one of the basic principles of ACP. This requires major changes in the way techniques and their spatio-temporal organization are implemented (Larrère, 2002). At an operational level, several studies have shown the importance of biodiversity in pest management (Beillouin et al., 2021; Ratnadass et al., 2012; Stomph et al., 2020; Thomine et al., 2022). However, the integration of biodiversity into agroecosystems and the use of nature as a driver of "positive action" (Barbier and Goulet, 2013), requires both a reassessment of actors' roles in the production process, and the introduction of crops with various natural elements. Protecting crops requires triggering their self-defense response, taking into account their complex physiology and behavior, and humans must let plants do some of this work their own way. To prevent disease from gaining a foothold due to extremely homogenized or standardized cropping environments, the "wild" aspect of plants must be acknowledged with room for maneuver in terms of adaptation to environmental change. The plant should thus be seen as an organism that actively interacts with its environment, thereby increasing the processes and interactions between animals, plants, biotic and abiotic factors, at a large spatio-temporal scale. Effects of agroecological practices have been documented at field scale (Petit et al., 2021). The landscape scale remains complex, with some clues provided by the recent expansion of organic agriculture (Muneret et al., 2018). Questions remain as to which landscape characteristics would most benefit local pest management practices.

3. Agroecological crop protection as an orderly strategy of best agronomic and landscape practices

This section presents the seven generic principles of the ACP strategy and their adaptation to the diverse contexts encountered.

3.1 Seven major principles of ACP strategy

The implementation of ACP in the field has seven principal assumptions:

(i) Ecological processes and functions are the cornerstone of the strategy (Altieri, 1989).

(ii) A systems redesign (R) at the field, landscape and regional level is chosen rather than input efficiency improvement (E, e.g., modeling tools for chemical treatments, fertilizer management, precision farming), or substitution of technical levers (S, i.e., replacement of chemical products by alternatives) (Hill, 2004).

(iii) The approach is systemic and participatory. Levels at which the ecological processes of natural pest regulation take place (i.e., climate, agroecosystem, landscape) combine with social organization levels at which agricultural management is implemented (i.e., field, farm), as well as the socioecological landscape integrating stakeholders, value chains and market linkages.

(iv) Successive agronomic and landscape management practices must be implemented in order (Fig. 1). Usually, no further intervention should take place until the previous step is complete (González-Chang et al., 2020).

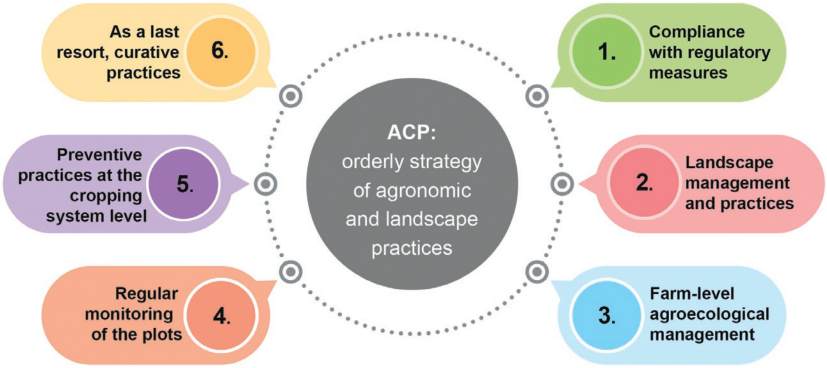

Fig. 1 Orderly strategy of agronomic and landscape practices in Agroecological Crop Protection (ACP).

(v) In compliance with regulations, priority is given to preventive measures, with curative measures (preferably non-chemical) only used if deemed essential. Some interventions may take time to achieve their maximum effect: for example, hedges begin to provide ES only several years after planting. Other improvements in pest control become evident 4 years after conservation agriculture is introduced (predation of seed-eating carabids; Petit et al., 2020).

(vi) Scales of ACP are broad and are seen from the viewpoint of collective management (Petit et al., 2020). Farmers and other key stakeholders will be invited to get involved. Upstream sectors (e.g., the production of healthy seeds from well-adapted varieties) and downstream sectors (e.g., new outlets with improved standards) sectors will also have to be involved.

(vii) While valuing traditional agroecological techniques, use of the most recent technologies (Migliorini et al., 2020; Shah et al., 2021), such as drones, should be considered (Burgués and Marco, 2020; Librán-Embid et al., 2020).

3.2 Preparation and implementation of agroecological crop protection on a broad scale

ACP success criteria need a carefully designed strategy, which is proposed by Deguine et al. (2021). This includes a regulatory crop protection framework; improved awareness and motivation of agricultural actors; ACP training for farmers and advisers; joint phytosanitary and sustainability priorities; collective actions and R&D partnerships; political support before, during and after the agroecological process.

ACP begins with a transition phase which includes halting calendar-based chemical treatments. Plant biodiversity at the scale of cropping, farming and landscape systems, is planned with a special focus on soil interactions. The training of local farmers must be carried out by technical boards supported by public policies.

Short-term management has long been the norm in chemical crop protection. The efficacy of insecticides on target pests or collateral impacts on beneficial fauna, have rarely been assessed in the medium or long-term. In ACP, practices must be appropriately managed at both spatial and temporal scales. Its practices are implemented at the landscape, regional or even national scale, embracing area-wide pest management (Vreysen et al., 2007). ACP also draws on engineering and communication experience to augment its impact: the area-wide management of the rice planthopper in Asia is an example (Heong et al., 2021b).

3.3 Preventive measures: The core of ACP strategy

Chemical pesticides remain the first choice for pest management on most farms, including those who label themselves as IPM, but are actually in contradiction with IPM's founding principles (Deguine et al., 2021). In ACP, halting pesticide use is required to allow bioecological equilibria to become reestablished in agroecosystems. The vast array of preventive measures is subdivided into six categories: discontinuation of pesticides, prophylaxis, soil health management, diversification of vegetation (Beillouin et al., 2021; Tamburini et al., 2020), biological control, and other measures.

If last-resort curative measures are required, chemical pesticides must be optimized and must not interfere with the biological regulations in place (i.e., targeted use of low risk and species-specific pesticides with little or no impact on natural enemies, with strict timing and application methods, and drift-reduction measures). This strategy requires reliable pest monitoring and early warning systems.

3.4 Observation, knowledge sharing, risk evaluation and decision-making: Cornerstones of ACP

A key benefit of ACP is to predict future changes in crop health status. Epidemiosurveillance systems inform farmers about the likelihood of pest infestation at different scales, worldwide. These predictions often use phytosanitary and yield loss risks models, using data accumulated over many seasons. At the landscape scale, local economic and environmental interest groups allow farmers to share field practices and adopt a collective and consistent local strategy.

Similarly, farmers may observe the plant health status at the farm or field level. When this is done regularly and accurately, the farmer is able to gauge soil health, pest populations, interactions with natural enemies, beneficial organisms or disease risk. The farmer can use sentinel plots or plants (e.g., roses at vineyard margins as a sentinel for powdery mildew, botrytis and red mite), or varying observation circuits depending on farm size and crops grown. An example is the Fall Armyworm Monitoring and Early Warning System (FAMEWS, http://www.fao.org/fall-armyworm/monitoring-tools/famews-global-platform/en), which aims to reduce or eliminate the need for chemical pesticides. ACP field monitoring requires targeted training and support, and must be independent of the vested interests of chemical phytosanitary companies (Dhiab et al., 2020; Villemaine et al., 2021).

3.5 A generic ACP strategy adaptable to any crop type and any agricultural context

The generic nature of ACP is an advantage, and means dedicated strategies can be tailored to many contexts and pests, as well as different stages of crop growth. Specific field practices are adapted to local situations, production objectives and demand for food. The effectiveness of ACP has been documented across both tropical and temperate conditions (Deguine et al., 2017). A plot level schematic representation of ACP for animal pests and pathogens is presented in Figs. 2 and 3, respectively.

