ECOSYSTEM SERVICES PROVIDED BY AGRICULTURAL ECOSYSTEMS

A CONTRIBUTION TO THE EFESE PROGRAM

SUMMARY OF THE STUDY CONDUCTED BY INRA - NOVEMBER 2017

INRA
SCIENCE & IMPACT

Although the concept of "services provided by nature" dates from the second half of the 19th century, the term "ecosystem services" only entered the scientific literature in 1970. At the beginning of the 2000s, the concept was formalized with the Millennium Ecosystem Assessment (MEA), which sought to provide a scientific analysis of the current state of and potential future threats to the ecosystems on which human beings depend for their survival.

In France, the National Ecosystem Assessment ("Evaluation française des écosystèmes et des services écosystémiques - EFESE"[1]) program is developing assessments of ecosystem services (ES) to inform national and local planning processes and to raise public awareness of the value of biodiversity. EFESE also seeks to introduce values for biodiversity into national accounting systems. Within the context of this program, the Ministry for the Environment requested the French National Institute for Agricultural Research (INRA) to contribute to the assessment of ES provided by "agricultural ecosystems." The resulting study, conducted according to the principles summarized in Box 3 (p. 11), was also supported by INRA's own research program on ES.[2] The objectives were to describe the underlying mechanisms and determining factors for a range of ES, and then to proceed with their biophysical and economic assessment at the national level, using indicators adapted to the agronomic context. The development of an open, scientific information system on agricultural ecosystems and associated ES, integrating all data provided by the study, is an additional objective of this project.

The study report emphasizes the need for a detailed analysis of the biophysical mechanisms underlying the provision of ES as a precursor to effective ES assessment. Among the range of ES provided to society by agricultural ecosystems, the study identifies those provided specifically to farmers by contributing to the production of agricultural goods, and proposes a preliminary assessment of the importance of such ES relative to the use of agricultural inputs. Furthermore, it stresses that caution should be used in any economic assessment of ES.

A framework for assessing ecosystem services from human-impacted ecosystems

For ecologists and agronomists alike, **the term "agricultural ecosystem" describes a "soil and plant"-based system existing at the level of the field or field unit**, including animals living in or passing through the field (livestock on pasture, wild animal biodiversity) as well as associated semi-natural features (hedges, isolated trees, wet areas, field margins, etc.). From a geographic perspective, agricultural ecosystems are defined as all arable, planted, or grassland areas used primarily for agriculture. Farmers alter and manage these ecosystems using a variety of practices, with the primary objective of producing biomass.[3] Among the issues at stake in the analysis of ES from agricultural ecosystems is whether agricultural production systems can rely more on ES and less on external inputs, and in this way respond to a range of societal demands (biodiversity conservation, the reduction of environmental impacts, etc.). To effectively address this question, any analytical framework for assessing ES from agricultural ecosystems must be able to distinguish between the role and importance of ES vs. external inputs in supporting agricultural production.

Many of the existing analytical frameworks for ES are based on identifying a chain, or cascade of interactions connecting ecosystem functioning and human well-being: this includes delineating the biophysical structures and processes that make up the ecosystem, the ES themselves, and their associated benefits. Scientific definitions of ES may be divided into two major types: i) those in which ES are defined as <u>the biophysical components of an ecosystem from which benefits are derived</u> – this is the definition adopted by the authors of the Common International Classification for Ecosystem Services (CICES); and ii) those in which <u>ES are the benefits</u> human beings receive from ecosystems – the definition used in the MEA. In the INRA study as in the CICES framework, **ES are defined as ecological processes or structural elements of ecosystems from which human beings derive benefits, in some cases through the application of labor, physical capital, or knowledge resources, in an effort to improve human wellbeing.** The benefits derived from ES are functionally disconnected from the ecosystem, and may be either material (goods) or immaterial (services[4]) in nature. A single ES may be the source of multiple benefits.

This definition of an ES is therefore based on a distinction between the **biophysical determinants** of ES, which are internal to the ecosystem and underlie the supply of ES, and **other factors, external** to the ecosystem, that can affect the level of supply of the ES as well as the level of agricultural production (Figure 1, p. 4). In the case of agricultural ecosystems, **the status of agricultural practices varies according to their nature**. **Practices that relate to ecosystem configuration** (choice of plant and animal genotypes, cropping sequences, etc.) will determine the potential for agricultural production for a given climate. Ecosystem configuration is also a key biophysical determinant of the level of supply of the ES. **Practices that relate to soil and biomass management** are considered to be external factors that affect the level of provision of ES: the influence of such factors is felt *via* their historic effects on the condition of the ecosystem (for example, the effect of tillage practices on soil organic matter), or *via* their impact on the expression of the ES across the time period considered for the assessment (for example, the effects of irrigation on water flow within the ecosystem, which will influence the level of associated ES across the course of a year).

The INRA study definition of ES also suggests the possibility of **assessing the ES potential of a given spatial and temporal ecosystem configuration, and then considering how that potential may be increased or decreased by external agricultural practices.** It is consistent with the agronomic view of cropping systems where, through a planned combination of managed vegetative cover and agricultural practices, multiple objectives regarding agricultural production, reduction of external inputs, and supply of ES to society can be achieved.

[1] https://www.ecologique-solidaire.gouv.fr/levaluation-francaise-des-ecosystemes-et-des-services-ecosystemiques
[2] http://www.ecoserv.inra.fr/en
[3] The term "agroecosystem" refers to the agricultural ecosystem (an ecological compartment) *together with* the individuals managing it (and the means they employ to do so).

[4] The terms *goods* and *services* are used here in the sense of national accounting systems, and refer to all products or outputs made or provided by businesses, governments, associations, etc.

It should be noted that **only processes linked to living organisms are defined as ES.** Thus, **the biodiversity of agricultural ecosystems is considered as a major biophysical determinant of ES.** At the field level, two components of biodiversity interact within agricultural ecosystems: so-called "planned" biodiversity, intentionally introduced into the ecosystem, in whole or in part, for agricultural production purposes (cultivated plants, livestock); and "associated" biodiversity, including weeds, soil fauna (endogenous macro- and meso-fauna, soil microbial communities), and the macro- and meso-fauna that move through the field at ground level or in the air.

Given the focus of this study on agricultural ecosystems and its underlying purpose to support the work of public decision-makers, **two categories of ES beneficiaries were identified: farmers and society as a whole.** As managers of agricultural ecosystems, farmers derive specific benefits from ES that contribute directly to agricultural production. Society as a whole is the beneficiary of ES provided by agricultural ecosystems both directly (e.g., from "Global climate regulation" ES), and indirectly *via* modifications in the behavior of the "farmer" beneficiary (e.g., "Regulation of weed seeds" ES can substitute for the use of herbicides that have the potential to contaminate the environment). As citizens and residents, of course, farmers also belong to the second category of beneficiaries, society as a whole.

The **"disservices" of the agricultural ecosystem were not examined within this study.** The concept can include two distinct ideas: 1) negative effects *on* human beings resulting from biodiversity or from certain ecosystem processes (to be distinguished from situations of low supply of ES); and 2) negative impacts *of* human activities on the environment, corresponding essentially to material flows from agricultural ecosystems into other ecosystems as a result of agricultural practices.

