

Transition to Pesticide-free agroecology-based agriculture: From theory to practices

1. Introduction: present policies on agroecology and crop protection

To ensure a sustainable farming sector, many actions, activities and regulations have to be developed and supported by different target actors. Food security is one corner stone of a sustainable farming system. This implies a new paradigm and disruptive changes of agricultural management principles, especially pest management. Nonetheless, the most used system implies the use of pesticides, which are harmful for the environment, biodiversity and human health. Pesticide-free agriculture appears to be one production system as an objective that several countries want to reach, especially that it fits with the objectives of the Sustainable Development Goals. Hence, pesticide risk reduction has been set as a key priority in governmental and agricultural policies in European countries. The European Union has set the objective of pesticide-use reduction by 50% by 2030, with a focus on the most hazardous pesticides (Finger et al, 2024a). The undermining element of these ambitious objectives is the choice of a common indicator. Indeed, based upon the SUD directive (2009/128/CE) defining the overall ambition of reduction of use and impact of pesticides, every country implemented its own plan with its own indicators.

One scheme that is currently emerging is a pesticide-free production system, different from the organic production system, as all innovations levers are considered as possible (Jacquet et al, 2022).

Pesticide-free agriculture

Pesticide-free production system lies in between conventional agriculture and organic agriculture. It advocates the non-use of pesticides while being less restrictive than organic production. Pesticide-free comprises the entire period after harvest of the previous crop until the moment after harvest of the pesticide-free crop (Finger et al, 2024a). Pesticide-free production can imply the use of pesticides already used in organic farming. However, it can also entail the non-use of any pesticides like copper-based products.

Finger et al (2024b) distinguish two types of pesticide-free systems: the weak model and the strong model. The first involves not using chemical synthetic pesticides in parts of crop rotations. The latter implies that no chemical synthetic pesticides are used on the entire farm level and in entire crop rotations.

The pesticide-free agricultural production is in the early stages of development, and is just getting off the ground in some pioneering countries like Switzerland and Germany. In Switzerland, since 2023, the government is supporting the introduction of pesticide-free farming. The weak model is used in grain production (e.g., spelt and rye). The farmers are following different regulations to cope with the restrictions. They receive a private price mark-up, interesting economically (Finger et al, 2024b).

Some inconsistencies still lie in the use of the term pesticide-free production, as well as in the public or private programs that were developed. Finger et al (2024a) stated that for Swiss farmers, those that comply with the public governmental program can be non-eligible for the private program that tends to be similar but with specific differences (i.e., the exceptions for pesticide use as well as the scope of adoption of pesticide-free production).

It is therefore crucial to clarify and adopt a unique definition and practices of a free-pesticide agriculture. Labels and regulations that will emerge have to be not confusing for consumers and farmers. Also, disparities between countries should disappear to ensure a coherent and sustainable farming in Europe.

However, a pesticide-free agriculture requires new modes, systems and practices to achieve a good crop protection, i.e. ensuring the production of a safe food which is affordable to all. A successful transition to a sustainable and efficient crop protection requires a fundamental redesign of cropping systems, based upon prophylaxis, crop diversification and restoration of ecosystem services, i.e. supported by agroecology. This redesign must be supported by robust digital supply-chain traceability, expanded independent advisory capacity, and value-chain de-risking mechanisms that compensate farmers for economic transition risks.

Agroecology

Agroecology has a crucial role in supporting the resilience to agricultural inputs scarcity. This concept has been increasingly used lately. However, there is not a clear definition of agroecology. The term agroecology emerged in the first half of the twentieth century. Lampkin et al. (2021) highlighted the lack of clarity in terms of its relationship to agricultural approaches, as agroecology is seen as an alternative to the dominant mass industrial farming practices currently at stage. This was further supported by the review paper of Ewert et al (2023).

The term is a mix of agriculture and ecology. Thus, agroecology is “a science, seen as a subset of ecology or biology given that this discipline addresses the relations and interactions between organisms and their environment, including other organisms (e.g., humans) in ecosystems managed for agricultural purposes” (IFOAM EU, 2019). Agroecology is defined differently depending on the cultural context, countries and production systems. In addition to a production system and scientific principles, it implies a social and knowledge framework that is supposed to represent a sustainable alternative solution to the more industrialized and global agricultural system. It is also defined as a movement, crucial for food security and a way for agricultural transformation that is deeply needed and requested (IFOAM EU, 2019).

