ENHANCING THE FUNCTION AND PROVISIONING OF ECOSYSTEM SERVICES IN AGRICULTURE: AGROECOLOGICAL PRINCIPLES

Etienne Hainzelin
CIRAD (Centre de coopération Internationale en recherche agronomique pour le développement)
Email: etienne.hainzelin@cirad.fr
Abstract

Agroecology is essentially based on the use of biodiversity and ecosystem services in agricultural production, and thus represents a true rupture from the way agriculture has been seen and analysed by mainstream science for over a century. Agroecology does not have a consensual definition; it represents a conceptual space to think about agricultural sustainability through strong interactions between science and society with a wealth of new concepts, questions and tools. Among the diverse ‘incarnations’ of agroecology, the lowest common denominator is found at plot level. The basic and common principle is to increase biomass production by enhancing the services provided by living organisms and by taking the optimal advantage of natural resources, especially those which are abundant and free (e.g. solar radiation, atmospheric carbon and nitrogen, rainfall). Agroecology aims to manage, and in some cases to increase, production in a sustainable and resilient way that will maintain and improve the natural capital in the long term. It will enhance the ecological processes and interactions of functional biodiversity above- and below-ground, over space and in time, by both intensifying biological cycles for nutrients, water and energy, and controlling the aggressors of crops. Because ecosystem services are involved, agroecology has long been working on larger scales (i.e. farms, landscapes, watershed basins, value chains, food systems). Agroecology has had a deep engagement with interdisciplinary research, in particular focusing on some of the drivers of agricultural development such as food industries and distribution, consumer health, public policies, etc. Because agroecology strongly depends on locally available natural resources including agrobiodiversity, it cannot prescribe ready-to-use technical packages to farmers. Rather, agroecological models and solutions are built by mingling scientific and traditional knowledge and by strongly relying on local learning and innovation processes. With the many challenges ahead, agroecology represents a true alternative avenue for agricultural transformation; while it questions the role and practices of agricultural research and calls for a significant renewal.

INTRODUCTION

As the challenges that the world has to face are becoming overwhelming: food and nutrition security, biodiversity erosion and ecosystems integrity, climate change, energy transition and decarbonation of the economy, etc., there is an acute need for finding sustainability and an urgency to be able to build concrete way of implementing it. Agriculture of the world, as with all other human activities, must reflect on how it can genuinely increase its sustainability.
Agroecology is a concrete approach to transform the agriculture of the world, in its huge diversity, into more sustainable forms and systems. Because agriculture uses nearly 40 percent of the Earth’s land, over three-quarters of available freshwater, and provides livelihood and jobs to almost half of the world’s labour force, it has intimate links with some of the most acute world challenges – as mentioned above (Hainzelin, 2014).

The future of agriculture is not written in stone; there is no universal law that requires agriculture in developing countries to follow the same steps of modernization by industrialization, as has happened in most of the rich countries. There is obviously a necessity to improve land and labour productivity to be able to cap the pressure on land, protect fragile ecosystems and avoid deforestation, but the intensification pathways and modalities is today’s acute question. Agroecology represents a new vision of intensification, a ‘family’ of pathways of transformation that concerns all agricultural systems: from manual and ‘organic by default’ agriculture in regions that have not yet started any intensification process, to industrialized agro-systems that need to rethink their model because of its unsustainability.

In this chapter, we will review the basic principles of agroecology, and discuss how its diverse incarnations mobilize ecosystem services to intensify production in a sustainable way. We will then see what these principles imply in terms of the consideration of local contexts and traditional knowledge. Finally, we will reflect on the role of scientific research in contributing to build agroecological intensification pathways.

