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Development and spatialization of a soil potential multifunctionality index for agriculture (Agri-SPMI) at the regional scale. Case study in the Occitanie region (France)

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A R T I C L E I N F O

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A B S T R A C T

Europe is faced to a competing demand for areas suitable for agriculture and areas suitable for urban development. To help building the general guidelines necessary for a sustainable development at the regional scale, we developed a soil potential multifunctionality index for agriculture (Agri-SPMI), which used the concepts of soil-based ecosystem services and soil functions. It considered the provision of a physical and chemical habitat for plant growth functions, the retention and transfer of water and pollutants function, and the carbon storage function. Three agricultural land uses were considered in this index: arable lands, perennial crops, and pastures. The assessment of the Agri-SPMI was done over a large territory, using a small set of inherent soil properties available in the French soil survey database at 1:250,000 scale. The output was in the form of two maps, which can be viewed in a GIS software: a map of areas with high Agri-SPMI and a map of the service of food, biomass, and fiber production. The concept of soil multifunctionality allowed highlighting environmental issues related to agriculture and to encourage land planners to take them into account in addition to the agronomic potential of soils. The framework used is fully transferable to other scales, other soil contexts, or other ecosystem services, with adaptation of the soil properties considered.

Abbreviations

Agri-SPMI	soil potential multifunctionality index for agriculture
SMU	soil mapping unit
STU	soil typological unit

1. Introduction

In Europe, urban sprawl occurs mainly to the detriment of agricultural areas (European Environment Agency, 2019). Artificialization tends to irreversibly modify soil properties (Cornu et al., 2021) so that some of these soils are definitively lost for agriculture. However, after the recent crises, a growing awareness for food security and food self-sufficiency is being felt (Moragues-Faus, 2020), together with an increased consciousness that soil plays a critical role for several environmental services (Montanarella, 2015; Keesstra et al., 2016). It is therefore necessary to identify which soils should be protected from artificialization to ensure food security and food self-sufficiency of a region on the long-term, while minimizing the negative impact of agricultural activities on the environment and optimizing the role of soils in carbon sequestration.

Mapping soil functions and the associated soil-related ecosystem services, including biomass production and environmental services, is a way to produce this information. Because the term soil function has been employed with different meanings in ecology, soil science or in ecosystem services studies, it has to be defined for our study (Jax, 2005; Baveye et al., 2016; Schwilch et al., 2016; Bünemann et al., 2018). In this paper, we consider that soil functions refer to intrinsic processes occurring in soils irrespective of any human interest. Identifying the most multifunctional soils (Nortcliff, 2002; Greiner et al., 2018; McBratney et al., 2019) would be the first step to preserve them from artificialization. Several interesting frameworks, able to manage the

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evaluation of soil functions, can be found in the literature: the concepts of soil quality (Karlen et al., 2003), soil health (Doran and Zeiss, 2000; Rinot et al., 2019), and the more recent soil security (McBratney et al., 2019; Murphy and Fogarty, 2019) and soil natural capital (Robinson et al., 2009; Dominati et al., 2010; Hewitt et al., 2015) concepts. Some other studies directly evaluate soil-based ecosystem services (Ellili--Bargaoui et al., 2021; Choquet et al., 2021). Different methods were thus designed to provide synthetic information about soil, by combining physical, chemical, and/or biological soil properties (Karlen et al., 2001). They assumed that it is possible to assess soil functions or ecosystem services through information-bearing properties called indicators.

Defining objectives, and particularly the spatial and time scales of the evaluation is particularly important in the choice of the indicators (Vogel et al., 2019). The inherent soil quality, equivalent to soil capacity in the soil security terminology, is related to the different factors of soil formation and is thus not influenced by land use or management practices (Karlen et al., 2001, 2003; McBratney et al., 2019). Inherent soil quality is used to compare the suitability of soils with each other or to evaluate the suitability of a soil for a specific land use (De la Rosa and Sobral, 2008). It can be part of traditional land evaluations/land capability classifications, often dedicated to the evaluation of the productivity potential of soils (e.g., Storie, 1933; Agronomic Interpretations Working Group 1995; Sanchez et al., 2003; De la Rosa et al., 2004). Studies that address inherent soil quality taking into account some other soil functions are rarer (e.g., Greiner et al., 2018; Vogel et al., 2019). Conversely, dynamic soil quality, also referred to as soil condition in the soil security framework, reflects changes caused by the current land use and management practices (Karlen et al., 2003), often on a fine scale, typically that of the pedon, up to the field (Norfleet et al., 2003). It allows monitoring the sustainability of a land use, the processes observed being reversible in the short term, for example when the effects of agroecological practices have to be monitored. These two types of quality, although evaluated with distinct objectives and scales, are nonetheless closely linked. The range of variation of the indicators of dynamic soil quality depends on its intrinsic quality (Norfleet et al., 2003), so that inherent and dynamic indicators are often mixed in these kinds of studies. While some methods use physical, chemical, and biological indicators (Greiner et al., 2018; Andrés-Abellán et al., 2019; Debeljak et al., 2019; Thoumazeau et al., 2019), others include only one of these types of indicators. This is particularly the case in the field of biology (e.g., Aravindh et al., 2020; Chaer et al., 2009; Parisi et al., 2005), because microbiological and biochemical indicators are considered to be very sensitive to variations of the environmental conditions (Franzluebbers et al., 1995). These methods, often at the forefront of advances in the scientific field under consideration, require a high degree of expertise, since reference data are not always available (Gil-Sotres et al., 2005).

In this study, we aimed at quantifying and mapping information on soil multifunctionality at the regional scale. Therefore, the method used had to respect the following general principles: (i) The suitability of soils for agricultural land uses has to be assessed, and not the current soil condition. Only indicators corresponding to inherent soil properties (in the soil quality terminology) or capacity attributes (in the soil security terminology) have to be used. Dynamic soil properties or condition attributes cannot be considered (e.g., organic matter content, topsoil pH, etc.). (ii) Since maps must be produced at the regional scale, no additional soil sampling will be possible. Indicators must be directly available in soil databases or through pedotransfer functions. (iii) The combination of the different indicators must be compatible with a cartographic rendering and should represent a potential soil multifunctionality. To do this, we used an unpublished framework that we previously developed (Robert et al., 2012). This framework, that we will describe in detail, provides a set of rules to link soil indicators to soil functions, and soil multifunctionality. Therefore, using this framework for our local concerns and spatial scale required defining the land uses, soil-based ecosystem services and soil functions of interest, to select relevant soil indicators, and to define their thresholds. We evaluated the potential multifunctionality of soils under three agricultural land uses (arable lands, perennial crops and, pastures), by using input data available in the French soil survey database. The application was done in the Occitanie region (southwest of France), where several agricultural, environmental and territorial development state agencies were interested in having maps synthetizing the potential of soils for agriculture. The target users were therefore people with knowledge of environmental science or agronomy, but not necessarily specialists in soil science, able to read a map under GIS.

2. Material and methods

2.1. Framework of the evaluation

As in many evaluations, we used the conceptual approach linking soil properties to soil functions and ecosystem services, as described in Dominati et al. (2010). Ecosystem services are defined as the benefits that human populations obtain from ecosystems (Millenium Ecosystem Assessment 2005). A soil-based ecosystem service can thus be seen as a couple between a soil function and the land use that we want it to render. The question to be answered was: which soils should be protected from artificialization to ensure food security and food self-sufficiency of a region on the long-term, while minimizing the negative impact of agricultural activities on the environment and optimizing the role of soils in carbon sequestration? Therefore, the assessment was based on three soil-based ecosystem services, selected as three current agronomic and environmental concerns of land planners which can be addressed at the regional scale: (i) food, biomass, and fiber production, (ii) flood regulation and surface and groundwater quality, and (iii) climate regulation. They can be related to the ecosystem services of the CICES v.5.1 nomenclature (Haines-Young and Potschin, 2018) as presented in Table 1. Soil-based ecosystem services were characterized by aggregating soil functions for a given land use. The service of food, biomass, and fiber production was the aggregation of two soil functions, whereas the last two services were characterized by a single soil function (Table 1). The definitions of our four soil functions are given in Table 1. To answer the question tackled in this article, the land uses considered were only agricultural land uses, compatible with the targeted soil-based ecosystem services: arable lands (ARA), perennial crops (PER), and pastures (PAS).

In the framework used, the link between soil properties and soil functions was expressed as follows: Let F_i be the i-th soil function used to assess soil potential multifunctionality. I_{ij} is the j-th soil indicator which represents a soil property considered as relevant for evaluating the F_i soil function. For a given location x, $A_{ij}(x)$, the adequation of indicator I_{ij} regarding F_i is set to 'True' if the value of I_{ij} at x is included in the restricted domain of values of I_{ij} compatible with F_i. The acceptable range of I_{ij} needs to be land use-specific (Bünemann et al., 2018). For a given land use k, this acceptable range is defined by one or several inequalities considering fixed thresholds T_{ijk}. The function F_{ik} is considered as satisfied at location x ($A_{ik}(x)$ = 'True'), if all $A_{ijk}(x)$ are 'True'. The soil potential multifunctionality index for agriculture Agri-SMPI(x) is finally calculated as the count of F_{ik} set as 'True' across land uses.