The FAO defined it as integrating “*ecological and social concepts in the design and management of agricultural production and food systems, while optimizing interactions between plants, animals, humans and the environment*”. Finally, the European Association for Agroecology stated that agroecology “*(...) encompasses the whole food system from the soil to the organization of human societies. It is value-laden and based on core principles. As a science, it gives priority to action research, holistic and participatory approaches, and transdisciplinarity that is inclusive of different knowledge systems. As a practice, it is based on sustainable use of local renewable resources, local farmers’ knowledge and priorities, wise use of biodiversity to provide ecosystem services and resilience, and solutions that provide multiple benefits (environmental, economic, social) from local to global. As a movement, it defends smallholders and family farming, farmers and rural communities, food sovereignty, local and short food supply chains, diversity of indigenous seeds and breeds, healthy and quality food (...)*”.

A new CAP for Europe, from 2023 to 2027

The new Common Agricultural Policy (CAP) entered into force in 2023. In addition to the Pillar 2 agri-environmental and organic farming policy support, a "Green Architecture" has been created. It involves a new Pillar 1 with initiatives for a “conditionality” enhanced, specifically with eco-schemes that aim at supporting farmers in applying practices and help them evolve towards more sustainable farming models (Lampkin et al., 2021).

All Member States had to design eco-schemes in their strategies, with a part of their direct payment budget spent on these schemes, up to 25% as suggested by the EU (Krishna et al., 2023). This new mechanism proposed a common list of actions aiming at supporting “practices such as organic farming, agro-ecological practices, precision farming, agro-forestry or carbon farming, as well as animal welfare improvements”.

The European Commission approved 161 diverse eco-schemes designed by the EU member states. Still, there are various degrees of measures to be adopted by the countries. Each country can have different eco-schemes to apply. However, the effective implementation, the funding and the scale are highly important.

19 countries have adopted eco-schemes with agroecological practices. The most favored ones are Low intensity grass-based livestock system and Practices and standards as set under organic farming rules (Krishna et al., 2023).

Pathways to pesticide-free agriculture: which consequences for policies?

There are several pathways towards a pesticide-free agriculture, at least on the theoretical point of view, each of them being possibly supported by an adequate policy and its translation into regulations.

Three types of strategies may be identified to reach this ambitious and disruptive objective.

The first one would be based upon a progressive reduction of the use. It corresponds to the scenario 1 developed by the CSA FORTUNA. It is the core of the present EU policy and it was at the very heart of the Farm to Fork strategy before its withdrawal. Such a strategy is based upon the implementation of practices that improve the efficiency of the levers that are already implemented and upon a substitution approach, where the chemical pesticides are replaced

by mechanical or biological substitutes. For instance, it mobilizes the mechanical weeding instead of using herbicides. Or it uses biocontrol substances to replace fungicides. This strategy is fully compatible with the preservation of the present cropping systems and is supported by most farmers organizations and by the downstream industries. However, it has been well documented that the present cropping systems, because of the low crop diversity, the lack of semi-natural areas and large mean field size are not favorable to biological regulations (Sirami et al, 2019). In this type of strategies, general agricultural policies and the CAP are the most relevant ones.

The second type of strategies would fully rely upon regulations, with a rapid phasing out of all chemical active substances. In such a situation, the farmers have to modify their cropping systems, where the crops that are the most sensitive to weeds, diseases and pests are withdrawn first. Such a strategy is very unfavorable to the present cropping systems and is met when an active substance, which is central to one crop is phased out. When neonicotinoids used as a seed treatment on sugar beet were withdrawn, this being confirmed by the EU Court of Justice on January 2023, the sugar beet producers and the sugar beet industries faced a severe dead-ends, when they did not anticipate. In order to avoid such a difficult situation, a slogan emerged within the European farming community: no active substance withdrawal if no alternative solutions. The fact that they used the word 'alternative solutions' means that they are mainly exploring the possibility of substitution approach. A similar scenario may occur, even in absence of regulatory withdrawal. Indeed, the emergence of pest resistance leading to loss of efficacy leads to the same situation of dead-ends, if the problem emerges for an active substance which is a cornerstone of the agronomic practices. In this type of strategies, the relevant policies are those related to regulations, such as the regulation 1107/2009 and the Omnibus X.

