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Biodiversity-based cropping systems: A long-term perspective is necessary

Matthieu Carof[1,*], Olivier Godinot[1], Edith Le Cadre[1]

[1]Institut Agro, INRAE, SAS, 35000 Rennes, France

*Corresponding author: matthieu.carof@agrocampus-ouest.fr

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Abstract

Biodiversity-based cropping systems are an interesting option to address the many challenges that agriculture faces. However, benefits of these systems should not obscure the fact that creating biodiversity-based cropping systems represents a major change for farmers. To address this challenge, we argue that designing biodiversity-based cropping systems requires transforming ecological concepts into technical opportunities. Indeed, integrating ecological concepts such as plant–soil feedback and plant functional traits more strongly into cropping system design offers promising opportunities for the provision of ecosystem services, such as pest and disease control, crop production (including crop yield stability), climate regulation and regulation of soil quality. Accordingly, we demonstrate that designing biodiversity-based cropping systems requires considering not only the short term but also the long term. This would ensure that the expected ecosystem services have enough time to build up and provide their full effects, that the cropping systems are resilient and that they avoid the

limitations of short-term assessments, which do not sufficiently consider multi-year effects. Considering long-term consequences of system change – induced by biodiversity – is essential to identify potential trade-offs between ecosystem services, as well as agricultural obstacles to and mechanisms of change. Including farmers and other food-chain actors in cropping system design would help find acceptable compromises that consider not only the provision of ecosystem services, but also other dimensions related to economic viability, workload or the technical feasibility of crops, which are identified as major obstacles to crop diversification. This strategy represents an exciting research front for the development of agroecological cropping systems.

Keywords

plant functional trait; plant–soil feedback; participatory design; conceptual modelling; process-based modelling; multicriteria assessment

Highlights

- Biodiversity-based cropping systems can reduce negative impacts of agriculture.
- Designing biodiversity-based systems mobilises concepts from agronomy and ecology.
- Designed systems must be assessed in the long term to ensure their sustainability.
- A framework for the design and assessment of cropping systems is proposed.

1. Cropping system design needs ecological concepts to propose both short-term and long-term beneficial innovations

Human societies face enormous challenges in reducing negative impacts of their activities on the environment (Rockström et al., 2009; Running, 2012), while ensuring that the necessary changes are socially just (Biermann, 2012). Among human activities, those in the agricultural and food sectors have strong impacts (Juniper, 2021; Meier, 2017), and many studies point to the urgency of changing, sometimes deeply, the current dominant food systems to innovative and sustainable ones (Béné et al., 2019; Frison and Clément, 2020; Meynard et al., 2016; Theurl et al., 2020). This transition concerns everyone – researchers, input suppliers, farmers, advisers, food processors, consumers, etc. – and should be driven by public policies (Cambeses-Franco et al., 2022; De Schutter et al., 2020; Galli et al., 2020; Kugelberg et al., 2021). Upstream of the food systems, agronomists and ecologists can work with farmers to design new cropping systems that meet social and environmental expectations (Lacombe et al., 2018). One promising way to design these new cropping systems is crop diversification (e.g. Birthal and Hazrana, 2019; Dwivedi et al., 2017; Juventia et al., 2021; Li et al., 2019; Massawe et al., 2016), defined by Gaba et al. (2015) as increasing the number of plant species on a given area of land. Crop diversification is an “intentional addition of functional biodiversity to cropping systems” (Tamburini et al., 2020) and indirectly influences the associated biodiversity (e.g. soil biota communities). A variety of agricultural practices can diversify crops on farms (Figure 1): all are based on complex biological interactions, which have long been studied in ecology (e.g. Lidicker, 1979), although recent knowledge has not been sufficiently implemented in practice (Lescourret et al., 2015; Perfecto and Vandermeer, 2015). Crop diversification provides many benefits for developing biodiversity-based cropping

systems, such as economic revenue from a variety of value-added crops, an increase in pest and disease control while reducing the use of inputs, improvement in soil and water quality, preservation of biodiversity, and enhancement of nutritional diversity (Duru et al., 2015; Peterson et al., 2018).

These biodiversity-based systems may differ greatly from existing cropping systems and can sometimes be technically difficult to implement and sociologically difficult to accept. Moreover, their potential benefits may not be visible in the short term, discouraging farmers from pursuing them. Even worse, agronomic production and economic revenue can be poor during the transition to more diversified cropping system (Wang et al., 2021). Overall, although diversification is an appealing option, it is considered a complex and high-risk strategy, which leads to reluctance to adopt it and ultimately slows the development of biodiversity-based systems.

In this Discussion article, we first argue that designing biodiversity-based systems requires considering not only the short term but also the long term (i) to ensure that the systems designed are sustainable and resilient and (ii) to avoid the limitations of short-term assessments, which fail to anticipate long-term consequences of system change. In other words, major changes in cropping systems can be beneficial in the short term, but detrimental in the long term because the long-term consequences are usually ignored when designing the new systems. For example, John and Babu (2021) illustrate this with the Green Revolution in India. In the 1960s, the main issue there was to produce enough food to avoid famines: this short-term priority led to the design of cropping systems that succeeded in increasing agricultural production, which reduced poverty and malnutrition, but that had unintended and adverse long-term consequences for human health and the environment. Assessing cropping systems over the long term would (i) reduce the risk of not anticipating future negative impacts

of these systems and (ii) allow for better assessment of future positive effects of these systems.