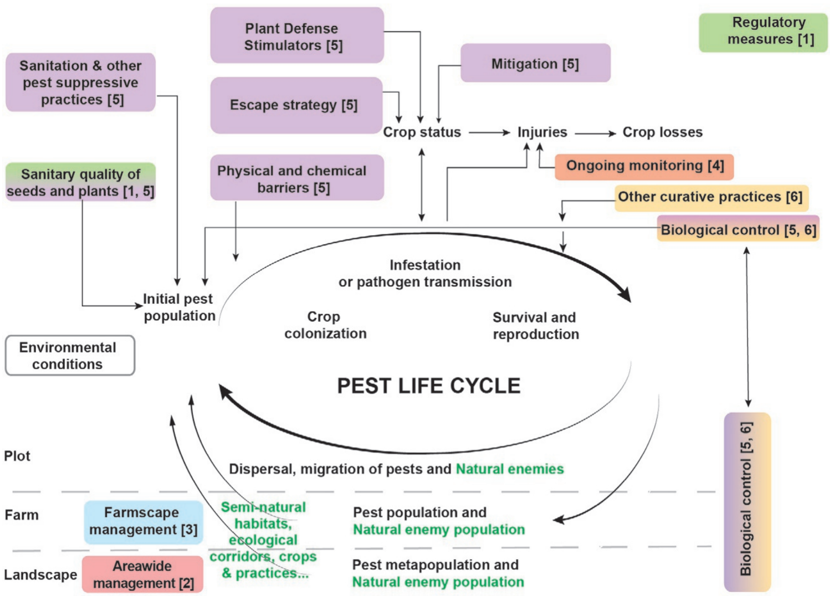

Fig. 2 Agroecological management of animal pests with a focus on the plot level. Numbers and colors in the boxes refer to the six agronomic and landscape practices in Agroecological Crop Protection (see Fig. 1): [1] Compliance with regulatory measures; [2] Agroecological management of pest populations at the landscape level; [3] Agroecological management of pest populations at the farm level; [4] Ongoing monitoring of the plots (soil, biodiversity, trophic groups, etc.); [5] Preventive practices at the cropping system level; [6] Last resort curative practices. Most ACP measures are preventive; their level of use depends on the cropping system and production. Biological control includes conservation biological control that promotes abundance and activity of natural enemies (NE) at various scales through the conservation of resources and habitat, and restriction of disruptive practices (e.g., mowing, pesticide use) and the provision of NE with plant food resources and habitats (e.g., companion plants meeting the trophic needs of NE). Effect of conservation biological control measures may vary by pest, NE species or functional groups, landscape and practices.

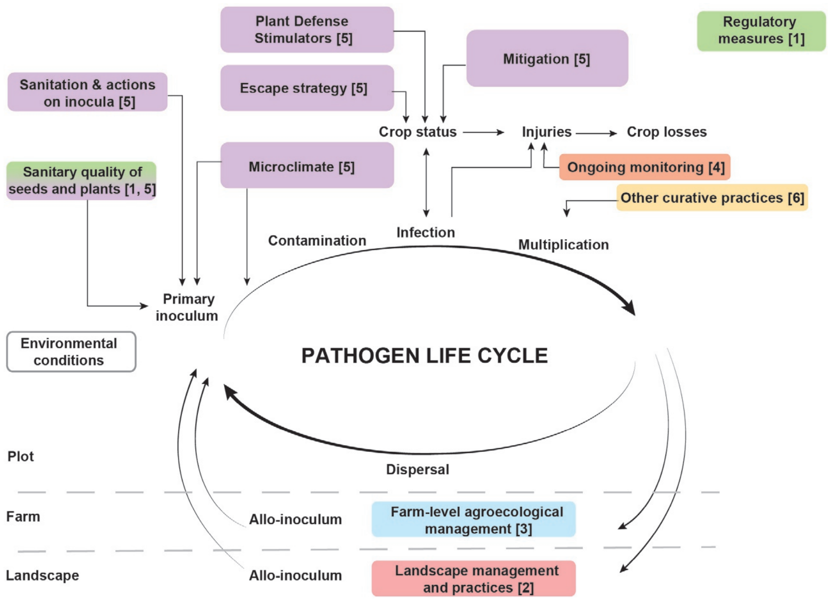

Fig. 3 Agroecological management of plant pathogens with a focus on the plot level. Numbers and colors in the boxes refer to the six agronomic and landscape practices in Agroecological Crop Protection (see Fig. 1): [1] Compliance with regulatory measures; [2] Agroecological management of pest populations at the landscape level; [3] Agroecological management of pest populations at the farm level; [4] Ongoing monitoring of the plots (soil, biodiversity, trophic groups, etc.); [5] Preventive practices at the cropping system level; [6] Last resort curative practices. Most ACP measures are preventive; their level of use depends on the cropping system. *Adapted from Attoumani-Ronceux, A., Aubertot, J., Guichard, L., et al., 2010. Guide pratique pour la conception de systèmes de culture plus économes en produits phytosanitaires. Application aux systèmes de polyculture. Ministères chargés de l'agriculture et de l'environnement, RMT SdCI.*

Similarly, agroecological weed management is well-documented, using a combination of methods which rely on ecological interactions between crops, weeds, soil and/or other taxa, assisted by agroecosystem management, with curative weed control only as a last-resort (Bàrberi, 2019). Agroecological weed management has three components: preventive, cultural and curative measures, which, coupled to regulatory measures and regular weed monitoring, allow the full array of approaches to be used (Fig. 4). Preventive measures are applied before a crop cycle, mainly to reduce weed emergence in the subsequent crop. Cultural measures are applied during a growing cycle to increase crop/weed competition while curative measures reduce in-crop weed development. Agroecological weed management aims to maximize the disturbance to weeds (Bàrberi, 2002) and to promote biotic interactions that regulate

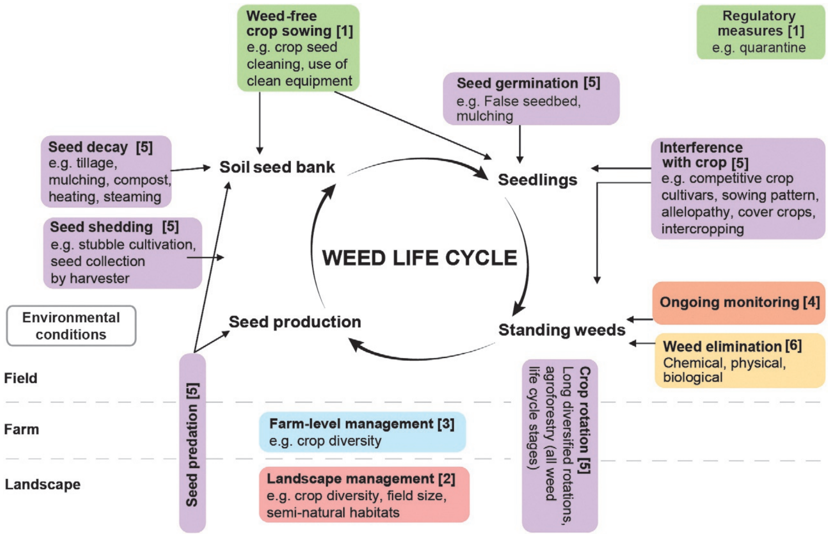

Fig. 4 Agroecological Weed Management (AWM). Numbers and colors in the boxes refer to the six agronomic and landscape practices in Agroecological Crop Protection (see Fig. 1): [1] Compliance with regulatory measures; [2] Agroecological management of pest populations at the landscape level; [3] Agroecological management of pest populations at the farm level; [4] Ongoing monitoring of the plots (soil, biodiversity, trophic groups, etc.); [5] Preventive and cultural practices at the cropping system level; [6] Last resort curative practices. For each of these six components (where a component has a different mechanism/approach to weed management), there is more than one box of the same color, with examples of practices for each component. Arrows indicate the weed life cycle stage(s) affected by each mechanism/approach. Those which operate at higher spatial scales or across spatial scales (e.g., seed predation, crop rotation) are indicated in the lower part of the graph. This design mainly refers to AWM in annual cropping systems (e.g., arable or vegetable crops) and for annual weeds, but many of the measures have general applicability.

weeds (Petit et al., 2018). Cropping system diversification results in taxonomically and functionally diverse weed communities. These communities generally cause lower yield loss (Adeux et al., 2019), and contribute to ES (pollination, natural pest control and soil fertility) (Bàrberi et al., 2018; Yvoz et al., 2021).

4. Agroecological crop protection promoting social interactions among agricultural stakeholders

This section highlights three key changes needed to promote ACP via the promotion of interactions between different actors to market diversification strategies.

