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Interdisciplinarity and multiagent interactions for innovations in horticulture – paradigms beyond the words

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Abstract

The progression towards sustainable horticulture is usually associated with scientific and methodological breakthroughs. As a consequence, the innovation processes in the fields of biology and ecology and their agronomic implementation are increasingly recognized as main drivers to improve horticultural systems. At the same time, a horticultural system cannot be designed without good knowledge of the social and economic contexts in which it is embedded; it has to be considered as an integrated social-ecological-agrosystem. For example, the cross-knowledge derived from interdisciplinary research constitutes the backbone for building ecologically-based crop ideotypes and cropping systems, including genetics, agronomy and social-environmental levers and constraints. Designing new horticultural systems in such a systemic framework is also relevant to develop and better implement knowledge exchange among agents. This strong intertwining of the different research fields poses new challenges. There is a need for more participatory research and scaling-up to achieve adoption of innovations along the horticultural chain. Thus, the former linear and top-down scheme, i.e., from basic science to applied science and fieldwork, is now reconsidered and the design of innovative agricultural production systems is viewed as an integrated, interactive and participatory process where agents are dynamically interacting. The new challenge is to better combine the detailed knowledge typical of the dominant reductionist paradigm generally oriented towards the "one-size-fits-all" objective and the paradigm of complexity where the "custom-fit" approach predominates. Progressing towards these frameworks of knowledge and relationships among agents poses epistemological questions about interdisciplinarity and hybridization between scientific and non-scientific (advisor, grower) knowledge.

Keywords: agroecology, innovation, integrated sciences, participatory research, social-ecological-agrosystem, systemic approach

INTRODUCTION

Following the Second World War, agriculture has evolved towards an industrialized and globalized model with the objective to increase animal and plant production thanks to a better control of production factors. This entailed specialization and a progressive gap between growers and consumers and also between agriculture and the ecosystems in which it developed (Bellon and Hemptinne, 2012). Productivity, i.e., the amount of product per area unit, has become the main objective disregarding any other, possibly negative, consequences. However, intensive horticulture is highly dependent upon a high consumption of external inputs (fertilizers, pesticides, water, etc.). The use of pesticides is a source of water and air contamination resulting in negative impacts on both surrounding ecosystems and human health (Margni et al., 2002; Altieri, 1999). As a matter of fact, food and health industries are

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co-existing without strong connections between them: "People are fed by the food industry, which pays no attention to health and are healed by the health industry, which pays no attention to food" (Wendell Berry, in McCormick, 2012), although things are slowly evolving.

There is an increasing demand for building and developing new horticultural systems that have the intrinsic ability to face or at least to buffer the known challenges (e.g., existing pests and diseases) and putative ones (e.g., climate changes, especially irregular and possibly extreme drought and high temperatures; emerging pests and diseases). Innovation is promoted as a way to challenge these issues. It can be defined as an idea, a practice or an object that is perceived as new by an individual or another unit of adoption (Rogers, 2003). It is also a social process of change, with collective and interactive dimensions between science and end-users (Hatchuel et al., 2006). These definitions help to describe agroecological innovations in horticultural systems. The concept of perception is particularly important if we consider that conventional/industrial agriculture has only existed for less than a hundred years (Reynolds et al., 2014). Some agroecological innovations can be perceived as new, but others may be a case of "rediscovery" (Stanhill, 1976). Indeed, they may refer to past practices and traditional knowledge which were put aside by industrial agriculture since the 1940s, and which are today revisited with our current scientific knowledge. Innovation may occur at various organizational levels depending on existing knowledge: a specific component of the agroecosystem (e.g., the crop variety; the use of already known host-plants for predators or parasitoids in or around the horticultural plot); an integration of a set of choices and practices that individually are not always new but whose combination is (e.g., the use of various community members of plant-based food webs with the objective to enhance plant defense at the level of the whole system; Poelman et al., 2008); a social organization at the food system scale; and so on. Innovation may lead to minor or major changes (e.g., the Efficiency-Substitution-Redesign (ESR) grid, Hill et al., 1999; or the 'step by step' vs. 'de novo' approaches used to (re)design systems; Meynard et al., 2012). Innovation can be connected to the concept of "emergence" which is defined as the unfolding of new functions and structures of a system on a higher scalar integrative level: there is an emergence when a phenomenon appears at a given level L_N whose properties are difficult or impossible to deduce from the properties of the constituent units and processes at level L_{N-1} (Bonnabeau and Desalles, 1997; Lüttge, 2012). As for innovation, this shift in scalar level is intrinsically related to the human observers and their conceptual constructs and therefore to the notion of "detection" (Bonnabeau and Desalles, 1997) which is equivalent to the notion of perception presented above for innovation.

