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Manon Dardonville, Baptiste Legrand, Hugues Clivot, Claire Bernardin, Christian Bockstaller, Olivier Therond

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Title

Assessment of ecosystem services and natural capital dynamics in agroecosystems

Abstract

Increasing the levels of ecosystem services that contribute to agricultural production (ES) is a challenge for the sustainability of agricultural systems. Agricultural advisors lack low-data operational approaches for assessing ES and knowledge to support development of ES-based systems. To fill this gap, we developed an approach that assesses relations between characteristics of agroecosystems and the ES they offer: pollination, pest, weed and disease control, soil structuration, nitrogen and phosphorus supply to crops, water retention and control of erosion. We distinguished four dimensions of ES: potential capacities, real capacities, levels actually used by farmers and dynamics of the natural capital that supports ES provision. We assessed them with a low-data indicator-based method at the agroecosystem level. It provided a score for (i) the quality of the agroecosystem's spatiotemporal configuration, (ii) positive or negative modulations in ES expression caused by agricultural practices, (iii) the farmer's strategy for using ES and (iv) four components of natural capital dynamics (soil quantity, soil organic matter, phosphorus cycling and the biodiversity that supports ES). We demonstrate the interest of the approach by applying it to 34 contrasting agroecosystems in France and subsequently identifying five agriculture models. Analysis of this case study identified several ways to attain high-yield agroecosystems based on anthropogenic inputs, ES or both. We discuss strengths and possible improvements of our approach and highlight key knowledge gaps to examine in future studies.

Keywords

cropping system, agroecosystem, multicriteria evaluation, indicator, biodiversity, farmer strategy

1. Introduction

Modern industrial agriculture depends strongly on synthetic inputs, mechanization and fossil resources (Cumming et al., 2014; Foley et al., 2005). It is now well-known that this production model is the source of high negative environmental impacts (Therond et al., 2017a). Duru et al. (2015b) identified two main pathways to address these environmental issues. The first involves increasing the efficiency of anthropogenic inputs (e.g. pesticides, fertilizers, tillage energy) or replacing anthropogenic inputs with organic inputs. The second involves increasing planned and associated biodiversity and, in turn, ecosystem services to reduce the use of anthropogenic inputs. In the latter pathway, ecosystem services

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are considered to be production factors to the same extent as anthropogenic inputs because they can ensure the same functions (i.e. counteracting limiting and reducing factors) (Bommarco et al., 2013a; Coomes et al., 2019; van der Linden et al., 2015).

While the first pathway remains actively under development in private and public research, the second pathway often relies on deep redesign of agroecosystem structure and functioning, is less supported and still lacks operational knowledge (Duru et al., 2015a, 2015b). However, supporting biodiversity-based systems requires clarifying which biological structures and processes to manage, and how (Garbach et al., 2017; Kremen and Miles, 2012). In other words, there is a need for operational knowledge on current levels of ecosystem services and how to enhance them (Kleijn et al., 2019).

Research on ecosystem accounting and mapping is increasing, addresses few ecosystem services and focuses mostly on ecosystem services provided to society (Malinga et al., 2015). When dealing with agricultural issues, however, two beneficiaries of ecosystem services are now commonly distinguished: farmers and society (Therond et al., 2017a; Zhang et al., 2007). Ecosystem services that contribute to agricultural production (ES) are related mainly to soil fertility, biological control and pollination (Bommarco et al., 2013b; Duru et al., 2015b). Three main types of approaches are applied to assess ES:

- accurate models (e.g. of crop growth, such as STICS (Therond et al., 2017b); of soil erosion, such as RUSLE (Panagos et al., 2015))
- field experiments and surveys, to assess levels of ES directly (e.g. predation maps (Boeraeve et al., 2020; Petit et al., 2017))
- indicators of the status of biophysical determinants of ES (which assess levels of ES indirectly), such as the abundance or taxonomic or functional diversity of organisms that support ES, such as pollinators (Potts et al., 2009) and natural enemies (Dainese et al., 2019); landscape characteristics (Burkhard et al., 2012; Martin et al., 2019) and soil organic matter (SOM) content (Vogel et al., 2019)

Most ES studies focus on few ES and thus do not capture the whole ES bundle (Wam, 2010). In addition, the methods used may be difficult to apply due to the need for scientific knowledge (e.g. on effects of ES on production), their complexity (e.g. dynamic crop models) or the data and resources required (e.g. experiments, models). These methods describe ES levels in detail but are resource-consuming and difficult to scale up to a large set of farms. To our knowledge, no operational method for assessing ES based on easily accessible and commonly-acquired data exists. However, such a method is required to allow agricultural support institutions to support the development of agriculture based on ES rather than on anthropogenic inputs (Duru et al., 2015b).

To help address this knowledge gap, we developed a low-data assessment approach to assess levels of ES and identify mechanisms to increase them. After presenting the conceptual framework that underlies our approach and the approach itself, we demonstrate its power of expression by applying it to a case study. We show the ability of our assessment approach to characterize agroecosystems through an ES lens, and thus to identify different agriculture models (i.e. types of farming systems), and how it overcomes limits, highlighted by Therond et al. (2017a), of simplistic and dichotomous classifications of agroecosystems (e.g. organic vs. conventional). Importantly, we analyze the potential trade-off between regulation services and agricultural production (crop yield).

2. Conceptual framework

Like Haines-Young and Potschin (2018), we defined ecosystem services as the ecosystem structure (e.g. landscape matrix) or processes (e.g. in the Common International Classification of Ecosystem Services (CICES)): filtration, sequestration, storage, accumulation) from which humans benefit. As Fisher et al. (2009) state, this definition clearly distinguishes ecosystem services, which are functionally connected to ecosystems (e.g. biological regulation), from benefits, which are derived from these services (e.g. crop protection) and part of socio-economic systems. As suggested by Zhang et al. (2007), we distinguished two types of ecosystem services according to the main beneficiaries: society or farmers (see also Duru et al. (2015a); Jones et al. (2016); Therond et al. (2017b)). We then focused on farmer beneficiaries (i.e. ES). Following Nelson and Daily (2010), we considered agricultural production as a good and ES as the processes or functions that support the provision of these goods. A conceptualization that clearly distinguishes goods from services specifies explicitly that anthropogenic inputs and/or ecosystem services can support production of agricultural goods (Figure 1, bottom right).

Following Bommarco et al. (2013); Duru et al. (2015b); Garbach et al. (2014); Therond et al. (2017b), we focused on nine ES: pollination (POL); pest (PEST), weed (WEED) and disease (DIS) control; soil structuration (STR); nitrogen (N) supply to crops (NS); phosphorus (P) supply to crops (PS); water retention and return to crops (WATER) and stabilization and control of erosion (ERO). The functional scale studied was an agroecosystem (Swift et al., 1996) which is defined as the soil-plant system(s) within the field area, including the cultivated vegetal cover rotation and the surrounding semi-natural habitats, and the crop managements along the cover rotation (Holland et al., 2017). In other words, it corresponds to the managed agricultural ecosystem with field area and the duration of the rotation as spatial and temporal extents respectively. Potschin and Haines-Young (2011) formalize a cascade that represents relationships between ecosystem structure or processes, ecosystem function, ecosystem services, benefits and human values. For levels of ecosystem services, as suggested by several authors (Burkhard et al., 2014, 2012; Guerra et al., 2014; Haines-Young and Potschin, 2010; Therond et al., 2017b; Villamagna et al., 2013), we distinguished four key dimensions (Figure 1):

- *Potential capacity* corresponds to the capability of an ecosystem to deliver ecosystem services in a given year (Bastian et al., 2012). It is determined by both the spatiotemporal configuration of vegetation (e.g. crop rotations, cover crops, semi-natural habitats) and the state of key "slow variables", i.e. manageable characteristics that change slowly over a year (e.g. SOM, soil P content, trophic network state), that determine the level of daily and yearly processes (e.g. nutrient supply, biological regulations). Both the spatiotemporal configuration of vegetation and slow variables determine directly, or indirectly through associated biodiversity (service providers), the supply of ecosystem services (Duru et al., 2015b).
- *Real capacity*, which corresponds to effective levels of ES over the cropping season (Villamagna et al., 2013). It results from modulation of the *potential capacity* by annual crop management, which directly increases or decreases (i.e. pressure) the expression of ES (Garbach et al., 2014; Gliessman, 2004; Kandziora et al., 2013), or through biodiversity-ES relations (Duru et al., 2015b).
- *Actual use*, which is the proportion of the *real capacity* that farmers actually use as a production factor (Schröter et al., 2014). It depends on the technology available to take advantage of an ecosystem service (Boyd and Banzhaf, 2007).
- *Natural capital*, which corresponds to the state of slow variables that determine the *potential capacity* (Dominati et al., 2010). Over several years, crop management influences *natural capital* through a positive or negative feedback loop (Dominati et al., 2010; Weyers and Gramig, 2017). Dynamics of *natural capital* (i.e. of the state of slow variables) determine the future *potential capacity* of ecosystems to deliver ES and thus dynamics of ES in the middle term (several years to decades).