Second, we argue that designing biodiversity-based cropping systems also requires using ecological concepts to expand technical opportunities for farmers, one of the difficulties being to transform ecological concepts into crop management practices. Indeed, using ecological concepts to design biodiversity-based cropping systems offers promising opportunities for the provision of ecosystem services (see, for example, the meta-analysis of crop diversification effects by Beillouin et al. (2021)). Moreover, using ecological concepts reinforces the importance of the long term, as considering the long term is necessary to ensure that the expected ecosystem services have enough time to build up and provide their full effects.

Finally, by using concepts from ecology and agronomy, we propose an approach to design and assess biodiversity-based cropping systems for both short- and long-term perspectives.

2. What are the short, medium and long terms for assessing changes in biodiversity-based systems?

In ecology, as in agronomy, there is no single definition of the short, medium or long term. For example, Rull and Vegas-Vilarrúbia (2011) highlighted that some ecologists consider data acquired from experiments that last one or more decades to be long term, whereas others consider paleontological data that covering centuries to millennia to be long term.

As this article focuses on designing and assessing systems on which humans deliberately act, we propose considering not only biogeochemical processes but also tactical, social, and even societal elements to define the short, medium, and long

terms. Regarding biogeochemical processes, not only must the dynamics of these processes be considered, but also the technological ability to measure in situ significant changes in variables that describe these processes (and these changes must make sense to farmers). The concept of fast and slow variables is of particular interest (Therond et al., 2017): the former (e.g. soil water storage, soil nitrogen dynamics) change over a time scale of less than one day to a few days or months, whereas the latter (e.g. soil carbon stock) change over a time scale of one to several years. Regarding tactical elements, farmers plan crop management practices by considering the state of the agroecosystem each day and anticipating effects of their crop management practices for the entire growing season and, for practices such as weed management, for the entire crop rotation. The temporal dimension of public policies must also be considered, as they structure on-farm activities (e.g. “Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides”). Public policies can have long temporal horizons of up to several decades (Commaille et al., 2014; Howlett and Goetz, 2014) (e.g. the agreement on global warming of the 2015 United Nations Climate Change Conference).

Consequently, we consider the short term to be a period of one day to one cropping year (0-1 year), the middle term to be a period of one cropping year to one crop rotation (ca. 1-10 years) and the long term to be a period from one crop rotation to the active life span of a farmer on the same farm (ca. 10-50 years).

3. Insights from ecology to address long-term trajectories of biodiversity-based cropping systems

3.1. The long-term stability and productivity of biodiversity-based cropping systems: theoretical background

Boivin and Crowther (2021) state that cropping system principles have yet to embody long-term issues, whereas the long term is an inherent temporal scale in ecology especially when studying the temporal stability of ecosystem functions (de Bello et al., 2021). In line with this, we argue that long-term issues are even more important for biodiversity-based cropping systems than for conventional cropping systems. Indeed, according to Thakur et al. (2021), positive productivity–diversity relationships become stronger over time. These authors particularly refer to an emerging concept: plant–soil feedback.

What is plant-soil feedback? The nature of soil influences the productivity, succession and reproductive success of plants, but in turn plants alter abiotic and biotic soil conditions that may influence other individuals in that soil after disappearance of causal plants. Plant–soil feedback is an important concept for explaining how terrestrial ecosystems respond to global land use and climate change (van der Putten et al., 2016). For ecologists, plant–soil feedback can be explained as modifications of pathogen populations (Ehrenfeld et al., 2005; Mariotte et al., 2018) and nutrient cycling mediated by soil microbes (Kulmatiski et al., 2011), which echoes the “pre-crop effect” of agronomists’ crop-rotation rules (i.e. benefits of one crop that carry over to subsequent crop). However, plant–soil feedback and the pre-crop effect, although similar at first sight, differ greatly. First, the timespan considered is several years to decades (van der Putten et al., 2016; Wurst and Ohgushi, 2015) for the former, but only one year (rarely more) for the latter. Second, plant–soil feedback embraces a more comprehensive and holistic interpretation because, for example, it considers a wide range of processes hidden in above- and below-ground interactions.

Accordingly, recent knowledge on plant–soil feedback can be used to replace the short-term, sometimes empirical, pre-crop effects of agronomists (Pernilla Brinkman et al., 2010). For example, metrics of plant–soil feedback were used successively to identify (i) the most productive crop rotations (Koyama et al., 2022) and (ii) the best combination of agricultural practices, such as fertilisation, irrigation (Wei et al., 2018) and soil inoculation (Pineda et al., 2020), to enhance positive carry-over effects. Positive plant–soil feedback should therefore be managed with respect to nutrient and water availability to ensure both overyielding effects, as in intercropping (Yu et al., 2016), and the success of entire crop rotations. Metrics of plant–soil feedback should also be included in the criteria used to design biodiversity-based cropping systems (Section 4). One should note that plants' abilities to compete are inextricably related to the outcomes of plant–soil feedback (Beals et al., 2020) and are associated with plant functional traits (Cortois et al., 2016), as described in the following section.