Methodology

In keeping with numerous other international studies, **the CICES classification was adopted as the reference typology** for identifying ES provided by agricultural ecosystems in France. The category of "provisioning ES" was not used, however, since **agricultural production was considered as an agricultural good** that benefits the farmer as a result of interactions between regulating ES and human-supplied (or external) inputs. A total of **fourteen ES were considered here (listed in Table 1).** For each of these ES, the following characteristics were specified: i) the nature of the ES; ii) the benefits received by "farmer" and "society" beneficiaries; and, iii) the principal biophysical determinants and external factors involved in ES supply. This specification led the study group to propose a revision of the CICES typology.

The scientific literature and other European work on ES assessment was reviewed to identify methodologies (indicators, data) used to quantify the level of supply of each ES, and in some cases to propose new ones. These methods should make it possible **to map ES provided by agricultural ecosystems: i) at the highest possible spatial resolution; and, ii) across the entire territory of mainland France.** The resulting spatial resolution of the ES assessment ranges from the plot level to the level of the Small Agricultural Region (SAR) (mainland France is divided into 714 SAR), or in some cases to the departmental level, depending on the ES or ES group in question.

Given various constraints with regard to the study's execution (availability of data, length of the project, researchers' areas of expertise, etc.), not all ES were quantified. A review of the available literature was completed for all non-quantified ES, however, in order to identify the methodological challenges involved in their assessment and to clarify additional research and/or data requirements for their examination. Other ES could only be quantified for certain types of agricultural ecosystems. As a result, **the assessment is not the same for all of the ES that were quantified.** Finally, ecosystems involving perennial crops, those used for market gardening, and those situated in the French overseas territories were not considered in most cases due to a lack of sufficiently detailed data.

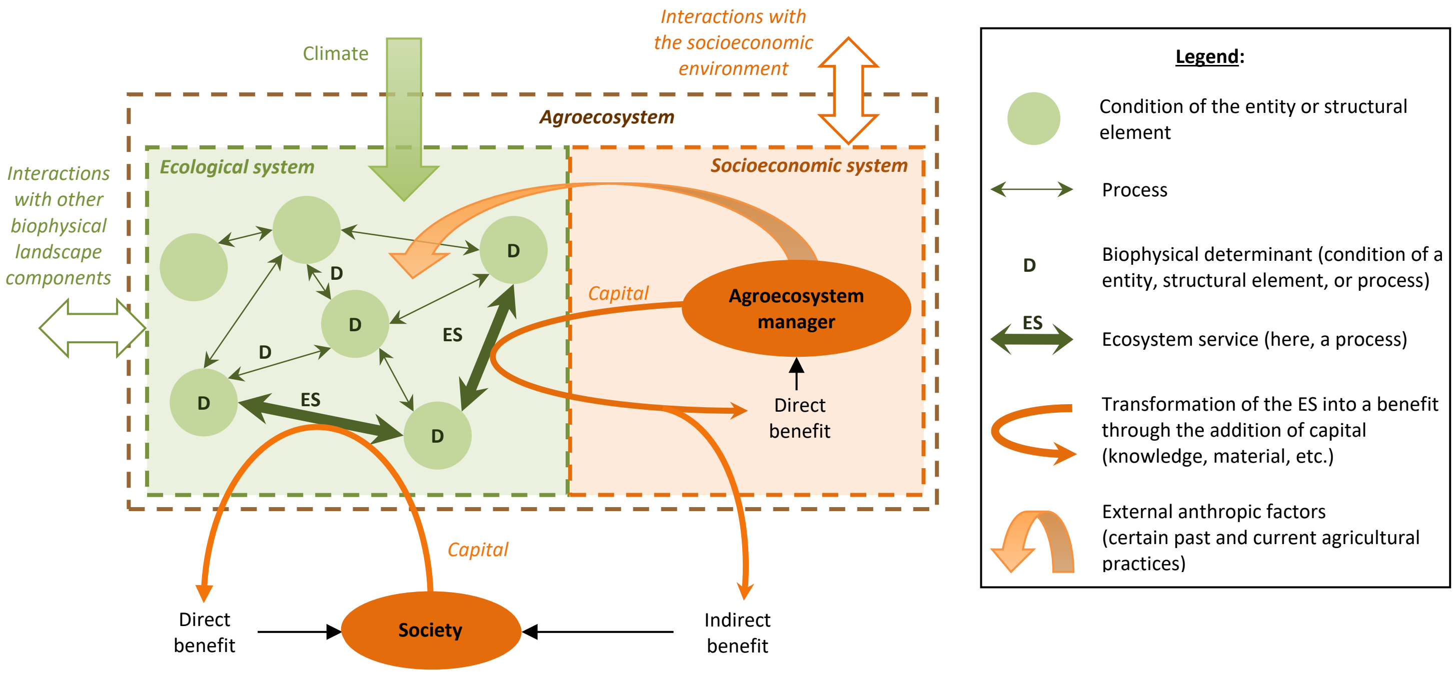
Table 1. List of ES considered by the study, and nature of the analysis completed by the expert group

Green cells: analysis completed

Ecosystem Service	Direct beneficiary *(indirect beneficiary*)*	Nature of the analysis completed		
		Specification	Biophysical quantification	Economic assessment
Soil structuration	Farmer			
Supply of mineral N to crop plants	Farmer *(→ Society)*			
Supply of other nutrients to crop plants				
Storage and return of water to crop plants	Farmer *(→ Society)*			
Soil stabilization and erosion control	Farmer and Society			investigated
Pollination of crop plants	Farmer			
Regulation of weed seeds	Farmer *(→ Society)*		partial	investigated
Regulation of insect pests	Farmer *(→ Society)*		partial	investigated
Natural attenuation of pesticides by soils	Society			
Regulation of water quality	Society		partial	investigated
Storage and return of blue water	Society			
Global climate regulation	Society			investigated
Recreational potential (outdoor activities without taking**)	Society			
Recreational potential (outdoor activities with taking)	Society			

* Society as a whole benefits indirectly from an ES due to changes in farmer behavior (practices) when farmers benefit directly from an ES.
** Recreational hunting, fishing and gathering

Figure 1. Schematic representation of key study concepts as related to the provision of two ES: one where society is a direct beneficiary, the other where the farmer is the direct beneficiary and society benefits indirectly.



Ecological system ("agricultural ecosystem"): includes all biotic and abiotic components contained in or passing through a defined geographical area (excluding built elements).
Socioeconomic system: includes the individuals (farmers) and all artificial means they use to establish and manage an ecological system for the primary purpose of producing biomass.

*Example: the ES **"pollination of crop plants"** refers to the process by which pollen is transferred from male to female flowers. Characteristics of pollinator communities (structure, abundance) are a key biophysical determinant for this ES. Climate and pesticide use are two external factors that impact its level of delivery.*

Box 1. Using dynamic simulation models of soil-plant(-animal) systems to assess ES related to the carbon, nitrogen, and water cycles

• Models

Two dynamic simulation models developed by INRA for the study of soil-plant(-animal) systems, STICS[5] and PaSim[6], were used to assess ES related to water, nitrogen, and/or carbon cycles. These models are designed to simulate day-to-day growth and development of vegetative cover and water, nitrogen, and carbon balances in cropping systems (soil-major field crops) and grass-based systems (soil-grasslands-grazing livestock), respectively. **A simulation device was developed specifically for this study.** Due to various constraints, however, **only the results obtained for STICS simulations of cropping systems were analyzed.** Implementation of the PaSim model and analysis of results related to grasslands will be addressed in an extension of the current study.