3. Assessment approach

We developed an assessment approach that explicitly considered the four dimensions of the conceptual framework (Figure 2). To do this, we first reviewed the literature on relations between agroecosystem characteristics (hereafter, "determinants") and the levels of *potential capacity* and *real capacity* of ES (section 3.1). Once relations were identified, we selected, existing or developed indicators of determinants' degree of influence on ES levels through a second literature review (section 3.2.1). Finally, we developed dimensionless indicators and summed them by ES.

Actual use of ES depends on the strategies and technologies that farmers use (Bagstad et al., 2013; Duru et al., 2015b). Thus, to assess *actual use* of ES, we characterized how farmers consider and observe an agroecosystem's state to assess ES before they perform a practice that fulfills a similar function. Indeed, if a farmer is aware of the ES levels available, he/she can adjust the agricultural practices to perform in order to avoid replacing or duplicating an ES that is already provided. We assigned a score according to the precision of the information that farmers use to assess levels of ES (section 3.2.2).

Natural capital was separated into abiotic and biotic components that help provide ES (section 3.1). The direction and intensity of the dynamics were evaluated for each component using indicators that resulted from modeling and multicriteria evaluation (section 3.2.3). Like for ES capacities, we developed dimensionless indicators and summed of them by component to assess overall dynamics of *natural capital*.

3.1. Literature review of determinants of *potential* and *real capacity* and components of *natural capital*

We focused the review on determinants of ES in temperate cropping agroecosystems at the field level to compare similar ecological functioning. We started from five recent qualitative reviews of the main determinants of ES levels (Aguilera et al., 2020; Kleijn et al., 2019; Palomo-Campesino et al., 2018; Rosa-Schleich et al., 2019; Therond et al., 2017b) and supplemented their findings with studies identified by "snowball" searches when details were required. We selected information only from reviews, meta-analyses and multi-site studies to ensure that the assessment approach was robust when applied to a variety of temperate agroecosystems and production situations.

The literature review identified that (i) the crop rotation, (ii) soil coverage, (iii) use of species mixtures, (iv) local semi-natural habitats and (v) abiotic soil composition (e.g. SOM content, texture, P content) are elements of the spatiotemporal configuration and composition of agroecosystems that influence the *potential capacity* to provide ES (Table 1; Supplementary Material 1). These determinants can influence ES directly or indirectly by influencing the biodiversity that supports ES (González-Chang et al., 2020).

The literature review also identified that (i) insecticide use, (ii) organic-matter application, (iii) tillage, (iv) harvest conditions, (v) non-crop plants that survive tillage and herbicide applications and (vi) conservation agriculture (a combination of diversified rotations, permanent cover crops and reduced tillage) are agricultural practices that can modulate an ecosystem's *potential capacity,* thus determining its *real capacity* (Table 1; Supplementary Material 1).

To our knowledge, there is no systematic inventory of the components of *natural capital* that underlie ES (i.e. slow variables that determine ES levels). Thus, based on the literature review and expert knowledge, we assessed dynamics of four key components: soil quantity (which depends mainly on erosion), SOM, soil P balance and the associated biodiversity (service providers) that supports ES. For this last component, we estimated the dynamics of abundance and diversity of the key above-ground and soil organisms that support ES by assessing practices that influence them (Supplementary Material 1, González-Chang et al. (2020); Weyers and Gramig (2017)). Supplementary Material 2 describes relations between the four components of *natural capital* and ES and provides details about mechanisms.

3.2. Indicators and multicriteria assessment of the four dimensions of ES

The indicators used for multicriteria assessment of the four dimensions of ES were either discrete (in five classes) or continuous. In both cases, values were scaled when necessary relative to the corresponding value of the case study region (NUTS 2); thus, the values were dimensionless so they could be aggregated by averaging them. The limits of each indicator were defined according to the range of potential absolute values of each indicator or according to local experts. For example, the maximum percentage of legumes in a rotation was 100%, while the maximum SOM mineralization rate was defined by experts according to that observed in the case study region.

3.2.1. Indicators for the evaluation of an agroecosystem's *potential* and *real capacities*

Based on the literature review, we identified or developed a set of consistent indicators to quantify the positive or negative contribution of each determinant on the one hand on the potential capacity and on the other hand, on the real capacity levels of each of the nine ES (Table 2). Each indicator represents an increase or decrease in each ES. Depending on the number of determinants considered for each ES (*n*), its indicator was based on one variable or a mean of *n* variables. Indicators of *potential capacity* (hereafter, I_potential) ranged from 0 (no contribution) to 1 (maximum positive contribution). Quantifying the I_potential required using information about crop rotations, cover crops, the number of cultivars, the location of semi-natural habitats around the fields and/or soil analyses (i.e. texture and SOM content). For each ES, *potential capacity* was the average of *n* I_potential scores. Indicators of the modulation of *potential capacity* (hereafter, I_modulation) provided information about how agricultural practices influence ES during the year. For each ES, the modulation was the average of *n* I_modulation scores. Adding I_potential ([0; 1]) to I_modulation([-1; 1]) yielded indicators of *real capacity* ([-1; 2]) for each ES (Figure 2). Quantifying the I_modulation indicators required information about agricultural practices (i.e. fertilization, pesticide application, organic-matter application, crop-residue management), local climate and the number of non-crop plants at harvest and before the first tillage or herbicide application, depending on the farm. We assumed that conservation agriculture that combines diversified rotations, permanent soil cover and minimal tillage provides a synergistic effect (Pittelkow et al., 2015). To reflect this, a bonus score of 1 was added to I_modulation if all three of these conditions were met. Indicators related to semi-natural habitats were calculated at the field level and averaged for the agroecosystem. *Potential* and *real capacity* scores by agroecosystem were aggregated by averaging all ES *potential* and *real capacity* scores, respectively.

3.2.2. Indicators of *actual use* of ES

Farmers can use a variety of actions (e.g. counting natural enemies) or tools (e.g. tensiometers to estimate soil water content) to assess an agroecosystem's ability to provide ES. Thus, for each of the seven ES that can be replaced with an anthropogenic input, we identified the main actions that farmers can perform to estimate the capacity of an agroecosystem to provide a given ES (Table 3). We then ranked them according to the precision of the information provided and assigned them a score from 0-1 (i.e. least to most precise). Two experts in agriculture practices defined each action's degree of precision. For example, they considered that the most precise technology available to farmers to assess soil structure is the spade test (even though it is low technology). They also considered that using an unmanned aerial vehicle or remote-sensing robot would allow farmers to estimate the spatial distribution of ES levels precisely and to adjust product doses accordingly. We determined that farmers in the case study had no technology at the field level (i.e. no action) that could replace the pollination or erosion-control ES, so no indicator was calculated for them. *Actual use* scores by agroecosystem were aggregated by averaging all ES *actual use* scores.

3.2.3. *Natural capital dynamics*

Among the variety of methods to assess dynamics of the n = 4 components of *natural capital* selected, we chose four that could be applied easily to data usually available on farms. *Natural capital* was assessed using dimensionless indicators that expressed the dynamics of its components and ranged from -1 (depletion) to 1 (capitalization).

Soil quantity dynamics were assessed using an index of the potential sensitivity to erosion, which equals the product of erodibility and exposure indexes for all crops in a rotation (van Dijk et al. (2016); Supplementary Material 4). It is based on monthly rainfall, soil bulk density, SOM content, the proportion of area covered by vegetation and the spatial structure of vegetation. According to Rosenfelder and van Dijk (2014), index values of 0.015 and 0.022 are considered acceptable and very high, respectively. From this index, we developed an indicator of potential sensitivity to erosion ([-1; 1]) with five classes that ranged from high to unlikely.

The trend in SOM was estimated from the trend in soil carbon content predicted by the AMG model (Clivot et al., 2019), considering the climate from 1997-2017. AMG explicitly simulates a rotation of crops and intercrops, the type and amount of organic matter applied and crop-residue management (Andriulo et al., 1999). The slope of a linear regression of AMG's predictions of annual SOM were transformed into an indicator of the trend in SOM. A positive or negative trend (i.e. score) indicated capitalization or depletion of soil carbon, respectively (Supplementary Material 5). We centered the data and defined five classes from the data's quintiles.

Due to the difficulty in estimating dynamics of the soil P stock, we considered the annual balance between the amount of P exported in harvested straw and grain and that imported by mineral fertilization, organic-matter application and straw left in fields (Supplementary Material 6). The indicator expressed the extent to which the cropping system increases or decreases the soil P stock. A positive or negative balance indicated soil P capitalization or depletion, respectively. We centered the data and defined five classes from the data's quintiles.