In other words, following this framework, a given soil can perform up to four soil functions. Given a land use, a function is fulfilled if the values of all indicators are inside their acceptable range of values. If there is at least one indicator in non-adequacy, it is considered as a limiting factor for the land use. The greater the number of soil functions fulfilled, the better the suitability of the soil for the land use. By summing the numbers of fulfilled soil functions for the three land uses, we obtain a score for the soil potential multifunctionality. A soil unit can get a maximum score of 12 (4 soil functions × 3 land uses). A high score means that the soil can fulfill many soil functions for many different land uses, i.e., non-demanding (pastures) and very demanding land uses (arable lands). This soil potential multifunctionality index for

Table 1
Soil-based ecosystem services and soil functions considered in the soil potential multifunctionality index for agriculture.

Soil-based ecosystem service	CICES v.5.1 section / division / group (Haines-Young and Potschin, 2018)	Soil function (and code)	Soil function definition
Food, biomass, and fiber production	Provisioning / Biomass / Cultivated terrestrial plants for nutrition, materials or energy	Provision of a physical habitat for plant growth (PHYS)	Capacity of a soil to provide a physical environment suitable for plant growth, in particular by providing water, aeration, and space for root development
Food, biomass, and fiber production	Provisioning / Biomass / Cultivated terrestrial plants for nutrition, materials or energy	Provision of a chemical habitat for plant growth (CHEM)	Capacity of a soil to provide a chemical environment suitable for plant growth, in particular by storing nutrients in a bioavailable form
Flood regulation and surface and groundwater quality	Regulation and maintenance / Regulation of physical, chemical, biological conditions / Regulation of baseline flows and extreme events	Retention and transfer of water and pollutants (WATER)	Capacity of a soil to limit flooding and rapid drainage phenomena, thus limiting the transfer of potentially harmful compounds to surface water and groundwater
Climate regulation (through carbon sequestration)	Regulation and maintenance / Regulation of physical, chemical, biological conditions / Atmospheric composition and conditions	Carbon storage (CARB)	Capacity of a soil to reduce the negative impact of increased greenhouse gas emissions on climate through carbon storage (Van de Broek et al., 2019)

agriculture, referred to as Agri-SPMI in the following, can be used for the preservation of agricultural soils of good quality, by identifying the most multifunctional ones under agricultural land uses. An intermediate output can also be given for each of the three land uses and three ecosystem services, in the form of a number of fulfilled functions.

2.2. Case study area

The area chosen as a case study is an administrative region of southwestern France, called Occitanie (Fig. 1). It is the third largest region in France with approximately 73,000 km^2. The area can be divided into four main geographic entities (Fig. 1). Massif Central corresponds to an eroded crystalline basement, forming low to medium mountains. The highest point is at 1,699 m. Large limestone plateaus, called Causses, and high volcanic and granite plateaus can also be found. A large proportion of the area corresponds to forests and pastures. Climate is a mountain climate (Joly et al., 2021). To the south of the region, we find the Pyrenees, a mountain range formed during the Eocene. The relief is marked by deep valleys and high peaks, the highest point being at 3,298 m. The soil parent materials correspond mainly to gneisses, schists, granitoids, and limestones. Land cover is made of forests, natural grasslands, and bare rocks. Mountain climate is observed (Joly et al., 2021). The Aquitaine basin is a sedimentary basin. It is a hilly region where the soil parent material is called molasse, a very heterogeneous carbonate sedimentary rock, accumulated during the erosion of the Pyrenees. Some wide valleys, with large fluvial terraces, cross the basin. The Aquitaine basin is largely devoted to agriculture, especially to field crops. Climate is oceanic, with Mediterranean influence (Joly et al., 2021). In the form of an arch at the foot of Massif Central and Pyrenees, we find the Mediterranean coast. It is a succession of hills and plains, with soils mainly developed from limestones and quaternary alluvial deposits, respectively. Plains and some hills are highly cultivated as vineyards. Smallest areas of irrigated fruit and vegetable production and field crops can also be found. The rest of the hills have a garrigue vegetation. The shore is made of sandy soils and large ponds. Climate is Mediterranean (Joly et al., 2021).

2.3. Input data

Soil input data were extracted from the French soil survey database at 1:250,000 scale, the harmonized “Référentiel Régional Pédologique” of the Occitanie region (Laffond et al., 2021), without the Aveyron department which was not covered yet by a soil map. To date, it is the only information on soils that covers a regional surface, over almost all of France. Soil Mapping Units (SMU) are represented as polygons in a graphic layer (Fig. 2). SMU correspond to pedolandscapes and were delineated by the soil survey authors by combining topographic, geomorphological, hydrological, geological, pedological, and land use information. An SMU consists of one or more soil types referred to as Soil Typological Units (STU) (Fig. 2). Unlike SMU, STU are not delineated at this scale, but their percentage of area in the SMU can be found in the associated database. The variation of each STU in their vertical dimension is represented by one or more soil horizons. Their thicknesses are not fixed, but correspond to the observations made during the soil survey. Soil horizons are characterized in the database by physicochemical analyses and visual observations.

2.4. Indicator selection

The set of soil properties selected as good indicators for each soil function and their acceptable ranges for a given land use are shown in the *adequacy table* (Table 2). These indicators are simple soil properties or combinations of soil properties calculated through pedotransfer functions. Their definition and method of calculation will be described in details in this section. Only inherent soil properties were selected as indicators. As in Hewitt et al. (2015), we focused our index on soil, so that non-soil limiting factors were not considered. We also avoided introducing highly correlated indicators inside individual soil functions (Spearman correlation coefficients). On the contrary, a duplicate indicator was not considered problematic across the entire Agri-SPMI, because it could be powerful enough to assess distinct soil functions.

Thresholds for these indicators were defined according to our local expertise, literature, or from the statistical distribution of the data if few reference data were available (Table 2). Arable land (ARA) is the most demanding land use in terms of soil properties. Thresholds for perennial crops (PER) were chosen close to ARA, but we considered the fact that they require less mechanized operations and that the roots of perennial crops can get their resources more deeply than ARA (Table 2). Regarding pastures (PAS), the species and varieties can be chosen and adapted to less favorable soil conditions than ARA. The thresholds are therefore much less restrictive than for ARA (Table 2). PAS also requires less mechanized operations than ARA, soil surface is covered all year long, and PAS is known to store large amount of carbon (Jobbagy and Jackson, 2000).

The calculation depth of each indicator is given in Table 2. It is the maximum depth taken into account to calculate an indicator value over the different soil horizons of a given STU. In order to take into account the link of some of these indicators with plant roots, the calculation was done from 0 to 100 cm, or down to a discontinuity preventing root penetration or water percolation, or down to the bedrock if they appeared before. The same maximum calculation depth was used in Greiner et al. (2018), Calzolari et al. (2016). In our framework, we chose to only consider inherent soil properties to calculate a potential for soil

