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A classification of European agricultural land using an energy-based intensity indicator and detailed crop description

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ABSTRACT

With agricultural areas covering almost half of European land, proper management of agro-ecosystems is key to achieve the European Union's environmental and climate objectives. This requires spatially explicit methods and indicators. We developed an approach for the classification of agricultural land by combining two main dimensions i) land cover, using detailed geo-spatialized census data covering 63 individual crops; ii) management intensity, measured as the anthropogenic energy required in the primary crop production. As a result we identified 10 main crop systems further classified into 30 'crop-management systems' at a spatial resolution of 5 arcminutes. The resulting maps show the spatial patterns of agricultural management intensity across Europe, both in absolute terms (total energy input per hectare) and relative to the dominant crop system in the spatial unit of analysis. The use of multiple intensity dimensions provides new, more detailed insights on agricultural intensity by which areas that were previously classified as low-medium intensive - some permanent crops systems or irrigated arable land - appear now as highly intensive. An expert-based evaluation was carried out on the intensity maps and corroborated the obtained results. The generated maps can be used to support decision-making in designing more targeted, context-specific agricultural and territorial policies. In particular, findings can be relevant in the context of the Common Agricultural Policy post 2020 and the Biodiversity Strategy towards 2030, both of which will benefit from more detailed spatially explicit information to achieve their stated objectives.

1. Introduction

Representing the spatial patterns and intensity of human-environment interactions is considered one of the most significant challenges in land systems science (Malek & Verburg, 2017; Rounsevell et al., 2012; Turner, Lambin, & Reenberg, 2007). This is a global issue (Verburg et al., 2015), and global research efforts are ongoing on these topics, including the Global Land Programme (GLP, 2020) and the Global Collaboration Engine (GLOBE, 2020). Agriculture is one of the main pressures on world's ecosystems and a major driver of biodiversity loss (IPBES, 2019); croplands cover 12% of ice-free land globally, while grazing occurs on 25% of ice-free area. Nearly three-quarters of available freshwater worldwide is consumed by agriculture and livestock raising, and almost one quarter of world greenhouse gas emissions comes from land clearing, crop production and fertilization (*ibid.*). The manufacturing of mineral fertilizers alone consumes 1-2% of global power supply and 4-5% of total extracted methane (Comer et al., 2019).

In the European Union (EU), farmland covers 48% of the terrestrial area; the agricultural sector is responsible for 10% of total greenhouse gas emissions (Simoncini et al., 2019) and requires annually some 380,000 tons of pesticides and 17MTon of fertilizers (FAO, 2020); intensive agriculture poses major threats to European biodiversity and on the provision of ecosystem services (Simoncini et al., 2019). The Farmland Bird Index, one of the most used environmental indicators of biodiversity in agro-ecosystems, has declined in Europe by 32% since 1990; similarly, the grassland butterfly index has declined by 39% since 1990 in 15 EU Countries (EEA, 2020). Only 16% of the assessments of habitats protected under the Habitats Directive have a favourable conservation status in the EU, agriculture being the most frequently reported threat or pressure by Member States (*ibid.*). Better understanding of crop agroecosystems, especially with respect to management intensity, is therefore an essential component to assisting in achieving the EU's environmental and climate objectives.

With land-use change being one of the most relevant drivers of environmental degradation worldwide (IPBES, 2019) and in Europe (EEA, 2020), observation of land-use transitions is a key area of

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research for informing policy. However, it is acknowledged that considering the land cover component alone is not sufficient to capture the complexity of land system dynamics and that changes in, and intensity of, land use management are relevant related factors (Erb et al., 2013; Kuemmerle et al., 2013; Mueller et al., 2012). To give an example, the benefits for biodiversity from organic agriculture or agro-ecology are widely acknowledged (Tuck et al., 2014), but a shift from conventional to organic farming would not necessarily be reflected in satellite-detectable land-cover changes. Kuemmerle et al. (2013) suggest that over time, effort will shift from land cover change analysis towards a focus on process-orientated monitoring of land use change and, in particular, assessment of land use intensity (Estel, Kuemmerle, Levers, Baumann, & Hostert, 2016).