Dynamic simulations seek to estimate the annual average level of ES provided by **major cropping systems in the various pedoclimatic conditions of France**. The functional unit of assessment is not the annual crop but instead the full crop rotation and associated practices, making it possible to account for the cumulative effect of crop sequences (e.g. preceding effects) and external practices on the average level of the ES.

One of the strengths of this type of simulation model is that it accounts for the day-to-day dynamic of interactions between applied inputs and ecological processes. These models simulate only abiotic processes and do not account for the effects of pest species or crop protection practices.

• Input parameters and simulation runs

Simulations were performed for land area units considered to be homogeneous in terms of soil and climate, or "pedoclimatic units" (PCU). A total of 23,149 PCU representing a minimum of 100 ha of agricultural land each were modeled. Input parameters were defined for these PCU using agricultural databases.

The models **simulated the dynamics of "current cropping systems,"** assuming currently prevailing practices in terms of fertilization (mineral and organic), type of biomass harvested (grain, straw), crop residue management, irrigation (for maize), and establishment of cover crops. Several **alternative simulation implementations** were also run in order to test the effect of specific practices on the level of supply of the ES (holding the other practices unchanged relative to the "current systems" simulations): *maize without irrigation*, *cropping system without nitrogen fertilization*, and *cropping system without cover crops*. After verifying the coherence of the simulation outcomes in terms of yield and annual aboveground biomass at harvest, a total of **30,580 simulations** (combinations of [pedoclimatic type x cropping system]) **were retained for analysis**.

[5] https://www6.paca.inra.fr/stics/Qui-sommes-nous/Presentation-du-modele-Stics
[6] https://www1.clermont.inra.fr/urep/

"Input ES" provided to farmers

Over the course of an agricultural production cycle (the cropping cycle), a certain number of ES have an impact on yield production by affecting the level of expression of factors that can limit or reduce yield, including water scarcity, nutrient deficiencies, insufficient pollination, and pest damage. Regulating ES that support crop production may thus be considered as factors of production, rather like external inputs (irrigation water, synthetic fertilizers, crop protection products, etc.). As managers of agricultural ecosystems, farmers are direct beneficiaries of these ES, referred to here as "input ES". By substituting for the use of synthetic inputs, some input ES can contribute to the reduction of environmental pollution, creating an indirect benefit for society as a whole.

Assessing absolute levels of input ES

Input ES can be divided into two major types based on their role in contributing to crop yields.

(i) **ES that regulate abiotic stresses** help provide vegetative covers (grasslands or crops) with the conditions suitable for root development, including limiting water deficits and nutrient deficiencies: these are described as ES for "**soil structuration**," "**supply of nutrients to crop plants**," "**storage and return of water to crop plants**," and "**soil stabilization and erosion control.**" All of these ES are strongly dependent on the biotic and abiotic components of "soil" – soil fauna, aboveground and belowground plant systems, organic matter, available water content, etc. A central role is played by the ES for "soil structuration," which interacts with the other ES in this group.

ES relating to the water, nitrogen (N) and carbon (C) cycles were assessed using the dynamic simulation tool for soil-plant systems, as described in Box 1.

Quantification of the ES "supply of mineral N to crop plants," "storage and return of water to crop plants," and "soil stabilization and erosion control" highlights the importance of crop rotations in determining the level of supply of these ES, especially crop seasonality (spring vs. winter crops) and the use or non-use of cover crops. Climate also plays a key role, of course. Selected indicators make it possible to estimate the absolute level of these ES and to observe their spatial distribution, but not to qualify ranges of values in terms of "low" or "high" levels of ES. To effectively inform decision-making, **it would be necessary to assess to what degree the ecosystem supplies crop requirements, particularly for mineral N and water, within a given pedoclimatic context.** In other words, the indicators must be reconfigured to determine the level of supply of these ES relative to agricultural production requirements (*cf. infra*).

(ii) ES that **regulate biotic stresses** protect yields by limiting losses, such as those resulting from insufficient pollination or the activities of pest species: these correspond to "**pollination of crop plants**," "**regulation of weed seeds**," and "**regulation of insect pests**" **ES**. The level of these ES is strongly determined by the agricultural ecosystem's "associated" biodiversity. Supply of these ES thus depends both on the agricultural ecosystem in the strict sense (the field or parcel level) but also on broader landscape characteristics that help determine biodiversity dynamics.

The level of supply of the "**pollination of crop plants**" ES is primarily determined by landscape composition and configuration and by climate. Although pollination is one of the most widely studied ES in the literature, to date there has been no generally accepted direct indicator for its level of supply. However, a newly developed indicator designed to estimate the effects of pollination on agricultural production suggests that this is a limiting factor for pollination-dependent crop yields in multiple regions of France.

In the absence of data that would make it possible to assess the level of supply of the "**regulation of pest species**" services for France as a whole (e.g., measurements of predation or parasitism percentages, yield losses), only a few estimates of the potential of these ES, based on international and local data, were explored for this study. Preliminary results, extrapolated to the whole of France, suggest trends in the spatial variation of levels of **regulation of weed seeds by granivorous beetles** and the **regulation of aphids**, but these relationships have only been validated for very specific pedoclimatic and agronomic contexts.

For these three ES of biological regulation, further work is needed to validate the methods used and preliminary assessment results.

Towards quantifying the relative contribution of input ES to agricultural production

To date, few studies have attempted to estimate the relative contribution of "natural" vs. "anthropic" production factors within the production of agricultural goods. The importance of this evaluation extends beyond the domain of agricultural ecosystems, but there is currently no consensus as to the best methodology to employ. In the present study, simulations of the soil-plant system were used for a preliminary assessment of **the percentage of production made possible by the input ES "supply of mineral N to crop plants" and "storage and return of water to crop plants"** (hereafter referred to as the input ES "N and water") **for a given agricultural ecosystem.**[7] In addition, these simulations were used to estimate the **relative contribution of the input ES "supply of mineral N to crop plants" vs. N fertilization practices to meet the nitrogen requirements of a cash crop**. The same procedure was followed to assess the **relative contribution of the ES "storage and return of water to crop plants" vs. irrigation in meeting crop water requirements** (see Figure 2 on the following page).

Results from these simulations should be interpreted with caution. Careful analysis suggests broad trends in the relationship between the input ES "N and water," fertilization and irrigation practices, and levels of agricultural production. **At the temporal scale of the rotation, the part of agricultural production attributable to the input ES "N and water" appears to be on the order of 50% as an annual average for France as a whole,** with 95% of values varying between 29% and 71%. Given the methods employed, these results are necessarily directly linked to the spatial and temporal distribution of the different crops within pedoclimatic units.

Cropping system contexts (combinations of [cropping system x pedoclimatic context]) with low absolute levels of the input ES "N and water" do not necessarily correspond to situations in which the percentage of production made possible by these input ES is low. This confirms the need to examine the level of each ES relative to crop requirements across the crop rotation sequence for a given pedoclimatic context.

[7] Levels of soil organic carbon and organic nitrogen are defined for each pedoclimatic context.