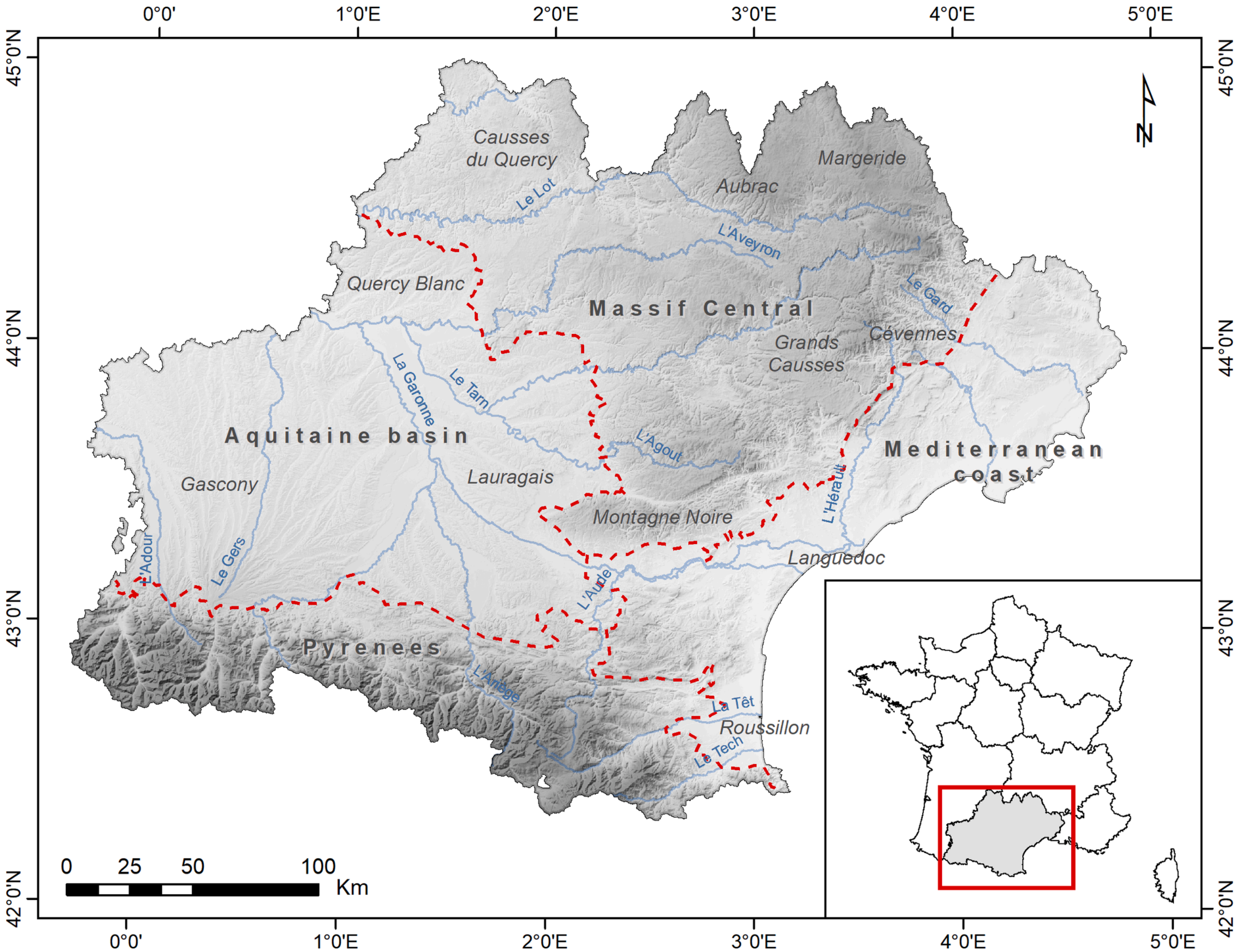

Fig. 1. Localization of the Occitanie region in France and its four main geographic entities: Massif Central, Pyrenees, Aquitaine basin, and Mediterranean coast. Basemap: Digital Elevation Model SRTM 90 m.

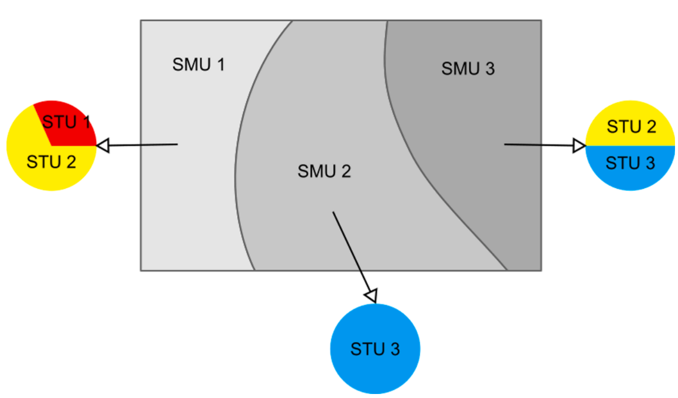

Fig. 2. Representation of three Soil Mapping Units (SMU) in a soil map, composed of different Soil Typological Units (STU) in the associated database. Each circle slice is proportional to the percent area of each STU within the SMU.

multifunctionality. Therefore, when indicators were considered to be affected by land use and management practices in the topsoil (dynamic soil properties), the first horizon was removed from the calculation. It was the case for some chemical soil indicators (i.e., pH_{water} and cation exchange capacity through the effect of the organic matter content, which can be easily changed by agricultural practices). However, for soils with only one horizon before the bedrock, the first horizon was used in the assessment.

2.4.1. *Provision of a physical habitat for plant growth function*

In this function, soil is seen as a physical habitat for various plant species, allowing them to ensure their biological activity. This function is linked to the long process of soil formation, which led to specific arrangements of voids and particles to finally provide water, aeration, and space for root development. In the context of agricultural production, farmers also intervene in the modification of soil structure to prepare soil for sowing. Therefore, the suitability for agricultural mechanization is also considered an important aspect of this function. It has to be noted that the provision of a physical habitat for plant growth function is one aspect of the “biomass production”, “agricultural production” or “primary productivity” functions that can be found in the literature (Greiner et al., 2018; Vogel et al., 2019; Sandén et al., 2019).

Available water capacity: It refers to the maximum amount of water that a soil can store and provide to plant roots (Veihmeyer and Hendrickson, 1927). Because this property considers the thickness of soil that can be prospected by roots, it was also used in the Agri-SPMI to characterize the space available for root development. The available water capacity of a STU was calculated according to Eq. (1):

Table 2
Indicators used to assess four soil functions and the ranges of values required to have adequacy between indicators and land uses: *adequacy table* (calculation depth: maximum depth taken into account to calculate an indicator value over the different soil horizons of a given soil unit, Reference: reference used to define adequacy for a given land use, ARA: arable lands, PER: perennial crops, PAS: pastures, RF: rock fragment content).

Functions and indicators	ARA	PER	PAS	Calculation depth	Reference
Provision of a physical habitat for plant growth function					
Available water capacity (mm)	> 60	> 60	> 40	100 cm*	Local expertise
Waterlogging	No mottling or Redoximorphic features > 80 cm depth	No mottling or Redoximorphic features > 40 cm depth	Not relevant	100 cm*	Local expertise and GEPPA (1981)
Topsoil texture (%)	Sand < 45 and Clay < 45	Sand < 45 and Clay < 45	Not relevant	30 cm*	Local expertise
Slope (%)	< 15	< 30	< 30	–	GEPPA (1981), Sanchez et al. (2003)
Rock fragment content in topsoil (%)	< 30	< 45	< 60	30 cm*	Local expertise
Provision of a chemical habitat for plant growth function					
Cation exchange capacity ($cmol^+.kg^{-1}$)	> 4	> 4	> 2	100 cm* without topsoil	Local expertise
Rock fragment content in soil profile (%)	< 30	< 45	< 60	100 cm*	Local expertise
pH_{water}	5.5–7.5	5–8.5	5–8.5	100 cm** without topsoil	Vrščaj et al. (2008), Sparks (2003)
Salinity ($mS.cm^{-1}$)	< 4	< 4	< 8	100 cm*	Richards (1984)
Retention and transfer of water and pollutants function					
Available water capacity (mm)	> 60	> 60	> 40	100 cm*	Local expertise
Water runoff (class)	< class 3	< class 3	Not relevant	Topsoil	Local expertise
Water percolation	Sand < 75%, RF < 80%, soil depth > 35 cm, no Fluvisol, no recent alluvial deposits	Sand < 75%, RF < 80%, soil depth > 35 cm, no Fluvisol, no recent alluvial deposits	Not relevant	100 cm***	Local expertise
Carbon storage function					
Carbon saturation potential	2nd quintile of the statistical distribution	2nd quintile of the statistical distribution	Not relevant	100 cm*	Statistical distribution in the study area

* or down to a discontinuity preventing root penetration or water percolation, or down to the bedrock if they appear before.
** or down to a discontinuity preventing root penetration or water percolation, or down to the parent material or bedrock if they appear before.
*** or down to a discontinuity preventing water percolation, or down to a hard bedrock if they appear before.

$$AWC_{STU,i} = \sum_{i=1}^{n} \left(\theta_{FC,STU,i} - \theta_{PWP,STU,i}\right) \times h_{STU,i} \times \left(1 - \frac{RF_{STU,i}}{100}\right) \quad (1)$$

With AWC: available water capacity (mm); θ_{FC}: volumetric water content at field capacity ($cm^3.cm^{-3}$); θ_{PWP}: volumetric water content at permanent wilting point ($cm^3.cm^{-3}$); *h*: horizon thickness (mm); RF: volumetric fraction of rock fragments > 2 mm (%); *n*: total number of horizons in a given STU; *i*: horizon.

Pedotransfer functions developed by Román Dobarco et al. (2019) for France were then used to estimate θ_{FC} and θ_{PWP} Eqs. (2) to ((4)). Following Román Dobarco et al. (2019), the value of pF = 2.0 was retained for the field capacity and pF = 4.2 for the permanent wilting point. Román Dobarco et al. (2019) offer several pedotransfer functions, depending on the available data. We chose not to include soil organic carbon content, because it is a dynamic soil property. Bulk density was not considered because this variable is rarely present in the soil database.

$$\text{For topsoils}: \theta_{FC,STU,i} = 0.269 + 0.00292 C_{STU,i} - 0.00117 S_{STU,i} \quad (2)$$

$$\text{For subsoils}: \theta_{FC,STU,i} = 0.276 + 0.00246 C_{STU,i} - 0.00142 S_{STU,i} \quad (3)$$

$$\text{For all horizons}: \theta_{PWP,STU,i} = 0.08 + 0.00401 C_{STU,i} - 0.000293 S_{STU,i} \quad (4)$$

With *C*: clay content (%) and *S*: sand content (%).