Consequently, policy design and monitoring needs spatially explicit indicators able to provide usable information on the pattern of both land use and management intensity. In Europe, CORINE land cover (CLC) is the main fine resolution, pan-European, regularly updated and taxonomically consistent dataset on land cover. However, it does not contain detailed information on different crop types (e.g. within the "arable" class). A first research gap in the production of pan-European maps is therefore the lack of more detailed information on specific crops coverage, as different crop types have different environmental implications e.g. in terms of fertilization or irrigation requirements.

CLC also does not provide information on management, except for the distinction between permanently irrigated and non-irrigated arable land. Other agricultural classes, like "complex cultivation patterns" and "agricultural land with high share of natural vegetation" can be broadly associated with less intensive agriculture, but this is only an indirect and weak correlation. Measuring land use intensity is acknowledged to be a complex task (Erb et al., 2013; Kuemmerle et al., 2013). Erb et al. (2013) identify three main dimensions for assessing agricultural intensification: i) output intensification, ii) input intensification, and iii) changes in system properties. Output intensification is the increase in production output per unit area and time. Output level has been used in several studies as an indicator of management intensity (Shriar, 2000; Rudel et al., 2009; Tieskens et al., 2017). Measurements of input intensity have considered temporal cropping patterns (Estel et al., 2016), often complemented by information on applied technology; indices combining inputs of labour and capital per land area; and single inputs per land area (Erb et al., 2013; Kuemmerle et al., 2013). Measuring changes in system properties entails identifying one or more key ecological processes affected by changes in land-use intensity and measuring the former, rather than trying to directly quantify the latter (Erb et al., 2013). This would entail, for example, measuring changes in functional biodiversity or soil organic matter, as proposed by Matson, Parton, Power, and Swift (1997), or the human appropriation of net primary production (HANPP), i.e. the share of ecosystem productivity that is appropriated by humans (Haberl et al., 2007). Overall, measuring management intensity still represents a major research challenge and comprehensive, detailed spatial indicators able to capture the different factors underpinning it are lacking.

Great efforts have been devoted in recent years to developing methods to identify and map agricultural systems and their management intensity, particularly in Europe (see Table I in SM). Levers et al. (2018) and Van der Zanden, Levers, Verburg, and Kuemmerle (2016) used Nitrogen input to measure intensity and both relied on the layer produced by Temme and Verburg (2011). Niedertscheider et al. (2016) combined Nitrogen input (from Mueller et al., 2012) with the share of irrigated area, using as a proxy a global map on areas equipped with irrigation infrastructure. Van der Zanden et al. (2016) and Tieskens et al. (2017) added, as a further dimension, the landscape structure component, described in terms of field size and presence of linear elements. Tieskens et al. (2017) used Nitrogen input to measure intensity in arable land and an output indicator of intensity in permanent crops, i.e. the energy content output of agricultural biomass developed by Pérez-Soba et al. (2015). A different approach was proposed by Estel et al. (2016), who used phenology-based indicators of cropping frequency, multi-cropping, fallow cycles and crop duration ratio as descriptors of input intensity. Malek and Verburg (2017) developed a land system classification specific for the Mediterranean Ecoregions using both input and output intensity (N input and area equipped for irrigation) in combination with field size. Andersen (2017) used statistical data from the Farm Accountancy Data Network to classify EU agricultural landscapes as distinct patterns of farming systems and landscape elements, and economic output per ha as a proxy of intensity.

The validation of obtained results remains problematic: in some cases (Van der Zanden et al., 2016), results were compared with national or sub national maps. In other cases (Tieskens et al., 2017) sensitivity analysis was performed to assess the degree of uncertainty associated with the assignation of areas to a certain category. Malek and Verburg (2017) carried out a documented expert-based validation by comparing their results with studies in literature reporting land management on single sites. Often, independent datasets with the same (or comparable) resolution and extent for validating outputs simply do not exist.