3.2. Ecological metrics to design and predict long-term biodiversity-based cropping system performances: insights from trait-based ecology

A "functional trait" is a physiological, morphological or life-history characteristic of an organism that can respond to environmental changes (response trait) or modify the process of an ecological function (effect trait) (Garnier and Navas, 2012). Trait-based ecology relies on this trait concept, and many studies describe how to measure plant functional traits, either root traits (Fort and Freschet, 2020; Freschet et al., 2021) or above-ground traits (Cornelissen et al., 2003; Ordoñez et al., 2009). Currently, considerable knowledge is available in databases such as the TRY Plant Trait Database (Pakeman, 2014). These databases can be used to design biodiversity-based cropping systems that combine short- and long-term issues.

In disturbed and competitive environments such as agricultural fields, there exists an interspecific trade-off between plant functional traits that infer rapid resource acquisition and those that infer resource conservation (Kurze et al., 2021). For example, high specific leaf area (a well-known plant functional trait) is associated with an acquisitive resource-use strategy, whereas high leaf dry matter content (another well-known plant functional trait) is associated with a conservative resource-use strategy. The plant economics spectrum was developed based on these different resource-acquisition strategies (Díaz et al., 2016): using plant functional traits, it ranges species from resource-conservative (i.e. slow-growing) to resource-acquisitive (i.e. fast-growing). This theory is used to explain shifts in and intensities of plant–soil feedback (De Long et al., 2019) but also competition or co-existence strategies (Mariotte et al., 2018). This theory is thus essential for predicting long-term ecosystem functioning (de Bello et al., 2021; Faucon et al., 2017) and can be fruitfully used in a new approach for designing biodiversity-based cropping systems (Section 5.2).

Originally developed for grasslands, trait-based ecology is beginning to be considered in farmers' crop management decisions (Barot et al., 2017; Martin and Isaac, 2018), sometimes because it has been included in decision support tools (e.g. Damour et al., 2018). For example, according to Gaba et al. (2014) and Fried et al. (2021), trait-based ecology can be used to interpret weed responses to environmental and cropping system changes and then to develop sustainable weed management that preserves positive aspects of weeds (e.g. limiting erosion, sheltering bees) while limiting weed impacts on crop yields. Moreover, the plant economics spectrum can be adapted to the design of cropping systems as well as agricultural management, such as intercropping (Faucon et al., 2017; Hinsinger et al., 2011; Li et al., 2014; Mariotte et al., 2018) and agroforestry systems (Cardinael et al., 2018). Beyond simply combining

plant species to avoid competition by temporal or spatial niche differentiation or facilitation (Hinsinger et al., 2011; Li et al., 2014), this theory helps to conceptualize community effects on ecosystem functioning in a variety of environments.

Trait-based ecology can indeed be used to build a community functional parameter (i.e. a weighted average of each plant functional trait) for process-based models, as described by Violle et al. (2007). This community functional parameter helps predict effects of a plant community on ecosystem functioning, for example by combining information at the species level to predict biomass of a community (Enquist et al., 2007). If this community functional parameter is used in process-based models to design cropping systems, plant community effects on ecosystem functioning can be modelled in response to external drivers (Violle et al., 2007).

3.3. Limits and future research in ecology for biodiversity-based cropping system design

Agronomists still under-use concepts related to plant functional traits and plant–soil feedback, especially when designing cropping systems. Such concepts are useful for disentangling complex interactions between above- and below-ground components and defining potential long-term outcomes. We are convinced that embracing ecological concepts provides information that can help to (i) cope with uncertain and changing environments (Schneider and Lynch, 2020), (ii) increase soil carbon storage (Kell, 2012, 2011), (iii) promote interactions with beneficial microbes to increase plant performances with limited nutrient resources (Cantarel et al., 2015; Hunter et al., 2014), (iv) improve plant health (Mitter et al., 2016) and (v) manage weeds sustainably (den Hollander et al., 2007).

We propose here an initial example of ecological research that will help design cropping systems. Selective breeding has generated high-yielding crops that often invest the bare minimum in defence against pests or longevity. Accordingly, new breeding programs address plants' abilities to interact with their biotic environment (Litrico and Violle, 2015) to reduce input needs (Jacquet et al., 2022; Schmidt et al., 2016). These programs must re-integrate some plant functional traits that were removed from existing cultivars (Abbo et al., 2014; Schmidt et al., 2016), such as root traits (Wang et al., 2020) for resource-acquisition and carbon-storage issues. Simultaneously, these programs should focus on plant functional traits (Cortois et al., 2016) and crop management practices (e.g. reduced tillage, fertilisation, soil inoculation) that may magnify positive plant–soil feedback. This becomes all the more necessary as plant–soil feedback has gained new interest in the face of extreme climatic events related to climate change (de Oliveira et al., 2020; De Vries and Shade, 2013; Seybold et al., 1999; Thorsen et al., 2010; Yang et al., 2018), which argues for integrating it into cropping system design in a long-term perspective.

However, some obstacles remain. Agronomists' reluctance to use ecological concepts may have been caused, in part, by different definitions of "long term" in agronomy and ecology (see Section 2 for analysis of the terms "short", "medium" and "long term"). However, as cropping system design has recently reconnected with the long term for agroforestry systems and perennial forage crops (Jose, 2012), we believe that the same could apply to biodiversity-based cropping systems that use annual crops, especially considering productivity–diversity relationships (Section 3.1). However, the processes that underlie productivity–diversity relationships are still debated in ecology due to their dependence on ecological contexts, including temporal and spatial scales, which argues for (i) further research in ecology to provide usable knowledge for

agronomists and (ii) using other sources of information to design biodiversity-based cropping systems (Section 5.2) to avoid “the exception that proves the rule” pitfall that discourages bridges between ecology and agronomy. Accordingly, incorporating recent ecological knowledge into process-based models (Sections 3.2 and 5.1) could be placed on the research agenda to investigate effects of more diversified cropping systems on ecosystem functioning by testing targeted beneficial plant functional traits in silico without waiting for the next generation of cultivars to be released. This approach could influence breeding programs and increase collaborative development of process-based models, as recently reviewed (Gaudio et al., 2022).

