Agriculture models at the crossroads of farming systems, food systems and territorial dynamics

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Abstract: Different agriculture models can be developed to deal with sustainability issues. The objective of this paper is to present a new analytical framework allowing the identification of key agriculture models at the crossroads of farming systems, food systems and territorial (local) dynamics. The first dimension of this framework is based on the distinction between three key types of farming systems: synthetic inputs-based, biological inputs-based and biodiversity-based. They are more or less dependent on exogenous inputs and ecosystem services. The second dimension is based on the identification of how each of these three types of farming system interacts with global food systems and territorial dynamics i.e. circular economy, local food systems and integrated landscape approaches. Our framework makes it possible to specify agriculture models corresponding to a type of farming system and to the nature and level of its interactions with its socio-economic context. Finally, in considering six key agriculture models we sketch out key associated scientific issues.

Keywords: biodiversity, ecosystem service, biological input, food system, industrial ecology, landscape

Introduction

At the end of the 20th there was a maelstrom of agricultural crises involving issues of energy, water, biodiversity, climate change, economics and food security (Capone et al. 2014). Organic farming systems are often considered as a possible model for sustainable agricultural systems (Niggli et al. 2008) with intense discussion about the possible production level (Seufert et al. 2012). On the other hand many people (researchers, politicians, agricultural agencies….) consider that either integrated, conservation or precision agriculture are also ways to improve the sustainability of farming systems (FS) (e.g. Garbach et al., 2016). However, each of these categories encompasses a wide diversity of FS exhibiting different environmental and socio-economic performances.

Social science research distinguishes between two main paradigms underpinning pathways towards sustainable agricultural systems: « shallow *versus* deep sustainability » (Hill, 1998), « weak *versus* strong ecological modernisation of agriculture» (Horlings and Marsden 2011), « life sciences *versus* agro-ecological vision » (Levidow et al. 2012). Elaborating on these conceptualisations, Duru et al. (2015a,b) characterise them by considering the role and status of exogenous inputs and ecosystem services (ES) in the agricultural production. In their analysis the first pathway seeks to deal with environmental issues through increasing the efficiency of exogenous input use (e.g. fertilisers, pesticides and water), recycling waste or by-products of one sub-system inside another (Kuisma et al. 2013) as well as applying sound agricultural practices (Ingram, 2008) or precision-agriculture technologies (Rains et al. 2011). A variant is based on replacing synthetic with organic inputs (Singh et al. 2011) or genetically modified organisms (Godfray et al. 2010). In accordance with the Hill (1998) classification, Duru et al. (2015a,b) call this approach “efficiency/substitution-based agriculture”. This usually consists of incrementally modifying crop or animal management practices in specialised systems so as to comply with environmental regulations while preserving economic competiveness (Duru and Therond 2014).

The second main pathway in Duru et al's analysis aims to strongly enhance ES to agriculture provided by biodiversity (Zhang et al. 2007). These ES depend on the level and management of biodiversity at field, farm and landscape levels (Kremen et al. 2012). Accordingly, Duru et al. (2015a) have named this approach "biodiversity-based". It seeks to develop diversified cropping and FS or even landscapes to enhance ES for both farmers and society while drastically reducing the use of exogenous inputs. It introduces a paradigm shift in the vision of agricultural innovations and systems, especially as regards their objectives and expected performances (Caron et al. 2014). It leads to a strong modification of the vision and thus the role and the management of the environment (nature) in agricultural production (Levidow et al. 2012). Developing a biodiversity-based agriculture requires the extensive redesign of FS. Of importance is the fact that in this agriculture, practices for increasing resource use efficiency and recycling are also implemented when using inputs. Duru et al. (2015b) highlight that development of a biodiversity-based FS requires both changes in natural resources management strategies as well as in agricultural supply chains.