The aim of this paper is to present an approach for a spatial classification of agricultural land that tries to partly overcome the research challenges and knowledge gaps outlined above, by providing an accurate representation of agricultural land uses (in terms of crops) and management intensity (in terms of input intensity). The results aim to be appropriate for use in supporting policy formulation and design, particularly to the post 2020 Common Agricultural Policy (CAP) and the new EU Biodiversity Strategy towards 2030. The approach is based on two main elements. First, the use of a comprehensive statistical census database on crops distribution, provided by Eurostat in a spatially explicit way at grid level (resolution 5x5 arcminutes[1]), comprising 63 individual crops. Second, the development of a layer on energy input in agricultural land, used to describe management intensity, accounting for the main relevant factors characterising input intensification, elaborated by Pérez-Soba et al. (2015). Additionally, we carried out an expert-based evaluation of our results by taking advantage of detailed information available at local level generated through a number of local case studies (IfLS & CCRI 2016). The work presented here is not to be intended as a definitive classification that should replace previous ones: each method has pros and cons, and we discuss them in section 4. Different classification systems can be used in a complementary, rather than competing, way, depending on the specific objectives of the study and the policy/research issues being considered.

The paper is structured as follows: in the next section, we outline the data and methods used to develop the crop system map (Section 2.1), the energy input indicator (section 2.2), and the expert-based evaluation (Section 2.3). Results are presented in section 3 and discussed in section 4 along with their potential use for policy-making. In section 5 we daw some general conclusions and point to possible developments. Additional information on material and methods, the expert-based evaluation and results is provided in Supplementary Material (SM).

2. Materials and Methods

2.1. Defining and mapping crop systems

The original raw data provided by EUROSTAT reported information collected by the 2010 official agricultural census[2] and consisted of approximately 76,200 entries, covering the EU (except Croatia) plus UK, Switzerland and Norway. The dataset included information on the

[1] 1 arcminute correspond to 1/60 of a degree, or 1/21600 of a turn. On the meridian, 5 arcminutes corresponds thus to approximately 9.2 Km; on the parallel, values in the EU rage from 7.7 Km in the extreme south to 3 km in the extreme North.

[2] When aggregating the census data to coarse geographical grids, disclosure control methods were applied by EUROSTAT in order to protect the privacy of the respondents to the questionnaire.

Table 1
Classification of amalgamated crop and grassland systems based on area dominance.

N0.	Crop systems	Crops/crop groups aggregated to calculate dominance
1	Specialist Vegetables, flowers and horticulture	Fresh vegetables, melons, strawberries Ornamental Plants
2	Specialist vineyards	Vineyards - total
3	Specialist fruits and citrus fruits	Fruit and berry plantations - total Citrus plantations - total
4	Specialist olives	Olive plantations - total
5	Specialist field crops cereals	All cereals crops
6	Specialist field crops – industrial crops	All industrial crops
7	Specialist forage crops	All forage plants
8	Grassland and meadows	Permanent grassland and meadow
9	Mixed systems with prevalence of arable land	No dominance of any of crop systems 1-8; largest share of arable land
10	Mixed systems with prevalence of permanent crops or grasslands	No dominance of any of crop systems 1-8; largest share of permanent crops

area of 63 individual crops and types of grasslands. Data were aggregated on a grid with a spatial resolution of 5 arcminutes. Individual crops were first aggregated in crop groups (see SM for details). We then aggregated crop groups with similar characteristics into eight classes that we termed "crop systems" (Table 1). The nomenclature we used is similar to the "Type of farms" official classification of farm holding of the EC (2003). However, in this study, "crop systems" does not refer to farm types as productive units, as in the EC classification, but to the presence of particular crops and grassland with similar characteristics and environmental implications in an agricultural landscape defined by the 5x5 arcminutes cell.