The AWC of peat or very organic soils (e.g., Histosols and Umbrisols in the WRB classification (IUSS Working Group WRB 2015)), for which it is not certain that the pedotransfer functions of Román Dobarco et al. (2019) are valid, was considered as not constraining for every land use. Thresholds were established through local expertise: available water capacity was considered to be a limiting factor below 60 mm for ARA and PER, PAS was considered as less demanding (Table 2).

Waterlogging: Prolonged waterlogging limits oxygen diffusion into the soil with possible detrimental effects on plants. The presence and abundance of redoximorphic and reductimorphic colors were used to characterize waterlogging. When spots cover more than 15% of the soil volume, they were considered to be representative of hydromorphic features as encoded in the soil database. Histosols were considered to be waterlogged. Transient subsurface waterlogging or permanent waterlogging was considered to be a limiting factor for ARA (Table 2). PER can adapt to limited water excess through the choice of rootstocks. Waterlogging was not constraining for PAS (Table 2).

Topsoil texture: A clayey texture in the topsoil leads to difficult tillage operations, waterlogging during rainfall episodes, and to the creation of cracks on soil surface during periods of drought. It can also be an obstacle to root penetration. A sandy texture leads to rapid drainage, so that these soils are sensitive to drought. An unfavorable soil texture was defined in the Agri-SPMI by the presence of a horizon with a sandy texture (sand content ≥ 45% and clay content ≤ 25%) or a clayey texture (clay content ≥ 45%) (Table 2).

Slope: A steep slope constitutes a heavy constraint to prepare soil for sowing with agricultural machinery. Mechanization constraints appear between 15 and 30% slopes, so that adapted equipment and techniques are required (GEPPA, 1981). The average slope of each SMU was calculated from a Digital Elevation Model with a pixel size of 25 m (BD ALTI v.2, IGN).

Rock fragment content in topsoil: An excessive rock fragment content on soil surface can also constitute a constraint to mechanization and installation of seedlings. The average rock fragment content weighted by the thickness of each horizon was calculated down to 30 cm. A rock fragment content ≥ 30% in topsoil was considered as a constraint to mechanization for ARA, following Sanchez et al. (2003). We chose higher thresholds for PER and PAS because they require less mechanized operations than ARA.

2.4.2. Provision of a chemical habitat for plant growth function

This function is also linked to the long process of soil formation, which led to specific chemical environments in soils and an ability to store nutrients in a bioavailable form for plant growth. As in the physical habitat for plant growth function, in this function, we limited the indicators to those able to characterize the chemical habitat for field crops. This function is also part of the "biomass production", "agricultural production", "primary productivity", or "nutrient cycling" functions that can be found in the literature (Greiner et al., 2018; Vogel et al., 2019; Sandén et al., 2019).

Cation exchange capacity (CEC): CEC reflects the potential of soil for the retention of cations, including some nutrients. The average CEC weighted by the thickness of each horizon was calculated. Thresholds of Table 2 were defined from local expertise.

Rock fragment content in soil profile: A large rock fragment content limits the quantity of fine earth, which contains the available nutrients. The indicator selected was the average rock fragment content weighted by the horizon thickness. A rock fragment content $\geq$ 30% was considered as an important constraint in the chemical habitat for plant growth function for ARA. The rock fragment content may be higher for PER, because the roots of perennial crops can get their resources deeper than ARA.

pH_{water}: pH was chosen to represent nutrient availability, essential for the growth of cultivated plants and soil microorganisms. For a given SMU, the most unfavorable pH_{water} along the soil profile was used in the Agri-SPMI calculation. For most cultivated plant species, the agronomic optimum is between 6.5 and 7.5 (Sparks, 2003). Below 5, there is a risk of aluminum toxicity for certain crops.

Salinity: The value used in the Agri-SPMI was the most unfavorable salinity value over the calculation depth. Crops are more or less tolerant to soil salinity. Yields of sensitive crops may be restricted between 2 and 4 $mS.cm^{-1}$ and yields of many crops are restricted above 4 $mS.cm^{-1}$ (Richards, 1984).

2.4.3. Retention and transfer of water and pollutants function

The retention and transfer of water and pollutants function has to take into account several processes: (i) water storage, (ii) water runoff, and (iii) water percolation (Wall et al., 2020). A high water storage limits runoff induced by a rapid soil saturation, thus limiting floods, and limits the rapid transport to groundwater. On the contrary, when runoff and percolation are high, the transport of sediments and potentially polluting substances for surface water and groundwater is also high and the soil's capacity to preserve water quality is low.

Available water capacity: calculated as previously described (Eq. (1)).

Water runoff: Large water runoff increases the risk of flooding and pollution of surface water by sediments and their associated compounds, such as phosphorus. A water runoff potential is therefore estimated by the combination of two indicators: soil crusting and clay content of surface horizons. Soil crusting decreases the hydraulic conductivity of the soil surface and therefore reduces rainfall infiltration, promoting Hortonian flow and soil erosion (Bradford et al., 1987). In the same way, high clay contents in surface horizons were supposed to limit water infiltration.

The water runoff potential was assessed by adapting the method developed by Antoni et al. (2006), originally designed to estimate soil crusting on the same database than that used in the present study, in the eastern part of the Occitanie region. A water runoff potential class was estimated from a decision tree combining rock fragment content and topsoil texture (Fig. 3). We modified the original tree by adding a criterion on the slope: when slope is near flat (< 5%), a class of 1 is automatically assigned to the soil, which means a low water runoff potential. The texture triangle (Fig. 3b) proposed by Antoni et al. (2006)

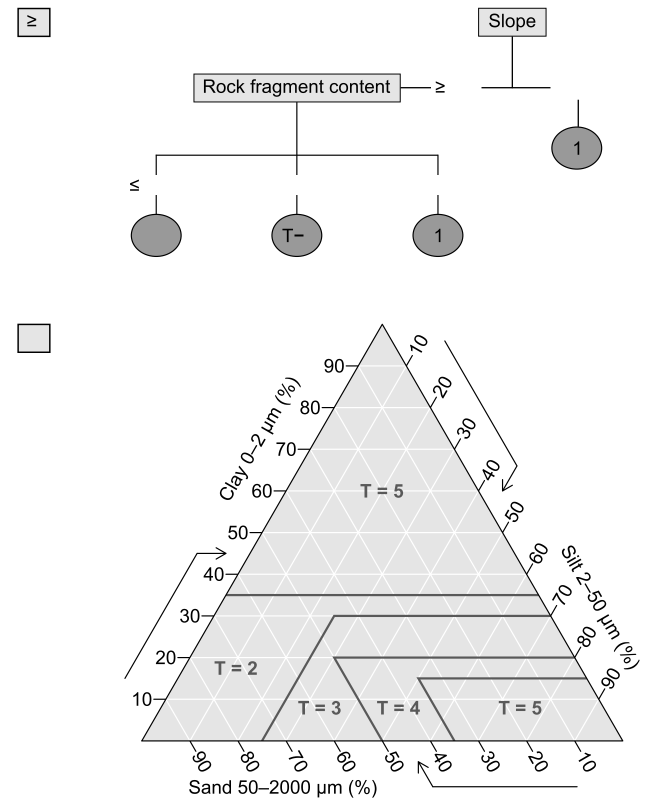

Fig. 3. (a) Decision tree for estimating the water runoff potential class from information on slope, rock fragment content, and soil texture of the first horizon. T: class of sensitivity to water runoff linked to the soil texture, resulting from the texture triangle in (b). The higher T, the stronger the sensitivity to water runoff.

was also modified to build our water runoff indicator, taking into account the effect of clay content $\geq$ 35%.

Water percolation: Rapid water drainage is seen to be detrimental to the preservation of groundwater quality as polluting substances may be applied to crops. Excessive drainage was defined here by a sandy texture (sand content $\geq$ 75% and clay content $\leq$ 12.5%) for each horizon of a given STU or by a rock fragment content $\geq$ 80% for all these horizons, or by any combination of these two conditions, or by a soil thickness $\leq$ 35 cm (Table 2). Fluvisols (WRB classification) and soils developed from recent alluvial deposits also lead to rapid water transfers because of their connection to the water table (Table 2).

2.4.4. Carbon storage function

This function is defined as the capacity of a soil to reduce the negative impact of increased greenhouse gas emissions on climate through carbon storage (Van de Broek et al., 2019). Carbon storage is the increase in soil organic carbon stocks over time in soil (Chenu et al., 2019).

