Matière à débattre & décider

Land Use and Food Security in 2050: a Narrow Road

Agrimonde-Terra

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éditions Quæ

11. Cropping Systems

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Introduction

THE CROPPING SYSTEM (in its French meaning, *i.e.* "système de culture") describes the succession of crops over time and the cultivation techniques applied to each crop at the field scale. The combination of cropping systems at the farm scale largely determines the production quantity, farmers' income and the environmental impact of agricultural activities. Cropping systems result from the implementation of more or less explicit decision rules, which can be adapted according to production conditions. The analysis of the evolution of cropping systems makes it possible to understand the dynamics of land use at the scale of the production unit. The four hypotheses for the evolution of cropping systems by 2050 presented in this chapter were developed from a workshop which brought together 20 agricultural production and cropping system specialists for two days (Box 11.1), followed by conceptualization work.[46]

In the following, we first specify our adopted definition of 'cropping systems'. Then, we focus on the cropping system performance: how to define it and how to measure it. Thirdly, we propose a set of variables allowing for describing cropping systems. Fourthly, we describe the methodology used for building hypotheses for the future cropping systems in 2050. Finally, we report the four hypotheses for the possible futures of cropping systems.

Definition

ACCORDING TO FRENCH AGRONOMISTS, a cropping system is defined (Sebillotte, 1990) as "all the technical methods implemented on plots cultivated in the same way. Each system is defined by the nature of the crops, their order of succession and the crop management techniques applied to these different crops, which include varietal choice". The crop management sequence is itself defined as a "logical and orderly combination of techniques that make it possible to control the environment and to derive a given output from it" (Sebillotte, 1974). The notion of cropping system used here differs from the usual

46. Conducted by the authors of this chapter and two members of the Agrimonde-Terra project team: Catherine Donnars and Olivier Mora.

Box 11.1. Members of the expert group on cropping systems.

Name	Institution
Expert present in workshops in Paris (11/08 2013 and 12/11 2013)	
Philippe Baret	Université catholique de Louvain, SST/AGRO, Louvain la Neuve, Belgium
Didier Bazile	CIRAD, équipe GREEN, Montpellier, France
Tamara Ben-Ari	INRA, UMR Agronomie, Paris, France
Elena Benett	McGill University Montreal, Dpt of Natural Resource Sciences Quebec, Canada
Nienke Beitema	CGIAR, IFPRI, Washington, USA
Patrick Bertuzzi	INRA, US Agroclim, Avignon, France
Philippe Brabant	AgroParisTech, UMR de Génétique Végétale, Gif sur Yvette France
Kate Brauman	University of Minnesota, IonE Saint Paul, USA
Thierry Brunelle	CIRAD, UMR CIRED, Nogent-sur-Marne, France
Thierry Doré	AgroParisTech, Département SIAFEE, UMR d'agronomie, Paris, France
Philippe Ellul	CGIAR Consortium, Montpellier, France
Guy Faure	CIRAD, UMR Innovation, Montpellier, France
Günther Fischer	IIASA, Vienna
Jean-Yves Jamin	CIRAD, UMR G-Eau, Montpellier, France
Luis Lassaletta	CNRS/ Pierre et Marie Curie University, Paris, France
Pierre-Yves Le Gal	CIRAD, UMR Innovation, Montpellier, France
Graham Mac Donald	University of Minnesota, IonE, Saint Paul, USA
Karen Macours	INRA, UMR PjSE, Paris, France
William Masters	Tufts University, Department of Food and Nutrition Policy, Boston, USA
Daniel Mueller	IAMO, Leibnitz Institute, Halle, Germany
Thomas Nesme	University of Bordeaux/INRA, France / McGill University Montreal, Canada
Chloé Salembier	INRA, UE Alénya Roussillon, Alénya, France
Florian Schierhorn	IAMO, Leibnitz Institute, Halle, Germany
Elise Thomazo	Total, Département de prospective, Paris, France
Emmanuel Torquebiau	CIRAD, Climate Change Correspondent Montpellier, France

Anglo-Saxon 'cropping system', which is considered to be all activities related to crops at the scale of the farm (Zandstra *et al.*, 1981), while the concept of cropping system used here applies to the scale of a cultivated area. It also differs from the concept of 'cropping pattern' which is very close to that of crop management sequence.