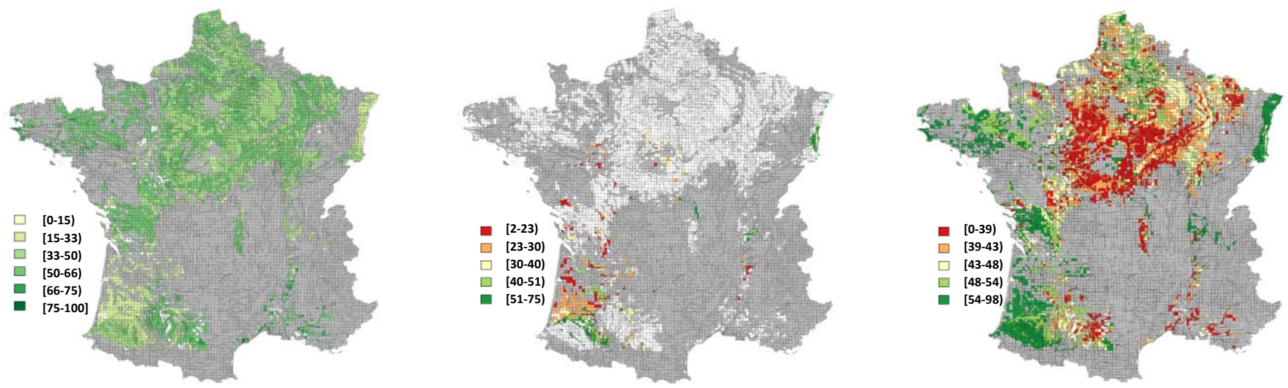
Wheat, having a relatively high average level of production enabled by the input ES “N and water,” was found to raise the average level of this indicator at the rotation level. This effect is amplified where wheat is in rotation with sunflower (e.g., in southwestern France), since sunflower shows the highest average percentage of production made possible by the input ES “N and water.” In contrast, in crop rotations that include oilseed rape, the average percentage of production attributable to the input ES “N and water” tends to be slightly lower: oilseed rape is a crop with high nitrogen requirements, and is predominantly grown in the greater Parisian basin, where average levels of the ES “supply of mineral N to crop plants” are relatively low. The lowest average levels for the percentage of production made possible by the input ES “N and water” are strongly correlated with grain maize grown in monoculture in climatic zones with a significant summer water deficit. In these situations, irrigation is essential to the production of high-yielding crops.

Finally, **it should be noted that at the level of the cropping system, total available mineral nitrogen** – that is, the sum of mineral nitrogen available at planting, supplied by the ecosystem during crop growth, and supplied by fertilization – **exceeds crop requirements in all the situations examined**. Even allowing for limitations in assessment methodologies, these findings suggest that significant potential exists to better convert an ecosystem’s capacity to supply nitrogen (ES potentially supplied by the ecosystem) into an ES effectively utilized by the farmer, in turn allowing for a significant reduction in the external supply of nitrogen by the farmer. Among other things, this highlights the need to develop improved technologies and application methods to assist farmers in determining the dynamics of the ES “supply of mineral N to crop plants” and, thus, necessary fertilization rates.

Additional research needed on the status and role of livestock in the provision of ES

Livestock on pasture was considered in this analysis both as a component of the agricultural ecosystem (planned biodiversity) and as a means of production of agricultural goods. This preliminary assessment of the status and role of livestock within ecosystems from the point of view of ES remains to be refined. The study included a quantification of the level of animal production made possible by crop production in the same area (results not presented here). In addition to the role of livestock as a means of production, an analysis of the role of livestock as an organism involved in the production of ES is needed (for example, the ES “regulation of disease among livestock”).

Figure 2. Percentage of crop production made possible by the input ES “N and water” (a.) and respective contribution of these ES in supplying crop requirements (b. and c.) (average annual values, in %)



Spatial resolution is the PCU (see Box 1). Grey pixels = no "major field crops" simulations; white pixels = excluded from the analysis.

ES provided by agricultural ecosystems to society

In addition to “input” ES, agricultural ecosystems contribute to the supply of other types of ES, from which society as a whole benefits (including farmers as members of society). These ES are essentially of two types: i) regulating ES that assist in moderating phenomena that are detrimental to human well-being, such as climate change or the movement of pollutants through different environmental compartments; and ii) so-called “cultural” ES, which provide society with recreational, aesthetic, and/or spiritual benefits.

Assessing ES from agricultural ecosystems and the environmental impacts of agricultural activities: two complementary approaches

Agricultural ecosystems contribute to the biophysical aspects of human beings’ quality of life *via* the **regulation of water quality** (as needed for consumption and other uses), and *via* **regulation of the global climate**. Comparative analysis of the various characteristics of these ES highlights the importance of three ecosystem features involved in their supply: i) the spatial and temporal configuration of the agricultural ecosystem (managed vegetative cover and livestock); ii) soil organic matter; and iii) soil biodiversity.

In addition to assessing the levels of these two ES, the study sought to estimate **negative impacts on the environment** resulting from agricultural activities. Analysis of the results obtained from these two types of assessments, **ES and environmental impacts**, suggests that they provide different types information about agricultural ecosystems: **information as the level of one does not make it possible to directly infer the level of the other**.

The **regulation of water quality** was assessed **with respect to nitrogen (N)**. Data are lacking to assess the mitigation of pesticides by soils and the regulation of water quality with respect to phosphorous (P) and dissolved organic carbon (DOC).

The level of the **"regulation of water quality with respect to N" ES,** measured *via* the amount of non-leached nitrogen, increases with the amount of biomass produced. It is primarily the process of **nitrogen being retained in harvested biomass and/or in biomass returned to the soil** that reduces nitrate leaching. In other words, as shown in previous studies, the extent of **soil cover during periods of potential leaching is a major determinant of this ES.** The quantity of non-leached nitrogen was estimated in absolute terms and relative to nitrogen inputs. Comparisons of these two values showed that a low absolute level of ES does not necessarily correspond to a low relative level of ES: a low absolute level of non-leached nitrogen can correspond to a high percentage of total supplied nitrogen, notably where the amount of external applied nitrogen is low (e.g. in the sunflower-based cropping systems).

The **impact of current cropping systems on water quality was estimated using two indicators: the quantity of leached nitrogen and the nitrate (NO_3^-) concentration in drainage water.** These two impact indicators are negatively correlated with the indicators of absolute and relative supply of the ES, suggesting that the impact of the cropping system on drainage water quality tends to be lower when the ES level is high. The correlation is not very strong, however, reflecting the fact that a given capacity of nitrogen "retention" by the "soil-plant" system can be associated with very different impact levels. For example, situations in which 80% of the nitrogen entering a system is not leached can be associated with quantities of leached nitrogen ranging from 20 to 100 kg N/ha/yr, and with nitrate concentrations varying from less than 50 mg NO_3^-/l to more than 150 mg NO_3^-/l.

With respect to the "global climate regulation" ES, two components of the ES were examined: the current soil carbon stock and annual carbon storage dynamics. With regard to the former, **the 0-30 cm soil horizon in major field crops and grassland areas in France represents a total carbon storage on the order of 1.75 billion metric tons, or 47% of the total carbon stored in French soils**.[8] This is equivalent to 16 years' worth of France's greenhouse gas (GHG) emissions across all sectors combined, or double that if the soil horizon from 0-1 m is considered. **Despite having lower carbon storage per unit of land area relative to grasslands, field crops represent a larger total carbon stock due to their greater total land area.** The geographic distribution of these results shows the combined effect of pedoclimate and land use: the greatest carbon stock is observed in upland and/or grassland areas, while the lowest stocks are observed in the lowland plains and major field crop zones. **Carbon stored in the form of trees and hedges within field areas represents on average 7% of the total carbon stored in these agricultural ecosystems (less than 5% if one considers carbon stored in the 0-1 m soil horizon), and is only very rarely greater than 20%** (in areas where woody vegetation is most prevalent). Although they contribute relatively little to total carbon storage in agricultural ecosystems, the conservation of woody field vegetation remains a key issue in ES assessment, given the importance of these semi-natural elements for the supply of many other ES (particularly ES of biological regulation).