A third type of strategy, designed for a pesticide-free agriculture (scenario 2 of the CSA FORTUNA), would be to support the transition towards cropping systems which are co-designed to increase the prevention of pests and diseases through increasing biological regulations, ie thanks to agroecology and ecosystem services. Such a strategy and the associated policies must not target the farmers only. They must address the value chains as a whole. Indeed, they must be supported by robust digital supply-chain traceability, expanded independent advisory capacity, innovation in the processing industry to use all agricultural products including those from new species planted as a source of diversification, and value-chain de-risking mechanisms that compensate farmers for economic transition risks. In this type of strategies, the most relevant policies are the policies related to research and innovation in order to foster agroecology transition, the possibilities for sustainable and prophylaxis-based crop protection in the redesigned cropping systems and adequate changes in the supply chains.

2. Research and innovations support a committed policy toward agroecology and chemical pesticide-free agriculture

Researchers in academia and in private companies are actively developing and promoting alternatives to chemical pesticides, which make it feasible to achieve an ambitious transition.

It is not possible to draw an exhaustive map of the research and innovation achievements that would be supportive of a successful transition. However, we may underline the changes in some key domains.

In Agronomic and Agroecological research, research focuses on redesigning cropping systems and on the understanding of ecosystemic and biological mechanisms and processes which could enhance natural pest resistance, diversifying biocontrol strategies, and developing pest-resistant cultivars. Jacquet et al (2022) proposed a first review of all the achievements and the new research fronts. These efforts aim to create sustainable, pesticide-free agricultural systems.

In order to illustrate those possibilities, let's focus on two domains

- Redesigning cropping systems to increase functional diversity. Many research worldwide are presently documenting without any ambiguity that increasing functional diversity with cropping systems, through diversification, use of intercrops, reduction of tillage leads to more ecosystem services and reduction in input use intensity (Carini et al, 2026). It is now also demonstrated that such diversified systems are able to produce more calories and macronutrients across Europe (Vico et al, 2026). These recent publications confirm the main messages published from the meta-analyses carried out by Tamburini et al (2021) and Beillouin et al (2021).
- Breakthroughs occurred in the understanding of the biological mechanisms. It is worth mentioning the tremendous achievements in the description of the plant microbiota and their links with plant health (see for instance Fournier et al, 2025). This may lead to either indicators to document the efficiency of prophylactic measures in the preservation of the most secure microbiota and/or to the development of synthetic communities of microorganisms which could be supplemented to the crops in order to better protect them. Similar breakthroughs have been achieved in chemical ecology with the characterization of the volatile organic compounds which determines the behavior of the insects, either the herbivorous ones or the predators. Creation of adapted odorscapes, either through the use of companion plant species or through the spray of chemicals is now accessible.

Technological innovations are numerous. It is worth quoting the major achievements due to digital and AI-based technologies in plant recognition, in treatment of signals and decision making and in precision application. The COST action CA21134 gathered many participants who were strongly involved in those technologies and their use in crop protection. Projects like WeLASER are exploring precision technologies for weed control without chemicals, demonstrating the potential of integrating technology with sustainable practices. UAV (drones) may be used to run quick survey of the crop health status and local application of chemicals or biocontrol. Robots are becoming more popular and efficient for weeding. Similarly, the technological innovations in breeding and especially through the emergence and use of gene editing is offering new perspectives to build polygenic resistances to pests and diseases and to foster the plant immunity.

Policy support: Institutions like ETH Zurich advocate for a "third way" in agriculture, promoting systems that forgo synthetic pesticides without fully converting to organic farming, thus offering a more accessible transition path for many farmers. Project FAST supported by the French Priority Program 'Growing and Protecting Differently' (<https://www.cultiver->

proteger-autrement.fr/eng/projects/fast) aims at providing evidence of the effectiveness of a variety of public actions for triggering a large-scale transition to pesticide-free agriculture, and at assessing the socio-economic consequences of such a radical change. The general objective of the project is to propose concrete solutions (political and organizational), directly usable by the public decision-makers and stakeholders more broadly, whose efficiency will have been evaluated by the most advanced techniques, which include lab and field experiments, research-action approaches, and the use of large-scale simulation models.