Nowadays, innovation in horticulture is usually related to keywords such as "sustainability", "agroecology", "ecosystem" and "agroecosystem" (Bellon and Hemptinne, 2012; Pretty and Bharucha, 2014). It is noteworthy that along with the increased number of documents (articles, proceedings, reviews, book chapters, etc.) published in horticulture in the past 10 years, the percentage of documents quoting the above keywords increases disproportionately from ca. 40% in 2004 to ca. 80% in 2013 (Figure 1). This may be due to horticulture being considered as an "applied science", i.e., addressing practical societal needs.

Therefore, horticultural scientists have to build integrative knowledge guided by the future action on agroecosystem, and increasingly interact with scientists from other research fields, especially from "basic" plant science, i.e., those who produce knowledge on biological processes and mechanisms. Although "basic" science has generally been viewed as the foundation of "applied" science, the distinction between the two is rather artificial and the idea that "basic" and "applied" sciences are complementary has progressively developed. Indeed, advances in basic understanding may arise from applied efforts, and reciprocally applied breakthroughs may arise from basic research (Malézieux, 2012; Reynolds et al., 2014). Moreover, a complementarity has to be built with social and economic sciences, not only to take into account the social and economic dimensions of technical innovations, but also because some innovations refer to the organizational or social sphere rather than to the biotechnical one.