Our objective is to enrich the above mentioned classification for identifying different key agriculture models at the crossroads of farming systems, food systems and territorial dynamics. In the following section we clarify the main agro-ecological differences between synthetic inputs-based, biological inputs-based and biodiversity-based FS according to the place and function of ES or of exogenous inputs in the agricultural production process. For each of these three types of FS we then identify their possible interactions with global food systems and territorial dynamics and in turn define typical agriculture models corresponding to a type of farming system and to its interactions with its socio-economic environment. Finally, we sketch out the key scientific issues associated with each agriculture model.

Farming systems and ES

Until the end of the 20th century, farmers were encouraged to develop the most suitable conditions for crop and animal growth. Most of them accordingly used high production level breeds to increase the "growth-defining" factors (potential production level for a given climate conditions) and implemented agricultural practices to control the "growth-limiting" abiotic factors (water and nutrients) as well as the "growth-reducing" biotic factors, i.e. negative pest effects (Ittersum & Rabbinge 1997). In addition they endeavoured to improve the physical production environment (i) soil structure determining water transfers, root growth and functioning and in some cases (ii) local climate conditions (e.g. temperature). Management of yield-increasing and yield-protecting inputs determined the level of growth-limiting and reducing factors and the input-use efficiencies.

The Millenium Ecosystem Assessment (2005) showed that human welfare strongly depends on ecosystem goods and services. Zhang et al. (2007), then Bommarco et al. (2013) and Duru et al. (2015a) clarified the status of ES in agricultural production, highlighting that regulation services determining soil fertility (soil structure and nutrient cycling), water storage and pest control are the key services provided by ecosystems to agriculture. Duru et al. (2015a) established the link between the theory of growth-defining, limiting and reducing factors of Ittersum and Rabbinge (1997) and the theory relating to ES provided to farmers (hereafter "input ES"). It is shown that the share of agricultural production depending on ES (vs. exogenous inputs) depends itself on the paradigm on which FS are based: inputs-based or biodiversity-based FS (Fig. 1). It is important to keep in mind that even inputs-based FS depend on ES (Bommarco et al., 2013.

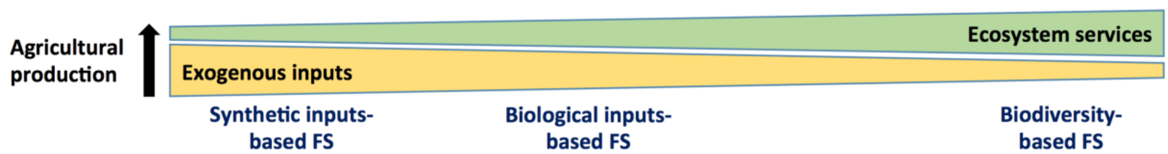

Figure 1: Types of farming systems (FS) according to the share of agricultural production derived from ES and anthropogenic inputs

Synthetic or biological inputs-based FS seek to address economic constraints and environmental regulations by means of optimising inputs according to the spatio-temporal plant/animal requirements and in turn to limit pollution (Table 1). In order to deal with sustainability issues and regulations, inputs-based FS implement an efficiency-based modernisation pathway (cf. introduction). One of the challenges of these synthetic inputs-based FS is to accurately assess the level of input ES in time and space needed to optimise the necessary level of additional anthropogenic inputs required to reach the targeted production level. Precision agriculture technologies based on sensors positioned in the soil, machinery, drones, planes and satellites permit the monitoring of the dynamic level of different variables and the optimisation of required input applications. They are well developed to deal with nutrient cycling - above all nitrogen - and weeds (e.g. weeding robot; targeted pesticide applications). In addition, farmers use cultivars and animal breeds which are less sensitive to limiting or reducing factors while exhibiting the same level of or better potential yields (defining factors). All these technologies may allow FS to increase input use efficiency, reduce environmental impacts and, depending on the technology costs, economic performance. The amortisation of these technologies may lead farmers to continue to increase their farm size in order to reach suitable economies of scale. Regulations can lead farmers to introduce more substantial changes such as resort to cover crops in nitrogen-sensitive areas. In this case, cover crops are sown during the bare soil period according to regulations relating to sowing and removal dates.