Several dynamic and inherent soil properties control soil organic carbon storage (Wiesmeier et al., 2019). As reviewed by Wiesmeier et al. (2019), the silt + clay indicator, an inherent soil property, could be an effective indicator for this function. Indeed, Hassink (1997) suggested that there is a maximum capacity for the physical protection of organic carbon in soil. The fine mineral fraction, composed of granulometric clays and silts, seems to play a major role in this protection. Hassink (1997) established a linear relationship between the content of mineral particles of size $\leq$ 20 μm and the amount of carbon associated with this fraction in the surface horizon of agricultural soils. Six et al. (2002) extended this analysis to two size boundaries for silt + clay (i.e., 20 and 50 μm), to cultivated soils, grasslands and forests, and to different clay types (i.e., 1/1 or 2/1). These relationships were used as an indicator of the potential carbon saturation of silt and clay particles in soils (Choquet et al., 2021; Vogel et al., 2019; Angers et al., 2011; Chen et al., 2018; Wiesmeier et al., 2014). In order to assess whether soils are capable of protecting a large amount of carbon in the long term, we used the equation proposed by Six et al. (2002) for cultivated soils (eq. (5)). The size limit of the silt + clay indicator was chosen to be 50 μm, because it is the only data available in traditional soil surveys in France. We chose to fix the land use of this equation, to carry out a relative assessment of the territory. Indeed, we did not try to quantify the amount of carbon that could be stored for the current land use, but rather to rank soils according to a carbon storage potential, all other things being equal.

$$C_{sat} = 7.18 + 0.2 \times (\text{silt} + \text{clay}) \tag{5}$$

With C_{sat}: carbon saturation potential (g silt + clay C.kg^{-1} soil) and silt + clay: proportion of particles $\leq$ 50 μm (%).

We also chose to communicate on the importance of preserving deep soils, which have a high carbon storage potential. Indeed, carbon storage in the subsoil is one lever for the carbon sequestration service (Chenu et al., 2019). The potential stock of carbon associated to the physical protection of silt and clay was thus calculated according to eq. (6), considering that carbon can be stored down to 100 cm or down to a discontinuity preventing root penetration.

$$C_{stock,STU} = \sum_{i=1}^{n} C_{sat,STU,i} \times \rho_{silt+clay} \times h_{STU,i} \times \left(1 - \frac{RF_{STU,i}}{100}\right) \tag{6}$$

With C_{stock}: potential stock of carbon associated to the physical protection of silt and clay (kg.m^{-2}); $\rho_{silt+clay}$: bulk density of the silt + clay fraction (g.cm^{-3}); h: horizon thickness (dm); RF: volumetric fraction of rock fragments > 2 mm (%); n: total number of horizons in a given STU; i: horizon.

The bulk density of the silt + clay fraction was fixed to 1.60 g.cm^{-3}, considering that it was the only fraction that interested us in the inherent soil properties approach. This value corresponds to the average standardized bulk density defined by Ruehlmann and Körschens (2009), that is to say the average theoretical bulk density for a mineral soil without organic matter.

Agriculture often leads to exports of organic matter not compensated by inputs. Therefore, the potential stock of carbon associated to the physical protection of silt and clay must be high for ARA and PER to fulfill the carbon storage function. In the absence of data available in the literature, the thresholds for determining adequacy were based on the quintiles of C_{stock}, weighted by the STU area. If a STU was classified as a peat or very organic soil, its capacity to store carbon was automatically considered to be good.

2.5. Spatializing the soil potential multifunctionality index for agriculture

Agri-SPMI estimations were performed for each STU of the database. For the map representation, only one value could be assigned to each SMU polygon. It was chosen to produce a map highlighting soils with the best Agri-SPMI. A class of percentage surface area with soils of high SMPI ($\geq$ 8/12) was represented in the map: $\geq$ 75% of soils with a high Agri-SPMI, and between 50 and 75% of soils with a high Agri-SPMI. An intermediate map was also produced, as the number of fulfilled functions for the food, biomass, and fiber production service, expressed out of a total of 6 possible functions (PHYS and CHEM functions × 3 land uses). Individual maps for ARA, PER, and PAS land uses were also produced and each expressed out of a total of 4 possible functions (PHYS, CHEM, WATER, and CARB × 1 land use). The dominant modality was represented. It is the number of fulfilled functions representing the largest area in the SMU. During the Agri-SPMI development, we consulted four local specialists in land use planning and in agriculture for two contrasted areas of the Occitanie region, to collect comments on these outputs and to adapt the index accordingly.

2.6. Data analyses

We checked the results by comparing the dominant class of food, biomass, and fiber production service (see Section 2.5) to the current land cover, with the hypothesis that the history of land use led to install field crops on soils with the best agronomic potential. The percentage of surface area covered by field crops in each polygon of the soil map was first calculated by combining the OSO 2016, 2017, and 2018 land cover maps (pixel size of 20 m) produced by the CESBIO with the methodology described in Inglada et al. (2017). Urban areas were removed from the calculation. Then, we tested whether the percentage of surface area covered by field crops differed based on the dominant number of fulfilled functions, by using a Kruskal-Wallis test, followed by a Dunn's post hoc test with p-values adjusted using the Bonferroni correction. Because STU are not delineated at this scale, the test was only performed for homogeneous polygons, chosen as those having a dominant class representing more than 50% of their surface area. This test was a way to check if the aggregation rules of the index were satisfying, if the input data at a scale of 1:250,000 were meaningful, and if the users can base their interpretation on the dominant class represented in the map. A redundancy analysis was performed to assess the added value of the multifunctionality concept. This was performed by calculating the percentage of surface area showing different results between pairs of soil functions (i.e., one fulfilled and the other not fulfilled). It was calculated considering every STU, and not only the dominant class. Correlations between indicator classes were assessed by the calculation of Spearman correlation coefficients R.

3. Results

3.1. Comparison with the current land cover

The percentage of surface area covered by field crops for each value of the service of food, biomass, and fiber production is given in Fig. 4. This percentage differed significantly based on the dominant number of fulfilled functions for the food, biomass, and fiber production service ($p < 0.0001$). A threshold is seen between the values 2/6 and 3/6, meaning that field crops are mainly found for scores $\geq$ 3/6 ($p < 0.0001$). The largest median of the percentage of surface area covered by field crops was not found for the highest scores, but for 4/6 and 3/6 values (Fig. 4). This can be explained by the fact that the area most cultivated with field crops in Occitanie corresponds to the Aquitaine basin (Fig. 5). These calcareous soils are often downgraded in the provision of a chemical habitat function by their alkaline pH and/or in the provision of a physical habitat function by a parent material at low depth. The highest scores were found in alluvial plains (Fig. 5). Considering the lowest scores for the food, biomass, and fiber production service, some outliers are visible in Fig. 4. It may be explained by the fact that climate and accessibility criteria were not included in the index and by the heterogeneity of soils in some SMU.

68% of the surface with scores between 3/6 and 6/6 for the food, biomass, and fiber production service falls in the agricultural areas delineated in the OSO land cover map. This high value shows that the method was able to capture the history of land use reflected by the current land cover. However, the results of this comparison with the current land use are not optimal because other physical, economic, or social factors influence land use, such as climate, accessibility, availability of irrigation systems, or existence of markets.

3.2. Soil potential multifunctionality index maps

The Agri-SPMI map and intermediate maps of the number of fulfilled functions for the three land uses considered in this study are given in Fig. 6. In Fig. 6a, some patterns could be identified for the different

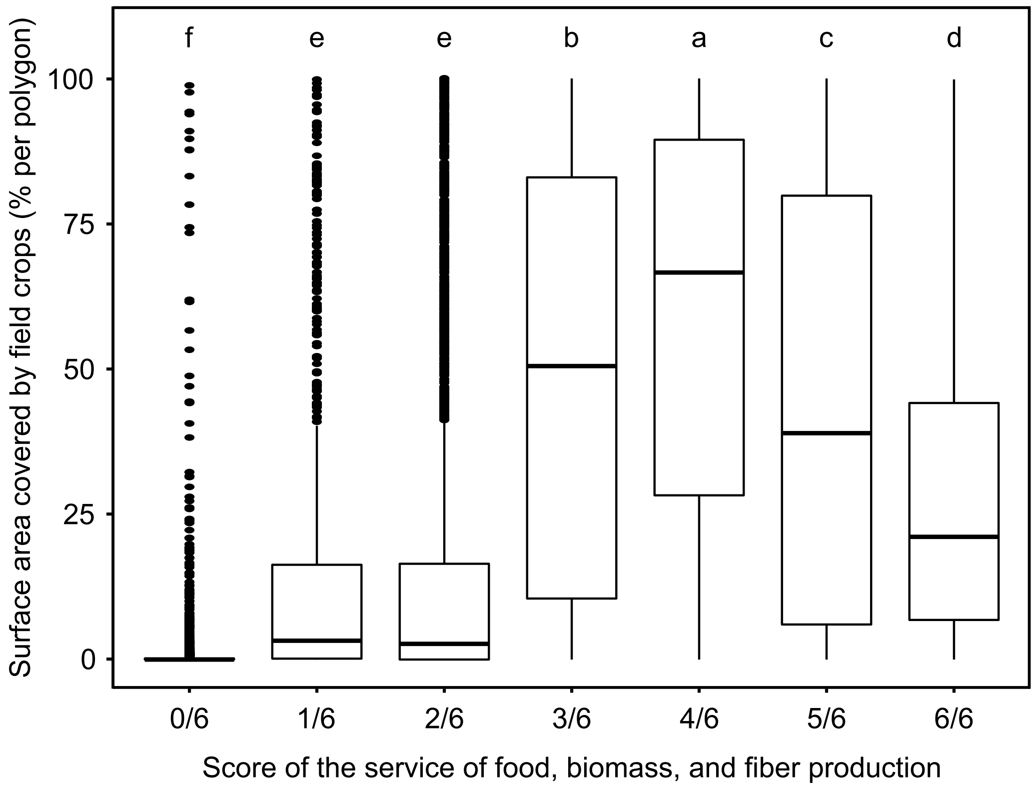

Fig. 4. Boxplot of the surface area covered by field crops (in % per polygon) for each possible value of the service of food, biomass, and fiber production (score out of 6). Different letters above each box indicate significant differences in the multiple comparison test ($p < 0.0001$).