Cropping system performance

A CROPPING SYSTEM is the result of the implementation on a given surface area of the technical, human and financial means available to the farmer to achieve a goal.

Socio-economic performance

The socio-economic performance of the system can therefore be measured by comparing the output obtained to the level of use of the various production factors (land, capital and labour) (Alston *et al.*, 2010). Partial indexes, factor by factor, can be calculated: the yield is thereby the index of partial productivity of the land factor. Each of these indexes does not take into account changes in other production factors, the role of which may be decisive. In theory, total factor productivity (TFP) provides a measure of the overall efficiency of the production process. But it is not always easy to calculate (Petit, 2011), in particular because of the lack of data on the cost of inputs, especially when they are not traded, as may be the case for land or labour (Fuglie, 2008).

Nevertheless, analysis of the productivity of individual factors is useful for analysing farmers' rationales. These will tend to maximise the productivity of the production factor which is most lacking. So, producers with a very small acreage and little technical or financial capital will tend to maximise production per unit area at the cost of a high investment in labour, under the hypothesis that they do not have a better option to draw value from their workforce. This is especially true in situations where farmers produce for their own subsistence. Those with few workers (in situations where little labour is available) but with larger land and capital resources will tend to maximise net output per unit of work (van der Eng, 2004), without necessarily trying to maximise the yield per hectare, but rather the margin per hectare. Finally, investors from outside the agricultural sector (*e.g.*, the Argentinean 'pool de siembra' model, Chapter 10) will tend to mobilise the combination of land, technical capital and labour to maximise the return on their financial capital in comparison to what they could achieve in other sectors (Cochet, 2011).

Agro-environmental performance

A cropping system's agro-environmental performance depends on the cropping techniques used, particularly the use of natural resources (such as water) and synthetic inputs, which can lead to impacts on the ecosystem. These impacts can be negative: pollution and soil degradation, the extraction and pollution of water resources, damage to wild biodiversity, air pollution and greenhouse gas emissions, to which we can add the consumption of fossil fuel resources. Conversely, agricultural practices can strengthen ecological processes for the benefit of the farmer or society in general. Here we are talking about ecosystem services (MEA, 2005a; Deytieux *et al.*, 2012; Tibi and Théron, 2017): soil enrichment through organic matter has a beneficial effect on the chemical fertility of soils, on their resistance to erosion and mitigates climate change (by increasing soil carbon stocks), degradation of pesticide pollutants through soil microbiological activity, recycling of excess nitrates through nitrate catch crops, maintenance or enrichment of wild biodiversity etc. Over longer time periods, an important component of crop system performance is resilience to hazards, especially those related to climate change (IPCC, 2006; Morton, 2007).

Measuring cropping system performance

From an agronomic point of view, the margin for increasing production in a cropping system can be measured by the difference between its current level (usually measured in yield per hectare) and the potential production according to local agro-climatic conditions (Doré *et al.*, 2008; Lobell *et al.*, 2009). When this output gap ('yield gap' in the scientific literature, Mueller *et al.*, 2012) is large, even a modest improvement in crop management sequence makes it possible for part of the gap to be filled: theoretically, in fact, merely improving the availability or efficiency of the most limiting factor, nitrogen for example, is enough to achieve a significant increase in yields. Conversely, the closer the current production level is to the potential level, the more difficult it is to improve by adding production factors (Licker *et al.*, 2010; Grassini and Cassman, 2012). This law, known as decreasing marginal returns, explains why the efficiency of nitrogen fertilizer use tends to be low when it is used in large quantities in intensive systems, which results in significant leaching into the environment. Often, the most intensive systems, which rely on high levels of synthetic inputs (fertilizers and pesticides), are also the least efficient regarding environmental performance (FAO, 2009a). From an agronomic point of view, the challenge is therefore to develop cropping systems that have both good economic performance and little impact on the environment, for example through substituting synthetic inputs with biological regulation (Jackson *et al.*, 2005; Doré et al., 2011).