AGROECOLOGY OPENS A WIDE RANGE OF SOLUTIONS TO TRANSFORM AGRICULTURE AND IMPROVE ITS PERFORMANCE AND SUSTAINABILITY

A shift of paradigm

Agroecology represents a rupture with the way agriculture has been seen and analysed by mainstream science for over a century – with an essentially reductionist viewpoint and an increasing dependence on external inputs. According to this mainstream perspective, the logical evolution of agriculture is one of yield intensification through the use of high-yielding varieties and high levels of external inputs (fertilizers, pesticides, irrigation, etc.). This model of ‘conventional intensification’ has been the base of industrialized, ‘Green Revolution’ agriculture. It promotes a strong specialization of crops, often reduced to a uniform and synchronous canopy, ultimately consisting of a single genotype of some major species, with the rest of the living organisms being systematically eliminated as ‘limiting factors’. It has long been seen as the ultimate way to produce, but its sustainability is increasingly questioned, because it has forgotten the importance of biodiversity as the driving force of production and regulation processes in ecosystems. Despite spectacular gains in terms of productivity (economy of scale, homogeneity, mechanization, etc.), it has caused an extreme impoverishment in biotic interactions (Figure 1).
Acknowledging the absolute double necessity of intensification and sustainability, several authors including Pretty and Bharucha (2014) have been developing the concept of “sustainable intensification” as a “process or system where agricultural yields are increased without adverse environmental impact”. This concept, on which everybody should easily agree, does not articulate a specific technological pathway; it emphasizes ends rather than means, which can be extremely diversified (Pretty and Bharucha, 2014).

On the other hand, agroecology is very focused on means: it is mainly based on a stronger provision and mobilization of natural resources and functionalities of biodiversity and the relevant ecosystem services that sustain agricultural production such as natural pest control, maintenance of soil fertility and pollination. In this way, it is an ‘ecological intensification’. It represents a rupture with conventional intensification, but it is in tune with the other transformative evolutions that agriculture has known since it started in the Neolithic: domestication and breeding processes, and later on association animal-crops, rotation with legumes crops, soil tillage, then no-tillage, etc.

A new way of looking at performance

Given the need for sustainability, what exactly does the performance of agricultural production mean? It is now widely recognized that agriculture is multifunctional, as stated in the following passage from the International Assessment on Agricultural Knowledge, Science and Technology for Development:

“other important functions for sustainable development include provision of nonfood products; provision of ecological services and environmental protection; advancement of livelihoods; economic development; creation of employment opportunities; food safety and nutritional quality; social stability; maintenance of culture and tradition and identity” (IAASTD, 2009).
Agricultural productivity cannot only be measured by labour or land productivity. Negative externalities as well as the supply of ecosystem services and amenities must enter into the calculation. Furthermore, they must be computed over time so that the long-term impact on ecosystem potentialities and resilience can be evaluated. This multi-criteria performance, a crucial element to evaluate sustainability, is being debated: numerous indicators are proposed but very few are agreed upon by consensus. A recent meta-analysis based on 49 research papers published in Europe identified over 500 sustainability indicators, of which the vast majority (431) were used only once (Buckwell, 2014). This illustrates the lack of agreed-upon tools to measure sustainability, although numerous research initiatives are in progress to be able to better characterize sustainability (Caron et al., 2014).

The principles of agroecology lead to a re-analysis of all technical interventions in cropping systems. This analysis is based on a long-term vision of ‘aggradation’, building on existing foundations, where natural capital improvement is one of the goals. The example of tillage illustrates the balance that needs to be made between the expected positive effects (e.g. reducing weeds, opening soil porosity) and the negative effects (e.g. energetic and equipment cost, erosion susceptibility and perturbation of soil biodiversity) (Griffon, 2013).

AGROECOLOGY DOES NOT HAVE A CONSENSUAL DEFINITION BUT IT HAS MANY ‘INCARNATIONS’

Although various scholars have described agroecology with considerable details and a sound conceptual basis (Altieri, 1995; Gliessman, 1998), today it has no consensual and clear definition. Its very nature is much discussed; it has been described as a science, a movement and a practice, showing how much its nature depends on the point of view of the author (Wezel et al., 2009). Agroecology has ‘incarnations’ that are many and very diverse. Within the family of practice, we can include permaculture, organic agriculture, eco-agriculture, conservation agriculture, evergreen agriculture, minimum or no-tillage, etc. – each focusing on one specific feature of agroecology. The expression “ecological intensification” refers even more to the range of means to be mobilized in priority to transform agriculture though agroecology (Griffon, 2013; Tittonell, 2013; 2014). On the science side, scholars could engage in endless debates as to whether agroecology is a new scientific discipline, or a trans- or an inter-discipline, noting that its concepts and methods are still quite fluid.