We defined that a crop system was "dominant" in a cell if its area accounted for more than a certain percentage of the total UAA. We tested four different values for crop dominance, namely 40%, 50%, 60% and 70%. When using the 40% threshold, we assigned the cell to the crop-system with the highest share in case of two crop-systems with a share > 40%. If none of the crop systems from 1 to 8 in Table 1 reached the dominance threshold, we classified the cell as "Mixed crop system". Subsequently, we divided this latter class into two further classes: mixed systems with prevalence of arable land or permanent crop/grasslands depending on which of these aggregates had the largest share. We therefore obtained 10 categories of crop systems as shown in Table 1.

2.2. Input intensity indicator

The indicator on input intensity in agricultural land is described in Pérez-Soba et al., (2015). The indicator was developed using the Common Agricultural Regionalised Impact (CAPRI) model (Britz & Witzke, 2014). The indicator utilises the same modelling framework to calculate an agricultural output indicator in the form of MJ/ha of burnable energy contained in agricultural production, which has been used in other studies as an output intensity indicator (e.g. Tieskens et al., 2017) or a quantification of the provisioning service from agriculture (Stürck & Verburg, 2017; Mouchet et al., 2017). In the present work, the approach is based on the estimations of different production input and activities, which are then converted to a common metric, i.e. the total energy necessary to manufacture them and subsequently use them in production. The following inputs and activities were included in the analysis: mineral fertilizers, application of manure, planting/seeding, irrigation (energy used for pumping and distributing water), pesticides (manufacturing and spreading), energy used to produce seeds, use of machinery (including fuel consumption) and direct consumption of electricity for building maintenance. The physical quantities were then transformed to energy through fixed conversion factors available in literature (see also SM). Results were first generated at regional (NUTS2) level and then, following a statistical procedure described in Leip et al. (2008), were downscaled at a finer spatial resolution of so-called Homogeneous Spatial Mapping Unites, i.e. pixel clusters of one or more 1 Km^2 cells with similar agronomic characteristics. These data refer to CAPRI baseline of year 2008 (average of data of 2007, 2008 and 2009).

The final indicator is expressed as the total amount of human-handled energy input per hectare of Utilised Agricultural Area (MJ/ha), excluding physical human labour, and it covers 25 European countries, namely EU Member States except Croatia, Malta and Cyprus, plus UK. Additional information and explanation is given in the SM.

2.3. Experts-based evaluation of the intensity indicator

The dominant crop system map is derived from the EUROSTAT official census data, so we assume it does not require further validation. The energy input component is instead the result of modelling; whilst the disaggregated result of the standard CAPRI model have been validated by Leip and G., Marchi, R., Koeble, M., Kempen, W., Britz and C. Li, (2008), in this case we use the result of an ad hoc study that collected additional indicators from a variety of sources to include different aspect of agricultural production (Pérez-Soba et al., 2015). A strict validation would require a thorough data collection at farm level, not possible in the context of any pan European study. As a substitute, we opted for an expert-based evaluation of the results, by asking a pool of experts with deep knowledge on 17 case study areas across Europe (Fig. 1) to provide their assessment on the intensity of agricultural management in that area (IfLS & CCRI 2016). For each case-study area of their competence, experts were asked to assess the intensity of management in a scale from 1 to 5 taking into account four main inputs: fertilization, irrigation, application of pesticides and use of machinery. Expert scores were then compared with the intensity scores from the model, discretized in five classes corresponding to the 5 quantiles of the distribution. Guidance including quantitative thresholds was provided to experts so that the scale of evaluation was as much as possible aligned with the scale derived from the discretization of the intensity score derived from the original values of the intensity indicator. Additional information on the set up of the exercise is provided in SM. Whilst this cannot be qualified as a full validation because the sample size is limited and case study location is not random, results could be nevertheless informative in supporting the whole exercise, also considering that they are distributed in different agricultural contexts (different Member States and Bio-geographic regions – Fig. 1).