4.1 Reorganizing the interactions between different agricultural stakeholders, ecological processes and institutions

Agroecosystem management frameworks highlight the need for transdisciplinarity and the importance of social coordination. One integrative approach concept (Fig. 5) consists of four main components providing multiple ES and disservices in the following areas: (i) ecological, (ii) social, (iii) institutional and (iv) agricultural landscape. Interactions between these components include competition and predation between taxonomic groups, conflicts and cooperation between actors, complementation or edge effects between socioecosystems. These components are affected by the sociopolitical and economic context, stakeholders and other external drivers (migration, urbanization, climate change). They are connected via four key processes: (i) the landscape ES provided to multiple taxonomic groups; (ii) the interaction of ES beneficiaries with ES co-producers which influence landscape management; (iii) the role of institutions in ES management who manipulate social and socio-ecological interactions, and (iv) individual and collective management, together with ecological functions, and the resulting co-production of ES and disservices at landscape level.

4.2 Joint initiatives to re-integrate nature into crop protection

Examples of innovative ACP schemes have been described in the scientific literature. Closely related to the systems for which they were developed (e.g., Shennan et al., 2005), such schemes not only constitute documented evidence of the practical implementation of concepts of agroecology, but they also show that contextualization is necessary. In Sulawesi (Indonesia), shade trees in cocoa agroforestry systems naturally regulate pests, using farmers' empirical knowledge (Wartenberg et al., 2020). Similarly, in California, partnerships between farmers, project coordinators and researchers gave rise to a significant reduction in organochlorine use in orchards (Warner, 2008). In Cuba, biocontrol began a century ago with a classical approach based on input substitution. This approach relied on association with other cultural techniques, and was supported by public policies that turned the country into a world leader of entomopathogen production in the 1990s (Karp et al., 2018; Pérez-Alvarez et al., 2019; Settele and Settle, 2018). In Andra Pradesh (India), a "zero budget natural farming" program was launched in 2015 that now involves tens of thousands of farmers (Bharucha et al., 2020). Much of the program focuses on plant protection and plant health, for which local, natural products are used.

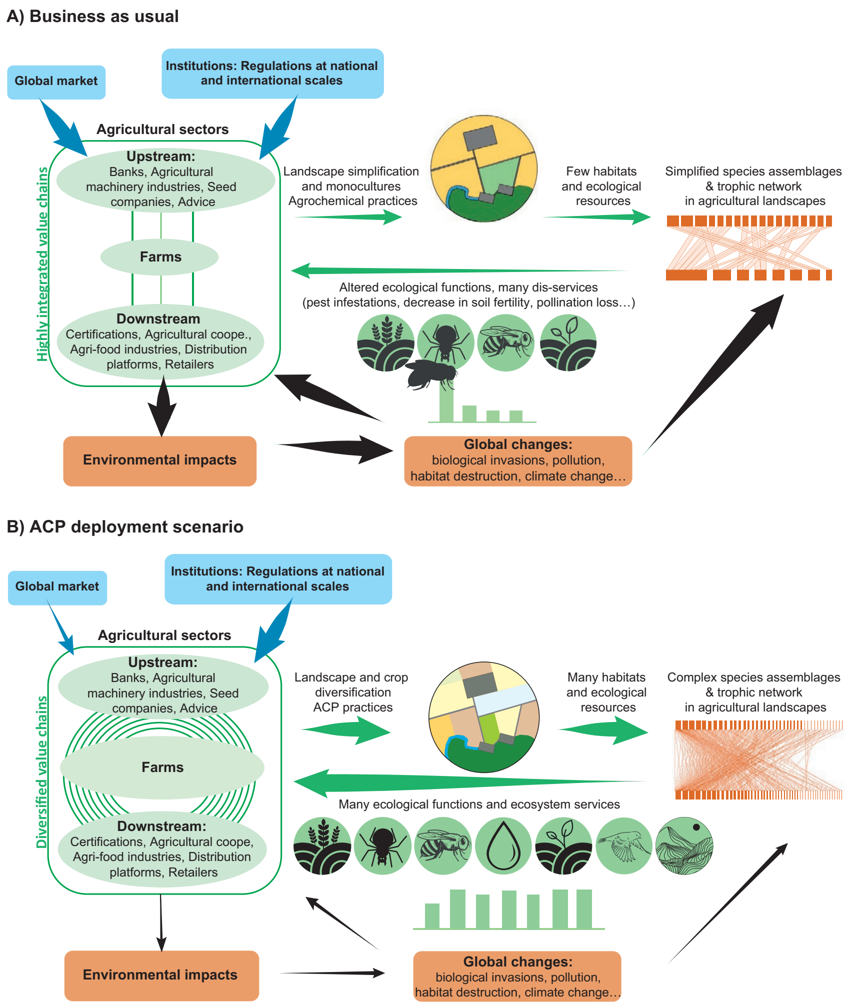

Fig. 5 Shift between (A) the current agricultural organization ("Business as usual", BAU) and (B) the implementation of Agroecological Crop Protection (ACP). ACP implementation involves the redesign of socio-technical and economic systems, and of their interactions with the ecological system. In ACP deployment scenario, notably under the action of public policies supporting crop diversification, value chains are more diversified, with multi-actor innovations and markets: the overall influence of the global market is decreased as compared to BAU scenario. ACP involves diversification of agricultural landscapes (diverse crops in space and time, semi-natural habitats), resulting in increasingly complex ecological networks, which in turn support numerous ecological functions and ecosystem services. These agroecosystems are more adaptable and resilient to global changes, in which agriculture has a lower impact. Arrow size represents effect strength. Ecosystem functions and services are symbolized by pictograms; barplot symbolizes the evenness in levels of ecosystem functions and services.

In France, the DEPHY Ferme network links 3000 farms backed by the national Ecophyto plan (Lamichhane et al., 2019). In parallel, two sets of approximatively 40 experimental networks (DEPHY Expe) have been funded since 2011, to test cropping systems less reliant on chemical pesticides.

In Asian mango and citrus orchards, weaver ants (*Oecophylla smaragdina*, Hymenoptera) have been used for over 1700 years to combat pests. This is the oldest known example of biological control in agriculture (Huang and Yang, 1987). In the Mekong Delta (Vietnam), smallholder farmers use weaver ants to protect their orchards in an ACP-type framework. An outreach program targets the farmers still using intensive pesticides, through simultaneous information, training, ad campaigns and participatory research (Van Mele and Cuc, 2000). The possibility of using *O. smaragdina* ants in other commercial fruit crops is being studied. Researchers working with farmers and project coordinators, are able to develop a highly effective ACP strategy. Similar research has been conducted on sister species *O. longinoda* in Africa (Adandonon et al., 2009).

Beyond the conventional farmer field schools (FAO, 2019a), these approaches lead to the development of social groups dedicated to crop protection and sustainable agriculture more broadly, combining empirical knowledge and scientific innovation. These groups have been involved in numerous schemes sharing the benefits of co-learning and "social ecology," "liberation education" and "epistemic change" (Pretty, 2020; Pretty et al., 2020). Beyond the realms of science and agriculture, there are many examples of open science benefitting from naturalists and citizen contributions (e.g., https://www.inaturalist.org/projects/che-bestiolina-c-e-nella-mia-siepe). Economic and environmental interest groups enable neighboring farmers to share ideas, agroecological know-how, and ACP tools and practices (Aulagnier, 2020). Interactive, collaborative knowledge management and exchange tools drive the agroecological and ACP transition at the national level (GECo platform: https://geco.ecophytopic.fr/), and the international level, including countries in the Global South (http://www.fao.org/agroecology/home/en/; http://www.endureinformationcentre.eu/?rvn=2; https://www.boost-ae.net/en/1/home.html).

4.3 Multi-actor and market diversification strategies for redesigning production systems

Diversification of agricultural activities remains the best option when redesigning systems toward agroecology. This relies on: (i) a wide range of actors signing up, (ii) research and development, and (iii) market opportunities.

This can be achieved by facilitating exchanges and co-design (Meynard et al., 2012; Simon et al., 2017). Prost et al. (2017) showed that the hybridization of heterogeneous knowledge "catalyses both the design process and knowledge production," especially when actors have diverging interests and/or viewpoints: this not only helps improve innovation, but also helps identify trade-offs (Penvern et al., 2015). ACP in mango crops in Réunion is a relevant example (Deguine et al., 2017).

Much has been written about farmers' contributions to the design of new production systems. Farmers have: (i) valuable experiential and local knowledge (Baars, 2011); (ii) diverse objectives, affecting agroecosystem design and management (Prost et al., 2017); (iii) the ability to convert their knowledge into workable solutions (Toffolini et al., 2017). An in-depth analysis reveals that farmers have diverse views on functional biodiversity, influencing the choice of best practices in their own production system (Penvern et al., 2019).