With regard to carbon storage dynamics, estimates of the annual average variation in stored carbon in field crop soils (assuming current agricultural practices) have concluded that **on average, major field crop systems result in an annual loss of 0.03% of soil carbon**. Values obtained for systems that accumulate carbon are **generally below 0.2% and rarely higher than 0.3%**; in other words, well below the annual increase of 0.4% of stored soil carbon targeted by the international "4 per 1000" initiative. Agricultural ecosystems that build soil carbon tend to be found in areas with low current soil carbon levels – in general, areas of intensive cereal production – whereas in livestock production zones, although the current soil carbon stock is often higher due to the pedoclimatic context and past history of the soil cover, cropping systems as currently practiced can lead to a considerable loss of soil carbon. Estimates of this ES for grassland systems will be addressed in a separate study currently underway.

The impact of current cropping systems on climate was assessed in terms of the net annual movement of **CO_2 and N_2O between the agricultural ecosystem and the atmosphere** (flows of CH_4 being considered as negligible for major field crops). **The results show that the vast majority of cultivated agroecosystems are sources of GHG** (net GHG emitters), **primarily as a result of N_2O emissions.** Only a very few simulated cases are sinks for GHG as a result of their low levels of N_2O emissions. **Emissions of N_2O increase as external nitrogenous inputs increase, confirming the significant role of nitrogenous fertilization in these emissions.** The relationship is nevertheless variable as a result of the many factors involved in N_2O production (temperature, water levels, pH, etc.). Finally, **the use of cover crops has a favorable effect on GHG budgets.** Cover crops increase soil carbon storage and reduce N_2O emissions. A preliminary qualitative comparison of the spatial distribution of these results again suggests that a single level of net GHG footprint may be linked to different levels of ES and *vice versa*.

The need for a multi-ecosystem approach to characterize "cultural services"

Agricultural ecosystems form landscapes that people often consider as attractive for the pursuit of recreational activities. Land use, field layouts, and the size and location of semi-natural habitats are key biophysical determinants of the potential attractiveness of agricultural landscapes. As defined within the CICES typology, recreational "services" correspond more closely to a typology of landscape uses and/or values than to ecosystem services in the sense adopted here. The study thus proposes to define these ES as an agricultural ecosystem's capacity to serve as a setting for the practice of outdoor recreational activities, or the "recreational potential of agricultural ecosystems." As with ES of biological regulation, **recreational potential** is a product of the total landscape. In contrast to ES of biological regulation, however, recreational potential **is also expressed at the scale of the total landscape,** a space within which several types of ecosystems exist side by side. The approach *via* major ecosystem type thus appears less relevant for the study of recreational "services," since these are provided both by nature and by the relative proximity of different ecosystem types within the landscape.

[8] Estimated at 3.725 billion metric tons in the literature.

From biophysical assessments to economic assessments of ES

Available methodologies

Whereas biophysical assessments of ES examine the interactions between ecosystem functioning and ES, socioeconomic approaches to ES seek to evaluate the link between ES and human well-being. Although they share the central idea of a supplied benefit, articulating the two approaches is recognized as a key challenge within the scientific literature. Biophysical assessments typically yield ES indicators that are difficult for economists to work with. **Economic approaches, on the other hand, frequently focus on *benefits* derived from ES rather than on ES themselves.** Assessing benefits that are functionally disconnected from ecosystems and relate to the socioeconomic subsystem requires accounting for a variety of capital inputs (material, human, institutional, financial) used to exploit the ES.

In keeping with the overall methodology, the approach adopted here consisted of **attributing an economic value to ES based on a biophysical assessment of their level of supply. Revealed preferences** approaches were favored as they are based on observations of the actual economic behavior of ES beneficiaries. The information required to implement these methods are generally unbiased and easily accessible. Such methods enable one to obtain values *ex post*, estimated indirectly based on prevailing prices for goods and services whose consumption is tied to the ES in question. In practice, the most frequently used approaches for the socioeconomic assessment of ES are those of **replacement costs** and **avoided damages**. These methods seek to estimate, respectively, the costs that would be incurred by society if recourse to substitute technologies were necessary (for example, synthetic nitrogenous fertilizers to replace the ES "supply of mineral N to crop plants"), and the losses that would result from a disappearance of the ES (for example, yield losses in the absence of the regulation of insect pests).

Challenges and caveats

The study sought to apply these economic assessment methodologies to the eight regulating ES previously quantified in biophysical terms. An economic assessment could only be completed for three of these ES, however.

Although biophysical indicators can be used directly for economic assessment, the resulting values must be considered with caution. Given the diversity of assessment methods employed, **moreover, the results are not cumulable**.

A review of the biophysical assessment of the "pollination of crop plants" ES *via* an avoided damages methodology illustrates the need for an accurate biophysical assessment of the portion of production linked to an ES. The "economic value of insect pollination" (IPEV) indicator currently in use in the scientific literature does not allow for the possibility of a pollination deficit (which biophysical assessments tend to indicate exists). The greater the pollination deficit, the more significant the overestimate of IPEV will be.

When applied to the **ES "supply of mineral N to crop plants" and "storage and return of water to crop plants"** (see Box 2), **the replacement costs method** should only be considered at a fine-grained level of spatial resolution (for example, the SAR level): calculation of a single national value would assume a situation that is both unlikely in biophysical terms and for which the repercussions in terms of the availability and price of substitution inputs (synthetic nitrogen fertilizers and irrigation water) are not accounted for by the methodology. A concurrent assessment of these two ES *via* the avoided damages method offers some additional information, but this should be considered very preliminary, and in any case it does not allow for the comparison of values, since these are based on different reference points.

Conversely, when the biophysical characterization of ES is based on indirect indicators of the level of ES supply, the methods described above are not applicable. This is the case, for example, with the ES "regulation of weed seeds" and "regulation of insect pests." The biophysical indicators for these ES predict densities of pest organisms or pest predators that cannot (based on current research) be linked to quantifiable levels of yield losses or the cost of compensatory technologies (for example, the use of crop protection products). This is likewise the case with the ES "soil stabilization and erosion control," for which it is difficult to draw a firm link between a quantity of non-eroded (stabilized) soil and a quantity of agricultural goods produced. To overcome these obstacles to use of the avoided damages approach, further research should be done on the quantitative relationships between ES, agricultural practices, production levels, and landscape management.

With respect to the "regulation of water quality" ES, an economic assessment *via* the replacement costs method would require knowing the quantity of water of a specified quality returned by an agricultural ecosystem for subsequent use. The biophysical *quantification* of this ES, however, merely specifies a quantity of non-leached nitrogen.

Finally, it should be noted that a key limitation of methodologies based on the use of market prices lies in the fact that they assume prices are reliable indicators of societal demand and of the scarcity of the goods and services used as substitute for the ES. In reality, market prices frequently reflect a wide range of other social and political factors, including public subsidies.