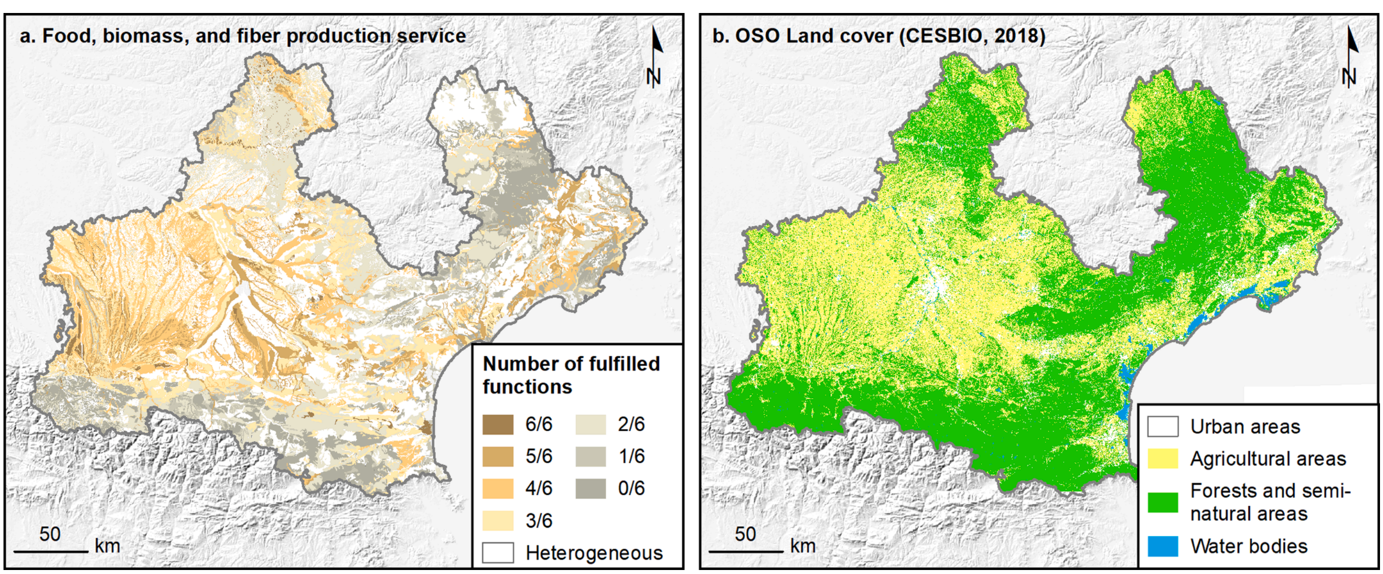

Fig. 5. Comparison of (a) the food, biomass, and fiber production service as a number of fulfilled functions to (b) the OSO land cover (CESBIO, 2018).

pedolandscapes of Occitanie. The most multifunctional soils are mainly developed from molasse in Gascony and Lauragais (see Fig. 1 to locate these geographic entities) and in plains along the Mediterranean coast. Conversely, the least multifunctional soils are shallow soils developed from limestone plateaus in the Causses du Quercy and Grands Causses regions, the highest summits of Pyrenees, mounts of Massif Central (Montagne Noire, Cévennes, Margeride), and some hills of Gascony. These trends make sense, according to our knowledge of the soils of the Occitanie region. However, we recommend studying this type of map with the variability linked to the different STU, by using the attribute table of the GIS layer.

For ARA, only 10% of the surface area get 3 or 4 functions fulfilled (Fig. 6b). This surface increases up to 24% for PER (Fig. 6c) and 53% for PAS (Fig. 6d). This increase is link to decreasing requirements for PER and PAS as compared to ARA in the *adequacy table* (Table 2).

A closer look to Fig. 6a is made by representing the four individual soil functions of arable lands (Fig. 7). They were built by displaying the dominant class in each SMU (function fulfilled vs function not fulfilled). Regarding the delivery of the food, biomass, and fiber production service, an antagonism can be seen on some occasions between the physical

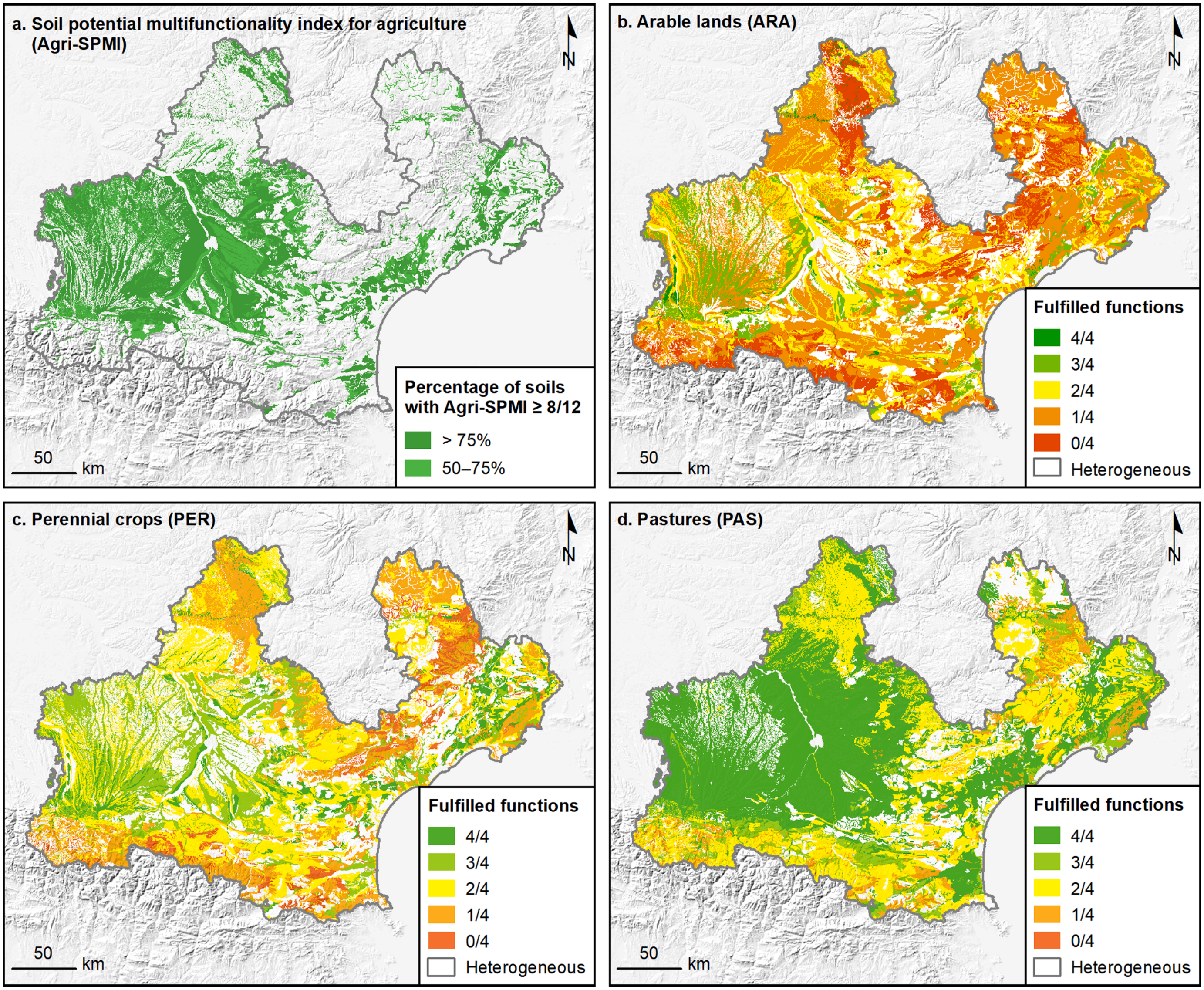

Fig. 6. (a) Soil potential multifunctionality index for agriculture Agri-SPMI and number of fulfilled functions for the three land uses considered in the study: (b) arable lands, (c) perennial crops, and (d) pastures.