3. Results

3.1. Crop Systems Map

Figure 2 shows the 10 dominant crop systems in 2010 using the 50% threshold for dominance. The map identifies the spatial pattern of cropping systems and thus the different degree of specialisation or diversity of Countries or regions, e.g. grassland in Ireland, forage crops in Brittany (North-Western France), specialist fruits in Murcia and Valencian Community (Spain). Among mixed systems, those with prevalence towards arable are overall more widespread across all Europe, whilst those with prevalence for permanent crops or grasslands are more abundant in Southern Europe. Here, even areas highly characterised by certain production (e.g. wine in Tuscany, central Italy, citrus fruit in Sicily) are mostly classified as mixed systems, which reflect the persistence of the complex and heterogeneous agro-silvo-pastoral landscape characterised by polyculture - orchards, vineyards and grains – of the so-called "Mediterranean Garden" (Sereni, 2014; Barbera and Cullotta, 2016).

Conversely, in France for instance larger specialist vineyards area are identified in Roussillon (Southern France) and the Boudreaux region, showing a higher specialisation of the agricultural landscape

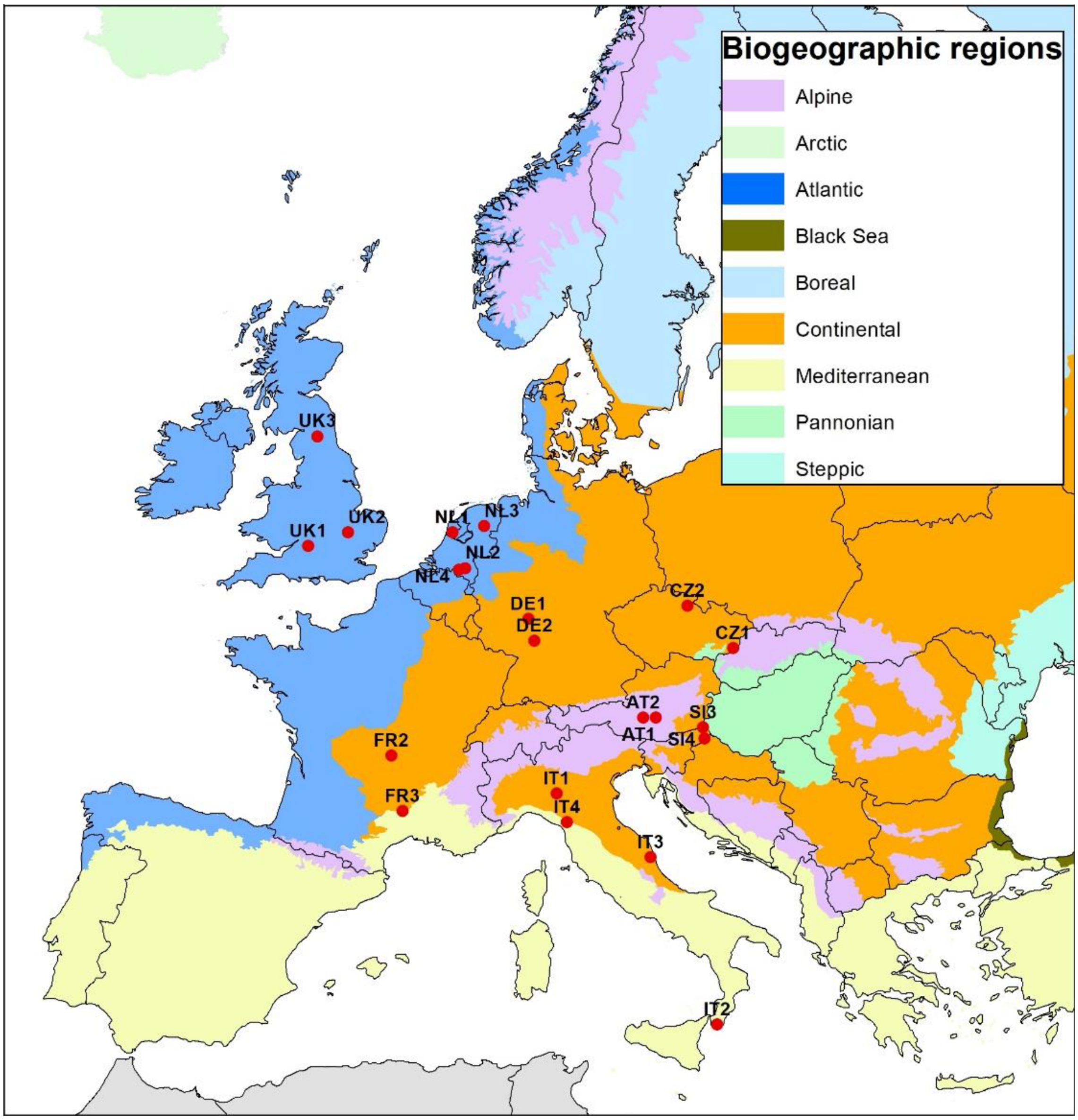

Fig. 1. Location of the case study areas used in the expert-based validation. See also Table III in SM for additional information on case study areas

there. Obviously, grassland systems dominate in mountain areas, but also in the Netherlands, western Britain and Ireland, the latter being almost homogeneously classified in this class. A large area dominated by Specialist Olives is identifiable in Andalusia (Southern Spain), reflecting the process of land specialisation occurred here in recent years (Infante-Amate & de Molina, 2013), and to a lesser extent in Puglia, Calabria (South Italy) and southern Greece, where olive groves are diffused but often intermixed with other cultivations.