The overall performance of cropping systems can be evaluated using multi-criteria analyses, long-term experimentation, modelling or by monitoring farmers' practices, either directly or through indicators.

A set of variables for describing cropping systems

To conduct a retrospective analysis or to draw up hypotheses for future changes in cropping systems, it is necessary to adopt a method for characterising systems. This method should take into account both the constitutive elements of cropping systems and their socio-economic and agro-environmental performance, in order to be able to evaluate the different dimensions of their sustainability.

Table 11.1. Descriptive components and variables of cropping systems.

Components	General description of cropping system	Choice of crop	Varietal choice	Pest management and weed control	Fertilization	Water management	Tillage
Variables	Destination of agricultural production (food, feed, energy, organic sector etc.) Ecosystem services Other services delivered (rural development, local food security, etc.)	Species cultivated Crop sequence	Earliness Disease resistance Landrace or commercial varieties (GMO or not)	Pesticides Pest-resistant varieties Biological control Weeding (chemical or mechanical)	Synthetic fertilizers Organic fertilizers produced on-farm or from beyond the farm	Drought-tolerant species and varieties Cultivation methods seeking to reduce water evaporation Irrigation	Manual Animal traction Mechanization No-till or simplified cultivation techniques (SCT)

The description of cropping systems adopted here uses all the criteria conventionally used by agronomists, breaking them down into components and variables as used in the foresight scenario method (ALEPH, 2004). A first set of components and variables describes cropping systems and how they work (Table 11.1). A second series characterises their socio-economic and agro-environmental performance (Table 11.2).

So, the diversity of cropping systems can be understood through four sets of variables which make it possible to describe how, in a given pedoclimatic and socio-economic context, farmers use the environment's resources, production factors and human resources to produce crops, with varying impacts on resources, the environment and land use. We can therefore distinguish:

– **The main characteristics of the system** (Table 11.1), in other words the different species cultivated, their succession over time and their organisation in space (rotation), the destination of crops (for food, feed or energy, organic sector etc.), and the production of services other than agricultural raw materials (for example, ecosystem services). The degree of crop diversification, which largely defines the level of cultivated biodiversity, is a structuring criterion, which has strong implications for all other variables (Malézieux *et al.*, 2009).

– **The technical functioning of the system** (Table 11.1), and more precisely its crop management sequence, including varietal choice, pest protection methods and weed control, fertilization, irrigation and tillage. This set of choices determines the production model and its relationship to the local environment, in particular whether it is based on biological

Table 11.2. Socio-economic and agro-environmental performance indicators for cropping systems.

Components	Energy sources used: human labour versus other sources	Production level (quantity and quality)	Environmental impacts
Variables	Measuring use of workforce Degree of mechanization of production: Cultivation techniques Irrigation Harvesting techniques Use of fossil or animal energy	Yield Yield gap Production quality	Water quality (N, P, pesticides) Pressure on water resources Emissions of greenhouse gases (GHG) Biodiversity Soil erosion Air pollution

and geochemical regulations (nitrogen fixation, recycling of mineral elements and biological control) or the use of exogenous inputs for the cultivated ecosystem (synthetic fertilizers and pesticides). It is at this scale that very important characteristics are defined, such as the level of intensification[47] and the option taken in terms of cultivation (till or no-till).