Considering societal reluctance to accept synthetic pesticides as well as human and ecosystem health issues, some farmers managing inputs-based FS seek to use more “environmentally friendly inputs” while still managing a specialised farming system. As such, they implement a substitution-based modernisation pathway to develop “biological inputs-based” FS. Beyond the classical use of organic fertilisers as substitutes for inorganic, new practices related to biocontrol are developing to mimic the ecological functioning of diversified agroecosystems. By implementing industrially developed natural enemies (e.g. trichogram in maize) and other service-providing organisms (e.g. azotobacters, probiotics, arbuscular mycorrhizal funguses), soil bio-stimulants and bio-inoculants, farmers seek to amplify ecological processes underpinning ES which naturally arise in biodiversity-based ecosystems (Phillipot et al. 2013). They can also use bio-pesticides to reduce the eco-toxicity of synthetic pesticides. Moreover they can grow cultivars selected to stimulate beneficial biological soil activity (Singh et al. 2011). All these technologies, whether or not they have a resilient effect, might enable the development of input ES in the short, medium or long term (Fig. 1).

In biodiversity-based FS, developing input ES requires developing species/breeds diversity (e.g. intercropping, diversified field margins as well as crop sequences) and of soil cover (cover crops*)* while minimizing disturbances of beneficial biological processes due to tillage and synthetic inputs use (Table 1) (Duru et al. 2015a). One of the challenges is to develop and manage planned biodiversity from fields and field borders (e.g. flower strips) up to the farmland area for developing naturally-present associated biodiversity which acts as a service provider while limiting the development of detrimental associated biodiversity (pests) (Fahrig et al. 2011). When these FS use synthetic or biological inputs to increase the production level beyond the level supported by input ES alone they have to use them sparingly so as to not reduce the expected short- and long-term benefits of input ES (Pisante et al. 2015). As shown by Biggs et al. (2011) these FS have to manage three key properties of the agricultural ecosystem to develop the production level and resilience of ES: diversity-redundancy, connectivity and state of slow variables. While the first is commonly identified in the literature on agroecosystems, management of the latter two are less classically highlighted. Connectivity between biophysical entities determines circulation of materials (including organisms) and energies and thus the system’s performance. It determines species dispersion capabilities between habitats (Tscharntke et al. 2005). The state of slow variables (e.g. soil organic matter, ecological networks) determines dynamics of associated fast variables (e.g. nutrient and water cycling, biological regulations). Short, middle- and long-term management of slow variables (e.g. soil organic and biological state) determines day to day (soil nitrogen and phosphorous availability), year to year (soil structure) as well as long-term system functioning (dynamic of soil organic matter). While managing these three properties over different scales, farmers may strongly increase ecosystem integrity, i.e. its self-organising capacity (Müller et al. 2000). It is important to keep in mind that the use of living biological inputs (e.g. industrially developed natural enemies) in a biological inputs-based farming system can be a step forward towards the development of a biodiversity-based farming system: the farmer starts to develop a production system based on biodiversity even it is imported into the agricultural ecosystem.

FS archetypes	Main objective and strategy	Nature of farming practices
Synthetic inputs-based	Increase of competitiveness and reduction of pollution via improvement of input efficiency ("Ecological intensification")	Standardised practices in specialised FS (small number of crops) based on external inputs
Biological inputs-based	Increase of competitiveness and reduction of impacts on biodiversity and human heath via substitution of synthetic by biological inputs	Standardised practices in specialised FS (small number of crops) based on external biological inputs. Possible integration with livestock
Biodiversity-based	Increase of competitiveness through development of biodiversity and ecosystem services ("Ecologically intensive agriculture")	Site-dependent agroecological practices in FS based on diversified crops and possibly on integrated crop-livestock interactions, allowing greatly reduced use of anthropogenic inputs

Table 1: Key features of three types of farming system archetypes (FS), (adapted from Duru et al. 2015).