4. Renewing the criteria for designing biodiversity-based cropping systems for the long term

Designing cropping systems with more attention to ecological concepts and the long term requires clearly defining the goals targeted, as these goals can be diverse and sometimes conflict with each other (Carof et al., 2013; Sadok et al., 2008). For example, it is challenging to design a cropping system that can simultaneously produce high crop yields at moderate cost with low environmental impacts. Multi-criteria assessment (MCA) tools generally consider this diversity of goals; thus, they are often used to design and assess cropping systems (Colbach et al., 2017; Iocola et al., 2020; Ravier et al., 2015; Reckling et al., 2016; Sadok et al., 2009). Most MCA tools assess cropping systems using economic, social and environmental criteria (Craheix et al., 2016). Assessing cropping systems in the three dimensions of sustainability is necessary for farmers to adopt them (e.g. Winters et al., 2006), even though the cropping-system level has relatively few economic and social aspects in itself (Sadok et al., 2009). Table 1 presents a summary of most common indicators of MCA tools

(Carof et al., 2013; German et al., 2017). These MCA tools have shown their utility in many situations for the design of cropping systems. They have been criticised, however, for their limited consideration of temporal effects, such as pre-crop nitrogen effects of legumes, yield variability due to climatic risks, price volatility, and changes in ecological properties of agroecosystems (German et al., 2017; Iocola et al., 2020). Indeed, many MCA tools are static and assess systems using only one or a few- years of data in a given soil and climate context, which do not reveal benefits of biodiversity-based cropping systems, especially in the long term.

Seeking high resource-use efficiency is often considered a relevant strategy to increase the sustainability of cropping systems. This strategy can cause crop diversity to decrease, however, as growing a few crops can be more efficient than growing many in a given context under stable conditions (Kahiluoto and Kaseva, 2016). In contrast, crop diversity is known to increase the stability of cropping system performances under variable conditions (e.g. Beillouin et al., 2021; Liu et al., 2019; Macholdt et al., 2020; Tilman et al., 2006; Section 3). Thus, trying to increase short-term sustainability may decrease long-term sustainability by altering the cropping system's resilience to variable conditions. An important characteristic of crop diversity is functional redundancy, which allows cropping systems to supply ecosystem services under variable conditions (Lin, 2011). We thus suggest examining not only the average performances of cropping systems but also their variability as a function of changes in soil properties and climatic conditions. Doing so will improve assessment of the long-term sustainability of cropping systems and their resilience to climate change or economic risks (e.g. Peterson et al., 2018). As a recent IPES-Food report (IPES-Food, 2016) outlines, biodiversity-based systems do not provide benefits immediately, given the time they need to increase soil quality, biodiversity and soil resilience.

We therefore propose several complementary indicators that focus more attention on long-term changes in cropping system properties as well as ecological aspects of cropping systems (Table 1). From an economic viewpoint, farmers specialise in a few crops as a short-term strategy to achieve economies of scale (e.g. labour, machinery) and to maximise annual income. However, crop diversification can sometimes provide higher average income (Kasem and Thapa, 2011; Pellegrini and Tasciotti, 2014; Reckling et al., 2016). Because this economic benefit may be observed at the crop-rotation level rather than the crop level, crop-rotation profit is more relevant than crop profit for comparing low- and high-diversification strategies. Carof et al. (2019) illustrate this for the introduction of protein crops into low-diversified cropping systems in western France. As protein crops are less profitable than other grain crops, a biodiversity-based cropping system that rotates protein crops with grain crops is less economically advantageous than a low-diversified cropping system when annual crop profits are compared. However, this conclusion no longer holds true at the crop-rotation level, as rotating protein crops with other grain crops decreased costs by 118 € ha^{-1} for grain crops following protein crops in the situation described by Carof et al. (2019). This is due to pre-crop effects of protein crops (lower fertiliser and pesticide costs, and higher yield, for subsequent crop). Only the crop-rotation profit reveals these economic benefits over time. Crop diversification can also be seen as an interesting strategy for long-term stability in income (Ridier et al., 2021), which is another interesting indicator to monitor. Reliance on public subsidies is also a more important indicator in the long term, as public-support policies usually must be renegotiated every few years (e.g. five years for European Union Common Agricultural Policy subsidies). Finally, to better represent plant–soil feedback, we also included an indicator based on Marques et al.

(2020) that reflects how a crop benefits the yield or growth of another crop ("Rotational - intercropping value").

For environmental aspects, we suggest estimating dynamics of soil organic matter content in addition to the soil organic matter content at a given time. This indicator, among others, requires using process-based crop models. Indeed, its annual change is often undetectable and difficult to measure, but the cumulative change over the long term can be modelled with sufficient accuracy and has a strong influence on soil properties and crops. We also suggest paying more attention to the soil phosphorus balance, which is often overlooked in short term studies, but is a major concern over the long term (Cordell et al., 2009; Sattari et al., 2012). Finally, we propose two indicators related to the changes in ecological properties of the agroecosystem – plant functional diversity[1] and soil resilience[2] (de Bello et al., 2010; Díaz et al., 2007) – both of which are likely to be influenced by crop diversity.