– **The choice of energy sources used** (Table 11.2), and in particular the relative proportion between human, animal and fossil energy. The combination of these three sources of energy is expressed in the form of two indicators. First, the degree of production's dependence on a non-renewable resource (fossil energy) whose accessibility and price are key factors regarding the economic sustainability of production. Second, the level of agricultural employment, which is an essential criterion both in situations where labour is scarce and in those where it is abundant and agriculture is one of the key employment sectors for local people (Losch *et al.*, 2011). One could even imagine in a multi-criteria analysis that the ability of a cropping system to allow sustainable substitution of non-renewable energy with human labour is a performance to be sought.

– **Agronomic and environmental performance of the cropping system** (Table 11.2). Yields are essential for estimating the availability of agricultural raw materials, but they are not very good for describing the level and type of intensification in production. Indeed, the volume obtained per hectare is not sufficient to characterise the production process: in a complementary fashion, the efficiency of the inputs, that is to say the level of production compared to the quantity used of each input, makes it possible to estimate whether

47. In this chapter, intensification is understood in the most general way as the implementation of practices leading to increased production in the cropping system, which may cover various strategies: increased yields through the greater use of chemical or organic inputs, or by improving their efficiency; irrigation; increased efficiency of interception of light energy through crop combinations, catch crops and agroforestry; use of varieties better adapted to the environment; disease and pest control using chemical or biological products etc.

these inputs are used efficiently or, conversely, to detect overconsumption and waste. The yield gap, in other words the difference between the production potential determined by pedoclimatic conditions and actual production, allows us to measure the system's potential for improvement. Environmental impacts affect the sustainability of systems both because these impacts can directly compromise production (including degradation of agricultural soils) but also because society can challenge systems that have an impact beyond the perimeter of the agricultural system itself (including excessive extraction or pollution of water, air pollution and greenhouse gas emissions).

Methodology for building the hypotheses for the cropping systems in 2050

THE USUAL APPROACH is to conduct a retrospective analysis of changes in different components of the system over past decades and then construct hypotheses for future evolutions for the system as a whole. However, in the case of cropping systems, it is very difficult, even impossible, to analyze past changes component-by-component and, based on these past trends, to imagine the future evolution of a cropping system. Hence, we thought more judicious to work from specific and localised cropping systems, for which we have analyzed the dynamics of past changes by trying to identify the determinants of their trajectory.

Selecting specific and localised current cropping systems

On the basis of several criteria, 12 cropping systems were selected (Table 11.3):
– Agro-pedoclimatic conditions: situations in the temperate zone versus situations in the tropics.
– A diversity of production structures and logics: small, medium and large family farms, and profit-driven farms (agribusinesses).
– A focus on a group of rice-based farms, because of the importance of this crop for food systems.

Following a small group brainstorming exercise, several evolution scenarios were drawn up for each case. These were based on retrospective information on the changes over the past 50 years. Some 44 scenarios were developed and then cross-analyzed to group them according to three typologies:
– A typology of agronomic evolution, close to the description of cropping systems, based essentially on the phenomena of specialization versus diversification, on issues of efficiency and level of input use.
– A typology based on modes of intensification, each type mobilizing different resources and logics. This typology was chosen for guiding the construction of hypotheses for the future evolution of cropping systems. Indeed, it is most relevant for discussing the question of land use.
– A typology of socio-technical transition modes, describing the degree of difficulty represented by the implementation of the proposed changes.

Table 11.3. Principal characteristics of 12 cropping systems used for the construction of evolutionary hypotheses.