The dynamics of biodiversity were estimated using a composite index of indicators that, based on a literature review (Table 1), provided information about average effects of the determinants and agricultural practices considered on six key communities of service providers: natural enemies of pests, pollinators, granivores, soil animals, soil bacteria and soil fungi (Table 4, Supplementary Material 1; González-Chang et al., 2020). These service-provider communities are influenced by the spatial and temporal configurations and compositions of the ecosystem, SOM content and crop management.

Indicators of effects of each determinant on each community ([-1; 0] or [0; 1], Table 4) were summed to estimate a score for each community. To assess the dynamics of all biodiversity that supports ES, these indexes were summed and then divided by the sum of maximum possible scores of the six communities. Because the number of determinants that influence each community can differ, this method aggregated information into a single score. A negative score indicates an expected middle-to-long-term reduction in biodiversity due to crop management.

Natural capital dynamics scores by agroecosystem were aggregated by averaging the scores of the four components.

4. Example of application

4.1. Materials and methods

4.1.1. Case study and data collection

Twenty-eight farms in the Grand Est region (NUTS2) of France were chosen by advisors from the Regional Chamber of Agriculture to represent a wide range of rotation complexity and input intensity in agroecosystems (Supplementary Material 7). The systems selected ranged from an irrigated monoculture of maize to a complex rotation in organic and conservation agriculture (Supplementary Material 8). Data required to apply the approach (Supplementary Material 9) came from a farmer survey conducted in 2019 and the farmers' computer-based management tool (2018 data). In the latter, farmers enter the crop rotation, cover crops and practices (i.e. sowing, tillage; pesticide and fertilizer applications) each year. Along with the survey, each farmer was interviewed for ca. 1.5 h. The survey was used to identify one or two main types of agroecosystems on each farm, the spatial configuration of associated fields of the farmland, characteristics of semi-natural habitats in these fields (using orthophotos) and farmers' strategies for their *actual use* of ES. On the 28 farms surveyed, we identified 34 agroecosystems (450 fields), each of which corresponded to fields with the same soil type and cropping systems (i.e. rotation, cover crops and crop management).

4.1.2. Methods

We analyzed yields and input intensity of the 34 agroecosystems. We defined the "relative yield" of each as the ratio of its mean yield of wheat (or, if not available, maize) from 2017-2019 to that of the French department in which it was located. Input intensity was estimated by aggregating scores of (i) mineral fertilization intensity relative to the regional mean, (ii) pesticide treatment frequency index relative to the regional mean and (iii) the frequency of plowing and irrigation (Supplementary Material 10). We performed principal component analysis (PCA) with R to help interpret relations among *real capacity*, *actual use*, *natural capital*, relative yield and input intensity. *Potential capacity* was not included because it was highly correlated (r=0.780) with *real capacity*, which exceeded the collinearity threshold (r=0.700) recommended by Dormann et al., (2013). To identify different agriculture models according to the four dimensions of ES, we performed clustering analysis with a partitioning (*k*-means) algorithm in the three-dimensional data space of *real capacity*, *actual use,* and *natural capital*. The optimal number of clusters (*k*) was defined according to the elbow method, which, for *k* ranging from 1 to *n* clusters, calculates the within-cluster sum of squares and the location of a "elbow" can be considered an indicator of the suitable number of clusters (Supplementary material 11). We compared cluster-specific means of input intensity and relative yield to each other with Tukey honestly significant difference (HSD) post-hoc tests to test all pairwise comparisons with 95% confidence. Analyses were performed using the open-source FactoMineR package of R software (Husson et al., 2010; MacQueen, 1967; R Core, 2013).

4.2. Results

4.2.1. Application of the assessment approach

For each agroecosystem, the scores of *potential capacity, real capacity, actual use* and *natural capital* of each ES was assessed and represented in absolute value and relative value compared to those of the entire group (Figure 3, Supplementary material 12). A group's ranges may not cover the ranges of all possible values. For example, for agroecosystem #26, pesticide use rendered WEED's *real capacity* only slightly lower than its *potential capacity* (Figure 3a). Relative to the group, the agroecosystem's configuration and crop management practices favored POL, WEED, DIS and PEST, since its *potential* and *real capacities* were among the highest in the group (Figure 3a). Moreover, since the farmer of #26 always used counting and field observations to assess biological regulation of pests, weeds and diseases before applying pesticides, fungicides or weeds, the *actual use* of these ES was also considered relatively high (Figure 3b). The *potential capacity* of the NS service was high but could be increased by improving agroecosystem configuration (e.g. increasing the percentage of legumes in crop rotations) and crop management (e.g. relying more on organic inputs than mineral N). The agroecosystem's *natural capital* components had contrasting dynamics (Figure 3c). Biodiversity and SOM capitals were relatively high, indicating that biological regulation services would continue for the farmer, while N provision should increase. Potential sensitivity to soil erosion (with a medium value) could be improved, while the P balance indicator had a low value, which indicated the risk of depleting the soil P stock.

Aggregated ES scores for each of the 34 agroecosystems ranged from [0.27; 0.66] for *potential capacity*, [0.03; 0.87] for *real capacity* and [0.13; 0.75] for *actual use* (Figure 4). *Real capacity* had a wider range than *potential capacity* because the agricultural practices investigated modulated the *potential capacity* in both positive and negative directions. In contrast, *actual use* had a narrower range than *real capacity,* which indicates that most farmers did not use it fully.

The difference between *potential capacity* and *real capacity* was small for some agroecosystems (e.g. #3, 6, 22) but large for others (e.g. #8-1, 18-2, 25). An overall trend emerged: agroecosystems with high *potential capacity* tended to increase it through beneficial practices, which yielded an even higher *real capacity*. This was confirmed by the Pearson correlation between *potential capacity* and *real capacity* minus *potential capacity*, which was significant ($p<0.05$) but weak ($r=0.357$) (Supplementary Material 13).

For *natural capital*, SOM, soil P and soil quantity dynamics ranged from [-1; 1], while biodiversity ranged from [-0.40; 0.51] (Supplementary material 14). Most of the agroecosystems were depleting P stocks (73%) but capitalizing soil carbon (67%), which illustrates the potential advantage of increasing SOM (which has a long response time and is a major determinant of most soil-related ES) rather than closing the P cycle, which can be done through a long response time. None of the systems were depleting or capitalizing biodiversity to a large degree.

The relative yield of the 34 agroecosystems ranged from [0.46; 1.31] (Supplementary material 15), and the yields of 10 of the 34 agroecosystems were lower than the mean regional yields. Input intensity ranged from [0; 0.83], from a system based on low levels of anthropogenic inputs (i.e. #2, in organic and conservation agriculture; Supplementary Material 8) to one based on high levels of anthropogenic inputs (i.e. #8-1).

The most intensive systems exceeded mean regional yields and were generally those with the lowest ES *real capacity*. The first axis of the PCA, influenced by input intensity and the relative yield on one side and *real capacity* on the other, explained 41.8% of the variance (Supplementary Material 16). This negative relation between input intensity (and thus relative yield, since they were strongly correlated) and *real capacity* was significant and moderately strong (Supplementary Material 17, $p<0.05$ and $r=-0.564$). However, there were a few notable exceptions, such as agroecosystems #25 and #23, which had, respectively, a *real capacity* of 0.80 and 0.27 and a relative yield of 1.27 and 0.61. In contrast, there was no relation between input intensity and the dynamics of *natural capital* or *actual use* of ES (e.g. agroecosystem #15).

4.2.2. Description of the agriculture models

The clustering analysis identified five clusters (Figure 7) that referred to five combinations of scores of *real capacity* and *actual use* of ES and dynamics of *natural capital*. The first cluster of (5 agroecosystems) had some of the highest *real capacity* ([0.57; 0.87]), above-average *actual use* ([0.51; 0.70]) and no specific *natural capital* dynamics (but no large depletion) (Figure 7, MH-H). This cluster had varied rotations (rapeseed-wheat-barley-legume-other or soybean-wheat-other) but which always included legumes and often uncommon crops (e.g. spelt, spring peas, mustard, alfalfa, sainfoin, flax). Rotation duration ranged from 3-9 years (mean: 5.4 years). These five systems performed reduced tillage or no tillage. One was an irrigated conventional farm, two were organic, and one performed conservation agriculture. They corresponded to models with “Medium-High use of High ES capacity” (“MH-H”).

The second cluster (8 agroecosystems) had a wide range of *real capacity* ([0.26; 0.68]), low *actual use* [0.16; 0.43]) and neutral or positive *natural capital* dynamics (Figure 7, I-M). This cluster had rotations based mainly on rapeseed-wheat-barley-other, with a mean rotation duration of 5.6 years, 5.5 crops in the rotation and varied types of tillage (plowing, reduced tillage, no-till). Only one farm in this model, a maize-based rotation (#1), was depleting its *natural capital*. Agroecosystem #23 was unique in this group since it had low *real capacity* despite having 9 crops and practicing reduced tillage. These systems corresponded to models with “Inefficient use of Medium ES capacity” (“I-M”).