Social indicators can also be added to consider long-term dimensions of cropping systems better. For example, working conditions and peak workload may be considered less crucial in the short term, but they become increasingly important for farmers over several years.

5. How should biodiversity-based cropping systems be designed over the long term?

5.1. Which tools should be used to design cropping systems?

[1] Functional diversity is "the range and value of those species and organismal traits that influence ecosystem functioning" (Tilman, 2001).

[2] Soil resilience is "the ability of soil to resist or recover from an anthropogenic or natural perturbation" (Lal, 1997).

As soon as the long term becomes a focus, mathematical or statistical modelling becomes a particularly useful tool for predicting effects of new biodiversity-based cropping systems and thus for designing them. In this long-term approach, we emphasise that designers are more interested in an indicator's predicted trajectory than its exact value. For example, it is more important to know whether the stock of soil organic matter will increase or decrease, and at what rate, than how much will be stocked after 50 years. From this viewpoint – in which trajectory is more important than exact value – common weaknesses of models (e.g. parameter uncertainty; Boote et al., 1996) are less problematic than when models are used as decision support tools for crop management, for example. Using multi-year data to calibrate models, however, is a good practice to improve the accuracy of modelled scenario results (Abi Saab et al., 2015; Angulo et al., 2013). In such approaches, long-term experiments are crucial, but they are encountered mainly in Europe and North America, and do not yet consider a wide variety of cropping systems. An open international database of these long-term experiments could serve to improve crop models in order to reconstruct trajectories of agroecosystem structure and functioning under climate change to project scenarios in the future. Metamodelling[3] has been applied successfully to crop models and should be encouraged for scenario projection and regional assessments (Florin et al., 2011; Ramanantenasoa et al., 2019). However, metamodels require a huge experimental design to test them before implementation and depend on the knowledge embedded in crop models. An intermediate approach is to combine existing process-based or statistical models with conceptual models (i.e. a representation of a system and its drivers using scientific assumptions and expert assessments). A sound conceptual model reduces the risk of over-parametrisation and helps to visualise

[3] Metamodelling is the process of constructing "a simplification of [an] original model that retains its salient features, or a single model created by combining the results of multiple models" (Sparks et al., 2011).

emerging properties (i) during discussions among experts, regardless of their disciplines or the type of knowledge, or (ii) when processes have yet to be described extensively enough for process-based models to capture. Figure 2 shows an example of a conceptual model we created to understand effects of crop diversification on seven ecosystem services; it was then used to compare three process-based models for the design of biodiversity-based cropping systems (Carof et al., 2020).

Besides scientists (agronomists and ecologists, at least), farmers and other food-chain actors, should be involved in the design, modelling and assessment of biodiversity-based cropping systems (Moraine et al., 2016). This participatory approach combines multiple sources of knowledge, including farm practices, industry requirements and scientific literature and experiments (Reckling et al., 2016). This expert knowledge can also be used to mitigate the weaknesses of crop models (Ballot et al., 2018). Participation can also broaden the set of indicators used for multicriteria assessment based on actors' priorities and concerns (Paas et al., 2021). Finally, such an approach encourages farmers to implement new cropping systems on their own farms (Le Bellec et al., 2012).

5.2. The approach we propose

In line with Meunier et al. (2022), who combined different types of models "to assess a bundle of ecosystem services provided by a diversity of cereal-legume intercrops", we propose an approach that combines, for the design of cropping systems, conceptual, process-based and statistical models with a participatory approach (and other resources) to balance the weaknesses of some with the strengths of others (Figure 3). This approach aims to better consider short- and long-term objectives and consequences of cropping systems at all stages of design. This is difficult, because short-term issues (e.g. the need to produce food in quantity, to earn enough money)

usually take priority over long-term issues, especially for farmers. However, by involving farmers and other food-chain actors at several key moments (using resources such as expert knowledge or participatory workshops), this is also why our approach is interesting. Indeed, assembling a variety of actors allows common knowledge, social networks and shared expectations to be developed, which can in turn favour crop diversification (Meynard et al., 2018). Using resources (e.g. projection models, prospective studies, process-based models) to think in the long term is useful for assessing long-term benefits of diversified cropping systems, but also for assessing long-term effects of climate change on these cropping systems, which is a major concern for farmers. On this topic, participative approaches have been useful for improving decision support for and the adaptive capacity of farmers (Bartels et al., 2013). Finally, we emphasise that the approach we propose requires the involvement of ecologists in addition to agronomists. Indeed, during the participatory workshops for the design step of the approach, ecologists will open up the field of possibilities by allowing discussion of new crop rotations and management practices based on ecological concepts (Section 3). During the assessment step of the approach, ecologists will propose new indicators to complement the most common ones (Table 1).

However, despite the potential of combining process-based crop models with other sources of knowledge, doing so has some limitations. Insufficient data availability is one of the main difficulties for long-term assessment of diversified cropping systems, especially for the needs of model validation and calibration. Moreover, most process-based models usually ignore some important characteristics of cropping systems, such as pest and weed pressure, pre-crop effects and soil biology (Reckling et al., 2016), and are not parameterised for many crops used in diversified systems, let alone their

functional traits. This stresses the importance of combining conceptual modelling, process-based modelling and participatory approaches.