Rice-based food systems constrained by water and other factors availability	Food systems constrained by integration into market	Agroforestry systems in humid tropical zones	Arable systems in temperate zones
Rice-based system, small farm (F), Vietnam, limited water	Sorghum-based system, small farm, Sahel, access to inputs and to market	Cacao agroforestry, small farm, Cameroon, opening of market, capital/labour	Maize monoculture, medium farm, France (Landes), impact on water and biodiversity
Rice-based system, small farm, Thailand, water and workforce (WF) limited	Cotton-food system, small farm, Burkina Faso, access to inputs, WF problem	Oil palm, small farm, Africa, land sparing/ sharing, link with agro-industry	Wheat-based system, large farm, Russia, context of climate change
Rice-based system, small farm/agri-business, Vietnam, limited water	Quinoa system, small farm, Bolivia, intensification, environmental impact		Maize-soya system, large farm, USA (Iowa), environmental impact
			Profit-driven soya system, Argentina, environmental impasses

Lessons from retrospective analysis

For the sake of simplification, two types of evolution were considered:

– Trajectories of great stability in the past, linked to highly resilient systems mainly focused on self-consumption or systems in stagnation due to an inability to invest and integrate into markets.

– Trajectories of an intensification of production to varying degrees, which result in an increase in yields. This trajectory is dominant among the cases studied.

From an agronomic point of view, production per hectare (species cultivated and yield per species) remains interesting for describing the evolution of cropping systems, especially when it increases: it is then possible to analyze which technical and human means have made this increase possible. The analysis of the cropping systems offered by the experts in the working group therefore made it possible to verify that, almost everywhere that it was possible and in very diverse socio-economic contexts, the retrospective increase in yields results mainly from a process of substitution of physicochemical and biological factors from the ecosystem with synthetic inputs (Miflin, 2000) and classical genetic progress (Takeda and Matsuoka, 2008). This evolution in production techniques has been accompanied by a simplification of cropping systems, itself linked to an increased separation of livestock and cereal production (Meynard *et al.*, 2013). This move to simplified rotations and regional specialization was made possible by the use of synthetic inputs, which came to replace the recycling of livestock effluent as a source of fertilizer for crops. The retrospective analysis has also sought to take into account the environmental consequences of this movement of simplification and increased artificiality of cropping systems, characterised by soil degradation, a decrease in wild and cultivated genetic diversity, consumption of fossil resources and pollution of different compartments of the ecosystem (water, air and soils). Under the banner of the 'green revolution', this intensification of agriculture took place in various parts of the world from the 1950s and 1960s. It relied on the dissemination of high-yielding varieties from agronomic research centres and the use of synthetic fertilizers and possibly pesticides, and irrigation in certain regions. Motorization has practically concerned only European and North American agriculture. This technological package has been driven by agricultural policies based on input subsidies and output price support in the context of the cold war (Griffon, 2006).

Future cropping systems in 2050

We have chosen to classify the potential evolutions of the 12 cropping systems according to four evolution hypotheses defined on the basis of the sets of variables described above, and whose combination produces different modes of production intensification: conventional intensification, sustainable intensification and agroecology, to which we have added a production impasse or collapse hypothesis.

However, we are aware that this classification is only one of many. Recently, based on types of production systems, characterized by the nature of their inputs and the types of socio-economic context in which they are based, Thérond *et al.* (2017) proposed a dynamic framework for analyzing diversity in the forms of agriculture, in which six sets were finally selected. The IntensAfrica project suggested a typology of 'pathways' from which we were partly inspired.[48]

In fact, the nature (and relevance) of these classifications is important in these times of debate between proponents of one model versus another, even if we know that we should rather move towards a co-existence between several systems.

Since this is a foresight study, the specificity of our four evolution hypotheses is to focus on the temporal dynamics of the systems. This means the type of intensification is not enough to characterise the dynamics of the evolution in cropping systems. The greater or lesser difficulty in implementing changes in systems aiming for greater sustainability is an essential complementary criterion. The description of these dynamics according to the ESR (Efficiency, Substitution, Redesign) socio-technical transition typology (Hill and Mac Rae, 1995) is suggested here. In organisational terms, this entails a growing degree of difficulty in transition: simple improvement of the efficiency of the system which remains in its current state (Efficiency), substitution of one element of the system (species cultivated or technical) with another

48. http://www.intensafrica.org/fr/diverses-voies-conduisent-a-une-intensification-durable-de-lagriculture/

(Substitution), or complete redesign of the system (Redesign). These socio-technical transition regimes are one of the criteria that led to the construction of the four evolution hypotheses.