Towards the improved management of ES from agricultural ecosystems

Processes underlying ES supply are strongly interconnected since common biophysical determinants may be involved in the supply of multiple ES. It follows that changes in ecosystem management (notably *via* changes in agricultural practices) are likely to affect the level of supply of multiple ES. When ecosystem management is considered from the perspective of a single ES or exclusively in terms of the production of agricultural goods, there is a risk that the maximization of one ES or one type of good will impair the supply of others. A widespread example of this is the maximization of agricultural production based on the use of inputs to the detriment of biological diversity, on which, ultimately, all ES depend.

Box 2. A proposed economic assessment of the contribution of "input" ES to agricultural production, based on the example of the ES "supply of mineral N to crop plants" and "storage and return of water to crop plants"

• Assessment of the ES taken individually

An economic assessment of the ES "supply of mineral N to crop plants" and "storage and return of water to crop plants" was carried out using the **replacement costs method**, estimating the cost of nitrogen fertilizers, on the one hand, and the cost of irrigation water, on the other, necessary to maintain production levels in the absence of these ES. (Calculations assumed that the agricultural ecosystem manager would compensate for the absence of the ES by optimizing inputs relative to crop needs.) The results of this preliminary economic assessment (*cf.* Table below) offer an approximate replacement cost for these two ES for agricultural ecosystem land areas for eight major crops (representing 91%, on average, of major commodity crop and industrial crop areas in mainland France from 2010 to 2012).

• Economic value of the input ES "N and water," taken together

In the **avoided damages** methodology, **an economic value for the two input ES "N and water"** was obtained by calculating the monetary value of the portion of agricultural production attributable to these two input ES. The results from this second economic assessment (*cf.* Table below) give a preliminary idea of the approximate value of damages (in terms of loss of production) associated with the combined absence of the input ES "N and water" for seven crops (corresponding on average to 89% of land area for major commodity and industrial crops in mainland France from 2010 to 2012).

• Interpretation of results

Average annual values of the ES "supply of mineral N to crop plants" and "storage and return of water to crop plants," evaluated separately *via* the replacement costs method, and together *via* the avoided damages method
(values for all of France, averages 2010-2012)

	Replacement costs method [a]			Avoided damages method	Total average value of agricultural production for all of mainland France (€M/yr)
	ES "supply of mineral N to crop plants" (€M/yr)	**ES "storage and return of water to crop plants"** (€M/yr)		**Input ES "N and water" taken together** (€M/yr)	
		Minimum cost	Maximum cost		
Sugar beet	45	86	719	456	1,373
Soft wheat	369	31	256	4,917 [b]	8,605
Hard wheat	*Not calculated*	*Not calculated*	*Not calculated*		
Barley	98	110	920	1,027	1,794
Oilseed rape	120	331	2 775	615	2,320
Silage maize	105	122	1 023	1,093 [c]	1,589
Grain maize	191	25	213	1,173	3,129
Spring peas	43	83	697	*Not calculated* [d]	/
Sunflower	43	15	122	539	757

[a] Average market price of nitrogen: €0.85/kgN for the period January 2008-January 2016 (agricultural statistics). Average cost of irrigation: from €0.04/m³ to €0.335/m³ (costs highly variable depending on the resources and type of irrigation equipment used; spatial variations could not be represented)
[b] Land area in hard wheat was treated in the same manner as land area in soft wheat in terms of the part of production made possible by the ES and in terms of price.
[c] The economic value of silage maize was estimated relative to that of grain maize using a coefficient (0.5) to convert average yields in tons of dry matter per hectare (t DM/ha) into an equivalent of tons of grain maize per hectare (t/ha), and then multiplying by the price of grain maize (in €/t).
[d] Analysis of spring peas was not completed because data on average costs for pea production were not available from the FAO.

These results should be considered with great caution, and are not intended to be used for decision-making purposes. The biophysical indicators used as a point of departure for the economic assessment present their own limitations, which necessarily affect the robustness of the economic analysis.

Calculating national figures for replacement costs and avoided damages would amount to imagining an extreme situation in which the two input ES become unavailable nationwide, making it necessary to fertilize and/or irrigate all land areas for the crops under consideration. Such a situation would necessarily have a dramatic impact on the availability and price of synthetic fertilizers and irrigation water, with knock-on effects on farmer behavior, two dynamics that are not otherwise taken into consideration in the analysis. By way of comparison, a widespread drought across all of France would likely result in a total loss of crop yields. For the purpose of analysis, it thus makes sense to limit the cost of irrigation or fertilization to the level of the farmer's gross profit margin. In practice, if these input costs rise beyond the farmer's gross profit margin, it becomes more profitable for the farmer to discontinue the crop or change the nature of the crop production – in other words, to reconfigure the agricultural ecosystem. Again, for the reasons cited previously, it is not possible to sum the values obtained for each crop in order to arrive at a total value for "all crops."

Other simplifying assumptions have also been made: for example, it is assumed that the farmer compensates for an absence of the ES "supply of mineral N to crop plants" exclusively through the use of synthetic fertilizers. In truth, however, other strategies might be followed, such as the use of organic fertilizers or a reduction in biomass exports. As mentioned above, excessively high replacement costs could also lead the farmer to reorganize the agricultural ecosystem, for example by introducing a leguminous primary crop and/or cover crop.

Finally, due to the different assessment methods employed, **these two series of results should not be compared**. The results obtained for the two ES "supply of mineral N to crop plants" and "storage and return of water to crop plants," evaluated individually using the replacement costs method, are based on different reference contexts and different substitution technologies, and are thus not comparable. To sum these two values would amount to assuming that the production factors involved are fully substitutable, which is not the case (due to the biophysical interactions among processes relating to nitrogen and water). In other words, **the first two values and the third value provide two complementary pieces of information about the assessment of input ES relating to water and nitrogen**.

To develop a management strategy for ES at the regional or territorial level, it is thus necessary to shift from an individual analysis of ES to a multi-services approach. Such an approach would seek to characterize the overall supply of ES, how these ES interact, and the existing mechanisms available to protect or enhance them.

From ES bundles to management strategies

An ES "bundle" is defined here as a group of observed ES within a given geographic area over a given period of time. The levels of these ES determine the size or "shape" of the bundle, even if all the interaction mechanisms among the different ES may not be fully known. Analysis of an ES bundle may help decision-makers make a diagnosis of overall ES supply for a specific geographic territory (a watershed, SAR, etc.). This can be a necessary first step in setting objectives for a territory's ES "bundle." Usually, however, different types of ecosystems (forests, wetlands, urban areas, various agricultural ecosystems, etc.) coexist within the area under examination. It is thus necessary **to identify indicators for each ES that are adapted to the specific features of the different ecosystem types within the study area.** The majority of current work on the assessment of ES bundles tends to sidestep this fundamental challenge by assuming a zero level of ES wherever an ES has not be quantified for a given ecosystem type.

The "ES bundles" approach thus continues to present methodological challenges, and its implementation is not straightforward. A number of different methods may be employed to identify ES bundles, each with its own strengths and weaknesses. Here, one was applied here to two groups of ES and agricultural goods, supplied to the farmer and to society as a whole, respectively, in order to gauge the potential of this approach to inform public decision-making. This ES bundle analysis was carried out at the French SAR level and, due to data constraints, only for SAR where cropping systems are dominant relative to other types of agricultural ecosystems. Statistical analysis of the ES bundles provided to farmers revealed three groups of SAR, each characterized by a distinct "shape" of ES bundles. Similarly, four groups of SAR were identified with respect to ES bundles provided to society as a whole. A partial congruence could be observed between the "farmer" bundles and the "society" bundles. This analysis offers a current snapshot of an average level of ES supply at the SAR level, but **does not provide information about the ecological mechanisms underlying interactions among the ES. A deeper understanding of the biophysical relationships among ES is needed** to elucidate the possible effects of ecosystem modifications on levels of ES supply.