Specialist cereal systems are identified in the Po Plain, in Castilla y León region in Spain, the Atlantic Plane in France, eastern England, Denmark, large areas of Poland, the Pannonia Plane (Hungary and part of Slovakia) and the Danubian Plane across Romania and Bulgaria. At continental scale, specialist industrial crops systems are rare, but nevertheless identified in Northern Greece and Bulgaria (where cotton is diffused) in the western part of Andalusia (SW Spain) due to sunflowers, or in Provence (SE France) where some areas are specialised in the cultivation of aromatic plants. Specialist forage systems prevail in the Boreal area and in Brittany: here, pastureland and arable land are often intermixed, a legacy of the traditional *bocage* landscape (see e.g. Thenail & Baudry, 2004). While the crop systems shown in Fig. 2 were calculated using the 50% dominance threshold, in the SM we show more maps resulting from the application of different thresholds. The general pattern visible at the continental level when increasing the dominance value is of course an increase of the mixed systems at the expense of specialised ones, when a lower threshold is used (40%) the opposite is obviously happening. Differences are not initially striking but significant changes became visible when the threshold is high (70%). For such high thresholds, mixed systems can be seen to cover large parts of Europe (see SM).

3.2. Agricultural input intensity in Europe

Figure 3 shows the input intensity indicator in European agricultural land with two different representations: Figure 3A (left) shows the absolute intensity measured in MJ per ha of UAA. Five classes of intensity are shown, using the quantiles method to define classes, considering the values' distribution across all Europe. Clear spatial patterns are identifiable at the continental level: highly productive arable land in the Po Plain (Northern Italy), the Parisian Basin and northern France and Eastern Britain show high to very high input intensity values. An East-West divide is visible in the map, with eastern countries having on average lower intensity. This is consistent with