Hypothesis 1: Productive impasse in crop production

The productive impasse hypothesis (Collapse) corresponds to a series of potential dead-ends in agronomic (climatic disruption or biotechnical impasses) and socio-economic terms (land insecurity, access to inputs, markets or credit, production profitability conditions, lack of labour etc.). These impasses may be the consequence of the weaknesses identified in 'Conventional intensification' (see hypothesis 2) or a sudden change in the environmental or economic context.

Hypothesis 2: Conventional intensification of agriculture

This hypothesis (Conventional Intensification of Agriculture, CIA) is based on specialization in production (Rastoin and Ghersi, 2010). This can produce high yields, but is highly sensitive to climate variability (except where irrigation is used) and biological hazards, generally related to the system's ecological uniformity. The system has a high degree of dependence on agro-industrial inputs and fossil energy, generating negative impacts on the environment. As a result, the socio-economic and agro-environmental sustainability of the cropping system is fragile. This is the reference scenario of the 'green revolution' of the post-war period, already identified in the retrospective approach, and constitutes an extension of this trend (Sinclair and Rufty, 2012). Depending on the degree of mechanization, the labour requirement in these systems is highly variable. This trajectory can bifurcate towards greater sustainability by improving input efficiency (without questioning its fundamental organisation) or by diversifying production (which means a complete reorganisation) or, if there is no adaptation, a productive impasse.

Hypothesis 3: Sustainable intensification of agriculture

The Sustainable Intensification of Agriculture (SIA) hypothesis is an option which seeks to combine an intensification of production with a reduction of the cropping system's environmental impact through maximizing the efficiency of the inputs used (Griffon, 2006, 2010). In addition to the very frequent use of mechanized direct seeding, with the possible planting of mixed species or undersowing crops, this hypothesis is based on the use of technologies designed by or in association with agribusiness: genetic technologies (including GMOs), biocontrol technologies (for the control of pests and diseases), precision agriculture and information technologies. Its yields are high. Its agro-environmental resilience is improved compared to conventional intensification, but it does not reach the levels of agroecology (see below). From a socio-economic point of view, the sustainable intensification hypothesis is based on the widespread use of technological inputs and therefore does not have the same degree of autonomy with regards to agricultural suppliers as the agroecology hypothesis.

Hypothesis 4: Agroecology

The Agroecology hypothesis (AE) is essentially based on the diversification of crops (including agroforestry) (Malézieux *et al.*, 2009) and/or the coupling of crops and livestock, which most often requires a complete redesign of the production system. Principally, under this hypothesis the cropping system uses biological regulations produced by the ecosystem itself, in a sustainable manner (Altieri, 2002; Malézieux, 2012). This hypothesis is characterized by the system's great autonomy and resilience, from both an agro-environmental and socio-economic point of view (Boyce, 2004; Kumar and Nair, 2004), with a very low dependence on industrial inputs (fertilizers, pesticides and seeds) and fossil fuels. However, it requires large amounts of labour or appropriate mechanization. Yield levels will depend on the characteristics of these systems, which are highly diverse. These cropping systems generally fit into production and food systems aimed at ensuring food security throughout the territory, where they are often the only possible way to improve production because of their autonomy from exogenous resources.

The principal characteristics of the four evolution hypotheses of the selected cropping systems are summarized in Table 11.4.

Table 11.4. Characteristics of the four hypotheses for cropping systems in 2050.