Understanding interactions among ES…

The biophysical determinants involved in the supply of several ES are recognized as **key ecosystem and landscape components by means of which farmers (*via* agricultural practices) and/or other land managers can modify or protect ES.** Since biodiversity is a central focus of policy debates and management strategies relating to ES, this study concentrated on the identification of key biodiversity components underlying the fourteen ES selected for analysis (Figure 3). These included the following biophysical determinants.

- The **spatial and temporal configuration of managed vegetative cover** within the field unit – including weeds and semi-natural areas within the field. These elements play a central role in determining all regulating ES. However, very little work on large-scale ES assessment has considered the effects of the temporal distribution of managed vegetative covers. In this study, the integration of cropping sequences into assessment methods for a number of ES thus represents an important methodological advance.
- **Levels of soil organic matter** directly determine the level of supply of eight regulating ES. Soil organic matter content is itself strongly determined by the state of managed vegetative covers, as well as by soil microbial and meso- and macrofaunal communities. Here again, dynamic modeling of soil-plant(-animal) systems made it possible to account for the dynamic of interactions among vegetative covers (cropping sequences), soil organic matter, and ES relating to the water, nitrogen, and carbon cycles.
- The abundance and diversity of three components of associated biodiversity – **beneficial species** (pollinators and natural pest enemies), **indigenous aboveground meso- and macrofauna**, and **soil microorganisms** – likewise determine many ES.
- Finally, **landscape composition and configuration** directly determine the recreational potential of an ecosystem, and indirectly determine – *via* beneficial species – ES of biological regulation.

This cross-cutting analysis also reveals **the indirect interactions that exist among the six ES linked to soil functioning**. Thus, the "soil structuration" ES is an indirect biophysical determinant of the other five ES relating to soils.

A deep understanding of agricultural ecosystem functioning and interactions from the field to the landscape level is a first step in the development of decision-making tools for the sustainable management of ecosystems and associated ES. Such tools should assist in better understanding how ES interactions depend on local pedoclimatic conditions, and may also help anticipate the effects of climate change. Ideally, they will allow for an improved characterization of the conditions determining ES supply, enabling us to overcome the weaknesses of approaches based on "generic" indicators of ecosystem condition or ecological health. Identification of these key ecosystem conditions provides the necessary information for developing field-based observation and monitoring systems for biodiversity and ES.

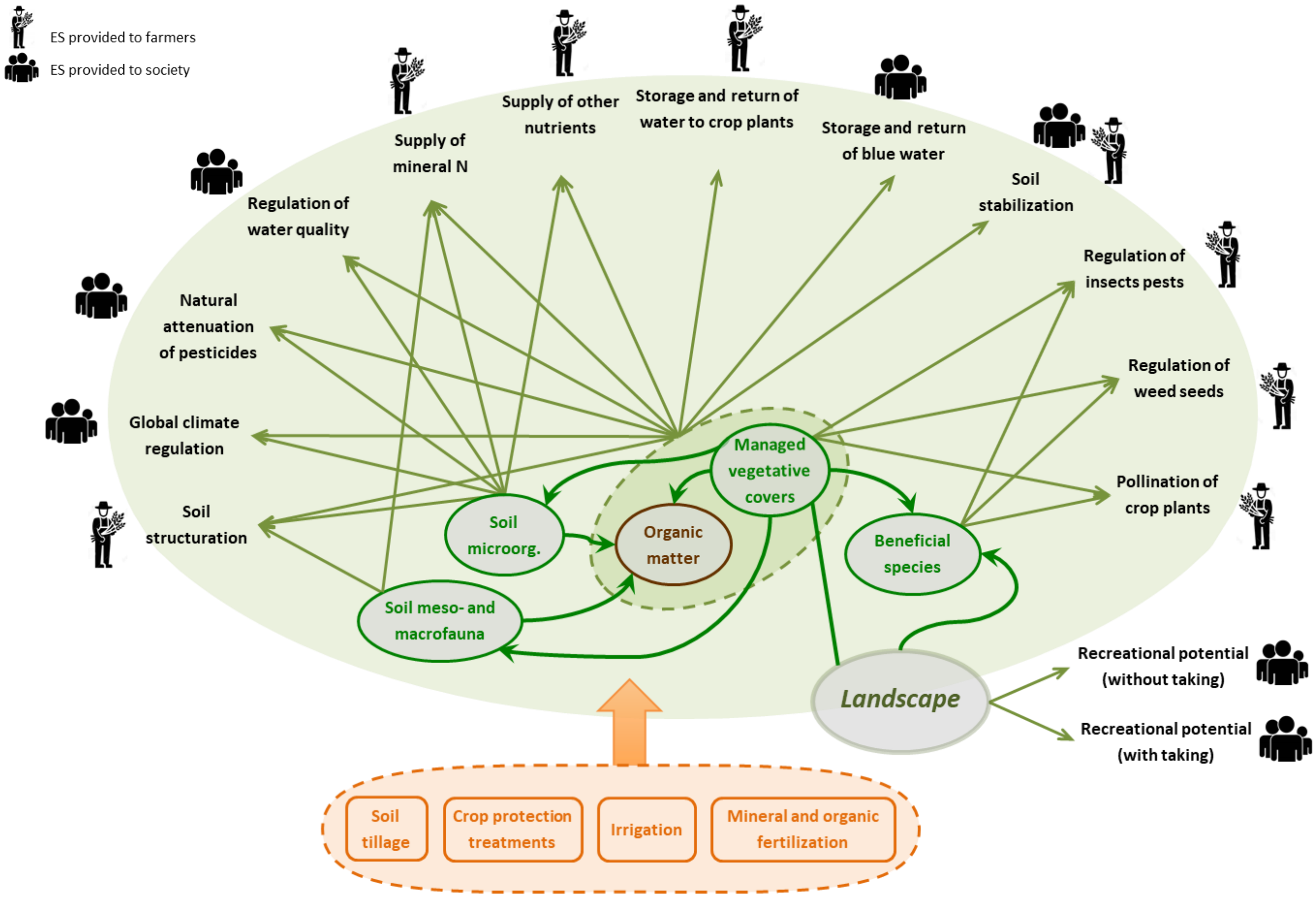
… to identify key levers for ecosystem management

Key levers for ecosystem management may be identified by considering the ecosystem components on which management strategies primarily act. Within the analytical framework adopted here, ecosystem management corresponds to external, anthropic factors that affect the level of supply of ES *via* their impact on biophysical determinants. **Four principal categories of management practices can be distinguished.**

- **Crop protection treatments** can affect ES of biological regulation *via* their effects on the structure and abundance of biological control communities and their host plants, including some weed species. Crop protection products can also affect the expression of a number of ES *via* their impact on soil microbial and meso- and macrofauna communities.