The scope of topics addressed by published research on agroecology is also extremely large. Xavier Reboud (pers. comm.) analysed more than 2 500 references of scientific papers published between 1975 and 2010, either using the word “agroecology” or being related to agroecology without using the term. His attempt to group and map the scientific questions or themes linked to agroecology resulted in a large variety of fields, research objects, scales, etc.

Agroecology represents a conceptual space to think about agricultural sustainability through strong interactions between science and society, with a wealth of renewed concepts, questions and tools. The fact that the definition of agroecology is itself somehow fuzzy is considered by some authors as an opportunity and richness; the diversity of perspectives generates active debates, and is a promising source of new ideas and concepts (Griffon, 2013).
Among the large diversity of agroecology ‘incarnations’, the lowest common denominator is found at plot level. The basic and common principle of agroecology is to enhance the services provided by living organisms taking the optimal advantage of natural resources, especially those that are abundant and free (e.g. solar radiation, atmospheric carbon and nitrogen, rainfall).

**HOW DOES AGROECOLOGY MOBILIZE BIODIVERSITY AND ECOSYSTEM SERVICES AT PLOT SCALE?**

**Three main levers of using ecosystem services to intensify**

First, agroecology seeks to optimize functional biodiversity above-ground, at different scales over space and time, to intensify biological cycles for nutrients, water and energy (Malézieux *et al*., 2009). The amplification of these cycles, each one of which is an ecosystem service, aims at increasing biomass production, focusing particularly on the harvested biomass (food, fibre, energy, etc.). Constant attention is paid to the need to maintain natural resources and increase the local ecosystem’s potential. Experimenting with the complementarity of niches, canopy architectures and root systems among species (including the ‘service species’ grown to provide specific services), and planning annual and perennial combinations, etc., maximizes the uptake of resources, both below- and above-ground.

Second, functional biodiversity is utilized to limit the population of bio-aggressors like weeds, pests and soil-borne diseases that reduce the harvested crop biomass. There are innumerable examples of the use of biological control, augmentation of pest predators and aggressors, allelopathic effects and stimulo-deterrent diversion techniques to control aggressors. Agroecology advocates building knowledge on how biological spatio-temporal stands and interactions, trophic chains and specific ecology, can enhance the fight against crop aggressors (Ratnadass *et al*., 2014).

Third, agroecology manages functional biodiversity below-ground by amplifying biogeochemical cycles in the soil, recycling the nutrients from deep profiles and increasing microbial activities. This is probably where conventional and ecological intensification differ the most; the former relies almost exclusively on fertilizers and amendments to provide the nutrient needs of the canopy, whereas the latter mobilizes and enhances the activity of the living communities of the soil to improve the nutrient cycles. Agroecology does not exonerate the need to compensate nutrient exports, but as it provides a larger and more active soil space, and reduces nutrient losses, fertilizers are used in a more parsimonious way. This is a completely different intensification mindset, but there is much to discover about the different ways to apply this principle. Soil cycles are a mostly unknown world and only 10 percent of the soil biodiversity – that represents one-quarter of the total living species – have been described. Moreover, little is understood about the way soil cycles and biodiversity work in different soils. The soil fauna and microbial biomass can reach up to 10 tonnes ha$^{-1}$, but can also be extremely ill-treated and depleted by modern cropping techniques (Eglin *et al*., 2010).
The expected advantages

Agroecology obviously depends much more than conventional cropping on the locally available resources and environment. Climate, particularly rainfall amount and distribution, nature and richness of the soil, available biodiversity, etc., will affect the equation of agroecology. Therefore, the expected advantages will differ depending on the context, but will generally be of three kinds:

» Increased biomass production and carbon sequestration in plants and soil throughout the year in a way that will maintain and improve the natural capital (enhanced soil biology and fertility) in the long term;

» Reduced input costs and technology dependency through agroecology by first tapping into free local resources, better energy balance of the crop and reduced externalities from inputs to human and environment health;

» Improved output stability and capacity to cope with and adapt to stress, perturbation and aggressors, because agroecology does not depend on synchronized and homogeneous mechanisms.