3. Potential drivers and barriers for agroecology adoption in practice, including multi-level perspectives

The present crop protection practices are characteristic of a Lock-in situation as described by Geels (2002). All stakeholders are in equilibrium in a situation where crop protection is massively ensured thanks to a massive use of chemical pesticides. It is thus very important to understand and document the barriers to change and the need for changing. A survey was undertaken during the COST action in its WG1 and barriers and needs were prioritized during dedicated seminars.

They prioritized the identified technological barriers, the main referring to the efficiency of bio stimulants/alternative solutions regarding the cost/benefit aspect.

Furthermore, the main need is related to training for advisory services regarding the use of alternatives and specific zero-pesticide practices.

For the social and markets topic, the main barrier is the lack of knowledge for producers and consumers and the need to overcome it by educating producers, policy makers and consumers about the negative effects of pesticides on human health and environment. The lack of evidence and data regarding the hidden costs are clearly a barrier to change.

Regarding the regulation, the main identified barrier quoted by many participants is related to the conflict of interests within the regulatory organizations and their connections with the phytosanitary industry. The main need is the development of interaction between legislators, scientists, industry and the establishment of clear political objectives.

4. Proposition for a Strategic Research and Innovation Agenda

A Strategic Research and Innovation Agenda (SRIA) was established in the CSA FORTUNA where participants to the COST action were very committed. They established implementation pathways that link research and innovation (R&I) priorities to the FORTUNA scenarios for reducing pesticide use in European agriculture. It also examines how the intermediary actions should be prioritised over time to support the implementation of the 50% pesticide-use reduction scenario by 2030 and the pesticide-free scenario by 2050.

The analysis was based on the inputs from more than 40 participants representing research, advisory services, farmers' organisations, policymakers and agri-food value chain actors.

For each cropping system (arable, vegetable and perennial crops) and transition scenario, the identified knowledge gaps were translated into expected alternative solutions, including prototypes, demonstrators and research outputs, prioritised these actions along a timeline, and identified the main actors responsible for their implementation and the stakeholders expected to benefit from them. This process resulted in implementation pathways connecting research outputs to the long-term transition scenarios.

Across the three cropping systems, participants agreed that reducing pesticide dependence requires more than the only development of new technologies. Future research should support integrated solutions combining resistant varieties, biological control, agroecological approaches, biodiversity-based management and digital technologies for monitoring and decision support. However, the successful implementation of these solutions also depends on enabling conditions beyond research itself, including effective advisory services, farmer training, demonstration activities, supportive regulatory frameworks, financial incentives, functioning value chains and greater consumer awareness. These complementary actions were consistently identified as essential for facilitating the uptake and scaling of research outcomes. The comparison of the two scenarios revealed different implementation pathways. The 50% pesticide-use reduction scenario represents an incremental transition that builds on existing farming systems by strengthening integrated pest management (IPM), improving knowledge transfer, increasing the adoption of biological control and digital technologies, and supporting farmers through targeted policy measures. In contrast, the pesticide-free scenario requires a more fundamental transformation of agricultural systems. It involves the redesign of cropping systems based on agroecological principles, greater crop diversification, stronger landscape-scale coordination, reorganisation of value chains, stable markets rewarding sustainable production, and broader societal support through coherent long-term policies and consumer engagement. Despite differences between cropping systems and scenarios, several common messages emerged. First, research and innovation must be embedded within broader implementation pathways that anticipate the institutional, economic and social conditions necessary for the uptake of alternative solutions. Second, advisory services, demonstration farms and participatory knowledge exchange are fundamental to accelerating adoption by farmers. Third, long-term policy commitment, appropriate regulatory frameworks and targeted financial support are required to reduce transition risks and create favourable conditions for innovation. Finally, the transition towards reduced pesticide use depends on coordinated action involving researchers, policymakers, farmers, advisory organisations, industry and consumers.