The third cluster (7 agroecosystems) had a wide range of *real capacity* ([0.03; 0.59]), medium *actual use* ([0.43; 0.63]) and positive *natural capital* dynamics (Figure 7, M-LM-C). This cluster mainly (8 out of 9) had rotations such as rapeseed-wheat-barley-other, included less common crops (e.g. sainfoin, faba bean, and hemp) and had a mean rotation duration of 5.6 years. All but one of the farms occasionally practiced simplified tillage, and only one irrigated. Agroecosystem #19-2 was unique in this cluster because it was a plowed maize monoculture. All of these farms applied pesticides and mineral fertilizers. These systems corresponded to models with “Medium use of Low-to-Medium ES capacity, with Capitalization” (“M-LM-C”).

The fourth cluster (8 agroecosystems) had low *real capacity* ([0.10; 0.50]), high *actual use* ([0.61; 0.76]) and negative *natural capital* dynamics (Figure 7, E-LM-D). This cluster contained only maize-wheat-other crop rotations (a mean of 2.5 crops in the rotation), with at least 2 years of maize and a mean rotation of 4 years. Three of the 8 agroecosystems sometimes practiced reduced tillage, and all but one irrigated. All farms in this cluster applied pesticides and mineral fertilizers, and four did not use insecticides or fungicides. These systems corresponded to models with “Efficient use of Low-to-Medium ES capacity, with Depletion” (“E-LM-D”).

The fifth cluster (6 agroecosystems) had low *real capacity* ([0.14; 0.59]), medium-low *actual use* ([0.25; 0.4]) and negative *natural capital* dynamics (Figure 7, I-LM-D). This cluster contained had only maize-wheat-other crop rotations (mean of 2.5 crops in the rotation, often with 2 years of maize). Its agricultural practices varied (plowing, reduced tillage, pesticides or not, irrigation or not). These systems corresponded to models with “Inefficient use of Low-to-Medium ES capacity, with Depletion” (“I-LM-D”). Relative yield and input intensity did not differ significantly among the five clusters, although the MH-H cluster had high variability in relative yield (p>0.05, pairwise Tukey HSD test, [0.66; 1.27], Supplementary material 18).

5. Discussion

We developed an original assessment approach to ES based on assessing relations between characteristics of agroecosystems and the main ES they provide. In agreement with the objective of developing operational tools for agricultural support institutions, the approach provides a detailed description for farmers of the *potential capacity* of each ES, effects that agricultural practices have on it, the *actual use* of ES capacity and the dynamics of *natural capital* under current agricultural practices (Figure 3). The approach is part of a large field of research that assesses ecosystem services in agroecosystems (Malinga et al., 2015). It focuses on ES involved in agricultural production (and not on those provided to the larger society) and characterizes relations between agroecosystems and ES at two temporal scales: the classic short term, which corresponds to the cropping season, and the medium-/long-term dynamics of *natural capital* (Robinson et al., 2012).

5.1. Strengths of the assessment approach

Our approach is an original development of the conceptual framework and its operationalization by integrating scientific knowledge and low-data indicators. One of the innovations is that it conceptually clarifies and renders operational the assessment of four components of ES, which separates components of the cascade that underlie the provision of ES in the short and medium/long terms. Accordingly, as claimed by Kleijn et al. (2019), this provides agricultural stakeholders with useful information about (i) “limiting services” (Bommarco et al., 2013a; Garibaldi et al., 2018; Sperfeld et al., 2012) and (ii) potential mechanisms to enhance the *potential* and *real capacities* of ES. In other words, it provides a sound conceptual framework with which to analyze the functioning of agroecosystems and define a strategy to manage it in the quest for ES-based agriculture models.

As also noted by Therond et al. (2017a), our assessment approach can classify agroecosystems more finely than broad typologies (e.g. organic vs. conventional agriculture, diversified vs. simplified farming systems) (Garibaldi et al., 2017). As Duru et al. (2015b) theorized, our fine-grained approach can identify multiple strategies that can be used to obtain given levels of ES and dynamics of *natural capital*. For example, three organic agroecosystems (#28, 2 and 15) that covered a range of rotation diversification (from 3-6 crops) differed strongly in *real capacity* and *actual use* of ES (Figure 5). This confirms that organic systems, which vary from complex biodiversity-based systems to simplified monocultures, can result in agroecosystems with greatly different functioning (Reeve et al., 2016; Seufert et al., 2012).

Our approach may also help assess payments for environmental services provided by agricultural support institutions, in which beneficiaries (society) pay ecosystem-service providers (here, farmers) for the services provided (Donohue et al., 2016). For the ES assessed in the present study, these payments would reward farmers for using ES instead of anthropogenic inputs and thus intentionally encourage biodiversity-based solutions and reduce negative environmental impacts related to input-based systems (Bommarco et al., 2013a). This method provides the strong scientific foundations needed to assess such payments, as required by Naeem et al. (2015), by developing a scientifically robust method that is operational and requires relatively little data.

5.2. Shortcomings and expected improvements of the approach

Since the approach developed is the first version, it will be improved. Applying it to the case study of the Grand Est required parameterizing it for this region; applying it to other regions will require expert knowledge of the regions and associated reference data. In particular, the range of technologies that could be used to assess the provision of ES and thus determine the *actual use* of ES needs to be adapted to the technologies available locally. It is currently defined from expert opinion, but other ways to estimate as closely as possible farmers' *actual use* of ES, both active and inactive, can be considered. Results of future studies of determinants of ES are also expected to improve the selection of low-data indicators and the method used to aggregate them for individual ES and entire sets of ES (as in Vogel et al. (2019) and Zhang (2020); see section 5.3 for details). This study is an initial assessment that can be compared to using field surveys to assess ES, like Birrer et al. (2014) did to assess biodiversity. Finally, to date, without available knowledge about the relative weights of determinants of ES, the aggregation remains simplistic (the same weight for all).

The application domain of the approach is currently limited to agroecosystems based on annual crops and needs to be extended to other types of agroecosystems (e.g. livestock farms, orchards, vineyards, agroforestry systems). Using the same logic, the method could be extended to other ES provided to farmers (e.g. local climate regulation) or to society (e.g. global climate regulation) (Aguilera et al., 2013; Techen et al., 2020). This could identify synergies and trade-offs between ES provided to different beneficiaries (Obiang Ndong et al., 2020). Finally, for the *natural capital* components, only the biodiversity that supports ES was considered, but the approach could be extended to consider all biodiversity from a larger conservation perspective (Lüscher et al., 2017; Moller et al., 2008).

Another key improvement would be to quantify the part of production that comes from using ES vs. the part that comes from anthropogenic inputs (Jones et al., 2016). For now, the approach developed does not exactly follow the recommendations of Therond et al. (2017a) for classifying agricultural models. However, partitioning production between these two types of production factors is complex due to intertwined ecological processes (Barot et al., 2017; Jones et al., 2016). Few studies have attempted to do this. Pérez-Soba et al. (2019) performed emergy analysis, which coarsely distinguished effects of natural (e.g. solar radiation) vs. anthropogenic flows. Therond et al. (2017b) and Tibi and Therond (2018) developed an approach based on a crop model to estimate the part of production related to groundwater-, rainwater- and nitrogen-related ES vs. N fertilization and irrigation.

Finally, this approach does not address ecosystem services provided to society or negative environmental impacts of agriculture (e.g. N leaching) (Uusitalo et al., 2019). As Soulé et al. (2021) proposed, performing traditional environmental impact assessments along with our ES assessment approach would provide more complete assessment of the environmental sustainability of agroecosystems.

5.3. Lack of knowledge and agenda for research

The literature review highlighted a substantial lack of knowledge. First, we were not able to consider effects of semi-natural habitats in the landscape beyond the farm scale. Karp et al. (2018) show that the influence of non-crop habitats on biological control depends on the context. Multiple communities may be involved in providing an ES, and little information about their interactions (e.g. inter-guild predation) is available. For example, results for the effects of carabids on weed regulation (Frei et al., 2019) are ambiguous, showing a positive effect (Chapman, 2014; Knapp and Řezáč, 2015) or negative effect (Jonason et al., 2013) of landscape heterogeneity. Dispersal distances of carabids depend on their guild, which causes variability among observations. Moreover, the relative contribution of carabids vs. birds and small mammals to weed regulation is still under research (Petit et al., 2011). In other words, landscape effects on biological regulation services may depend strongly on the functional characteristics of ES providers (Martin et al., 2019).