Agroecology is no magic bullet. It takes a considerable amount of both knowledge and innovative spirit to build these new systems and attain these advantages. One of the challenges will be to maintain the mineral balance as the system intensifies and the exported biomass increases. For some macronutrients, such as phosphorus, the equation will be particularly hard to solve, but this can be a common research venture between conventional and agroecological approaches, both having to apply the principle of parsimony. Most of the time, applying agroecological principles means a ‘complexification’ of cropping systems. This may be considered as a drawback, hampering the standardization and mechanization of techniques, especially on larger-scale farms. There is also an on-going argument about the comparison of performances between conventional and agroecological systems. If we limit this comparison to yield, the results can favour conventional intensification. However, when the analysis of production efficiencies is combined with the overall cost of the crop including negative externalities, the comparison is rarely in favour of conventional systems. Furthermore, agroecology applies the commonly accepted principle that there are trade-offs between short-term yield and long-term sustainability, whereas conventional systems are more short-term centred. This is why new multi-criteria tools are needed to measure the performances of different cropping systems.

Some concrete illustrations of applied agroecology

The basic principles that have been described above are already being applied with success at large scales, both in large mechanized farms and smallholders’ farms. Planning and managing spatial and temporal biodiversity for functional optimization means dealing with genetic diversity but also species and ecosystem diversity. It always means ‘complexification’ of cropping systems, not only on the plot but also in the landscape around the plot. Among many possible examples, four illustrative cases of this ‘complexification’ are provided below.
No-tillage techniques in Mato Grosso, Brazil:

In the Amazonian regions of Mato Grosso (Brazil), no-tillage techniques associated with different combinations and the succession of multiple crops have been used over an area of 10 million ha. Rainfall is very high in these regions and the conventional monocropped soybean cultivation, after clearing the forest, leaves the ground uncovered and provokes high levels of erosion. Using service plants in intercropping with commercial crops, the principles applied are: (i) to keep the soil covered by a crop canopy or biomass on the ground; and (ii) develop a powerful and deep root system and ensure its viability all year-round, during very humid months as well as the dry months. These two applied principles permit the maintenance of soil biological activity and biomass production throughout the year, the elimination of erosion, and the amplification of nutrient cycles from very deep horizons (Séguy and Bouzinac, 2008). The total acreage under conservation agriculture (no-tillage, cover crops) in Brazil is now around 18 million ha, both within very large-scale farms and smallholders’ farms (Scopel et al., 2005).

‘Push-pull’ systems in Africa:

To control corn stem borer in Africa, the International Centre of Insect Physiology and Ecology (ICIPE) designed a combined use of ‘trap plants’ (Sudan grass or elephant grass) and ‘repellent plants’ (molasses grass, Desmodium uncinatum), which respectively attract and repel the borer for its oviposition, with a view to optimize their individual partial effects. Such processes are called ‘stimulo-deterrent diversion of pests’ or more simply ‘push-pull’ systems. They open innumerable combinations of species and designs of settings (intercropping, ‘peri-cropping’, etc.) to control crop aggressors (Ratnadass et al., 2014). This family of techniques, which are not costly but mobilize farmers’ intelligence and innovative spirit, are being used by a fast growing number of smallholders in Africa.