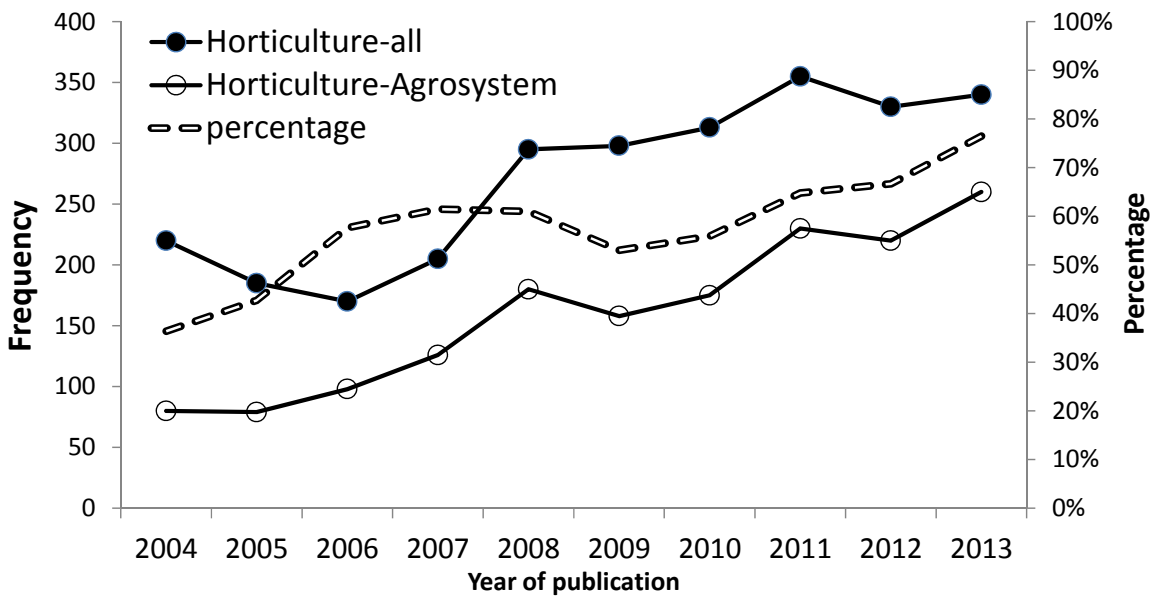

Figure 1. Annual frequency of published articles in all document types and all Web of Science (WOS) categories, with topics: "horticulture" and "agroecology" or "sustainability" or "agrosystem" or "agroecosystem" (Citation Report: 2268) ("Horticulture-Agrosystem"), expressed as a percentage of all articles mentioning topic: "horticulture" (Citation Report: 3488) ("Horticulture-All"), from 2004 to 2013 (access, March 2015).

We commonly assume that innovations are needed at various biological, agronomical, ecological and technological levels to develop and improve agroecosystems. However, the added value of the agroecosystemic paradigm is undoubtedly to pool ideas, data and expertise from various disciplines in an integrative way. As mentioned in the Brundlandt report (1987) and as stated by Richter and Billings (2015): "we who study Earth's terrestrial environments, whether our core expertise be plants, animals, microbes, soils, hydrology, geomorphology, geological processes, social sciences or the humanities, need to redouble the breadth of our professional interactions and become involved in more integrative studies". The need for interdisciplinarity, i.e., to synthesize and harmonize links between disciplines into a coordinated and coherent whole (Choi and Pak, 2006), has long been known as necessary to explicitly integrate the multifaceted aspects of plant growth and production in its environment. For example, the ideotype concept has been proposed by geneticists and breeders as a model plant "that will produce an economic yield that approaches the maximum in a particular environment (or on a certain site), using a prescribed cultural system and assuming a well-defined end-use for the harvested products" (Dickman et al., 1994). Initially developed for annual plants (Donald, 1968), it has been later extended to perennial plants in various conditions, e.g., apple, for high-density planting (Dickman et al., 1994) or for organic and low-input systems (Parisi et al., 2014). This broad definition already entailed that a plant ideotype cannot be proposed without comprehensive knowledge not only of the plant itself in its ecological and agronomic context (tree architecture, adaptation to soil conditions, pest and disease pressure, etc.), but also of the social-economic context in which the harvested product(s) will be used.

In the following, taking the example of pest and disease management, we will illustrate how basic science meets applied science in various research fields in biology to contribute to sustainable horticultural production. We will also show that interdisciplinary approaches including social and economic science (Choi and Pak, 2006) enable to tackle adaptation of horticultural systems to new environmental constraints and societal demands, and to facilitate their adoption through more participatory processes.

BIOLOGICAL AND ECOLOGICAL CONSIDERATIONS FOR INNOVATION IN PEST AND DISEASE MANAGEMENT

The high levels of chemical inputs such as pesticides and fertilizers are questioned simultaneously on the economic cost, and human and animal health, product safety and environmental quality (Altieri, 1999). This is especially true for fruit trees (Parisi et al., 2014). Focusing on reducing pests and diseases, several sources of knowledge combining basic and applied sciences have to be considered together to re-design agroecosystems. In the following, we illustrate three of them, biodiversity, genetic resistance or tolerance (the ability to limit the effects of disease) to pests and diseases, and interactions between pests and diseases and plant architecture.