We felt that certain relations between determinants and ES already mentioned in the literature were not yet sufficiently documented to include them. For example, non-crop plants in and around fields might have a key influence on dynamics of natural enemies by providing a diverse habitat and food resource for biodiversity (Marshall et al., 2003; Petit et al., 2015; Pocock et al., 2012). However, we could not find key reviews or meta-analyses that provided usable information. Cover crops appear to influence disease control, but this seems specific to each combination of host/disease/cover crop (Justes et al., 2012). Soil cover influences the soil structuration service via the canopy and root exudates (Bardgett et al., 2014; Scavo et al., 2019). Although the influence is well established, we did not find a suitable database of root exudates from crops to be able to consider this effect. More generally, Techen et al. (2020) present key soil research challenges for a few management practices such as nutrient efficiency in agroforestry, the influence of rotations and crops on microbiome composition, ecotoxicity of plastics, stoichiometry management, biotic inoculations and pharmaceuticals.

Finally, there is a serious lack of information about the relative influence of determinants on the provision of each ES. For example, weed control is promoted by spatial (species mixtures) and temporal (rotations) plant diversity and permanent soil cover, but their relative influence is unknown. Therefore, we assigned the same influence to all *n* determinants for a given ES and to the contributions of potential and modulation effects to the ES level. Until studies provide information about these relative effects, improving our approach could mean bringing a group of experts together to refine the aggregation method, as van Leeuwen et al. (2019) and Zahm et al. (2018) recommended. Ultimately, this information is also needed to integrate potential trade-offs that may exist among the determinants of ES (Garibaldi et al., 2018; Obiang Ndong et al., 2020).

5.4. Insights into agriculture models

In general, agroecological practices, such as organic, biodiversity-based practices (e.g. rotations, species mixtures) and conservation agriculture, are expected to provide higher ES capacity (Palomo-Campesino et al., 2018). We show that this is true when several agroecological practices are implemented together, as in the MH-H agriculture model in which organic farming, reduced or no-tillage, soil cover and diversified rotations were combined, as suggested by Duru et al. (2015b). To a lesser extent, and because agroecological practices are usually combined less often, the I-M agriculture model also followed this pattern. However, our results suggest that implementing these practices does not necessarily mean that farmers use the *potential capacity* of ES well.

In the present study, *real capacity* was significantly negatively correlated with input intensity and relative yield. In other words, agriculture models with higher *real capacity* of ES are often those with lower input use and relative yield. However, this trend hides high variability. First, excluding organic agroecosystems weakens this correlation because they have the lower relative yields and input intensity due to organic specifications (Supplementary Material 19) (Knapp and van der Heijden, 2018). Second, no significant difference in input intensity or relative yield was observed among clusters. Indeed, variability in relative yield among agroecosystems was high within each cluster, particularly in the agroecological agriculture models with high/medium *real capacity*. Thus, there are many ways to obtain high yields, based mainly on anthropogenic inputs, ES or both (Therond et al., 2017a). For example, within these agroecological models, the yield of agroecosystems #25, 16, 12, and 3 was higher than the regional mean. Agroecosystem #25 was unique in the present study since it obtained high yields with a high input intensity but also used ES capacity efficiently (Supplementary Material 20). It was also the only agroecosystem that met our requirements to be classified as conservation agriculture and thus to benefit from the bonus. The farmer of this agroecosystem increased the yield greatly by using ES as much as possible and supplementing them with inputs, and the ES levels could have been increased even further.

In the M-LM-C agriculture model, system #19-2, a maize monoculture, which had the lowest ES *real capacity* of the group, was managed by the same farmer as system #19-1, which had higher ES capacities. This large difference between two agroecosystems of the same farmer reflects a separation of the land that results from two different rationales and European Union Common Agricultural Policy (CAP) regulations. System #19-2 is based on maize, which is the most economically profitable crop locally and usually managed intensively in monoculture with irrigation and plowing on the best soils. However, due to CAP regulations on the proportion of farm area that can be planted in monocultures, farmers cannot plant monocultures over the entire farm. Consequently, system #19-1 was based on a multicrop rotation that was managed less intensively. CAP regulations allowed the farmer to open up space for testing solutions based on planned biodiversity. This pattern was repeated on other maize farms (#8, 10, and 19).

Finally, we highlight that all maize-based agroecosystems depleted *natural capital*, regardless of the agriculture model to which they belonged. Soil erosion due to the absence of cover crops drove this negative trend, which could be addressed by adding cover crops to maize-based systems (Laloy and Bielders, 2010). However, weather conditions after the late maize harvest period make it difficult to plant cover crops (Marcillo et al., 2019).

6. Conclusion

We developed a new conceptual framework to clearly distinguish multiple aspects of ES and an operational low-data indicator-based approach to assess them. It highlights the important distinction between short-term ES capacities and medium/long term dynamics of *natural capital* that underlie these services and the *actual use* of them. The literature review performed to develop this approach enabled us to build upon well-known relations between characteristics of agroecosystems and ES, identify consistent indicators of these relations, and identify areas in which knowledge is lacking. This indirect evaluation of ES allows for (i) the use of easily available data on characteristics of agroecosystems and their management instead of resource-consuming field measurements, (ii) detailed description of ES associated with an agroecosystem and (iii) identification of agronomic mechanisms to use to increase the provision or use of ES. Through better understanding of the ability of agroecosystems to generate ES, and how to enhance them, our approach may help farmers build agroecosystems based on natural production factors instead of importing petrochemicals.

We demonstrated the utility of our approach by applying it to a set of 34 French agroecosystems. This application provided key insights into the biotechnical functioning of arable agroecosystems: (i) combining agroecological practices maximizes the *real capacity* of ES and (ii) there are many ways to reach high-yielding agroecosystems based on anthropogenic inputs, ES or both.

Contributions

M.D., B.L. and O.T. developed the conceptual framework; M.D. and B.L. performed the literature review and indicator selection with the guidance of O.T. and C.Bo.; H.C. developed the AMG model used; M.D., B.L. and C.Be. performed the farm surveys and calculations; M.D. and O.T. wrote the manuscript; and C.Bo., B.L. and C.Be. proofread the manuscript.

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Tables

Table 1. Summary of the main determinants of ecosystem services that contribute to agricultural production (ES). The spatial and temporal configuration and composition of the cover and soil composition determine an ecosystem's potential capacity. *The crop management of soil and biomass determined an ecosystem's* real capacity. *The 9 ES studied include pollination (POL); pest (PEST), weed (WEED) and disease (DIS) control; soil structuration (STR); nitrogen supply to crops (NS); phosphorus supply to crops (PS); water retention and return to crops (WATER) and stabilization and control of erosion (ERO). The effects of crop management on ES provision can be positive (+) or negative (-). References are mainly meta-analyses, reviews or multisite studies. *Depends on the type of habitat. **Several combinations of soil characteristics are suitable for ES, see Table 2.*

	Determinant	**ES and direction of the effect**	**References**
Potential capacity	**Crop rotation**	WEED, DIS, PEST (*diversified*: +) NS, PS (*legume presence*: +)	Bender et al., 2016; Dassou and Tixier, 2016; Duchene et al., 2017; El Mujtar et al., 2019; Ghosh et al., 2007; Hinsinger et al., 2011; Kleijn et al., 2019; Letourneau et al., 2011; Palomo-Campesino et al., 2018; Rosa-Schleich et al., 2019; Scholberg et al., 2010
	Soil coverage	WEED, STR, NS, ERO (*permanent*: +)	Aguilera et al., 2020; Bertrand et al., 2019; Justes et al., 2012; Kleijn et al., 2019; Palomo-Campesino et al., 2018; Rosa-Schleich et al., 2019; Scholberg et al., 2010; Shackelford et al., 2019
	Use of species mixtures	WEED, DIS, PEST (+)	Bedoussac et al., 2015; Dassou and Tixier, 2016; Duchene et al., 2017; Iverson et al., 2014; Kleijn et al., 2019; Letourneau et al., 2011; Malézieux et al., 2009; Palomo-Campesino et al., 2018; Rosa-Schleich et al., 2019, p.; Scholberg et al., 2010; Vandermeer et al., 1998; Verret et al., 2017
	Local semi-natural habitats	POL, PEST (*close to fields**, +)	Bartual et al., 2019; Bianchi et al., 2006; Blaauw and Isaacs, 2014; Holland et al., 2017; Palomo-Campesino et al., 2018; Rega et al., 2018; Tscharntke et al., 2007; Tschumi et al., 2016; Zulian et al., 2013
	Abiotic soil composition	STR, NS, PS, WATER, ERO **	Bender et al., 2016; Boyle et al., 1989; Chen and Tessier, 1998; Clivot et al., 2019; El Mujtar et al., 2019; Green et al., 2003; Johannes et al., 2017; Lado et al., 2004; Olsen et al., 1954; Saxton and Rawls, 2006
Real capacity	**Insecticide use**	POL, WEED, PEST, STR (-)	Brittain and Potts, 2011; Colin et al., 2004; Desneux et al., 2007; Emmerson et al., 2016; Geiger et al., 2010; Labruyere et al., 2016; Potts et al., 2009; Wang et al., 2012
	Organic-matter application	STR, NS, PS, WATER, ERO (+)	Abiven et al., 2009; Aguilera et al., 2020; Boyle et al., 1989; Khaleel et al., 1981; Lado et al., 2004; Liu et al., 2014
	Tillage	WEED, PEST, STR, WATER, ERO (-)	Aguilera et al., 2020; Blanco-Canqui and Ruis, 2018; Blevins et al., 2018; Blubaugh and Kaplan, 2015; Hamza and Anderson, 2005; Kuntz et al., 2013; Menalled et al., 2007; Soane et al., 2012; Trichard et al., 2014
	Harvest conditions	STR (*wet*: -)	Hamza and Anderson, 2005
	Non-crop plants	POL, WEED (-)	Bretagnolle and Gaba, 2015; Dassou and Tixier, 2016; Petit et al., 2016, 2015
	Conservation agriculture	WEED, STR, NS, PS, WATER, ERO (+)	Blanco et al., 2016; Kleijn et al., 2019; Lee et al., 2019; Pittelkow et al., 2015; Rosa-Schleich et al., 2019