Temperate agroforestry systems in Europe:

Agroforestry is a traditional farming system in many tropical regions, as it used to be in the temperate regions before the process of intensification. The association between annual and perennial species can be very complex and brings a wealth of benefits: better exploitation of resources, diversity of products, complementarity over space and over time, improved capacity to buffer shocks, etc. Research has shown great interest to re-introduce tree species in large intensified and mechanized crops. The results from the large European project “SAFE” that worked in seven countries on the association between cereal crops and different tree species (walnut, cherry, poplar, oak) have been quite positive (i.e. one plus one can be more than two) in terms of global yield (up to 30 percent more than separate plots), with additional benefits for carbon sequestration, profitability, adaptive capacity, etc. The re-introduction of tree species in large mechanized monocrop farms in Europe will not happen overnight; it will take time as it requires a kind of a mental revolution, but eventually it might impact up to 65 million ha in Europe (Dupraz and Capillon, 2005).
Service species for pest control in the French West Indies:
In general, banana crops are heavily treated with different pesticides (up to 80 treatments per year in Central America) and this is a cause for serious concern with respect to human and ecosystem health. In the French West Indies, an original scheme of research and development with a producers’ organization was launched to find ecological ways to reduce pesticide use without losing control over crop pests. A wide range of ‘service species’ to cover the ground at different stages of the banana crop, as well as crops to be grown between banana cycles, have been tested to reduce pest populations (nematodes, weevils), increase soil porosity, and contain weeds and erosion. Finely detailed research has been carried out in spatial and trophic ecology involving different species in association with other agroecological techniques (pheromone trap techniques, fallow management, varietal improvement, etc.). The results are quite encouraging; the pesticide dose has been reduced (from 12 kg ha\(^{-1}\) in 2006 to 4 kg ha\(^{-1}\) in 2012), especially for insecticides, while keeping control of nematodes and weevils, and reducing the overall production cost (Risède et al., 2010).

AGROECOLOGY HAS LONG BEEN WORKING ON LARGER SCALES THAN THE PLOT

Because it is dealing with ecosystem services that are often mobilized at scales larger than plots, agroecology has long been working on innovations at higher scales – farms, landscapes, watershed basins, value chains and ultimately, food systems. These innovations generally go in the same direction, which means diversification and ‘complexification’ of production systems that require planning, management and coordination at higher scales (Tittonell, 2013). To deal with pests or insects at the plot level requires a consideration of the different trophic aspects, including the population of natural enemies occurring at the landscape level. To deal with soil erosion on a watershed slope, measures to increase the ‘roughness’ of the land across the slope are needed. To optimize crop production and the efficiency of the food system, communities may often need to better coordinate their different production strategies. Agroecology must consider the living communities in the plot, around the plots, and in non-cultivated ecosystems at the landscape level. This need for coordination, between farmers and between communities, may represent both a constraint and an opportunity in agroecology.

In fact, in regions where agroecology has been applied for a longer period of time, it is clear that there is a co-evolution between technical systems and rural societies – between ecological and social systems. Altieri and his colleagues have effectively shown the degree to which smallholders’ initiative is central to agroecological innovation and outscaling (Altieri 1995; Altieri and Nicholls, 2012). This means that interactions between the social dynamics among farmers (organization, cooperation, learning process, connection with other stakeholders of the value chains, etc.) and technical innovations at different scales are crucial for a beneficial transformation.

Finally, many drivers of agricultural transformation are outside of the control of producers (e.g. the economy of agribusiness, agro-inputs upstream and value chains downstream), or even completely outside of the agriculture world (food industry and distribution systems, urban
consumers’ markets, public policies and regulation, etc.). As a consequence, the transformation towards agroecology depends substantially on parameters that can be either ‘enabling’ or ‘handicapping’.

For all these reasons, agroecology has been dealing with complex problems since its inception, mingling basic biological and ecological mechanisms, sometimes at a very fine scale, with human, social and political questions that can reach global scales (Wezel et al., 2009). Integration of these extreme differences in scales generates radically new questions for which scientists are generally poorly equipped (Chevassus-au-Louis et al., 2009).

AGROECOLOGY STRONGLY DEPENDS ON LOCALLY AVAILABLE NATURAL RESOURCES

Agroecology gives priority to the use of local resources including agrobiodiversity. Therefore, it strongly depends on the local context and potential. The different climatic, edaphic and biological parameters of a specific local context will affect the available resources and fashion the possible technical systems that will make the most of these resources. For this reason, agroecology does not prescribe ready-to-use technical packages but seeks to meet farmers’ needs with an optimized range of technical options that farmers will combine and refine (Caron et al., 2014). This is a crucial difference in approach from conventional intensification; models and solutions are built from a mingling of scientific and traditional knowledge and they strongly rely on learning and innovation processes among local stakeholders.