6. Final remarks and future perspectives

Beginning in the 1960s, the Green Revolution transformed agriculture by mobilizing researchers, policy makers, advisers and farmers. The existing wealth of environmental, social and economic data has forced a re-examination of the short-term perspective of cropping system design based on a few crops, as promoted in the last few decades. This article provides strategies to engage research efforts in order to better include ecological concepts and long-term perspectives in the design and assessment of biodiversity-based cropping systems. To do so, multi-actor and multidisciplinary research must be developed and then supplemented by multicriteria assessment of the cropping systems designed. This approach is not simple and faces several obstacles, such as data availability, model limitations, aversion to change by a variety of food-chain actors and aversion to economic risk. However, these obstacles must be overcome and transformed into opportunities to respect the rights of the next generation to live sustainably in an era of global change.

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Tables

Table 1. Most common indicators in multicriteria assessment tools and additional indicators proposed to better consider long-term and ecological aspects of cropping systems.

Dimension	Commonly used indicator	Proposed indicator
Economic	Crop yield	Crop yield
		Yield stability
		Rotational - intercropping value
	Crop gross profit	Crop rotation gross profit
	Annual farmer income	Annual farmer income
		Farmer income stability
		Sensitivity to subsidies
Environmental	Nitrogen balance	Nitrogen balance
		Phosphorus balance
	Soil organic matter content	Soil organic matter content
		Soil organic matter dynamics
	Greenhouse gas emissions	Greenhouse gas emissions
		Soil microbial index (Shannon)
		Resilience of soil microbial activity
		Plant diversity index (Shannon)
Social	Average workload	Average workload
		Peak workload
		Farmer's health risks due to pesticide use
	Working conditions (qualitative)	Working conditions (qualitative)

Figures

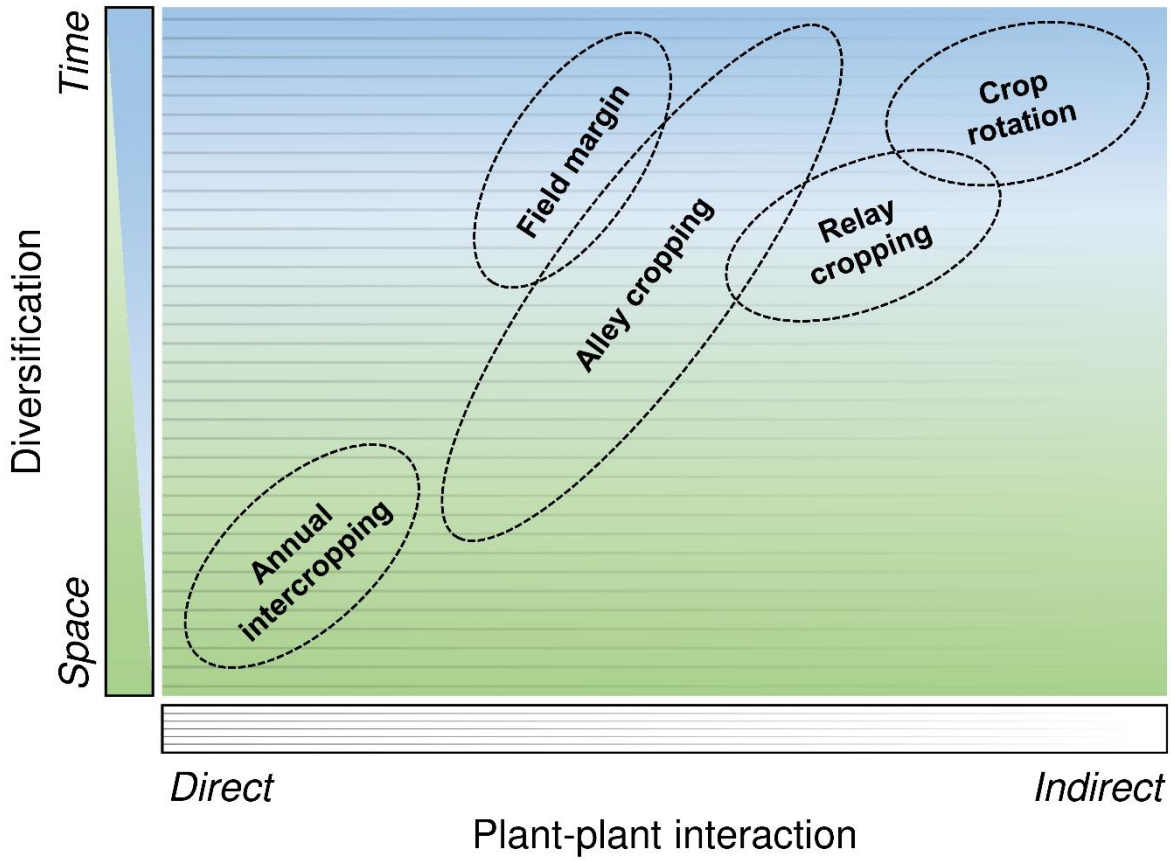

Figure 1. On a given area of land, various non-exclusive cropping patterns for crop diversification are possible, such as annual intercropping (i.e. growing two or more annual crops on the same area at the same time), alley cropping (i.e. growing one or more crops between rows of trees), field margins (i.e. growing groups of plants at field edges, such as grass margins, hedgerows and wildflower strips), relay cropping (i.e. sowing then growing a crop into another standing crop before the latter is harvested) and crop rotation (i.e. growing crops – including cover crops – in succession on a given area). These cropping patterns differ in the degree to which crop diversification occurs in space and time (Y-axis) and the degree to which direct or indirect interactions between plant species predominate (X-axis).