Biodiversity can be defined as the variability among living organisms from all sources and among the ecological complexes of which they are part, including diversity within species, between species and of ecosystems (United Nations, 1992). It is related to composition, structure, and function of living organisms (Noss, 1990), and is composed of the planned biodiversity associated with crops and livestock introduced by the farmer, and the associated natural biodiversity including soil flora and fauna, herbivores, carnivores, decomposers that colonize the agroecosystem (Altieri, 1999). The ability of biodiversity to enhance plant health, and, as a consequence, yields of the horticultural systems has been raised (Simon et al., 2010; Malézieux, 2012; Deguine et al., 2015). Going further, the concept that agricultural yields can be increased without adverse environmental impact, i.e., sustainable intensification, is promoted (Pretty and Bharucha, 2014). As regards pest control, a review of literature in apple, pear and peach orchards shows that if the effect of biodiversity management (i.e., flower strips, understory plants, ground covers, hedgerows) on pest control is mostly positive (16 cases) or null (9), it may also be negative in some cases (5) (Simon et al., 2010). Similar results have been shown in banana production (Duyck et al., 2011; Mollot et al., 2012; Djigal et al., 2012). These findings clearly support the idea that there is a need to better identify and analyze the processes involved at different spatial and temporal scales for biological control. It also reinforces the concept that the key agroecological strategy may not be to increase biodiversity in itself but more functional biodiversity that provides agroecosystems services (Moonen and Barberi, 2008).

For a given plant, resistance and tolerance to pests and diseases are defined as the ability to reduce the impacts on plants, and to reduce the loss of yield quantity and quality, respectively (Schafer, 1971). Genetic improvement of this resistance or tolerance is a main issue for sustainable agroecosystems. The apple scab pathosystem (fungal pathogen, *Venturia inaequalis*) gives interesting benchmarks on how pathologists interact with plant geneticists, breeders and horticulturists to significantly improve breeding schemes. Most commercial apple cultivars are susceptible to scab and its control requires up to 23 fungicide treatments per year, especially in regions with a wet climate (e.g., in France; MAAF (Ministère de l'agriculture, de l'agroalimentaire et de la forêt, France, 2014). In the past, scab resistance studies have been focused on identifying major resistance genes, mainly in small-fruited Asiatic *Malus* species, such as *Vf* from *Malus floribunda* 821. However, different fungal races overcame apple scab resistance genes, fostering the need to develop new breeding strategies to promote durable resistances. Combining only major genes within the same genetic background through pyramiding has proven to be risky and the choice has been made to combine major and minor resistance genes (Baumgartner et al., 2015). Research programmes have then been oriented towards the detection of quantitative trait loci (QTL) for scab resistance (Soufflet-Freslon et al., 2008). Possible strategies aiming at minimizing resistance erosion have already been proposed: the pyramiding of broad-spectrum factors or the use of a mixture of apple genotypes that carry narrow-spectrum resistance factors (Lê Van et al., 2013). The use in breeding schemes of ancient cultivars with partial or quantitative resistance to scab is surely a promising way to provide growers with apple cultivars having durable resistance. However, under high disease pressure, resistance or tolerance to scab should be associated with durable resistance and/or tolerance to the other pests and diseases such as powdery mildew (*Podosphaera leucotricha*) and fire blight (*Erwinia amylovora*) mainly present in the area of apple cultivation (Parisi et al., 2014;

Baumgartner et al., 2015). But, beyond this genetic dimension, innovation in breeding directly sends back to the social-technical system in which it is embedded, in order to breed alternative cultivars fitted to farm functioning and quality requirements of markets (see Vanloqueren and Baret, 2004 and following section).

Growth and yield of a plant result from endogenous, genetically-determined, processes, exogenous constraints imposed by the environment and cultural practices aiming at controlling plants and the environment. This environment includes biotic (e.g., pests, diseases) and abiotic (e.g., water, temperature) components, and also all manipulations made by the farmer. For vegetables, farmer decisions and actions are mostly focused on crop sequences and on the technical management of each crop. Crop sequence may be used to break the lifecycle of major pests and pathogens and preserve soil fertility, although today's crop and farm intensification tends to weaken this technical lever, the ending point being monocropping in some vegetable farms (Navarrete, 2009). For fruit trees, the permanency of the crop raises several issues: the ontogenetic progression of the individual tree with a non-bearing stage followed by a productive stage, fertilizer applications and ground-cover management with different practices between permanent tree rows and alleys, the permanency of pests and diseases over consecutive years on the tree itself and in the surroundings of the orchard (Simon et al., 2015). These issues constrain the farmer to conceive a dynamic design of the orchard encompassing space and time components. For example, the planting density has to take into account the growth of the tree during the orchard lifespan which is related to the vigour of the cultivar but also, depending on the species, of the rootstock (e.g., apple; Maguylo and Lauri, 2007). During the tree life-span the farmer also has to manage tree growth and branching with the objective to increase yield but also to improve regular bearing which is a main concern for fruit tree cultivation (Monselise and Goldschmidt, 1982; Lauri and Laurens, 2005). In apple, several studies have shown that each cultivar can be characterized by a proper architectural strategy tightly related to the fruiting pattern (Lauri and Laurens, 2005). Combining basic knowledge on tree architecture and functioning with grower's and advisor's knowledge on the apple tree growth and fruiting pattern in the orchard has been shown to significantly improve training and pruning of the various cultivars (Lauri et al., 2011).