Table 2. Indicators used to assess effects of each determinant on the potential capacity *of an agroecosystem to provide ecosystem services that contribute to agricultural production (ES) (I_potential,* [0:1]*) and the modulation (I_modulation,* [-1:1]*) of this* potential capacity*, thus determining the* real capacity *to provide ES. References: * from Craheix et al. (2012), [1] from Rega et al. (2018), [2] from Saxton and Rawls (2006) [3] from Johannes et al. (2017), [4] from Olsen et al. (1954) [5] from Chabert (2017)[6]. For references [a, b, c, d, e, f, g, h, i, j], see Supplementary Material 3. Abbreviations: semi-natural habitats (SNH), treatment frequency index (TFI), soil organic matter (SOM), conservation agriculture (conservation agr.).*

	Determinant	Pollination	Disease control	Pest control	Weed control	Water retention	Soil structuration	Nitrogen supply	Phosphorus supply	Erosion control
I_potential	**Crop rotation**	-	Number of crop families in the rotation*	Number of crop families in the rotation*	Number of sowing periods in the rotation*	-	-	Proportion of legumes in the rotation [a]	Proportion of legumes in the rotation [a]	-
	Soil coverage	-	-	-	Quality of coverage of each crop and intercrop*	-	95% root density depth and proportion of cover crops in the rotation[b]	Proportion of crops and intercrops in the fall to avoid leaching[c]	-	Lack of coverage during the rainy period*
	Use of species mixture		Proportion of crops and intercrops with a species mixture [d]	Proportion of crops and intercrops with a species mixture [d]	Proportion of crops and intercrops with a species mixture [d]	-	-	-	-	-
	Local semi-natural habitats	Proportion of field areas close to an herbaceous habitat[e]	-	Quality and distance of SNH to field barycenter[1]	-	-	-	-	-	-
	Abiotic soil composition	-	-	-	-	Saturated conductivity[2]	SOM/clay[3]	SOM	P Olsen[4]	SOM/clay[3]
I_modulation	**Insecticide use**	TFI relative to mean regional TFI[f]	-	TFI relative to mean regional TFI[f]	TFI relative to mean regional TFI[f]	-	TFI relative to mean regional TFI[f]	-	-	-
	Organic-matter application	-	-	-	-	Annual humified carbon inputs [g]	Annual humified carbon inputs [g]	Annual organic nitrogen inputs [g]	Annual organic phosphorus inputs [g]	Annual humified carbon inputs [g]
	Tillage	-	-	Cumulative depth of tillage [5], [h]	Cumulative depth of tillage [5], [h]	Cumulative depth of tillage [5], [h]	Cumulative depth of tillage [5], [h]	-	-	Cumulative depth of tillage [5], [h]
	Harvest conditions	-	-	-	-	-	Proportion of crops harvested in often wet conditions*	-	-	-
	Non-crop plants	Abundance and diversity of non-crop plants at harvest and before the first tillage or herbicide application[i]	-	Abundance and diversity of non-crop plants at harvest and before the first tillage or herbicide application[i]	-	-	-	-	-	-
	Conservation agr.				Synergistic effect of conservation agriculture: crop diversity, permanent soil coverage and no-till[j]					

Table 3. Method used to assess the actual use *of ecosystem services that contribute to agricultural production (ES), based on the precision of the action performed by farmers to use ecosystem services, considering the ability of the agroecosystem to provide services instead of using anthropogenic inputs to replace them.*

ES	Action or technology used by farmers	Precision	Score
Disease control	No action before applying fungicides	Very low	0
	Adapting fungicide application to the crop, field and position of the crop in the rotation	Low	0.25
	Observation of disease pressure in the field	Medium	0.5
	Counting and identifying impacts of disease in the field	High	0.75
	Unmanned aerial vehicle, remote-sensing robot or risk models	Very high	1
Pest control	No action before applying pesticides	Very low	0
	Adapting pesticide application to the crop, field and position of the crop in the rotation	Low	0.25
	Observation of the pest pressure and presence of natural enemies in the field	Medium	0.5
	Counting and identifying pests and natural enemies in the field	High	0.75
	Unmanned aerial vehicle or remote-sensing robot	Very high	1
Weed control	No action before intervention to control weeds (tillage or herbicide application)	Very low	0
	Adapting intervention to the crop, field and position of the crop in the rotation	Low	0.25
	Observation of non-crop plant abundance and communities in the field and/or granivore presence	Medium	0.5
	Counting and identifying non-cultivated plants in the field and/or granivore presence	High	0.75
	Unmanned aerial vehicle or remote-sensing robot	Very high	1
Water retention and return	No action before irrigating	Very low	0
	Adapting irrigation to the crop, field and position of the crop in the rotation	Low	0.33
	Water balance	High	0.66
	Use of tensiometric or capacitive probes	Very high	1
Soil structuration	No action before tilling	Very low	0
	Adapting tillage to the crop, field and position of the crop in the rotation	Low	0.33
	Spade test occasionally performed	High	0.66
	Spade test always performed	Very high	1
Nitrogen supply	No action before mineral fertilization	Very low	0
	Adapting mineral fertilization to the crop, field and position of the crop in the rotation	Low	0.25
	Recommendation-based nitrogen-balance method	Medium	0.5
	Decision support tool	High	0.75
	Unmanned aerial vehicle and application with section cutting	Very high	1
Phosphorus supply	No action before phosphorus fertilization	Very low	0
	Adapting phosphorus fertilization to the crop, field and position of the crop in the rotation	Medium	0.5
	Measuring Olsen phosphorus	Very high	1

*Table 4. Indicators used to evaluate biodiversity dynamics through the effect of determinants on each community. References are shown in Table 1. * From Craheix et al. (2012), [1] from Rega et al. (2018), [5] from Chabert (2017). For [e, f, h, i, j, k, l] indicator-calculation details, see Supplementary Material 3. Abbreviations: treatment frequency index (TFI), soil organic matter (SOM).*

Determinant	***Characteristic with a positive effect on ->***	**Community of ecosystem service providers**					
		Natural enemies	**Granivores**	**Pollinators**	**Soil animals**	**Soil bacteria**	**Soil fungi**
Crop rotation	*Diversified*	Number of crop families in the rotation*					
Soil coverage	*Permanent*					Proportion of cover crops in the rotation[k]	Proportion of cover crops in the rotation[k]
Local semi-natural habitats	*Close to fields*	Quality and distance of SNH to field barycenter[1]		Proportion of field areas close to an herbaceous habitat[e]			
SOM content	*High level*				SOM	SOM	SOM
Insecticide use	*Low level*	TFI relative to mean regional TFI[f]	TFI relative to mean regional TFI[f]	TFI relative to mean regional TFI[f]	TFI relative to mean regional TFI[f]		
Organic-matter application	*High level*				Diversity of carbon inputs[l]	Diversity of carbon inputs[l]	Diversity of carbon inputs[l]
Tillage	*Reduced*	Cumulative depth of tillage [5], [h]	Cumulative depth of tillage [5], [h]		Cumulative depth of tillage [5], [h]	Cumulative depth of tillage [5], [h]	Cumulative depth of tillage [5], [h]
Non-crop plants	*High abundance and diversity*	Abundance and diversity of non- crop plants at harvest and before the first tillage or herbicide application[i]		Abundance and diversity of non-crop plants at harvest and before the first tillage or herbicide application[i]			
Conservation agriculture (CA)	*Compliance with CA*	Synergistic effect of conservation agriculture: crop diversity, permanent soil coverage and no-till[j]					