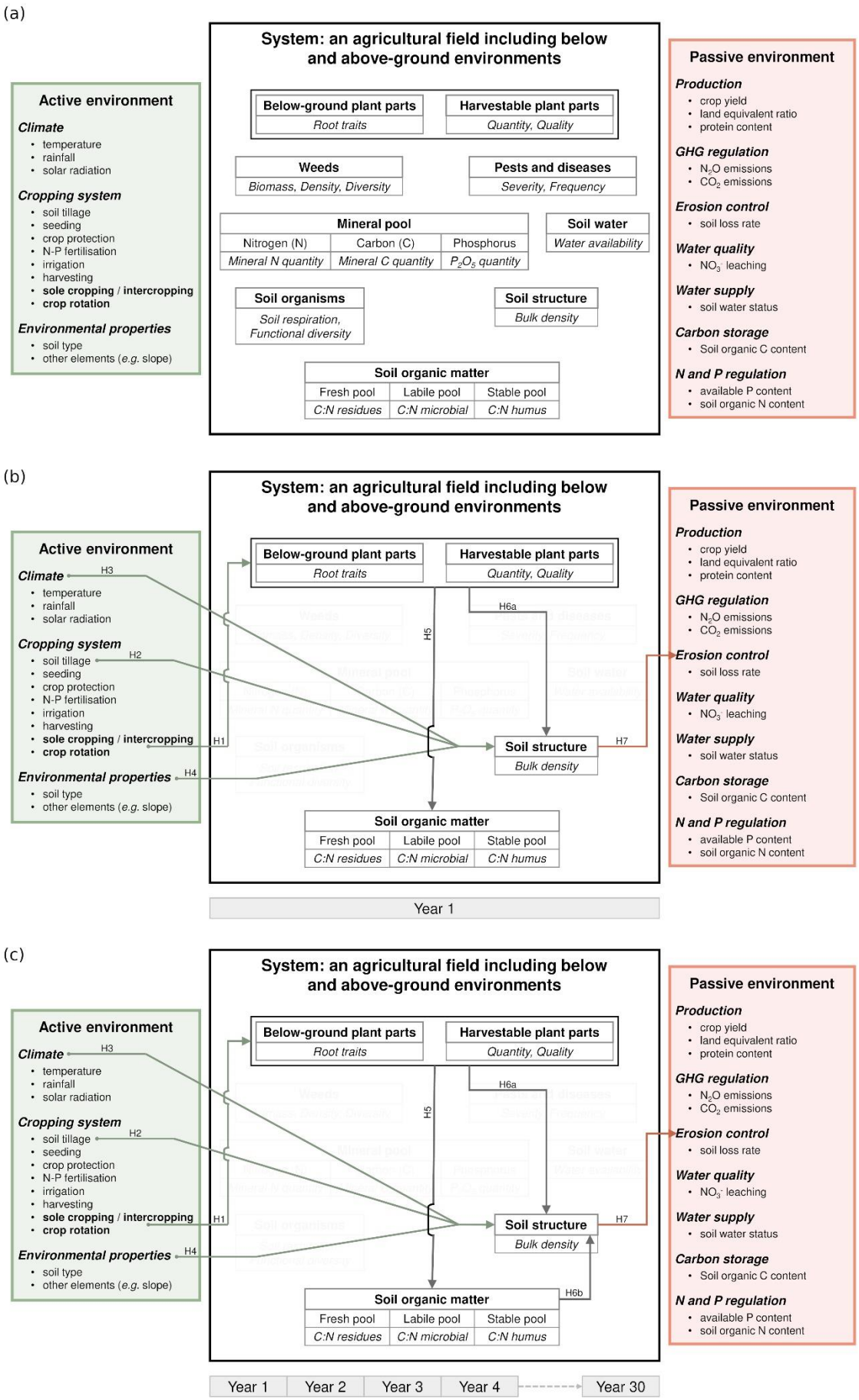
(a)
System: an agricultural field including below and above-ground environments
Active environment
Climate
temperature
rainfall
solar radiation
Cropping system
soil tillage
seeding
crop protection
N-P fertilisation
irrigation
harvesting
sole cropping / intercropping
crop rotation
Environmental properties
soil type
other elements (e.g. slope)
Below-ground plant parts
Root traits
Harvestable plant parts
Quantity, Quality
Weeds
Biomass, Density, Diversity
Pests and diseases
Severity, Frequency
Mineral pool
Nitrogen (N)
Carbon (C)
Phosphorus
Mineral N quantity
Mineral C quantity
P2O5 quantity
Soil water
Water availability
Soil organisms
Soil respiration, Functional diversity
Soil structure
Bulk density
Soil organic matter
Fresh pool
Labile pool
Stable pool
C:N residues
C:N microbial
C:N humus
Passive environment
Production
crop yield
land equivalent ratio
protein content
GHG regulation
N2O emissions
CO2 emissions
Erosion control
soil loss rate
Water quality
NO3- leaching
Water supply
soil water status
Carbon storage
Soil organic C content
N and P regulation
available P content
soil organic N content
(b)
H1
H2
H3
H4
H5
H6a
H7
Year 1
(c)
H6b
Year 1
Year 2
Year 3
Year 4
Year 30