Some more precise research questions were identified in the discussions of the COST action, in the Management Committee meetings, in the training schools, in the C-K workshops and in the meetings of the Core Groups. The most acute ones are listed here.

- In the cropping systems, there are plenty of individual measures for individual components, but little considering the system level. How to do it? More systems analyses are needed, on the long run, documenting all issues related to all dimensions. In practical terms, it means that are needed either longer projects and/or dedicated designs to run long-term surveys of pesticide uses and impacts and all crop protection levers.

- How to better consider the lack of adoption by farmers? IA and digital will not solve all. More consideration to be paid to capacity building of farmers and advisors including more knowledge, and more training (which is necessary for the adoption of new and disruptive practices)
- Regulations must be based upon the most recent scientific knowledge. How to make the best use of it, to facilitate transition to production systems which are safe for environment and human health?
- Less active substances (withdrawal and few new approvals), more use of a limited number of pesticides, leads to an increasing rate of pesticide resistance. How to deal with this situation in order to avoid dead-ends for most supply chains? In case of dead-ends, the farmers will stop the considered crops. This leads to loss of crop diversity and loss of ecosystemic services provided by diversity. There is a need for addressing specifically these situations, both for designing solutions and adapted systems and for supporting farmers during the transition phase.
- How to document and reduce the large context-dependency of the 'alternative' methods for crop protection? Or, how can we learn from one situation and disseminate lessons to other contexts?
- The research lacks of 'holisticity'. How to combine research on individual levers and holistic approaches? How to design research on individual levers, considering that they will be used in complex systems?
- How to deal with climate change? Is it only a new context, or does the climate change create a new situation where we do not know the mean and the variance of extreme events (non-stationnarity). Furthermore, climate change will increase the rate of introduction of new invasive species and will modify the equilibrium between pests and predators, for the pairs already present in our environment, and this equilibrium will be unbalanced in favour of the pests. This must be taken into account without delay.

The Common Agricultural Policy and the EU Research framework are not paying anymore a sufficient attention to the crop protection. The priority at the EU level for projects devoted to crop protection and pest management has faded out. A risk exists of reduction of devoted research efforts and on the maintenance of the research capacities and facilities (researchers, expertise, experimental sites), leading to long term weaknesses. The COST action showed that Europe has a tremendous research potential in this domain which must be kept at the highest quality level and to whom challenging objectives must be addressed.

5. Design of a roadmap for pesticide-free agriculture based upon a wider adoption of agroecology

The pathway towards a pesticide-free agroecology-based agriculture, implies major changes in systems, practices and choices, throughout the whole value chains and in the society. This will only be accessible with deep changes are implemented in policies regarding research and innovation, agricultural supports,...

Pesticide-free production systems must be implemented in conditions where the crop health is ensured and where food security is achieved.

This may be achieved if and only if all IPM principles are implemented in a coherent manner, i.e. starting from the implementation of principle 1 for maximizing prevention of pests and diseases and increasing the suppression of reservoirs and thus reducing the risks. Without implementation of such a strategy, there is little chance to achieve a pesticide-free agriculture. But, beyond this global target, the same issue holds true when production systems have to deal with either the withdrawal of a key active substance or with the emergence of pest resistance to pesticides.

It is clear that under the present policies and in the present dominant production regimes, prophylaxis is the very weak step of most crop protection strategies. This may be surprising considering the very large number of levers that have been identified as contributing to Principle 1 of IPM and the possible role of agroecology and its regulation services provided by an increasing functional diversity. What should be done to foster this?