Tree training and pruning not only affect yield and fruit quality, which are primary purposes, but may also affect pests and diseases as shown in the apple through an indirect (e.g., micro-climate) or a direct (e.g., branching frequency) effects. Although these effects are weaker than genetic ones for resistance or tolerance, they indicate that tree architecture manipulation related to orchard design can be an effective and sustainable cropping practice for partially regulating pests and diseases (Simon et al., 2006, 2012).

Since a strong pressure selection related to plants (e.g., pest resistance, as illustrated for apple scab) or practices (e.g., recurrent use of a given pesticide as in codling moth management) is likely to induce resistant strains in the targeted pest or disease, a single method (a gene, an active ingredient) fails in managing efficiently and durably one pest or disease. On the other hand, levers giving only partial control of the pest (e.g., sanitation) can hardly be used alone, and combining several levers in a multilateral approach to control the crop pest complex is a key towards the design of agroecological horticultural systems. Therefore, innovation in agroecosystems relies more in the mastering of interactions among components of the agroecosystem (i.e., biodiversity, plant genetics, plant assemblage design, tree architecture manipulation), and among practices, than in the adoption of a single innovative method. Designing alternative technical systems also raises the question of their assessments which have to be performed in a systemic manner rather than on each factor independently of the others. System experiments are a way to assess the agronomical performances of such systems, their consistency as regards cropping decisions and local conditions, and their feasibility when performed in farmers' fields (Deytieux et al., 2012; Simon et al., 2015).

INTEGRATING THE SOCIAL, ECONOMIC AND AGRONOMIC ISSUES FOR INNOVATION

The sustainable economics concept

The orthodox definition of economics is the study of how societies use scarce resources to produce valuable goods and services and distribute them among different individuals. Alternative definitions of economics encompassing sustainability consider not only scarce resources but limited and finite resources on Earth. For example, the "steady state economy" (Czech and Daly, 2004) aims at restraining fluctuation of population and per capita consumption. On the other hand, sustainable economics (Baumgärtner and Quaas, 2010) refers to the idea of efficiency, that is a non-wastefulness in the use of scarce resources, for achieving the two normative goals of (1) the satisfaction of the needs and wants of individual humans, and (2) justice, including justice between present and future human generations and justice towards nature, in the setting of human-nature relationships over the long term. Sustainable economics have several implications. For example, what are the corresponding ethics which deal with the long-term future which is inherently uncertain? What are the different types, degrees and patterns of uncertainty and knowledge in dynamic human environment systems? What are the conditions and mechanisms that affect the transformability of human environment systems? Who bears the responsibility for sustainability, for which entities, to what extent, and towards which authority?

Moreover, sustainable economics strongly involves the agents. An agent can be defined as someone who acts and brings about change, and whose achievements can be judged in terms of his/her own values and objectives, whether or not we assess them in terms of some external criteria as well (Sen, 1999). This concerns the role of the individual as a member of the public and as a participant in economic, social and political actions. In the horticultural context, the question is raised to what does sustainable economics imply for the assignment and limitation of power, duties and liability among political, economic and citizen agents. The efficient use of resources depends on the opportunities that the agents have and their freedom of choice with the search of equity capabilities at the intra- and intergenerational levels (Ballet et al., 2011). All these implications are central for the study of the adoption of agroecological innovations.