Figures

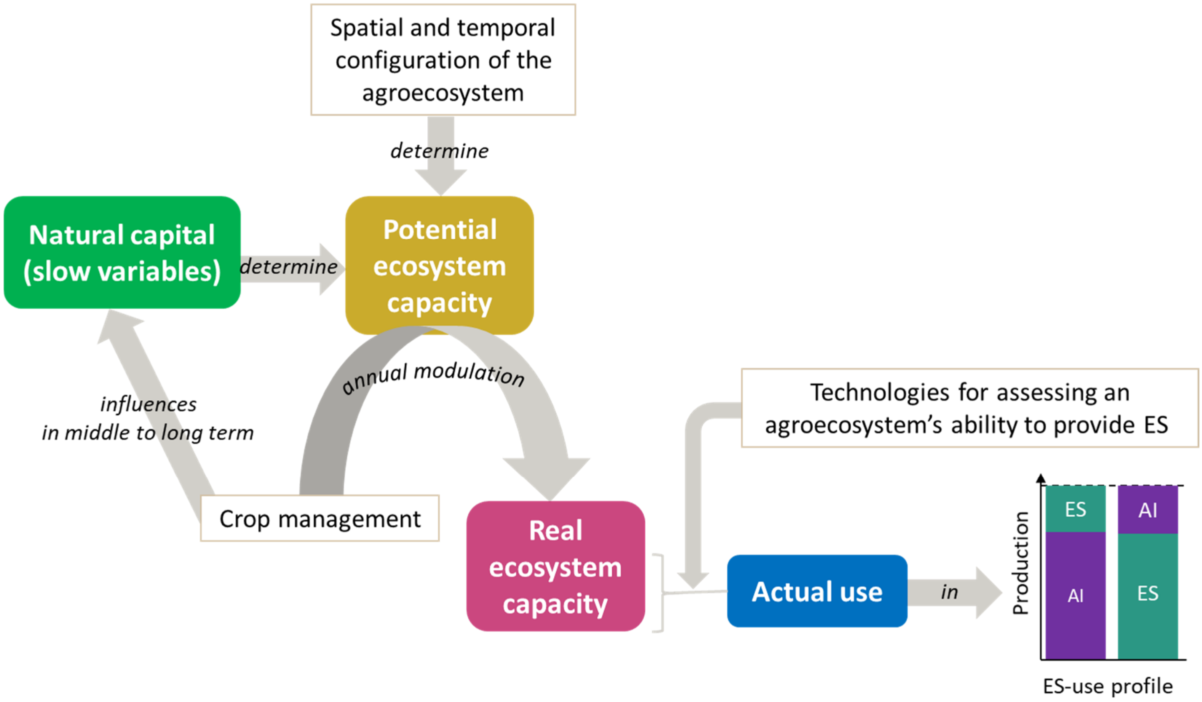

Figure 1. Framework for assessing the four dimensions of the levels of ecosystem services that contribute to agricultural production (ES) and used by them. AI: anthropogenic inputs

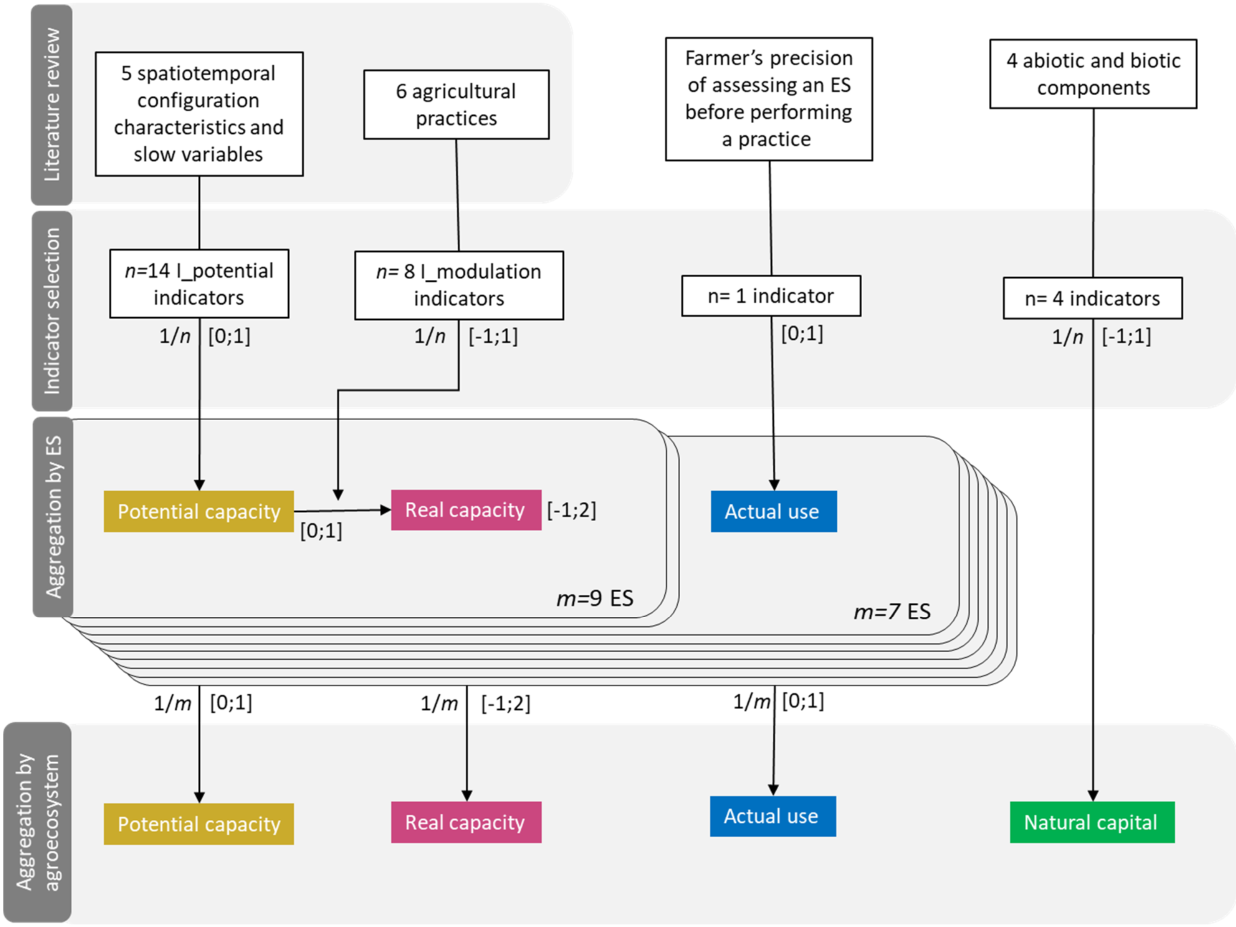

Figure 2. Approach used to assess ecosystem services that contribute to agricultural production (ES) and the dynamics of natural capital *of an agroecosystem. Brackets indicate ranges of indicator scores.*

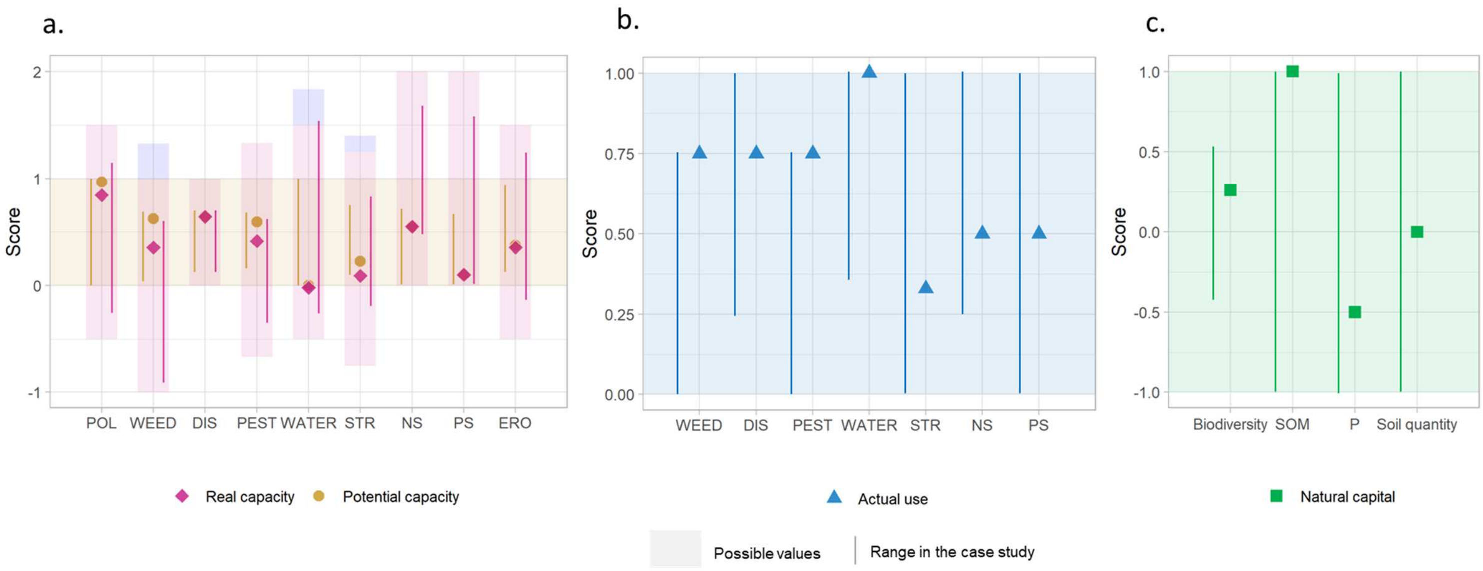

Figure 3. Scores (symbols) for agroecosystem #26 of a) the potential capacity *(tan) and* real capacity *(magenta) to provide nine ecosystem services that contribute to agricultural production (ES), b)* actual use *of ES by the farmer (blue) and c)* natural capital *dynamics (green). Shading and lines indicate the ranges of possible and observed values, respectively, of the 34 agroecosystems studied. Violet shading indicates the range added by the conservation agriculture bonus.*