Hypotheses for 2050	Collapse	Conventional intensification of agriculture
System characteristics: orientation, choice of crops and crop sequences	Highly simplified crop sequences, sensitive to economic and biotechnical hazards, including climate change.	Production of raw materials for generic markets, without specific quality criteria. Highly simplified crop sequences. No ecosystem services.
Varietal choice	Classic varieties or self-saved seed to reduce costs.	Varieties with high yield potential (pure lines, hybrids and GMOs) from seed companies.
Pest and weed control	Biotechnical impasses generated by pesticide use (pesticide resistance in weeds, diseases and pests). Or crop losses caused by lack of access to pesticides.	Systematic pesticide use combined with the use of resistant varieties.
Fertilization	Excessive use of synthetic fertilizers (over-fertilization) and lack of organic fertilization. Or no use of synthetic fertilizers and low organic soil fertilization.	Synthetic fertilizer, potentially excessive use.
Management of water resources and irrigation	Gravity-fed irrigation and sprinkler systems, no attempt to reduce water use.	Gravity-fed irrigation and sprinkler systems, no attempt to reduce water use.
Tillage	Annual ploughing of fragile soils, reduction of organic matter.	Annual ploughing, mostly mechanized.
Energy used: human work versus other sources	Use of human labour or highly variable levels of mechanization.	Use of human labour or highly variable levels of mechanization.
Production level, change in yield gap	Acceleration of fall in yields, growth in yield gap.	Higher yields, weak input efficiency. Small but unstable yield gap.
Environmental impact	High environmental impact, to the point of compromising agricultural activities (in particular water, soil and biodiversity).	High impact on air, water (quantity and quality), GHGs and biodiversity.
Socio-technical regime and degree of resilience	Socio-technical or economic impasse. Zero resilience.	Continuation of the logic from the green revolution (intensification). Low resilience.

Table 11.4. Continued.

Hypotheses for 2050	Sustainable intensification of agriculture	Agroecology
System characteristics: orientation, choice of crops and crop sequences	Production of raw materials for generic or specialized markets. Quite diverse crop sequences but not systematic. Ecosystem services support production.	Production designed to satisfy local food needs. Great diversity of crops, agroforestry, link with livestock. Production of a wide range of ecosytem services, production of rich and diversified landscapes.
Varietal choice	Varieties with high yield potential, disease resistance and maybe tolerance to herbicides (pure lines, hybrids and GMOs).	'Population' varieties or lines bred locally. Good adaptation to local climatic conditions and disease resistance. No use of GMOs.
Pest and weed control	Non-systematic use of pesticides. Occasional use of biological control. Varieties resistant to pests and diseases and, where appropriate, tolerant to herbicides (no tillage).	Pesticides are used only exceptionally or not at all. Biological control for pests and weeds through the choice of crop succession and maintenance of biodiversity areas (hedges and groves) for beneficials. Mechanical weeding. Resistant variety populations.
Fertilization	Judicious use of synthetic fertilizers, precision agriculture. Possible use of legume crops.	Fertilization based essentially on the cultivation of legume crops and organic fertilizer from livestock. Very low or no use of mineral nitrogen.
Management of water resources and irrigation	Varieties tolerant to water stress. Precision irrigation to maximize water efficiency.	Reduction of water needs through the choice of species and varieties. Techniques for preserving rainwater. Parsimonious irrigation possible.
Tillage	Growing use of no-till direct sowing techniques.	Frequently tillage is manual or uses animal traction. Ploughing maintained for weed control. Possible use of no-till techniques.
Energy used: human work versus other sources	Highly mechanized: direct sowing and precision agriculture techniques, robotisation.	High intensity of labour and low mechanization (very small farms). Or use of mechanization (large farms).
Production level, change in yield gap	Higher yields, strong input efficiency. Slight reduction of yield gap where it is already small (most common) and sharp reduction in yield gap where it was high (less common).	Yields difficult to assess because of the complexity of rotations. Reduced yield gap, reduced more strongly in situations with low prior yield levels (the majority of cases).
Environmental impact	Low impact on air and GHGs, and variable impact on biodiversity. Preservation of water resources, soil improved (no tillage).	Very little or no impact on water and air quality and GHGs. Preservation or improvement of water resources, soils and biodiversity.
Socio-technical regime and degree of resilience	Transition based mainly on a strategy of efficiency (E) or substitution (S). Average resilience.	Transition based mainly on a strategy of substitution (S) or redesign (R). High resilience.