The difficulty of marketing ACP-derived goods and services can be an obstacle to its adoption (IPES-Food, 2020). Visibility and consumer recognition is a challenge without a recognized quality label, such as that of organic farming. However, "nested markets" exist; although often localized, they are well-represented worldwide. Organic certification offers added-value in the short term but does not cover all aspects of agroecology. Short-circuiting the incumbent food system could also reconnect farms to the food system (Magrini et al., 2019).

5. Research approaches to agroecological crop protection

In this section, we summarize the research approaches required for ACP, from a systemic approach in the design of healthy agroecosystems to designing and managing orchards based on ACP.

5.1 A systemic approach for healthy agroecosystems

A shift to a system-wide approach requires re-defining the system as more than just the crop (soil, plant diversity and other features crops interact with). Re-defining the system means interactions can be identified and understood and in particular, the areas requiring action become evident. For example, target pest populations are parts of metapopulations that require large-scale management, as seen in area-wide pest management approaches (Brévault and Bouyer, 2014; Vreysen et al., 2007). Changing the boundaries of the system, which is also defined by its purpose, may have major consequences on its ability to achieve its given purpose, and hence on the success of crop protection attempts.

5.2 Interdisciplinarity and transdisciplinarity in ACP

Further research is needed to assess the direct and indirect economic benefits of the biodiversity-based strategies at the core of ACP. Surprisingly, $<1\%$ of research papers in the field of "economic entomology" actually cover the economic aspects of crop protection (Onstad and Knolhoff, 2009). Transdisciplinarity is encouraged in ACP just as in agroecology (Fernández González et al., 2020). In addition, ACP scientists may benefit from reaching out to nutritionists, food toxicologists and food safety regulators (Wyckhuys et al., 2020a,b). Anthropological studies are useful for exploring the cultural dimensions of ACP practices. New ACP-derived ecological knowledge cannot be standardized due to different environmental contexts. This boosts interest in "local," "peasant" or "traditional" knowledge. To make good use of nature, knowledge must be "intimate," i.e., developed with both humans and non-humans during meetings, training, discussions, etc. This evolutive model of knowledge combines scientific, experiential, intellectual and sensory insights. Anthropology allows us to build bridges between culture and practices ("means of action on culturally defined materials"). Anthropology also helps to determine the status accorded by actors to elements of the agroecosystem, as well as their relationships, and this provides a collective drive in crop protection (Larrère, 2002).

Farmers need know how to effectively apply ecological principles to their farm's site-specific context. This was the aim of the FAO-endorsed farmer field school program in the 1990s and resulted in tangible reductions in chemical inputs on millions of farms. Yet, its successes have so far been scattered and short-lived. Socio-technical facets such as markets, user preferences, policy environments or vested interests of technology manufacturers, prevent improvements in sustainability (Deguine et al., 2021). In crop protection, these issues have not received the exposure they deserve, and insufficient attention has so far been given to multi-stakeholder innovation systems (Schut et al., 2014; Van der Jagt et al., 2020). Transdisciplinary weed research shows how the mobilization of natural and social sciences can integratively analyze difficulties at multiple levels and dimensions, hand-in-hand with stakeholders (Jordan et al., 2016). Without this type of integrative adapted support (e.g., Chaplin-Kramer et al., 2019), individual farmers are unlikely to bear the costs of switching production methods. Reaching a "tipping point" in sustainable crop health management may then become more unlikely.

5.3 Participatory approaches as a key route to ACP

Participatory approaches such as farmer field schools (see below) or local agricultural research committees can offer non-formal education, fill critical knowledge gaps and engage farmers in "discovery-based" learning (Braun and Duveskog, 2011). For instance, consultative farmer field schools are useful tools for cropping systems (Bakker et al., 2021). These can shore up farmers' knowledge of ecology, (re-)establish their awareness of biological control and ultimately remove their reliance on pesticide (Wyckhuys et al., 2019). By coupling the above approaches with information and communications technology (ICT), locally-validated practices can be shared through on- and off-line farmer networks and information can be tailored to the heterogeneous socio-ecological context of smallholder agriculture (Heong et al., 2021a; Nelson et al., 2019; Sinclair and Coe, 2019). Crowd-sourced citizen science, farmer-to-farmer educational videos or phone-based sensors and observation aids, e.g., digital microscopes, can all be integrated into ICT platforms (van Etten et al., 2019).

Participatory approaches work in two directions: complementing farmers' knowledge and expertise with scientific information, but equally drawing on it. Participatory plant breeding is a good example of collaboration in the co-construction of solutions and has been developed to meet the needs of low-input, small scale farmers, leading to fundamental changes in the way crop genetic diversity is managed (Sperling et al., 2001). Inspired by farmers' traditional management of crop genetic diversity and by co-construction with stakeholders, participatory plant breeding is built on site-specific context of soil-crop-water management. Well adapted to exploiting crop biodiversity potential, it has rapidly developed over the last 20 years (Ceccarelli and Grando, 2020). Participatory plant breeding matches the social dimension of ACP, and involves five key aspects: (i) decentralizing breeding to the farm; (ii) breeding multiple and diverse varieties and populations; (iii) promoting potentially promising traits (e.g., competitiveness against weeds); (iv) making use of a broad genetic base; and (v) incorporating the empirical knowledge of farmers and other stakeholders into the process. In addition, participatory plant breeding allows the simultaneous adoption of crop varieties or populations developed far away from the local network, as shown for rice in Nepal (Joshi et al., 2001), maize in Brazil (Machado and Fernandes, 2001) and barley in Syria (Ceccarelli et al., 2001).

A participatory plant breeding program on common wheat in France (Goldringer et al., 2020; Rivière et al., 2013) has developed varieties with long stalks that were more competitive against weeds and provided more organic matter to the soil, or bedding for animals. Genetically heterogenous and phenotypically diverse (van Frank et al., 2020), they adapt to changing environments and contribute to the farm's resilience. At the end of the value chain, participatory systems can provide guarantees to consumers while avoiding the entry barriers of third-party certification (Home et al., 2017).

5.4 A transdisciplinary case study: Designing and managing ACP orchards

Fruit orchards are one of the most pesticide-intensive systems. Substitution strategies maximize ES and pest regulation in multi-species, mixed fruit-vegetable or grazed orchards (Alaphilippe et al., 2013; Lauri et al., 2018). To compensate for the lack of empirical knowledge on unconventional orchards, co-design workshops take place with representatives from different concerns and disciplines (Simon et al., 2017).

During this process, ecologically-based pioneer orchards will require work to be re-organized (Legendre et al., 2021). Scales and agroecosystem dynamics are connected; the number of items to observe, monitor and manage increases (e.g., number of crop species, pests), with new indicators, more frequent interventions and increased coordination between and within tasks. However, some uncertainty will persist, and a period of vigilance, constant learning and adaptation will be necessary.

To design sustainable agroecosystems, Belmin et al. (2022) suggest using the full range of available knowledge, whether holistic or reductionist, both on the agronomic system and the human system. In addition, they strongly recommend considering the long, non-linear, transformational nature of agroecosystem design.

6. Agroecological crop protection research needs

This section highlights six research needs for ACP ranging from building sustainable seed resources and breeding to the integration of human and social sciences into the ACP framework.

6.1 Sustainable seed resources and breeding

Seed management provides immense added-value to the sustainability of food systems. The argument driving seed system improvements is that even modest expenditure can bring about major benefits, even in high-risk/ challenging field contexts (Sperling et al., 2001). The type, quality and phytosanitary status of the seeds of spacially adapted varieties not only determines the productivity of a given crop, but also the sustainability of the entire food system.

The use of certified seeds limits contamination of seed-borne pests and diseases and ensures improved seed germination, seedling vigor, crop establishment and yield under field conditions (Hitaj et al., 2020; Lamichhane, 2020). However, the main paradox is that key certified seed and plant resources are either not readily available for farmers or not adapted to the local pedo-climatic conditions (Chable et al., 2012). As most seeds are still marketed in "one-size-fits-all" package with a priori treatment for all cropping situations (Lamichhane, 2020), millions of farmers cannot choose the type of seeds for their fields. A wider choice of seeds (i.e., farm-saved, untreated, certified or pesticide-treated seeds) would increase profit margins for farmers while providing sustainable environmental and human health.

Having access to a range of crop varieties will allow farmers to make strategic management choices to sustain their farms. Countries need to understand the R&D status of the seed sector, the importance of genetic resources, plant breeding and related research, for the development of ACP at a national level, as in Switzerland (FOAG, 2008, 2016).