Figure 2. (a) Conceptual model of an agroecosystem, defined here as an agricultural field including below- and aboveground environments, to understand effects of crop diversification on a variety of ecosystem services, following the protocol of Lamanda et al. (2012). From left to right: (i) The active environment includes elements (i.e. climate, cropping system management, environmental properties) that act on the system; they are characterised by state variables such as temperature, rainfall and soil type. (ii) The system includes components (e.g. weeds, pests, diseases) that are influenced by the active environment and that influence the passive environment. They are characterised by state variables such as weed biomass and disease severity. (iii) The passive environment includes outputs of the system (e.g. ecosystem services such as agricultural production, greenhouse gas (GHG) regulation, nitrogen (N) and phosphorus (P) regulation), which are characterised by indicators such as crop yield and soil organic N content. As an example, relationships among the active environment, the system and the passive environment for the output "Erosion control" are illustrated for (b) one year and (c) over the long term (30 years). Each relationship relies on an assumption (H1 to H7): for example, strategies for crop diversification influence spatial crop structure over time (H1), which enriches soil organic matter through crop residues and rhizodeposition (H5).

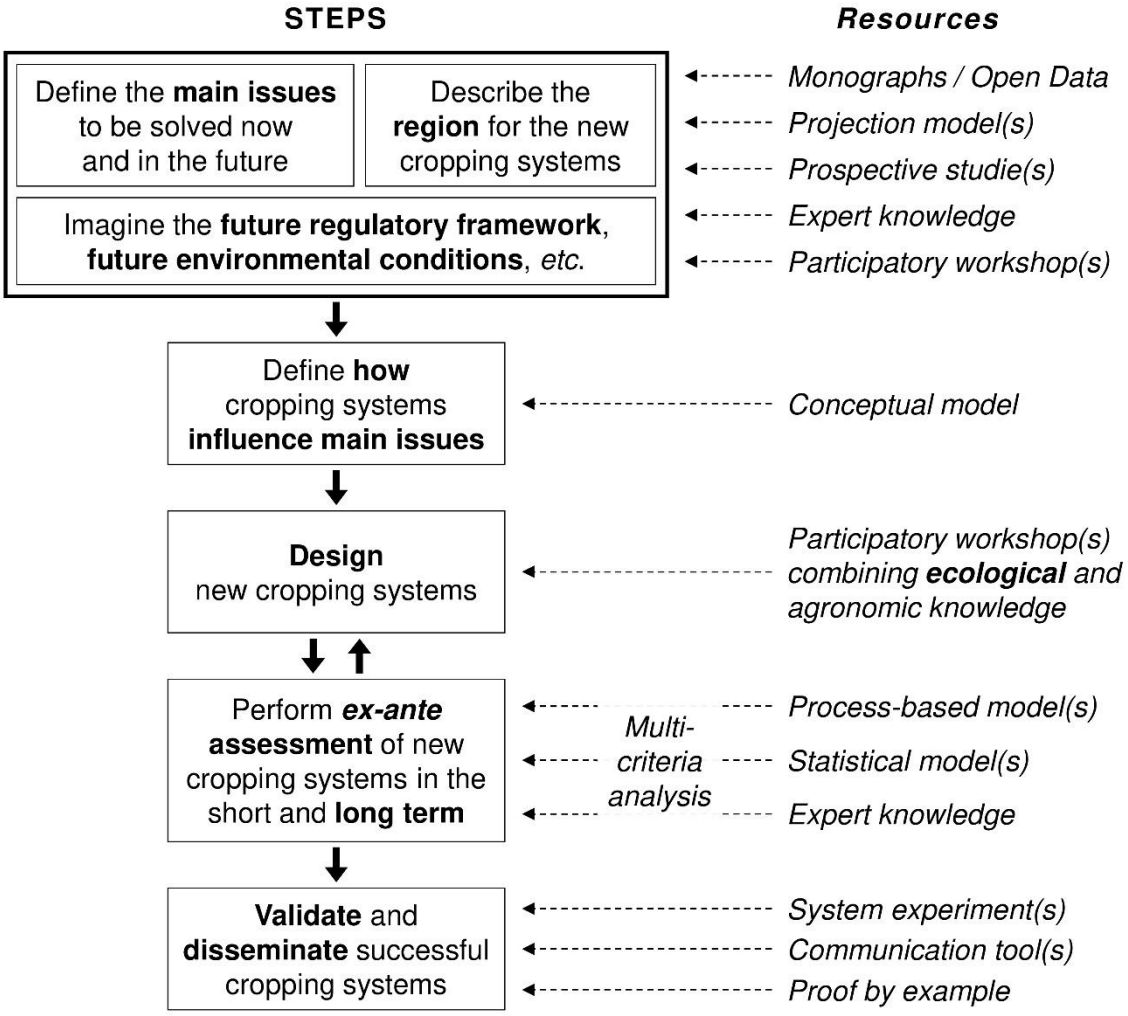

Figure 3. A framework for the design of cropping systems assessed in the short and long terms.