Interactions between farming systems, food systems and territorial dynamics

FS are embedded into food systems representing diverse sets of institutions, technologies and practices for producing, processing, packaging, distributing, retailing and consuming food. Food systems influence not only what is being consumed and how it is produced and acquired, but also who is able to eat and how nutritious their food is (Capone et al. 2014). Institutions and practices for management of natural resources (water, soil, biodiversity) used by agriculture, i.e. the social structure and dynamics of social-ecological systems interact with farming and food systems (Foran et al. 2014). Global food systems (e.g. soybean and grain wheat market) have developed in recent decades with a strong impact on the homogenisation of national food systems (Khoury et al. 2014) as well as on health (e.g. Monteiro et al. 2013). While FS are embedded in global food systems, they can also be more or less embedded in different territorial (local) dynamics (e.g. circular economy) (Fig. 2).

For each of the three types of FS described above, we characterise the main types of interactions they may develop with global food systems and different key territorial (local) dynamics (including local food systems).

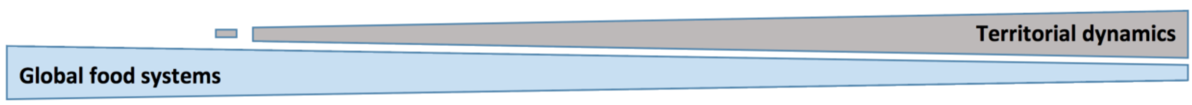

Figure 2: Schematic of the relationship between global food systems (including agricultural non-food commodities) and territorial dynamics (circular economy, local food systems and integrated landscape approaches) in which farming systems are more or less embedded

Synthetic inputs-based FS are generally embedded in and mainly interact with large food supply chains in which power is concentrated in large retailers (Marsden, 2011). In the context of the strong development of the composites market (vs. agricultural products) and the bio-economy, raw agricultural products are sold as commodities on the market - just like any other product in the marketplace (O'Kane, 2012). Accordingly, evolution of this type of FS is mainly driven by these global food systems. Economic resilience of these FS to price variability and biophysical hazards can be supported respectively by contracts and insurance schemes, both provided by global food supply chains. These insurance instruments may lead farmers to increase the share of riskier cash crops resulting in an increasing share of monocultures (Müller & Kreuer, 2016). Due to integration in the dynamics of large-scale food systems these FS are often poorly connected with local natural resource management issues and strategies, leading to conflicts regarding e.g. water shortages due to irrigation, water quality due to pollution, erosion due to bare soils. A typical example of this decoupling of global food systems from local environmental issues is the world soybean market, which grew strongly during the 1990's and led to high environmental impacts in regions where soybean is grown (e.g. pesticide pollution and deforestation) as well in those where it is used as feed for specialised and concentrated livestock enterprises (nitrogen emission) (Billen et al. 2014).

Biological inputs-based FS are most often also embedded in and mainly interact with large food supply chains providing biological inputs (e.g. bio-stimulants and bio-pesticides, exogenous organisms) and sell raw products that feed the global composite and bio-economy markets. However, they may evolve according to opportunities to substitute synthetic with biological inputs provided by both large-scale supply chains or by local dynamics. Development of a circular economy at a local scale may offer such opportunities. A circular economy aims at limiting the use, of and protecting finite natural resources, by the improved closure of material and energy cycles. It seeks to develop recycling loops between economic agents: outputs or wastes of one economic agent becoming the input of another or others. In such local dynamics, environment is considered on the basis of concerns about resource scarcity, pollution and waste limitation. This form of territorial integration of economic activities may allow for examples to develop (i) the use of locally produced organic matter and nutrients derived from wastes to improve the organic soil state and associated SE and (ii) the use of agricultural products for energy purposes (dedicated crops or residues such as straw). In this form of territorial integration, the development of trading between specialised livestock and crop farms (e.g. especially organic fertilisers like manure, straw or even animal feed), without questioning crop rotation, is a model of circular economy. Logistical (transport, transformation) and economic issues (market stability) can be managed directly by farmers or by the food supply-chain (Moraine et al. 2016). Trading can also be developed between FS and other operators of the food supply-chain (e.g. food processing, transporting) or with other sectors of activity (e.g. production of organic "wastes") (Nitschelm et al. 2015). Accordingly, while embedded in large supply-chains, biological inputs-based FS can also be strongly integrated into the territorial dynamics of a developing circular economy. For example, an organic farming system with low levels of crop and animal biodiversity can be strongly integrated into local trading between farms so as to acquire organic fertilisers (e.g. Fernandez-Mena et al. 2016).