(PHYS) and chemical (CHEM) aspect of the habitat for plant growth function (Fig. 7a and b). As an example, CHEM is fulfilled in Gascony while PHYS is not. The opposite can be observed in the Lauragais region. The decomposition of this service between chemical and physical aspects allows identifying limiting factors for agriculture. In Gascony, the limiting factors are a low AWC and a waterlogging on a few occasions. In Lauragais, a high pH is mainly constraining.

The WATER function downgrades soils with shallow bedrock, extremely sandy, clayey and stony soils, and soils susceptible to crusting. These types of soil can be found in several parts of the Occitanie region. In the study area, downgrading is mainly due to clayey soil textures (in soils developed from molasse in Gascony, Lauragais, and Quercy Blanc). Soils with shallow bedrock are found in the Pyrenees, Massif Central, Causses, and in the hills of Gascony. Extremely high sand and rock fragments contents are found at only a few locations in Occitanie.

The CARB function was built using a single indicator, the potential stock of carbon associated to the physical protection of silt and clay, without introducing any reference to the current land use. The soil thickness used for the carbon stock calculation had a high impact on the results: the function was not fulfilled in shallow soils of some parts of the Pyrenees, Massif Central, Causses du Quercy, and Cévennes (Fig. 7). These areas are occupied by 67% forests and semi-natural vegetation (OSO land cover).

3.3. Redundancy analysis

The percentages of surface area showing redundancy between pairs of soil functions (i.e., both fulfilled or both not fulfilled) are given in Table 3. A large proportion of the territory received different results for the different soil functions, the percentage of surface area which was redundant ranging between 31% and 91%, with an average of 59%. The lowest redundancy was found between PHYS and CARB for ARA land use (Table 3, Fig. 7).

These results depended on the land use under consideration. The highest redundancies between soil functions were found for the less demanding land use, PAS, because it was easiest to get fulfilled soil functions for this land use, increasing the chance of having redundancies. They were also found for the most demanding land use, ARA, for which it was easiest to get unfulfilled soil functions.

High redundancy was also found when comparing the provision of a physical habitat for plant growth function (PHYS) to the retention and transfer of water and pollutants function (WATER). Going into the

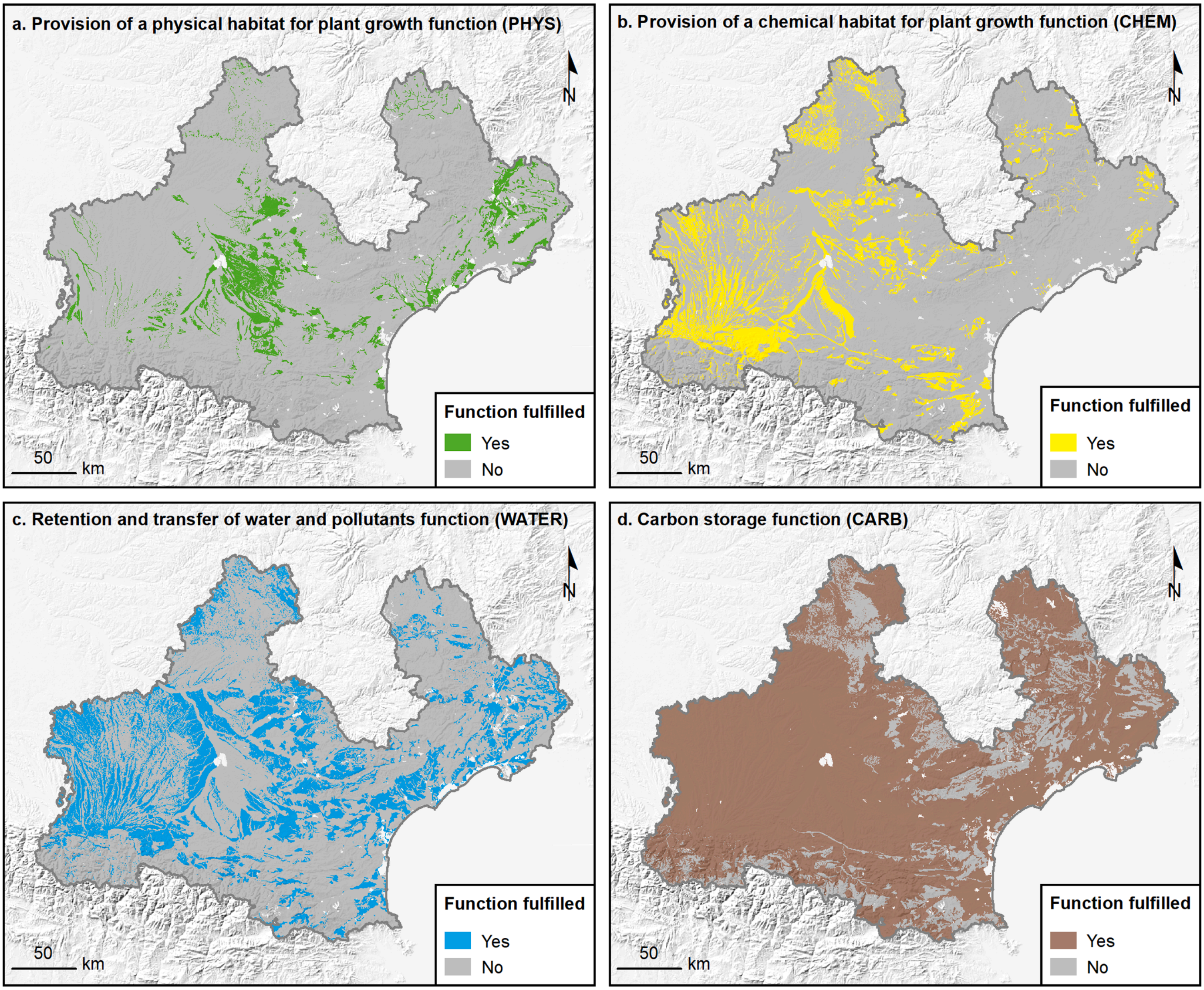

Fig. 7. Evaluation of the four individual soil functions (a) PHYS, (b) CHEM, (c) WATER, and (d) CARB for arable lands (ARA land use).

Table 3
Percentage of surface area showing the same results between pairs of soil functions (both fulfilled or both not fulfilled), for the three land uses considered in this study. PHYS: provision of a physical habitat for plant growth function, CHEM: provision of a chemical habitat for plant growth function, WATER: retention and transfer of water and pollutants function, CARB: carbon storage function.

Arable lands	PHYS	CHEM	WATER	CARB
PHYS				
CHEM	74			
WATER	72	68		
CARB	31	35	49	
Perennial crops	PHYS	CHEM	WATER	CARB
PHYS				
CHEM	48			
WATER	74	44		
CARB	42	72	49	
Pastures	PHYS	CHEM	WATER	CARB
PHYS				
CHEM	63			
WATER	91	64		
CARB	55	77	64	

details, the strongest redundancy was found between PHYS and WATER for the PAS land use. These functions were characterized with a common indicator, the available water capacity, which remained the most restrictive indicator of PHYS and WATER for all land uses, while the other indicators were little or not constraining for PAS (Table 2).

Redundancy was also held by the rock fragment content in topsoil and in the whole soil profile, since these two indicators appeared to be highly correlated ($R = 0.83$, $p < 0.0001$). C_{stock} and AWC were also positively correlated ($R = 0.91$, $p < 0.0001$) because they were both estimated from soil texture and soil thickness. However, the framework used to calculate the Agri-SPMI, using several indicators and the limiting factor concept, led to a low level of redundancy for the PHYS and CARB function, as previously said. No correlation coefficient was found ≥ 0.6 or ≤ -0.6 between indicators of individual soil functions, showing that effort was made to avoid redundancy inside individual soil functions. Inside the PHYS function, the AWC was moderately correlated to the rock fragment content in topsoil ($R = 0.52$, $p < 0.0001$), because the rock fragment content enters into the calculation of the AWC (Eq. (1)).

4. Discussion

4.1. The multifunctionality approach

The Agri-SPMI was designed with an objective of preservation of soils of good quality for agriculture, with additional environmental concerns illustrated by the services of flood regulation and surface and groundwater quality and carbon sequestration. The assessment of soil multifunctionality was done over a large territory, using a small set of spatialized soil properties available in a national database. This vision based on soil multifunctionality is broader than that based on the agronomic potential of soils (e.g., Storie, 1933; Agronomic Interpretations Working Group 1995; Sanchez et al., 2003). It is a way to highlight environmental issues related to agriculture and to encourage land planners to take them into account. We show land planners that very multifunctional soils are not so common and must be protected from artificialization. In studies using also dynamic soil properties, the assessment of soil multifunctionality makes it possible to propose optimization of soil functions considering societal demand, such as done in the Soil Navigator (Debeljak et al., 2019; Zwetsloot et al., 2021). Moreover, the concept of soil multifunctionality allowed to account for the complexity of soils. Indeed, in a redundancy analysis, we showed that a large proportion of the territory received divergent results for the different soil functions. Such a divergence between soil functions has often been found (Greiner et al., 2018; Calzolari et al., 2016; Zwetsloot et al., 2021).