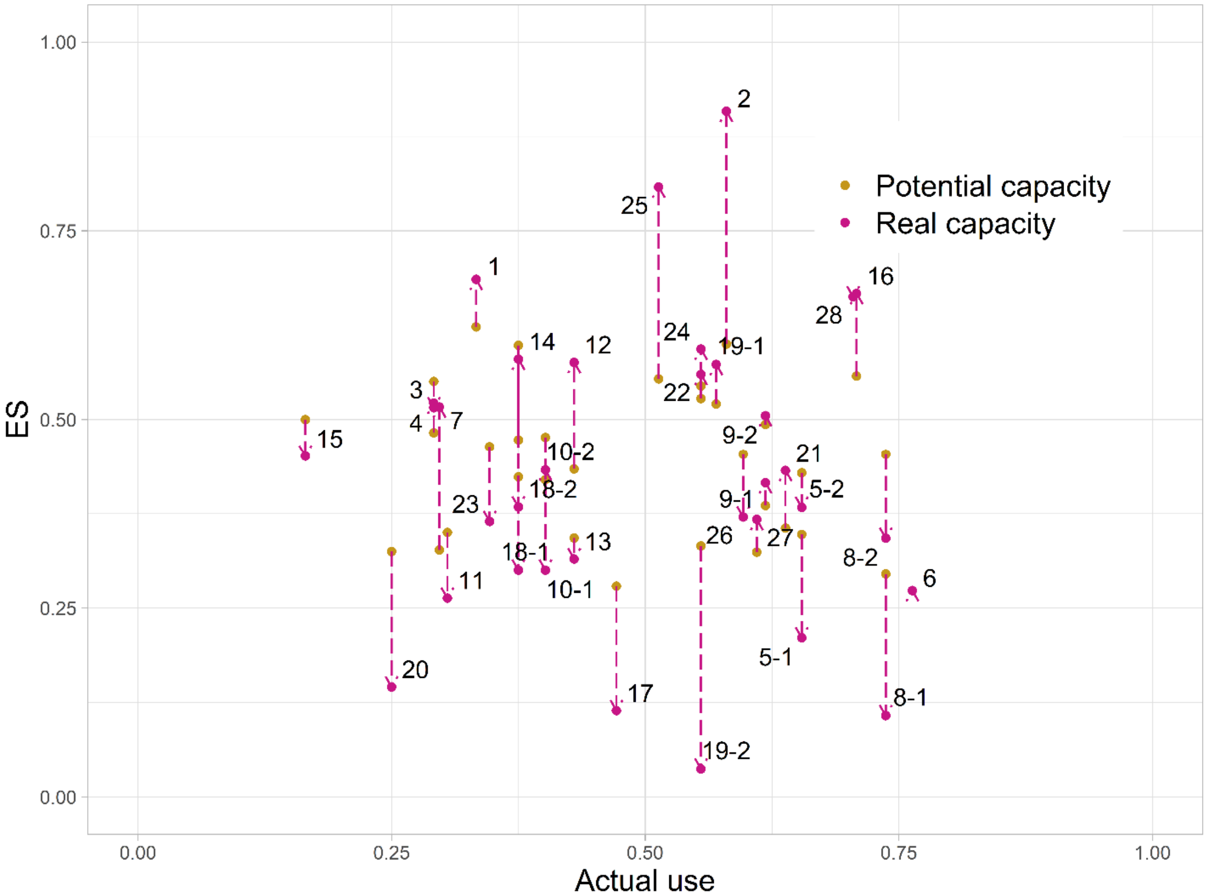

Figure 4. Levels of the potential capacity *and* real capacity *to provide ecosystem services that contribute to agricultural production (ES) as a function of* the actual use *of ES by farmers for 34 agroecosystems on 28 farms in the Grand-Est region (NUTS2) of France. Arrows indicate the direction in which agricultural practices modulated* potential capacity *to* real capacity.

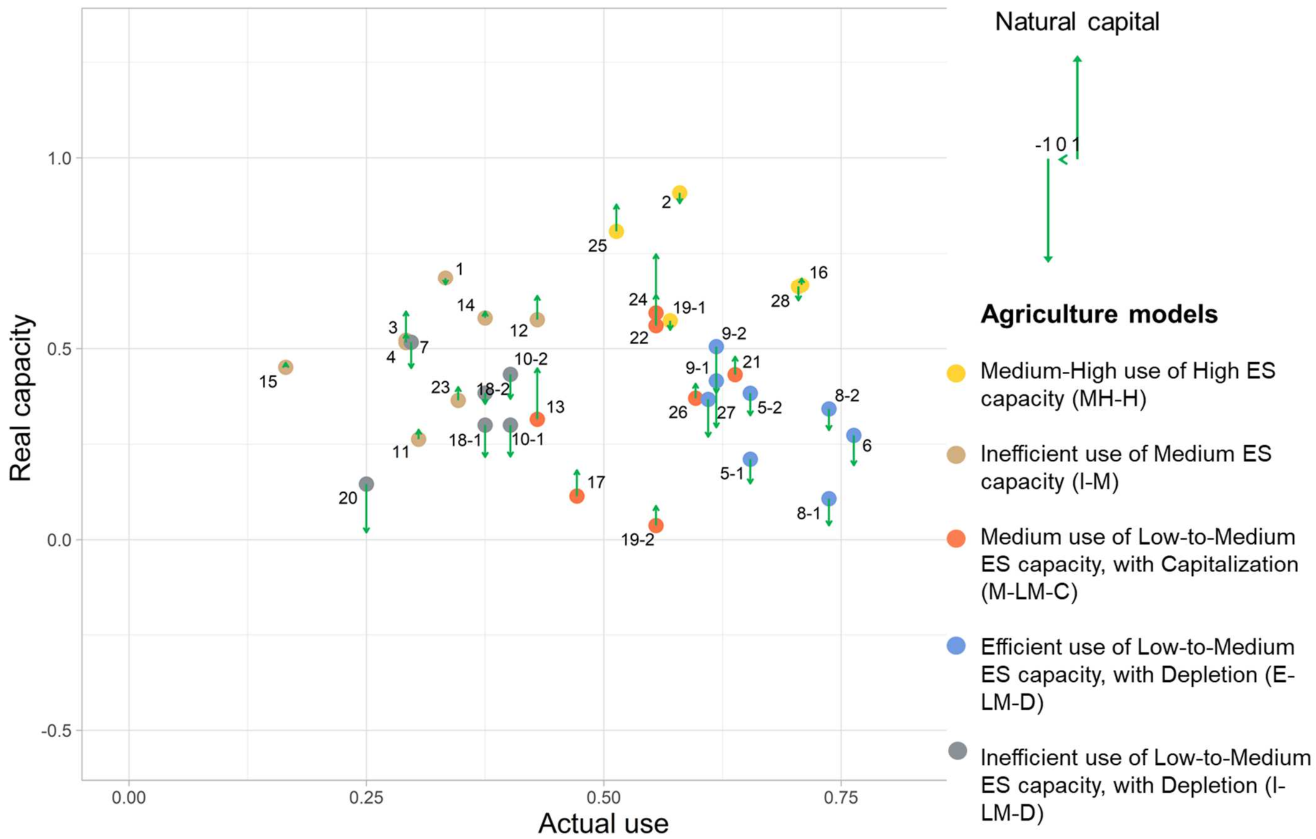

Figure 5. Five clusters of agriculture models identified by k-means clustering according to (i) the ecosystem's real capacity *to provide ecosystem services that contribute to agricultural production (ES), (ii) actual use of ES by farmers and (iii) direction and intensity of* natural capital *dynamics for 34 agroecosystems on 28 farms in the Grand Est region (NUTS2) of France.*