In biodiversity-based FS, farmers develop planned diversity (plants and animals) for improving input -ES and -self-sufficiency. When there is no other solution or if prices are attractive, products are sold through large-scale food supply-chains as seen above. The lack of attractive markets for some key crops required to strongly diversify cropping systems is a major limitation on the development of such FS (Meynard et al. 2013). Development of trading between crop and livestock FS allowing diversification in cropping systems (e.g. introduction of alfalfa, grain legumes, grasslands) constitutes a first level of territorial integration offering opportunities for diversification of biodiversity-based systems. Such trading between crop and livestock systems can offer opportunities to improve soil organic matter through application of manure as well as to enhance biological regulations through spatiotemporal diversification. Here, the most important concerns are the health/integrity of soils, plants and livestock as well as collective action issues (e.g., craftsmanship, stewardship). Another form of territorial integration corresponds to the development of local markets (including collectively organised short food supply chains). The challenge can consist of developing "territorialized food/non-food systems" that support the development of a local diversified agriculture meeting local consumer and lifestyle demand and even human health issues. Their development may be part of a larger territorial development project where agriculture is one of the key sectors involved. A higher level of integration of biodiversity-based FS within territorial dynamics can occur when local actors seek to develop sustainable landscapes that jointly supply multiple ES (Mastrangelo et al. 2014). The challenge consists in developing collective governance of the diverse land managers so as to design the spatial distribution of land use (crop-grassland pattern) and semi-natural habitats which may increase ES depending on the composition and configuration of the landscape (e.g. biological regulations, mass and liquid flow regulations). This requires a landscape design approach (Nassauer & Opdam 2008) for example for water management (Murgue et al. 2015), strong territorial crop-livestock integration (Moraine et al. 2016), hedgerow networks (Groot et al. 2010) or biological regulations (Steingröver et al. 2010). As in the case of biological input-based FS, biodiversity-based FS can also be involved in a circular economy. Development of a circular economy and of local food systems offering important diversification opportunities to local FS coupled with integrated landscape management corresponds to the highest level of territorial integration i.e. the development of an integrated landscape approach (Reed et al. 2016). It may permit the development of an "eco-economy paradigm which replaces and indeed relocates agriculture and its policies into the heart of regional and local systems of ecological, economic and community development" (Marsden, 2012). Here the main concerns are about natural resources management, landscape/ecosystem integrity, human welfare and local social dynamics. However, some agricultural products may be still sold through global food system. Local and global markets are then considered as complementary and thus co-exist.

From diversity of agriculture models to knowledge gaps in agronomy

Considering the three types of FS and their possible interactions with local to global food systems and local dynamics, it is then possible to identify different key "models" of agriculture. Here, each agriculture model corresponds to a type of farming system and its interactions with its socio-economic environment (Fig. 3). Some are developed; others correspond to niches or represent potential forms of agriculture within a given region or country.