In the transition to ACP, the breeding focus should be on new crops, including minor and non-cash crops (e.g., cover crops) providing a range of ES with a particular emphasis on adaptation to climate change and reduced reliance on cropping system inputs (Lamichhane and Alletto, 2022).

In France, the yield gap between conventional and organic cropping systems is highly variable (20–60%). Boosting plant breeding research and a cooperative selection process between breeders and stakeholders produces selection criteria adapted to sustainable cropping systems (i.e., yield, bread value or biscuit quality, competitiveness against weeds). In this collaborative framework, the results of work on breeding are discussed during regular informal meetings and open days, including field trial visits. Field experiments are shared with partner networks, while breeding work (crosses, nursery and results analysis) is conducted at public research stations (Rolland et al., 2021).

6.2 The electrochemical soil-plant health model and a re-examination of the soil health concept

There is increasing evidence to support the importance of reduction-oxidation and acid-base reactions in the soil-plant system (Husson et al., 2021). This model postulates that Eh (redox potential) and pH homeostasis are key in soil-plant health and are fundamental to interactions between soil, plants and associated microbiota. Significant Eh-pH spatio-temporal variations have been linked to soil structure, organic matter and biological activity, affecting plant nutrition and plant-weed interactions (Husson, 2013).

Maintaining Eh-pH homeostasis is an energy-intensive process for plants, particularly in changing environments (Soares et al., 2019). The alteration of Eh-pH homeostasis through abiotic and biotic stresses increases susceptibility to pests (Anjum et al., 2016). In particular, plant oxidation increases susceptibility to most pathogens and renders plants more easily digestible by herbivorous pests, in contrast to sustained reduced conditions. Plants regulate and compartmentalize Eh-pH conditions both internally in plant tissues and externally in their rhizosphere by recruiting a specific microbiota through root exudation (Rolfe et al., 2019). In turn, rhizosphere microbiota contribute to soil structure and redox regulation, thereby improving plant protection (Mhlongo et al., 2018). Overall, a soil-plant health model integrating Eh-pH homeostasis would help understand soil processes in ACP.

6.3 A new outlook for plant health by controling microbiota-mediated plant-soil feedback

Crop diversification is a major agroecological lever (Beillouin et al., 2021; Duru et al., 2015; Tamburini et al., 2020; Zhang et al., 2020). In particular, it influences plant-soil feedback through soil microbiota (Marques et al., 2020). Several studies have demonstrated the beneficial effects of crop rotation on soil microbial biomass, diversity and function (Kim et al., 2020; Lienhard et al., 2013; McDaniel et al., 2014; Yang et al., 2020). However, the extent of benefits is dependent on the type and timing of agroecological practices (Garland et al., 2021; Wang et al., 2020), and pedological contexts (Degrune et al., 2019). To date, the role of soil microbiota has been mainly seen from the perspective of soil health (Lehmann et al., 2020; Zhang et al., 2020), rather than plant health (Hirt, 2020). Soil microbiota is a major stimulus of biodiversity both below and above ground, improving ecosystem multifunctionality (Delgado-Baquerizo et al., 2016). Moreover, soil and plant microbiota are a major feature of the phytobiome, a recent concept encompassing plants, their environment and the surrounding community of organisms (Beans, 2017; Bell et al., 2019).

Plant microbiota, and its associated rhizosphere, affects plant fitness via biomass production, acquisition of nutrients and phenology (Compant et al., 2020) or stress resistance (Liu et al., 2020; Vannier et al., 2019). Plant microbiota is expected to contribute to 60% of biocontrol products by 2025, for a $11 billion market globally (Sessitsch et al., 2018). Consequently, understanding and optimizing plant–microbiota interactions in ACP constitutes one of the biggest challenges of 21st century agriculture.

Soil-borne pest management represents a promising opportunity for ACP in two ways: (i) altering soil microbiota composition via crop rotation or cover crops, selected plant genotypes or organic amendments; and (ii) transplanting beneficial microbiota into soil (Arif et al., 2020; Fan et al., 2020; Peralta et al., 2018; Pineda et al., 2017). For instance, altering the soil microbiota to induce plant resistance to aboveground pests has been theorized (Pineda et al., 2017), and applied to major insect pests, namely the thrips *Frankliniella occidentalis* and the mite *Tetranychus urticae* (Pineda et al., 2020).

Volatile organic compounds constitute a major component of the plant–insect–microbiota interactions described above (Garbeva and Weisskopf, 2020). The volatile environment of crops, the odorscape, and plant–insect–microbiota interactions need to be better understood (Friman et al., 2021; Marques et al., 2020; Mony et al., 2020), to maximize the efficacy of ACP solutions.

6.4 The potential and limitations of "at scale" innovations and proofs of concept

Organic farming is a useful model to study the potential levers and implications of upscaling ACP. Constrained by its specifications, organic systems are proof of concept that chemical-free agriculture is possible, even if it more often uses the substitution approach than being chemical pesticide-free (see below). This is especially true if preventive pest management is used (Zehnder et al., 2007), as well as a combination of technical alternatives and premium pricing (to compensate for lower yields). Development of organic systems prefigures future challenges linked to large-scale ACP implementation (i.e., food productivity and sovereignty), as well as limits (biopesticide or pesticide alternatives, with as yet unknown ecotoxicological profiles) (Bahlai et al., 2010; Legrand et al., 2011). This scaled-up production, its accessibility to farmers, and its economic sustainability, will require the involvement of stakeholders and numerous regulatory processes. Outbreaks of pests previously controlled with chemical pesticides are a risk (Bianchi et al., 2013), even if manageable through natural regulations (Muneret et al., 2018). Processing and valorization at upstream (producers) to downstream (consumers) level are performed within short food circuits, key levers in the reduction of post-harvest chemical pesticide use. One feature of organic farming (unlike ACP) is its use of pesticides (copper, sulfur, biopesticides) and intensive soil tillage to control weeds, which could negatively impact soil function. Nonetheless, organic farming as a model for ACP may also extend the scope of research to nutrients, soil fertility management (Nicholls and Altieri, 2004), and indeed the entire food system.

The agricultural systems in Cuba and Sikkim (India) mentioned below are examples of scaling out and scaling up of organic farming at the state level. In both these cases, agriculture can be considered as organic by default, as in sub-Saharan Africa (Ratnadass, 2020), for different reasons and via different routes. In Cuba, organic production became compulsory during the "Special Period" when imports of petroleum, agrochemicals and farm machinery from the Soviet bloc ceased. This was further aggravated by restrictions imposed by the US trade embargo at the beginning of the Revolution (Acosta de la Luz, 2001; Altieri and Toledo, 2011). Sikkim's organic transition began in 2003 with a resolution in the state assembly to convert all agricultural land to organic (Meek and Anderson, 2020). An interesting point is that scaling up organic systems in Sikkim goes against certain agroecological principles (Meek and Anderson, 2020). In contrast, in Cuba, many farmers still view increasing production as a higher priority than maintaining agroecological commitments (Nelson et al., 2009), and may return to conventional or integrated production if this option becomes politically and economically viable.

6.5 Supporting farmers in their adoption of innovative methods

Identifying and understanding factors, decision criteria and values driving farmers' adoption of new crop protection and pest management methods are necessary to see how farmers design their strategy and accept certain practices when piloting a new system (Larrère, 2002). Compared to conventional agriculture, the effectiveness and benefits of ACP measures should be quantified, for example via life cycle impact assessment, accounting for pluri-spatio-temporal scales and ES (Alaphilippe et al., 2013). Quantified, these outcomes can be used to assess different scenarios in a given country or territory, in diverse of production situations, and the resulting macroeconomic consequences will be of interest to farmers (food production, farming income, energy saving, pesticide use, etc.).

Shifting from conventional farming to ACP overturns many practices; this can be seen by some farmers as taking a gamble. This is especially true in an economic crisis without insurance safety nets. Conventional crop protection takes short-term views and is often considered less risky (although rarely studied to date), whereas delegating crop protection to plants and beneficial organisms should be seen as a form of long-term insurance. Another barrier is the perception of "going backwards" when renouncing high-tech, with the fear of what neighbors may think. The adoption of technology to support "smart" pest management (e.g., plant and soil sensors) has been successful. Beyond mere food production, the management of complex systems and contributions to ES should be highlighted: enthused by agroecology, some farmers are motivated by a more interesting professional activity.