Adopting and scaling up agroecological innovations

Agroecological innovations are characterized as follows. (1) They are complex in terms of underlying basic and applied science and they are also complex in terms of performance assessment due to the various criteria that have to be taken into account. (2) They are often local, limited to a territory, a commodity chain, independently from their level of complexity. (3) They are embedded in a long-term perspective as the biological processes between action and results generally stretch over several years. This is particularly true for perennial crops and soil management.

These three main characteristics have the following implications for innovation adoption and scaling up. (1) Complexity aggravates the perceived uncertainty in adopting an innovation from a farmer perspective as the results may not be visible immediately or even difficult to estimate and observe. The adoption process needs to focus on the transmission and understanding of knowledge between the farmer and the advisor (Le Gal et al., 2011). (2) Local contexts hinder the generic range of agroecological innovations in opposition to the "one-size-fits-all" concept which may shape the sociotechnical environment of farms (e.g., international fruit size standards constrain cultivar, tree and fruit management, packing and sales), leading in some cases to lock-in effects in the food chain (Vanloqueren and Baret, 2004). Scaling up agroecological innovations, i.e., basically using successful small-scale projects as a basis for effecting large-scale changes, therefore must consider the diversity between farming systems (Kohl and Cooley, 2004). (3) The long-term perspective needs to consider the dynamics of social changes (diversification strategies in off-farm activities, change in labour force, etc.) and the economic and political trends (land concentration; farmers moving out of agriculture; new regulations).

From these implications, human capital becomes central in terms of knowledge:

understanding agronomic principles, combining information and knowledge from various sources to make choices, and adapting to, or reinventing for, the local context. Information is also central for preventing uncertainty and social dysfunction.

Sustainable agriculture and agroecological innovations are also connected to a different vision of society and trade. Different commodity chains and networks are required to scale up agroecological innovations. As they are embedded in a territory or an agroecological zone, they need to value and use the local resources in a process promoting local, endogenous, and safe agricultural production models. These new commodity chains and networks need to be adapted to the local constraints and institutions. In such configurations, complex adaptive systems are required. Such systems can be considered as self-organizing systems whose properties cannot be analyzed by studying their components separately, and they are formed by many agents of different types where each defines his/her strategy in ways that fit his/her goals (Spielman et al., 2009; Hall and Clark, 2010). These new configurations are challenging as they involve a new conception of agriculture and its supporting services: endogenous resources (substituted partially or totally to imported goods), short food circuits between farmers and consumers, custom-fit extension services, and so on. These new configurations require the creation of new markets and new value assessments. In the case of compost in developing countries, for example, there is a need to know its real agronomic and economic value in order to promote its manufacture, trade and use (Sotamenou and Parrot, 2013), and how it fits the needs of the users (Parrot et al., 2009).

However, institutional and technological lock-ins and path dependence hinder structural changes (Fares et al., 2012). Economic assessments are still needed to forecast where our agricultural systems could be in 10 or 20 years if agricultural science and technology massively switched to agroecological innovations (Vanloqueren and Baret, 2004). The economic value of agroecological innovations for farmers and the commodity chains need to be investigated with a strong focus on locally adapted technologies, local markets, and the local pioneers and early adopters. The perspectives of complementary approaches between different paradigms need to be discussed. However, strong oppositions between the pros and cons of the present industrial agriculture paradigm and agroecological agriculture outreach the limits of local agronomic and economic sciences.