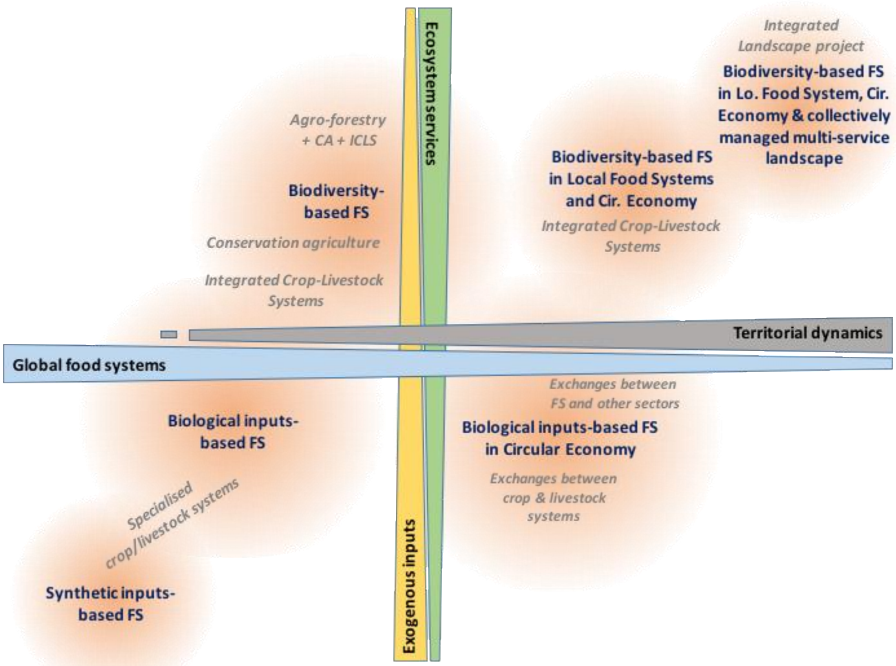

Figure 3: Six key forms of agriculture (in blue) in which farming systems (FS) are more or less based on ecosystem services vs. anthropogenic exogenous inputs (Y-axis) and connected to global food systems or different territorial dynamics (X-axis). Iconic examples are presented in grey; CA = Conservation Agriculture. ICLS = Integrated Crop Livestock Systems

Synthetic inputs-based FS embedded in global food systems corresponding to specialised cash crop and livestock farms (lower left quadrant fig 3), is the dominant agriculture model in Western Europe (Levidow et al. 2014). To increase (weak) sustainability of this type of agriculture, much research focuses on developing smart agricultural technologies (e.g. genetic engineering, precision farming). Through integration of up-to-date scientific knowledge within decision support systems there exists a potential for improving agricultural as well as environmental performances (reducing soil, water resources and atmospheric pollution) of this type of agriculture model. In this case, changes generally require only incremental adaptations (Park et al. 2012).

Biological inputs-based FS are strongly promoted by both European Union (Levidow et al. 2014). They correspond to two agriculture models (lower left and lower right quadrants fig 3). In both models the use of living biological inputs for biological control are in their infancy (e.g. Philippeau et al. 2014). While effects are well known and efficacy has been demonstrated for some uses of iconic living inputs such as inoculation of Rhizobia into leguminous (Philippeau et al. 2014), actual effects at field level of many biological inputs such as bio-stimulants have not been soundly demonstrated. Moreover, their resilience is generally low, leading farmers to apply them regularly (e.g. annually). One reason may be that these products are used in the same way as synthetic ones while "being biological these products have to be applied in accordance with their ecological requirements" (Alabouvette et al. 2006). Furthermore, it is still necessary "to carefully study the effect of inoculum type, application rate and time of application to ensure efficacy of biological control" (ibid). The development of biological inputs-based FS embedded in a local circular economy is strongly supported by regional and national policies (e.g. European Union) which promote the development of circular economies for increasing the economic and environmental performance of economic activities (including agriculture). Much research is emerging in the field of industrial ecology (biogas production, recycling…). Moving from farm to landscape level for coupling nutrient and water cycles requires coordination between agricultural actors and those in other sectors. Considering specificities of food supply-chains, Fernandez-Mena et al. (2015) argue that such researches should be developed in order to provide methods to analyse, assess and design recycling loops and to explore circular economy options in these particular complex social-ecological systems. Development of this type of agriculture model usually requires system adaptations (Park et al. 2012).