- In Research: A literature survey shows that prophylaxis is not receiving a lot of attention in research. The scientific literature appears to be poor in three main domains. The first is the low number of studies that relate the levers of IPM P1 to a better crop protection. It is sometimes quoted in the introduction and conclusion of the papers. For those who are relating the levers to a better crop protection, very few quote the possible pesticide reduction that may be achieved thanks to these levers, by documenting either the lower pest pressure or the lower use of pesticides. The economic dimension of the Principle 1 levers is never documented. So, it should become a priority, in public and applied research, for creating new levers for prophylaxis and for documenting their benefits.
- Prophylaxis is a cornerstone of future cropping and production systems, and has to be combined with many others. Progressively, prophylaxis should become the rule and be the permanent part of no regret strategies. Thus, we should also imagine scientific exploration for designing prophylaxis-based production systems. It is a real agroecological engineering that must be built, with adequate scientific backgrounds and theoretical frameworks and adapted tools. In such prophylaxis-based cropping systems, the intervention thresholds in decision support systems will be different from the existing ones. This will have to be explored in research.
- For business: Prophylaxis is often seen as a poor basis for the present business models of the companies which are based upon selling pesticides. However, alternative business models based upon prophylaxis as a keystone are possible. Indeed, part of the biocontrol levers are prophylaxis related, such as the use of macro-organisms when released in the pest reservoirs, or all tools provided by pheromons and kairomons as they will reduce the occurrence of pests and increase in the population sizes. The regulatory policies make no difference between a biocontrol solutions targeting prophylaxis and a chemical product used as a biocide. Moreover, there are new business models to be built in order to document the reality of the weed, pest and disease pressure. The clear information on the actual pressures is absolutely compulsory for reducing the farmers' mental load, for designing the other interventions required for a good crop protection and for measuring the efficiency of the prophylactic measures. This was already claimed for by Zijlstra et al in 2011. However, recent advances in technologies such as molecular detection of pathogens (Faedda and Silva, 2024), image analysis for weed detection (Yang et al, 2024), pheromone-based

detection (Malou et al, 2025), offer new perspectives that have to be transformed into tools for farmers decision or for rural extension.

- For training and extension: As a heritage of decades of pesticide-based crop protection, extension services are primarily based upon decision-support systems where pesticides are the core of the strategy. Moreover, the extension services are often working with the most advanced farmers. These farmers, who could correspond to the 'early adopters' as described by Rogers (1995), may be the most receptive on alternative strategies where prophylaxis could play an increasing role. The situation is much more difficult for approaching the farmers who are far from regular advice and support and who are influenced by the sellers of inputs, and especially pesticides. From this observation, several points should be considered
 - Changing the mindset of the extension services and their capability. There has been debates in some countries such as France on whether extension and marketing could be done by people in a same company. As an output of these debates, there was no clear evidence of the benefit of the separation, but it was pointed out that the quality and the training of the advisors were essential. This would lead to the need to better define what is expected from extensionist in crop protection and crop production and to better qualify them. The system created in Quebec, Canada, would deserve attention and evaluation
 - Training and education. When the new farmers enter their farming business, they have convictions on which they develop their business, but they are often seeking for advices and support and looking for financial support and cheap loans. This situation is offering the possibility for a training dedicated to agroecology and prophylaxis-based crop protection, for those who will set plant productions. This also implies adapted curricula to be designed and produced.
 - Adoption of new practices is encouraged and facilitated when farmers are working together. This was described by Arthur (1994) as direct network effects. In the case of prophylaxis-based crop protection, it is even more important. Indeed, in most situations when pest and disease reservoirs have to be controlled and reduced, it implies that all farmers at a local level work together and implement prophylactic methods. We may here quote the example of the sugar beet virus whose reservoirs are residues of the previous crop and regrowth of remnants from the previous crops. The situation may be trickier when the reservoirs may be in private gardens. This is for instance the case for *Drosophila suzukii* where the possible reservoirs may be the fruits and the composters in the private gardens or the berries of wild shrubs. In order to have a wise and efficiently implementation of prophylaxis, it will be necessary to define new rules at a local level, beyond the only farmers. These new rules will require to have possibility for controlling how all actors implement these rules.
 - However, all the difficulties that may be met for implementation of prophylaxis lead to the fact that farmers mindset and all social norms of crop protection are relying upon pesticide-based strategies, and where little space is given to biological regulations offered by agroecology and increasing functional diversity and by adapted strategies.
 - To foster the transition, especially regarding the mindset and the capability of groups of farmers to work together for co-designing and co-implementing future pesticide-free crop production systems, the approaches based upon

agroecosystem living labs, as defined by McPhee et al (2022). This could also be beneficial in order to capture knowledge from practitioners and for setting adapted governance.

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