Co-designing agroecological innovations and implications for interdisciplinary and multiagent approaches

From what has been said about sustainable economics, a main concern is to avoid implementing public policies – whether economic, social or environmental – that could have the unintended consequence of generating uncertainty and social dysfunctioning. Applied to sustainable horticulture, this implies the need to look at the social interactions and networks that connect the various agents along the fruit chain in order to reduce uncertainty, and to fight against extreme poverty and exclusion. It is also necessary to ensure that access to social services, the constitution of human and social capital, and the improvement of capability are not jeopardized for the current generation or for those to come (Dubois, 2009). Moreover, as some agroecological innovations for sustainable horticulture represent major technical changes for farmers, participatory researches, which combine various sources of knowledge, enable to build the innovative systems that reduce uncertainty and are more easily adopted by end-users. These methods are used for co-designing new technical systems with the key agents, i.e., those who put the innovation into practice and continue with it (growers, advisors, traders) as they embody the necessary local knowledge (Meynard et al., 2012). However, other key agents influencing indirectly the innovation adoption process should be considered. They can be competitors or government officials involved in regulation. Such considerations bring the necessary distinction between variables that are endogenous to the fit between an innovation and a specified group of potential users, and those that are exogenous (that is, prerequisite conditions such as access to credit or access to land) (Sumberg, 2005). These variables should be made explicit during the innovation-development process. In opposition to a standard or classical approach

which builds purely rational and universal arguments in order to convince, the pragmatism approach starts from the intuitions and principles of the agents, as a realistic representation of a concrete situation (Maris, 2010; Francis et al., 2012; Méndez et al., 2013). These participatory approaches need to be interdisciplinary (Etienne, 2010). But most importantly, they also need to evaluate the retrospective and prospective consequences of the planned actions, and advocating prudential and precautionary social principles (Ballet et al., 2005). These principles should ensure that the human costs are minimized. This stems naturally from the prospective responsibility of the agents, especially those responsible for deciding public policies (Mahieu, 2008).

Such an approach was used for co-designing new cropping systems in different horticultural sectors and/or different geographic areas. In vegetable production, the innovative cropping systems aimed at controlling soil pests and diseases with agroecological levers and they are currently under evaluation (Navarrete et al., 2010; Caporalino et al., 2015). In tropical cucurbit agroecosystems, the aim was to suppress applications of insecticide on the crops (Deguine et al., 2015). In citrus production, the aim was to reduce pesticide loads despite unresolved weed control issues (Le Bellec et al., 2012), whereas in apple the 'BioREco' system experiment aimed at controlling pests and diseases through the combining of various agroecological practices to limit pesticide use (Simon et al., 2015). In the three cases, participatory methods enabled agents to make their points of view explicit, on the aims of the co-design, the levers to mobilize and the way to combine them, and possible conflicts among agents. For example, participants considered how to combine several constraints such as the cost of the agroecological levers, the organization of practices at the farm level, the agronomical risks, and the regulation and marketing requirement. Participatory approaches also foster the exchange of knowledge between scientists and other agents, and new knowledge elaboration. When agroecological levers are used, the prototypes built are very dependent on local conditions but the participatory methods and the knowledge built can be re-used by agents in other situations.

IDEOTYPING SOCIAL-ECOLOGICAL-AGROSYSTEMS

All human activities, including scientific ones, are partly conditioned by the cultural, historical and geographical contexts in which they are developed. As a consequence, scientific objectivity, i.e., a unique knowledge valid for all contexts, cannot exist. This indicates that the scientist has to consider what societal values he/she is supporting with his/her research. This also means that as concerns innovation in agroecosystems for horticulture, the "one-size-fits-all" paradigm governing the capital-intensive industrial horticulture has to shift towards "custom-fit" approaches with a local, decentralized, biodiversity-promoting vision of the link between horticulture and economics (Reynolds et al., 2014).

Developing socio-agroecosystems well adapted to their social-economic contexts intrinsically needs crosstalk among the various research fields in biology and ecology, and also with the social and economic sciences (Lescourret et al., 2015). Let's consider the genetic ideotype concept proposed at the plant level which has proved its heuristic interest for the breeder, the advisor and the grower (e.g., on apple; Parisi et al., 2014). We propose that such concept becomes an analytical framework for better defining social-ecological-agrosystems well fitted to their specific ecological, social and economic environments.

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