Discussion and conclusion: Differentiated effects of different evolution hypotheses on land use and production volumes

Expert discussions during the cropping systems workshop showed that there is a great deal of uncertainty about the comparative changes in yields induced by the different hypotheses made. However, the expert group managed to agree on certain expected effects specific to each evolution hypothesis under consideration, in particular taking into account that they are likely to be adopted in a differentiated way, some of them being more suited to certain contexts and types of agricultural structures. These effects are summarized below.

In the short term, the conventional intensification hypothesis can lead to an increase in production through the use of synthetic inputs and irrigation, even in the absence of mechanization: it is an extension of the historical 'green revolution' model. However, because of its weak agro-environmental and socio-economic sustainability, this hypothesis does not appear to constitute a long-term solution. In its agronomic version, the hypothesis of a production impasse is often the failure of a conventional intensification trajectory which has exceeded a threshold of sustainability. For example, the low levels of additional organic matter in soils lead to a decline in their water storage capacity and therefore greater sensitivity to the effects of climate change. Decreasing soil carbon levels can lead to irreversible degradation and release CO_2 into the atmosphere. In addition, the excessive use of nitrogen fertilizer is common in these conventional systems and contributes to increasing greenhouse gas emissions (N_2O released during spreading, CO_2 from the fertilizer manufacturing process).

The sustainable intensification hypothesis assumes access to the advanced technologies available on the market and is therefore applicable mainly to larger farms with significant investment capacity and a level of conventional intensification which is already high. In this case, its implementation will lead to little change in yields, so little increase in production, but an improvement in product quality and a reduction in environmental impacts thanks to the more targeted use (and therefore lower use) of synthetic products. Its environmental sustainability is therefore greatly improved compared to conventional intensification. More marginally, this hypothesis can concern farms which are initially of lower intensity and have lower economic size but for which strong public support policies are established to provide farms with access to advanced technologies, mechanization and synthetic inputs. In this case, the increase in yields is significant, but the effect on the overall increase in production is low because few areas are affected.

The hypothesis of an evolution towards agroecology assumes the mobilisation of the biological regulations of ecosystems. Although it can affect all types of agricultural structure, it is particularly well suited to small farms, of lesser economic importance (land

and access to productive capital). Indeed, based on the diversification of production and biological regulations from the ecosystem, agroecological farming systems are not very demanding in terms of capital, and have a strong agro-environmental and socio-economic sustainability. In terms of implementation costs, it is essential to quantify the direct savings generated by the introduction of biological regulation to replace synthetic fertilizers and pesticides, and to put them in relation to the mobilisation or remobilisation of agricultural employment. Indeed, for the most part this hypothesis is likely to apply to smaller farming situations, where the means to invest in the conventional or sustainable intensification models are not available and for all types of pedoclimatic conditions, including those where mechanization is difficult or impossible. For all those farms facing a production impasse, or close to it, this hypothesis leads to a sharp increase in production and diversity, even if it only partially closes the potential yield gap. This hypothesis can also be applied to medium or large conventionally intensive farms. There is little change in yields, but an improvement in product quality through the reduction in the use of synthetic inputs. In the context of mechanized agriculture in developed countries, the shift to agroecology is an alternative to sustainable intensification, involving more radical changes in cropping systems because it is based on a greater diversification in production. Such analyses can feed the future advocacy which is essential to the formulation of public policies, in both the Northern and Southern hemispheres. In all cases, the transformation of systems and support for this change requires strong public support policies to produce or share the necessary knowledge, and to train farmers.