Some implications

A consequence of the importance of local context and the shift from ‘ready-to-use’ to ‘custom-made’ cropping systems, is that producers and their networks become the centre of local innovation systems. There is no longer a uniform technical prescription; farmers are being empowered in technical but also in social, organizational and political ways.

This means that science must be able to feed local innovation systems with pertinent scientific knowledge and provide new knowledge engineering, using the farmer’s knowledge as a base. Agroecology needs cutting-edge science not only to be able to cross different disciplines and scales, but also to combine knowledge of different origins and reliability levels, in a way that enhances learning and innovation dynamics. Practical experiences, including through farmer field schools and sharing between innovative peasants, show how demanding these participatory processes are, but also how rewarding they can be.

Another important consequence of the transition towards agroecology is the status of agrobiodiversity. This key component of resilience is the principal lever that farmers can mobilize to intensify, and it must remain accessible to small farmers at no cost. Its erosion must be stopped because it is essential capital for future adaptation; in situ conservation of agrobiodiversity must be supported as an indispensable complement of ex situ conservation (Louafi et al., 2014).
Agroecology is a radically new intensification avenue for most farmers of the world, but the pathways are diverse and many. These pathways could touch virtually any farmer in the world, including smallholders as well as larger producers. In some regions, agroecology has been applied with success for many decades by innumerable farmers. However, there are different policy environments, with some more enabling than others. Agroecology transitions will reinforce the resilience of agriculture and reduce the dependency on inputs, but it has a cost and will not happen without specific public policies, including transition policies for family agriculture, payment of environmental services, training, etc.

**CONCLUSION: CRITICAL QUESTIONS ON THE ROLE AND THE PRACTICES OF AGRICULTURAL RESEARCH**

With the many challenges ahead, agroecology represents a true alternative for an agricultural transformation while at the same time posing some critical questions on the role and practices of agricultural research; it calls for a significant renewal of what is expected of agricultural science. Because of the specificities of agroecology, there are direct consequences for the role and the practices of researchers (Caron et al., 2014):

» Research should reflect on its role and input into agroecology – opening new questions of research, trying to shake the ‘path dependency’ wherever it may exist, and finding new and open ways of managing knowledge. This requires a reinforcement of the capacity of collective action among researchers, at team and project level, but also at institutional level, because a better research ‘orchestration’ of the many institutions working in this field is needed, to avoid redundancy and build critical mass.

» Researchers cannot be only knowledge producers and technology prescribers; together with engineers in charge of assembling existing knowledge, they should also become catalysers of change and innovation, which means to be able to work with different kinds of stakeholders, sometimes through asymmetric partnerships, with unbalanced strengths and powers. Scientists should take into consideration local knowledge and maintain strong personal interactions with agricultural realities and local innovation systems.

» Agricultural research will need more connections with basic knowledge to be instrumental in the implementation of agroecology (functional ecology, predictive biology, etc.), but also the capacity/tools to integrate and explore the long-term effects and consequences of the different options.

» Biologists, especially breeders that work to improve living organisms, must re-think their approaches and open up to the consideration of a broader range of species (domestication of ‘service species’ providing key ecosystem services, including animal species or micro-organisms) and new kinds of varieties (multi-crop and multi-genotype breeding, participatory

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1 Predictive biology is a field of biological research centred on a fine understanding of gene expression (and therefore prediction) by integration of different disciplines and tools.
breeding, varieties-to-be-refined, etc.) (Ahmadi et al., 2014). Genetic progress should be reassessed in the light of the multi-criteria concept of performance, as defined earlier. Making the most of biodiversity at different scales could open a new era for biotechnologies.

Agronomists will have to deal with management of complex cropping systems, the combination of many species, cyclic successions and practices, and cope with multi-criteria performance. The diversity of points of view among the various agroecology movements is a source of richness, but we need to build common concepts, tools and metrics that encompass this diversity and facilitate constructive comparison and invention.
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