This method projects over the long term, which is compatible with use for regional development plans. As a consequence of the targeted temporal scale, no specific land use was considered, but several agricultural land uses able to produce biomass. The fact that this index considers the long-term may nevertheless cause difficulties of adoption, because of the shorter-term vision of some stakeholders, aiming at an immediate economic profitability. For example, some agricultural products that have been granted protected geographical status may allow immediate profitability without ensuring food security and food self-sufficiency (e.g., wine, walnuts, or garlic in the Occitanie region).

4.2. Cartographic representations of soil multifunctionality for end-users

For the cartographic representation, we delineated soils with the highest multifunctionality to easily communicate the Agri-SPMI results (Fig. 6a). Since all soils perform useful functions for society, we however advise to study soils outside of these areas with suitable methods. Other representations are possible. We submitted a first draft of the Agri-SPMI map to potential end-users in the form of 5 classes, colored from green (high multifunctionality), yellow, to red (low multifunctionality). It followed the example of the Nutri-Score label for nutritional rating (Egnell et al., 2018) or the SEQ-eau index for evaluating surface water quality (Oudin and Maupas, 2003), both officially adopted in France. These indices are both established on a scale of 5 colors, going from green (good), to yellow, then red (bad). We detected reluctance of some end-users because of the presence of red areas for soils that they perceived as suitable for agriculture. Actually, in these areas, soils were not able to produce biomass in the sense of food security (short-term vision of economic profitability) or were not able to do so without affecting the environment.

For the cartographic representation of the food, biomass, and fiber production service, we used the results of the comparison with the current land cover to define the color ramp. Indeed, field crops were mainly found for scores $\geq 3/6$ (Fig. 4). Therefore, gray colors were applied between 0/6 and 2/6, and orange/brown colors were applied from 3/6 to 6/6. Following the methodology used to perform the Kruskal-Wallis test, we also chose to color areas with very heterogeneous results in white (areas with a dominant class representing less than 50% of the surface). The goal was to encourage the users to read the attribute table with their GIS software, rather than interpreting the dominant class too quickly.

Greiner et al. (2018) showed that different methods for aggregating soil functions give very different maps. Aggregated representations are a summary that does not allow decision makers to explore all the richness of the information produced, in particular the scores of individual land uses and individual soil functions shown in Figs. 6b-d and 7. To avoid aggregation and to better visualize synergies and trade-offs (Bennett et al., 2009) between soil functions, other types of data representations have been used, like bar charts (Debeljak et al., 2019) or radar charts (Greiner et al., 2018; Calzolari et al., 2016). They allow reading the score of all soil functions of a given soil at a glance. Of course, this type of representation is best suited to fine scales. Having a less aggregated map than the Agri-SPMI, for the service of food, biomass, and fiber production, was a request from the potential end-users we met. We decided thus to distribute this map and the Agri-SPMI among all possible map outputs. It was thus necessary to discuss the cartographic representations with the future end-users. These maps with aggregated scores are a first step for people who are not expert in soil science or agronomy. For those who want to go further, we decided to also distribute the data for all indicators in tabular form.

4.3. Limitations of the Agri-SPMI

There are known limitations in the use of these maps, linked to the methodology and to the input data, which must be communicated to the end-users. To do so, we produced short videos for users to understand how maps were produced and what are their limitations. We provided a ready-to-use tool in the form of two maps that can be read under GIS software. The downside is that these data cannot be used beyond the specific question asked. Indeed, the evaluation was based on a particular point of view of soil multifunctionality: it assumed an equal preference of users for the ecosystem services considered since no weighting was applied, and the services and land uses taken into account were pre-established. As illustrated by the comparison of methods of Choquet et al. (2021), this kind of evaluation is strongly method-dependent. The method is flexible, but it would be necessary to adapt the soil properties and their thresholds for the Agri-SPMI to meet specific demands, such as the integration of other soil-related ecosystem services. In the same way, using the methodology for another region may require redefining the acceptable range of value of some indicators. This development would require a high degree of expertise and consultation would be necessary to adapt the tool to local priorities. Because the method is flexible, the pedotransfer functions used to calculate some indicators (e.g., available water capacity, carbon storage potential) may also be updated with future research developments.

Choices were also made considering the properties considered. Non-soil properties such as climate, irrigation, and accessibility were not included in the Agri-SPMI. According to Mueller et al. (2010), the soil moisture and thermal regime, which are climate-influenced, are the main constraints to the soil productivity potential on a global scale. Vogel et al. (2019), for example, included the water deficit in their evaluation, calculated from the climatic water balance and the plant available water capacity. However, given that our method projects over the long term, we deliberately did not introduce any reference to climate in the Agri-SPMI, so that these maps could be used for projections on climate change. There is no reference to irrigation potential either, because irrigation cannot be guaranteed in the long term. These non-soil properties together with the existence of markets are responsible for the discrepancies observed in Fig. 5 when comparing the service of food, biomass, and fiber production to the current land cover.

There is a the lack of consensus to quantify a soil biodiversity or activity function and the corresponding data representing large areas are limited (Rutgers et al., 2019). A habitat for biological activity function was not explicitly included in the Agri-SPMI. For the regional scale of our study, we assessed the physical and chemical habitat function for cultivated plants. However, we considered that access to water and nutrients, aeration, and root abundance are suitable conditions for most of the beneficial organisms in agriculture. Consequently, the PHYS and CHEM functions also underlies the biological activity of soils, which is itself favorable to plant growth in our agricultural context. Biodiversity is usually addressed in terms of habitat potential, species diversity and/or rare species (Grêt-Regamey et al., 2017). An interesting discussion of what should be a “habitat for biological activity” function is given in Vogel et al. (2019). They postulated that systems with low species diversity contain fewer species within each functional group, and are thus more susceptible to losing entire ecosystem functions. Therefore, Vogel et al. (2019) considered assessing the inherent part of this function as the potential of soils to harbor a diverse community of soil biota, depending on soil texture, local moisture and temperature regime. In their assessment of soil multifunctionality, Calzolari et al. (2016) used the land use, soil bulk density and soil organic matter content to evaluate their “potential habitat for soil organisms” function. Greiner et al. (2018) used the microbial biomass, estimated with a pedotransfer function requiring the land use, organic matter content, pH, and soil texture, for their “habitat for microorganisms” function.

4.4. Spatialization limitations

Because of the scale of the soil input data (1:250,000 scale), the maps produced do not have the precision required for an assessment at the sub-municipal level. The harmonized “Référentiel Régional Pédologique” does not allow characterizing specificities of very local soils. The map reading must be done considering the different STU in each SMU in case of high soil heterogeneity. In the absence of more detailed data, Choquet et al. (2021) also used a map at a scale of 1:250,000 in France. According to the literature review of Grêt-Regamey et al. (2017), the regional scale was the most widely used to assess provisioning and regulating ecosystem services, such as those of the present article. Producing maps at the regional scale is a first step for awareness increasing, since no soil data are currently used to make planning decisions. We hope that awareness will also concern the provision of means to produce soil maps at finer scales. In the absence of any soil survey program for obtaining better maps that could be harmonized over the whole Occitanie region, digital soil mapping approaches (McBratney et al., 2003) represent a promising alternative. In addition to a gain in resolution, producing pixel-based maps would avoid managing SMU which are not pure but made of several STU. Digital soil mapping approaches have already been used to produce the map properties needed to assess soil functions in a few studies (Greiner et al., 2018; Calzolari et al., 2016). By applying digital soil mapping in the eastern part of the Occitanie region, Vaysse and Lagacherie (2015) obtained large gains of precision for the soil properties considered in the Agri-SPMI.

5. Conclusion

We calculated a soil potential multifunctionality index for agriculture (Agri-SPMI) from a small set of inherent soil properties usually available in soil databases. We spatialized the index over a large territory, using the French soil survey database at 1:250,000 scale. The output was in the form of two maps: a map of areas with high Agri-SPMI and a map of the service of food, biomass, and fiber production. 68% of the surface with high scores for the food, biomass, and fiber production service fell in the agricultural areas delineated in a land cover map. This high value showed that the method was able to capture the history of land use reflected by the current land cover. The concept of soil multifunctionality allowed highlighting environmental issues related to agriculture and to encourage land planners to take them into account in addition to the agronomic potential of soils. These maps are intended to be used to build the general guidelines necessary for sustainable management at the regional scale. The framework is flexible and fully transferable to other scales and other issues, with adaptation of the soil properties considered.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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