In accordance with possible interactions between biodiversity-based FS and global food systems or territorial dynamics, three main associated agriculture models can be identified. The first corresponds to FS developed in socio-technical niches (e.g. farmer collectives) such as those related to conservation agriculture, agroforestry, integrated crop-livestock systems, self-sufficient grassland-based livestock systems (fig 3 top-left quadrant). In these systems, farmers sell their products within global food systems or via direct markets (to consumers or other farms). Development of these FS raises questions about how to manage the "transformational" transition from a specialised system to a well-established diversified one. During this transition variability in ES may significantly increase until slow variables and ecosystem structure reach a state permitting the provision of ES at the expected levels and degrees of biophysical resilience and stability (Duru et al. 2015a). For example, positive effects of conservation agriculture, through implementation of its three principles (no-tillage, cover crops and long rotations) may emerge after than ten years. During the transition ambiguous biophysical phenomena can be observed. For example, landscape complexity with various and well-represented semi-natural habitats may exhibit more diversified natural-enemy communities but may also provide better and more abundant overwintering sites for pests (Duru et al. 2015a). The particularity of this type of FS is that if ecological principles are generic, management practices are highly site-dependent (Giller et al. 2015). To support farmers in managing this transition research on agroecology has to develop knowledge that farmers can use in order to choose the best practices they can implement, considering the characteristics of their production situations. The characterisation of the different species/breeds that farmers can introduce (cash crop and "service crops") and their mixtures through functional ecology approaches (response and effect plant traits) is a promising way to provide operational knowledge (Duru et al. 2015a). New technologies of communication and information can be mobilised to render scientific knowledge accessible and operational as well as collecting feedbacks from farmer experiences (Dowd et al. 2014). Integrated participatory design and assessment of diversified cropping and FS methodologies also have to be developed (Duru et al. 2015a). Breeding of "service species" selected to provide a given function (e.g. soil structuration) in mixture or sequence with cash crops is also a key research area.

The second form of biodiversity-based agriculture is when diversified FS has developed significantly in a given territory thanks to the development of local food systems (e.g. integrated crop-livestock system on fig. 3). Beyond research questions regarding management of diversified FS, the management of a local food system in the light of existing global food systems is an issue for socio-economic research

but also for agronomy regarding the development of agricultural systems promoting soil, plant, animal, ecosystem and in turn human health.
Development of an integrated landscape approach combining collective landscape management with local food systems and a circular economy correspond to the third agriculture model involving biodiversity-based FS. In this case, research has to provide adapted knowledge and participatory methodologies to support the collective design of multi-service landscapes i.e. crops-grasslands-semi natural habitats patterns providing expected levels of targeted ES. One key research issue here is to clarify the effects of landscape configuration and composition in relative to the effects of cropping systems (field level) for different ES during the farming system transition as well as once a biodiversity-based FS is well-established. Research should analyse and highlight trade-offs, synergies or neutral relations between SE from field to landscape levels.
These two latter agriculture models are currently very marginal or do not really exist in most developed countries due to many lockins (Vanloqueren and Baret, 2009). Overall, it is important to bear in mind that organic agriculture, often presented as a promising pathway towards sustainable agriculture, can be present in the fifth last different agriculture models. As the different agriculture models can and may exist in the same area, conditions under which they co-exist should also be clarified. More precisely, biophysical and socio-economic trade-offs, synergies or neutral co-existence between them at landscape and territory to global levels have to be analysed. For example, it is necessary to clarify to what extent and under what conditions the presence of inputs-based FS in the landscape is compatible with the objectives of developing ES at the landscape level.

Conclusion

During the last decade, current research made some progress to better support the development of the two systems involving biological inputs-based FS. However, research activities presently dedicated to the development of biodiversity-based FS need to be strengthened. Our classification should help to better address the knowledge gaps, particularly regarding the development of locally integrated forms of agriculture based on diversified FS (integrated in local food systems and collective landscape management) (DeLonge et al. 2016; Levidow et al. 2014; Vanloqueren & Baret 2009). Further progress in research strategy should address the challenge of a correct balance between researches on agroecology, bioeconomy and technology and, furthermore, should favors the integration of these three approaches. Most of all, the different models of our typology can be used for examining where funds are mainly allocated for researches, training and development, identifying possible deviations from targets and, in fine, designing adapted agricultural policies and research agenda**.**

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