6.6 Exploration of human and social sciences

To improve under-developed ACP markets, the benefits of product quality, human health, environmental and societal vigor need to be acknowledged by all actors, providing added-value and financial returns for producers (Loconto and Hatanaka, 2018). To foster the agroecological values of ACP, more focus should be placed on standardization, case studies, and the way actors reorganize rules, markets and networks (Lamine et al., 2019). A new field of research on alternative marketing strategies, using consumers as food ambassadors, is opening up. These "ambassadors" mediate between producers and consumers, re-creating their dialog on a larger scale (Andersson and Ekman, 2009).

The ontological turn of repopulation of social sciences by non-human entities (Descola, 2005) compels us to think beyond nature and culture (Houdart and Thiery, 2011), and takes non-scientific views of the world seriously (Henare et al., 2007). It offers an ontological explanation of the changes of attitude toward plant life. ACP practitioners benefit from the "wilderness" in their production systems (see Section 4.1); their willingness to increase it will determine the extent of variation in production systems, and the development of "diplomatic" vegetable supply systems (Javelle, 2020). Social sciences will focus on a continuum of interacting components: plants (cultivated or not), animals (wild, bred, or domesticated, pests, beneficials), microorganisms and humans (with a wide range of roles in society). ACP thus entails a new approach toward social and human sciences. Usually, human ecology is defined as "the study of the form and the development of the community in human populations" for which the unit of analysis "is not the individual but the aggregate which is either organized or in the process of being organized" (Hawley, 1950, cited by Frisbie, 2001). We propose to go beyond human ecology to better analyze the links between social structures, such as the social organization of food supply chains, or in agroecosystem "structures."

7. Methodological breakthroughs in agroecological crop protection

In this section, we briefly describe the five key methodological developments forming the basis of ACP research.

7.1 New methods to characterize soil functions

Harnessing the microbial functions and managing soil interactions in an agroecosystem designed to suppress disease, for instance, presents great potential (see Section 6.3) (Chave et al., 2014; Chellemi et al., 2016). Classical microbiological assays have revealed the groups playing a major role in soil function (Agaras et al., 2014). More recently, high-throughput nucleic acid sequencing has provided access to hidden taxonomic and functional diversity (Nelkner et al., 2019), while metatranscriptomics identifies the functional groups contributing to disease suppression (Hayden et al., 2018). Drawbacks of these methods (e.g., incomplete reference databases), are countered by classical microbiological methods using high-throughput cell culture "culturomics" (Kambouris et al., 2018).

Recent advances have led to a better understanding of the key processes, including Eh-pH spatio-temporal variability at various scales (see Section 6.2), reflecting the importance of soil structure in Eh-pH regulation (Husson et al., 2018; Liptzin and Silver, 2015). Fenton reactions should receive more attention: coupled with enzymatic activity, they strongly impact soil organic carbon mineralization (Merino et al., 2020; Yu and Kuzyakov, 2021). At the plant-leaf level, improvements in Eh-pH measurement make them useable as plant health indicators (Husson et al., 2018). However, electrochemical measurement methods remain too sensitive, fastidious and time consuming. Near Infrared Spectrometry is currently under development and would assist the measurement and use of these indicators.

An integrative approach to soil health assessement, capturing the emerging properties of soil biota interactions (rather than biota structure), can focus on resulting soil functions (Kibblewhite et al., 2008; Lehmann et al., 2020). This concept is developed in a set of soil health indicators, Biofunctool®, which assesses three soil biological activity functions: carbon transformation, nutrient cycling and structural maintenance (Brauman and Thoumazeau, 2020). Thus, nine in-field, cost-effective indicators assess impacts of agricultural management practices on soil health (Thoumazeau et al., 2019). Better ways of measuring pest regulation functions are still needed, especially soil disease suppressiveness. Few certified indicators can be applied to a wide range of contexts, and methodological improvements are required to improve their reliability (Bünemann et al., 2018; Janvier et al., 2007).

7.2 Above-ground functional biodiversity and trophic interactions

Farms are the management units of agroecosystems. Assessing biodiversity at farm level is crucial (Herzog et al., 2017). An example is "Syrph the Net," the database of European Syrphidae (Speight, 2020). Ecological networks using holistic system-level evaluations have also been developed in recent years, and provide complementary information (Ma et al., 2019).

Semi-natural habitats surrounding fields can play a significant role in pest and natural enemy movements, although their impact on pest levels and management is poorly documented (Holland et al., 2016). Several methods can trace insect movements across the agricultural landscape mosaic, ranging from simple use of transects and directional trapping, to various marking/tracking DNA-based methods (El Sheikha, 2019). Tracking devices are sufficiently small to fit on pests and natural enemies such as carabid beetles (Batsleer et al., 2020). However, simple and efficient habitat-scale methods without the need for species sampling or identification, are still to be developed.

In plant-diversified systems, interaction networks are complex, involving small species with poorly understood behaviors. Unpicking trophic and non-trophic links and understanding how they are modified by agroecological practices is one of the major challenges facing ACP. Inference of links between pests and regulatory species is largely based on two factors: (i) co-occurrence measurements, recently improved through machine learning (Bohan et al., 2017), and (ii) use of ratios of stable isotopes of nitrogen ($^{15}N/^{14}N$) and carbon ($^{13}C/^{12}C$), helping position each species within the food web (Ponsard and Arditi, 2000). However, these methods rarely provide evidence of trophic links. DNA metabarcoding can identify plants or animals consumed by a given organism (Derocles et al., 2018). Of limited use, this method has good potential for studying food webs and detecting new trophic interactions. Advances in digital technology make in situ imagery in the field possible, and artificial intelligence algorithms are now used in automatic observation and minimal disturbance detection (Tresson et al., 2019), providing a dynamic picture of interactions.

7.3 New methods to characterize field odorscapes and to dispense volatiles

Natural pest regulation can be partly managed with volatile organic compounds (VOC). Deployment depends on our ability to develop new methods to describe odorscapes created by multiple components in space and time, and to dispense blends activating key regulations in agroecosystems. Real-time VOC characterization in the field urgently requires new, high-resolution technologies such as PTR–time of flight–MS, although adapting them to field conditions is challenging (Turlings and Erb, 2018). Analyzing complex VOC data using machine-learning algorithms such as Random Forests or based on artificial neural networks will also be essential (Vivaldo et al., 2017). Other developments include the need to upgrade pest monitoring sensors in the field (Turlings and Erb, 2018). Current advances in high-throughput phenotyping methods for modern crop breeding may overcome many of these challenges (Jin et al., 2020). Advances in formulation and diffusion technology will be necessary to combine different compounds, adjust carriers, ensure their continuous release, prevent early evaporation or degradation, or adjust emission rates and temporal release patterns of emitted volatile organic compounds (Garbeva and Weisskopf, 2020). Microorganisms, inoculated on the plant or in its environment (Garbeva and Weisskopf, 2020), can also be used as natural emitters, overcoming the various limitations of chemical volatile dispensers (Mofikoya et al., 2019).

7.4 Renewal of experimental and systemic modeling

Agroecological Crop Protection involves a range of practices whose future impacts are difficult to assess (Lechenet et al., 2017). There is a need to account for cross effects, as well as cascading relationships between technical levers and other agroecosystem elements. Systemic experimental designs can test and quantify the impact of cropping systems with adjacent semi-natural habitats on pests and natural enemy distribution at the farm scale (Gagic et al., 2021).

Modeling key components of agroecosystems is necessary to: (i) better understand how they work, (ii) integrate existing knowledge, and (iii) design ACP strategies. Any modeling framework can be used for ACP, provided that it includes cropping practices and environmental conditions affecting pest or injury dynamics. For the sake of simplicity, here we address only three important fields of modeling for ACP: qualitative modeling, network analysis and modeling of crop damages.

Aubertot and Robin (2013) propose a qualitative method to integrate all forms of available knowledge in a decision tree. This approach allows all relevant knowledge sources to be combined, including experts, farmers, advisers, simulation models, and datasets obtained from field experiments or diagnosis of commercial fields. It is particularly suitable for ACP, a field with significant knowledge gaps (Deguine et al., 2021).