Figure 3. Major relationships among ES *via* biodiversity components

Simplified graphic representation of the relationships among key biodiversity components determining the level of ES provision for the fourteen ES considered in this study. Consideration of additional ES may require inclusion of additional biodiversity components. Four key categories of agricultural practices impacting these ecosystem components are also shown (in orange).



Key interactions among biodiversity components are shown; feedback loops between ES and biodiversity components are not shown. The graphic is simplified with respect to numerous existing interactions and is intended to help identify priorities for the management of agricultural ecosystems to enhance ES provided to farmers and to society as a whole.

Box 3. Study principles and methods

This study was conducted by INRA according to the principles and methods established by the Delegation for Scientific Expertise, Foresight and Advanced Studies (DEPE) for the completion of collective scientific assessments (or ESCo for *Expertise Scientifique Collective*).

• Scientific knowledge to support public decision-making

The institutional activity known as the ESCo, undertaken by INRA since 2002 and governed by a French national charter signed in 2011, is defined as a process of multi-disciplinary knowledge-gathering and analysis to inform public action. It identifies existing scientific knowledge, points of uncertainty, notable areas of scientific debate, and future research needs. As has been the case for this study, an ESCo may be extended by the assembly and analysis of available data (statistical analyses, calculations, simulations using existing models, meta-analyses, etc.), based on published scientific work. All such exercises lead to the production of a **scientific report** written by the experts, a **synopsis of the report** and a **short summary**.

ESCo and this study are conducted according to explicit guidelines intended to ensure the robustness of the resulting output. Core principles include competence and disciplinary range of the expert group, impartiality (guaranteed through the completion of conflict of interest disclosures on the part of the expert group, reviewed by INRA's Ethics Oversight Committee), transparency of methodology, and traceability with respect to the activities and resources mobilized over the course of the project.

• Context and organization

This study forms part of the French National Ecosystem Assessment (EFESE), led by the Ministry for the Environment (*via* the *Commissariat général au développement durable* – CGDD – and the *Direction de l'eau et de la biodiversité* – DEB). The EFESE agenda exists within the European Strategy on Biodiversity for 2020 and, as such, represents France's contribution to the European Commission working group called *Mapping and Assessment of Ecosystems and their Services* (MAES). The scope of the EFESE includes all terrestrial and marine ecosystems of mainland France and its overseas territories, divided into six major ecosystem types: forest ecosystems; agricultural ecosystems; urban ecosystems; wetlands; marine and coastal environments; and mountain areas. The study presented here focused on agricultural ecosystems.

Forty scientific experts, and about twenty other scientific contributors, with complementary disciplinary expertise (ecology, agronomy, hydrology, animal science, economics, etc.) were called upon for this study. Experts were identified by the DEPE based on their publications as evidence of their disciplinary expertise. They were drawn from a variety of public research and higher education institutions. **Expertise in data management**, a key component of such a study, was provided primarily by INRA.

• **Soil tillage practices**, like crop protection treatments, result in a disturbance of the biological functioning of soil microbial communities and soil fauna. They can also impact beneficial species (e.g., beneficial insects) that live or lay their eggs in the soil. Finally, soil tillage plays a key role in determining soil organic matter distribution and its changes over time.

• **Irrigation**, by modifying soil moisture levels, influences the growth of vegetative covers, characteristics of soil biodiversity, and the dynamics of soil organic matter.

• **Organic and mineral fertilization** influence the state of vegetative covers, a key determinant of ES. Organic fertilization will also influence soil microbial community dynamics, soil meso- and macro-fauna and soil organic matter.

In addition to these external factors, all **practices that determine** the distribution and diversity of vegetative covers and animal populations will, by definition, constitute a strong lever for ES management.

Perspectives on future research and other developments

This study intentionally focused on cropping systems making significant use of external inputs, which account for the majority of production contexts currently existing in France. Developing production systems that rely more on ES and less on the use of external inputs will require **advances in our understanding of the interconnections between ecosystems and landscape configuration, external agricultural practices, climate, the provision of ES, and the production of agricultural goods**. It will also require a better understanding of **the temporal dynamics of ES and how they are impacted by different types of cropping systems (e.g. conservation agriculture)**. In some instances, preliminary studies suggest the potential for a profound rethinking of the relative importance of field-level vs. landscape-level factors in agricultural ecosystem performance (notably with respect to ES of biological regulation). In the immediate term, comparative analyses of different types of low-external-input cropping systems and/or production systems – for example, conservation agriculture or integrated crop-livestock systems – may facilitate progress in this direction. The development of computer models for simulating the effects of a wide range of ecosystem configurations and external agricultural practices on the supply of different ES should also assist in the design of management strategies for agricultural ecosystems to reduce antagonisms among ES.

Additional research of this type may build on the information systems produced by this study, but will also require **more precise data characterizing existing agricultural practices**. The only such information currently available on a broad scale is from the "Agricultural Practices" survey conducted by the statistical and foresight division within the French Ministry of Agriculture. The geographic level of detail of this database (the administrative region) constitutes the principal limiting factor with respect to its use for the type of study proposed here.

Agricultural ecosystems were considered here as currently organized and managed. Changes in ecosystem properties, for instance due to the effects of climate change or due to changes in land-use (for example, urban expansion, reforestation), will necessarily have an impact on the functioning of ecosystems and, consequently, on the provision of ES. Identifying the conditions necessary to "dynamic sustainability" in the supply of ES in the face of different types of future change will require identifying the biophysical and socioeconomic factors that may be altered in order to maintain ES levels, or, alternatively, to adjust the range of ES according to societal demands.

Finally, the key levers identified above relate specifically to the management of agricultural ecosystems and to the development of the ES analyzed here. **These levers will not necessarily be the same when considering other types of ES and/or ecosystems, or if decision-makers pursue different objectives.** To fully address the critical issues associated with agricultural ecosystem management, methods of multi-criteria assessment, in which the environment is represented using indicators from three key domains, are needed: i) levels of ES provided to farmers and to society as a whole; ii) the environmental impacts of agricultural activities; and iii) conservation of biodiversity as a whole (not only those species involved in ES provision). Improved accounting for ecosystem "disservices," not considered here, is also needed. These types of methods should enable the identification of antagonisms and synergies within a given domain (e.g., between ES provided to farmers and ES provided to society as a whole) or between different domains (e.g., between the supply of ES and environmental impacts) at the relevant scale (e.g., the field, agroecosystem, landscape, etc.).

To learn more:

Tibi A. and Therond O. (2017). *Evaluation des services écosystémiques rendus par les écosystèmes agricoles. Une contribution au programme EFESE.* Synthèse du rapport d'étude, Inra (France), 118 pages.

Therond O. (coord.), Tichit M. (coord.), Tibi A. (coord.) *et al.* (2017). *Volet "écosystèmes agricoles" de l'Evaluation Française des Ecosystèmes et des Services Ecosystémiques.* Rapport d'étude, Inra (France), 966 pages.

The full scientific report, its synthesis, and this short summary are available *via* the INRA web site.

Translated by Laura Sayre - Cover photo: © G. Brändle, U. Zihlmann (Agroscope) and A. Chervet (Office de l'agriculture et de la nature du canton de Berne)

INRA
SCIENCE & IMPACT
Délégation à l'Expertise scientifique collective, à la Prospective et aux Études
147, rue de l'Université
75338 Paris Cedex 07
France
Tél. : + 33(0) 1 42 75 94 90
www.inra.fr

Liberté • Égalité • Fraternité
République Française
MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE ET SOLIDAIRE