During the last 20 years, network analysis has been a dynamic field: studies examining the relationship between food web structure (e.g., connectance, size, modularity) and ecosystem operation (stability of communities) (Dunne et al., 2002) identified the importance of food web stability in pest regulation (Crowder et al., 2010). With a reduced number of trophic groups, dynamic models are useful to understand the role of cropping practices on pest management (Malard et al., 2020) and more widely on ES (Tixier et al., 2013b). The next challenge will be to link such tools to the overall management of agroecosystems, especially the soil-plant system (Tixier et al., 2013a). Semi-quantitative (Gaucherel et al., 2017) and statistical methods (especially structural equation modeling) are holistic tools to establish the links between food webs and other ecosystem processes (Poeydebat et al., 2017).

Pest damage was initially modeled using descriptive or explanatory methods as a decision-making tool in chemical protection, rather than for long-term damage-limiting strategies. These models simulate pest effects on crop carbon processes such as carbon fixation and storage (Boote et al., 1983). While helping to understand and assess damage mechanisms, these approaches were limited to only one pest, or a host-pest couple (Bevacqua et al., 2016) at the plant or field scale, per cropping cycle (Caubel et al., 2017), with little or no crop feedback. Improvements are required to upscale from plant–pest interactions to agroecosystem functions and the key processes triggering pluriannual epidemics, which combine fine-grained mechanistic models (e.g., Zaffaroni et al., 2020) and landscape models (Poggi et al., 2018), or integrating ecological concepts into agronomic models (Wood et al., 2015).

7.5 New tools to enhance the individual and collective innovation process

Integrating diverse agro-food contexts and other key community actors may help innovate ACP strategies. This is because a range of methods to implement ACP can be built which take into account the expectations of each group. This implies researching and adopting tools supporting facilitation between actors. Many tools now take biological processes into account in participatory research approaches with stakeholders (Barnaud et al., 2018; Prost et al., 2017). However, questions remain about the best way to integrate soil and plant health indicators in ACP.

Serious games may aid in the local adaptation of new systems by improving learning outcomes, personal or social development and engagement, and user-centered learning (Campo and Dangles, 2020; Rebaudo and Dangles, 2013). Several games encourage crop protection learning and engagement in farming communities. An example is the Azteca Chess game, which teaches biological pest control to coffee farmers (García-Barrios et al., 2017) or the Innomip game board, which helps support coordinated management of invasive potato pests (Rebaudo et al., 2014). Use of serious games can modify farmers' views of entomofauna and support the adoption of agroecology, tipping the balance toward beneficial insects at the expense of pests.

In addition, social networks and crowdsourcing, such as the citizen science application iNaturalist, can be used to create and share entomological knowledge with farming communities (https://www.inaturalist.org/projects/agri-andes-ecuador). Importantly, many now have access to mobile devices: an opportunity to increase the participation of women and young farmers.

Another area of research looks at the performance of ACP strategies (see Section 6.5), raising questions about relevant scales and indicators. This change of perspective also addresses the "clean field" and "zero defect" myths and the variability of agricultural products.

8. Supporting farmers in the transition to agroecological crop protection

This section describes six strategies supporting farmers in their transition to ACP.

8.1 Co-construction of knowledge in ACP systems

The effectiveness of ACP systems depends on their adaptation to local environmental conditions. As such, farmers have extensive (but not always explicit) knowledge of their agroecosystems (see Section 4.1). With their unique position observing nature and production situations, the farmer is well placed to identify the conditions when plant resistance to pests is at its most effective, and transmute them into agricultural management (Molia et al., 2015). In this sense, the farmer is no longer a recipient of advice, but becomes co-designer of new management strategies (Malézieux, 2017).

Supporting farmers redesigning their activity in design workshops or more formalized multi-stakeholder setups (e.g., innovation platforms) (Dabire et al., 2017) makes use of exploratory solutions to empower farmers to propose and implement specific adaptions to cropping systems (Leclère et al., 2021). Farmers thus directly contribute to agricultural knowledge (Reau et al., 2012). Using existing knowledge and data from trial results is essential, and it would be worthwhile identifying farmers with successful ACP strategies, to inspire and motivate new ACP research and design projects (Laurent et al., 2021; Quinio et al., 2021; Périnelle et al., 2021; Salembier et al., 2016).

Managing crop health at the territory scale requires coordination and organization in rural communities (see Section 4.2). New ACP approaches should include social capital, common goods, group decision-making, inter-group relations, commitment and persuasion; these play a role in the influence farmers have on the decisions taken by their peers (Coll and Wajnberg, 2017). Creating crop protection networks between farmers (Nelson et al., 2019) and partnering with researchers, development organizations, farmer organizations, policy designers, pesticide sellers (and other broader networks), has much potential.

8.2 Making products and equipment available for farmers

Farmers transitioning to ACP, require seeds of locally adapted varieties, (Bergtold et al., 2019) (see Section 6.1), but farmers often use their own propagation materials without considering pest presence. Introducing minimal quality standards with safe agronomic and prophylactic practices could avoid the spread of diseases (Sastry, 2013).

Farmers also need access to appropriate mechanization and digital tools as they transition to ACP. Examples of solutions are small-scale machinery hire, tool-sharing, call platforms (Anidi et al., 2020), agricultural machinery

(Baudron et al., 2015), and various patent-free methods (Giotitsas, 2019). Digital technologies offer better technical support to farmers (Santos Valle and Kienzle, 2020; Wei, 2020) during the systemic design of production systems (Schnebelin et al., 2021). Such area-wide pest management requires cross-farm, community-wide, and sometimes national cooperation.

8.3 The specific role of bioproducts in ACP

Bioprotection is a set of potentially appealing practices for farms transitioning to ACP (see Sections 3.1 and 3.3) (Belmain et al., 2022). ACP requires a rethinking of relationships between farmers and input suppliers. As plant pests compete with humans for the same resources (crops and their products), the term "pest," in this context, has solely economic implications. However, pests must be considered in a broader context, addressing all aspects of sustainabililty. Pest management strategies are no longer designed to destroy pests, but rather repel and manage them. Now, it is a question of cohabiting with pests and fostering biodiversity, of which pests are a part. This will dramatically reduce the demand for plant protection products (Gliessman, 2016; Mishra et al., 2015). This paradigm shift is likely to modify the current industrial power struggle: conventional players will have to reinvent themselves, while new opportunities will appear for smaller pioneering companies, promoting new bioproducts and strategies adapted to local conditions.

Most farmers (particularly in the Global South) have little access to high-quality inputs for ACP (e.g., biopesticides and microorganisms) which tend to be far more expensive than older chemical pesticides (Schläpfer, 2020). Similarly, soil biostimulants (amendments, microbial treatments) or biofertilizers (nitrogen fixing bacteria, mobilizers of specific nutrients such as zinc, sulfate, or mycorrhizal fungi) enhance plant health but are inaccessible. Microbial biocontrol supply chains can be delicate to manage due to the short lifespan of living components, limited or unpredictable demand, and low farmer awareness. It is possible to envisage a system in which vendors are no longer paid by quantity sold, but on the savings made on pesticides. Moreover, suppliers must meet smallholder needs and diversified investment challenges, promoting non-market strategies for ACP (Wyckhuys et al., 2020a). This may entail group coordination and cost efficiencies, while lowering transactional risks for farmers. Finally, registration authorities have to revisit data requirements faced with new biopesticides.

8.4 ACP enhancement via downstream market conditions

The economic profitability of ACP is crucial to: (i) generate viable incomes for farmers, (ii) minimize risks related to the modification of production systems, and (iii) recover any production overcosts.

Cropland certification may offer more remuneration, better market conditions, and help share the risk (or perceived risk) of more sustainable pest management strategies with consumers. Such standards have been found to promote sustainability in more than 133 countries (Tayleur et al., 2017), of a global cropland coverage with an 11% annual increase between 2000 and 2012. Very few standards explicitly promote ACP practices. For instance, several GlobalGAP crop standard criteria only record farmers' practices with no mandatory reductions in pesticide use (Schreinemachers et al., 2012). Label organizations have a great potential to attract farmers to ACP and other sustainable methods by establishing standards supporting this shift. This is a particularly powerful tool; these organizations link producers with key retailers and, ultimately, consumers. IP-Suisse (www.ipsuisse.ch) and Biosuisse (www.bio-suisse.ch) are examples of this approach in Switzerland.

Voluntary sustainability standards must focus on better efficiency and strengthened links with the transformation sector. Food processing and storage are fundamentally affected by ACP. Conversely, damaged products can be repurposed instead of being discarded, and chemical preservatives can be reduced with appropriate food processing technologies (Penvern et al., 2015).

Downstream market conditions must represent the seasonality of agroecological production. Direct contact between producers and consumers is an important tool in reconnecting consumers to agricultural seasons. In the management of apple scab, Vanloqueren and Baret (2004) identify almost two dozen protection strategies operating on different levels (fungal pathogen, tree, orchard and marketing system). In a systemic and agroecological framework, these strategies are complementary, providing links between technical and institutional innovation. ACP becomes embedded in agroecosystems and the wider food system (food processing, product quality, consumer expectations and value chains), as well as in regulatory and political standards (sociotechnical systems). Consequently, ACP will contribute to the emergence of new political and sociotechnical opportunities for innovations in food systems (Busch, 2011). Market reorganization is necessary to provide diversified markets for diversified farmers, with a guaranteed remuneration supporting additional sustainable production. Again, digitalization makes traceability easier to achieve which in turn will improve communication, extend interactions with consumers or create direct marketing chains (Schnebelin et al., 2021).

8.5 Instruments and policy tools supporting ACP

Transition to ACP will strongly depend on our capacity to change (and modernize) the sociotechnical environment. Ecological science provides powerful tools which support the transition to ACP by facilitating the creation of sustainable agroecosystems (Lavigne et al., 2021). Improved availability of key services, inputs and supplies are supported by public policies at both the local and international scale. Market innovations could further remunerate ACP farmers and impart a positive image of agriculture, working with nature, not against it. Regardless of the scale of decision-making and application of these mechanisms, favorable public policies can be placed into three main categories:

(i) *Creating a favorable downstream environment for ACP*: These policies provide financial facilities for ACP practitioners, such as payment instruments for ES, lower pesticide residues in harvested products (de Blas Ezzine et al., 2017), and training. Some policies ban specific products or regulate pesticides (Rhiannon et al., 2019; Vryzas et al., 2020); however, such policies are hindered by the short-term financial interests of agribusiness (Aulagnier and Goulet, 2017; Niederle et al., 2021; Sabourin et al., 2018). Banning plant protection products has often led to the development of alternative control methods (via ACP), but not in all countries. This has distorted competition between farmers from different countries, often at the expense of good agroecological practices. On the other hand, care should be taken when prohibiting herbicides, as alternative methods such as conventional tillage can lead, in some cases, to increased soil erosion and increased long-term carbon emissions.

(ii) *Improving ACP*: This is the technical aspect of improving and adopting ACP methods, such as supporting research and the communication/publication of results (Colmenárez et al., 2016; Lefebvre et al., 2015). Incentives for the creation of new ACP companies, training in new professions, or subsidies/laws to make bioinputs more affordable than conventional inputs (Goulet, 2021) are needed. In funding scientific research, there are large discrepancies between genetic engineering, chemical pesticides or big data solutions, vs nature-based solutions (biological control, area-wide pest management, multi-level biodiversity, systems analysis, and preventive measures). These discrepancies have a major effect on research, delivery and dissemination (Vanloqueren and Baret, 2004). Funding and implementation at the international level must be strengthened and must stringently control chemical pesticides. This is essential to incentivize transition to ACP.

(iii) *Global regulation & support for agroecological transitions*: We need broad policies encouraging and supporting cooperation and innovation in agroecology through farmer organizations and cooperatives, e.g., Ecoforte policy in Brazil from 2012 to 2019 (Giraldo and McCune, 2019; Niederle et al., 2021). Proactive ACP policies will ultimately have little impact if they are not part of a collective global transition toward more sustainable food systems (Gliessman, 2016, 2021; Rastoin, 2018).

(iv) *Promoting and supporting ACP*: One of the main obstacles hindering ACP public policies is the financial interests and influence of agribusiness and the agrochemical industry, and seed/agri-food companies and their lobbies (Le Coq et al., 2020). Insights provided by the technical trajectory of IPM can guide the scaling out of ACP.

The co-construction of ACP knowledge requires farmer training and high levels of stakeholder engagement—and needs to take into account farm-level preferences and needs of growers. The alignment of national and international stakeholders is also needed. Heong et al. (2021a) recommends introducing organizational arrangements, incentive systems and communication strategies to sustain adoption of IPM- or ACP-based ecological practices and support the new norms and systems.

8.6 From public policy to ecological literacy: Pitfalls to avoid in the popularization of ACP

An enabling policy environment is crucial when promoting ACP worldwide (Wyckhuys et al., 2022). Furthermore, considering the pesticide industry's vested interests, it is crucial to pay attention to any ambiguities that seep into policy. The experience of IPM showed that although sustainability is a priority in public policies, practical notions of how pest management should be achieved, and to what extent crop production should be protected "at all costs" and the interpretation of policies may differ (Deguine et al., 2021). France provides an example of the need for a clear policy to ensure systemic changes: assessment of reduced use of plant protection products (Ecophyto Plan) showed negative results (an increase of 20% in their use) after more than 10 years. The agricultural sector, as well as the administration, attributed these poor results to the absence of substitute products or methods (Guichard et al., 2017). Political and socio-technical analyses, however, show that the cause instead stemmed from an inadequate consideration of the upstream and downstream changes required by the technique (Delon, 2015). The failure was mainly due to the abandonment of a systemic approach (Aulagnier, 2020; Aulagnier and Goulet, 2017; Cornu, 2014). As shown by IPM, some policy mechanisms can have unintended effects (Matyjaszczyk, 2019). Thus, ACP-enabling policies do not automatically generate the supportive context needed for their adoption. A critical review of policies, implementation mechanisms and *ex-ante* impacts is thus needed.

As shown by IPM, there are various pitfalls which growers and farming communities must avoid. A notable weakness is growers' poor ecological literacy combined with well-anchored beliefs and perceptions on the difficulty and/or incompatibility of ecological pest management (Parsa et al., 2014; Wyckhuys et al., 2019). This results in a lack of empowered ecological decisions, meaning grower knowledge can be circumvented by pesticide solutions. Building an ACP knowledge base helps to avoid falling into the trap of focusing on pest monitoring and economic thresholds, which lends itself to appropriation of pesticide industry paradigms (Deguine et al., 2021).

Another pitfall to avoid while implementing ACP is the limited integration of local preferences and knowledge. While research and innovative technologies are being produced, a lack of attention to growers' community preferences can limit the success of ACP. If local, indigenous grower knowledge is ignored or missed, the opportunity to integrate effective technologies and take advantage of the acceptability of locally-preferred practices could be missed (Abate et al., 2000; Nampeera et al., 2019).

As knowledge, norms and practices are changing, policies that bind these together are crucial (Wyckhuys et al., 2022). This support should at the very least (1) promote market entry and increasing returns from biocontrol or other ACP technologies, (2) encourage research that enables context-specificity of ACP recommendations, and (3) break current path dependencies and challenge the narratives around pesticide-dependent practices.

9. Conclusion

Agroecology is an efficient and practical way to create healthy, safe and sustainable food systems in the future (ECR, 2021; FAO, 2019b; HLPE, 2019). The aim of this paper was to promote ACP as a compelling and powerful crop protection concept which is inspired by principles of ecology, agronomy and agroecology, and to develop sustainable agriculture and food system challenges with "One Health" at its core. We provided evidence that the success of ACP implementation and dissemination will be determined by stakeholders and the socio-technical system, as it is the case for agroecology in general (Côte et al., 2022). In the current context of climate change, global biodiversity loss and spread of invasive pests, stable and well-adjusted agroecosystems are expected to be more resistant and resilient (Lamichhane et al., 2015). Research toward large-scale ACP deployment should focus on biological issues and ecological issues (e.g., related to biodiversity and soil health) as well as social issues (e.g., systemic and participatory approaches) to enhance its socio-economic and environmental performance. In this regard, ACP promotes research on pesticide-free agriculture (Jacquet et al., 2022). Another challenge for ACP research is the need for cooperative studies to obtain new knowledge (description, classification and understanding of the biology, ecology and socio-economy of agroecosystems and food systems) and to prevent and manage risks related to crop pests and diseases, without favoring one over the other. This is in agreement with Chevassus-au-Louis (2006): "*The challenge for agricultural research is to move from a linear and sequential vision to a vision of a system in which the three aspects of description, understanding and management develop simultaneously and interactively, so that each activity benefits as quickly as possible from the results of the others*" and with Shennan et al. (2005): "*An agroecological approach to agriculture involves the application of ecological knowledge to the design and management of production systems so that ecological processes are optimized to reduce or eliminate the need for external inputs. Nowhere is this more apparent than in the management of agricultural pests.*" ACP is fully consistent with these holistic positions in its aim to renew crop protection practices.

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