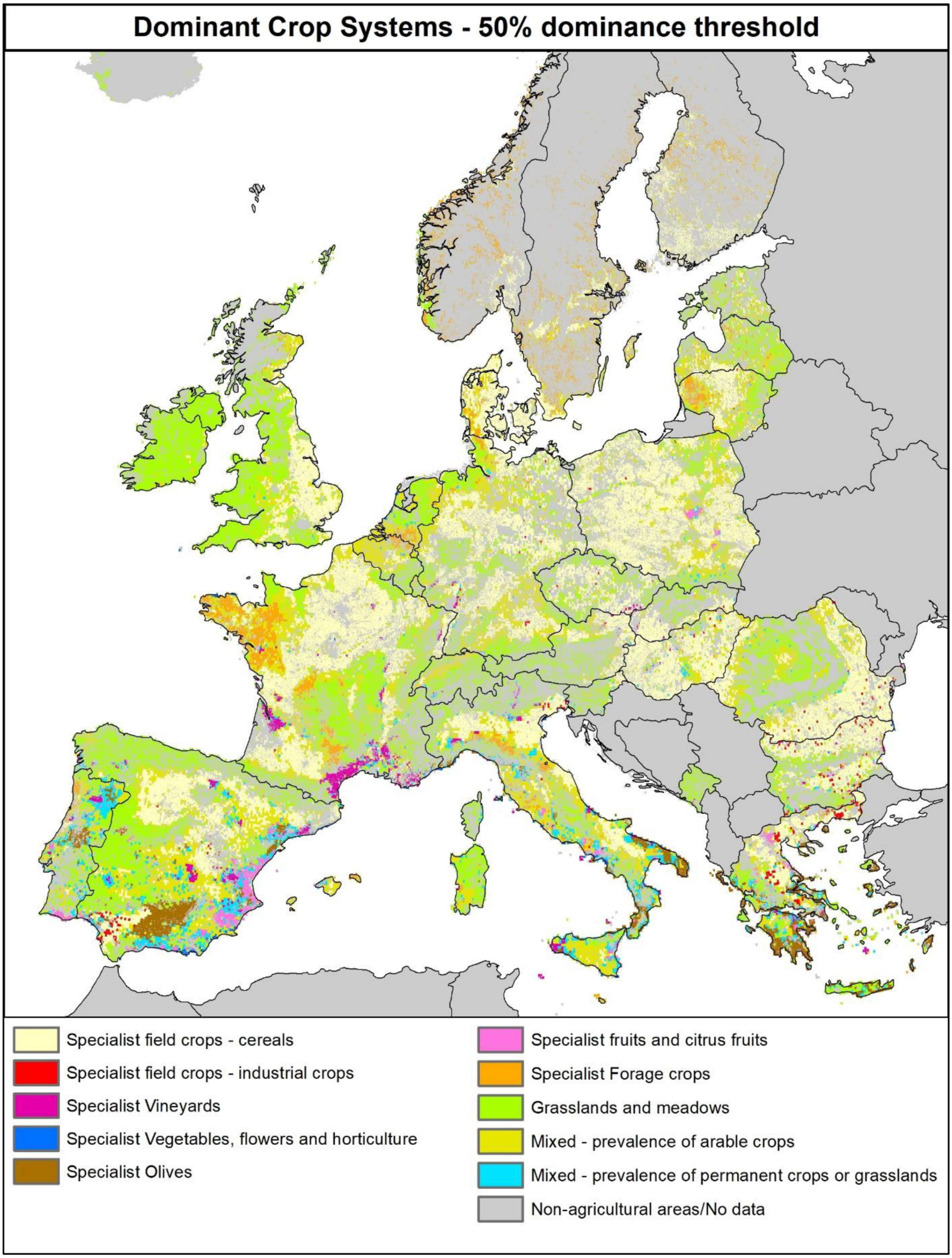

Fig. 2. Distribution of the 10 defined Crop Systems in Europe, based on the 50% dominance threshold

results from previous studies (e.g. Levers et al., 2018) and is partly explained by the de-intensification processes occurred in these countries following the collapse of socialist regimes. This is evident in Romania, Bulgaria and the Baltic States. Mountain areas expectedly have medium-low to low values, as visible in the Alpine range, the Pyrenees, or the Cantabrian Range (Northern Spain). In the Mediterranean Region, high-intensive areas correspond to olive plantations in Andalusia, Puglia (SE Italy), Southern Greece, and orchard-dominated landscapes

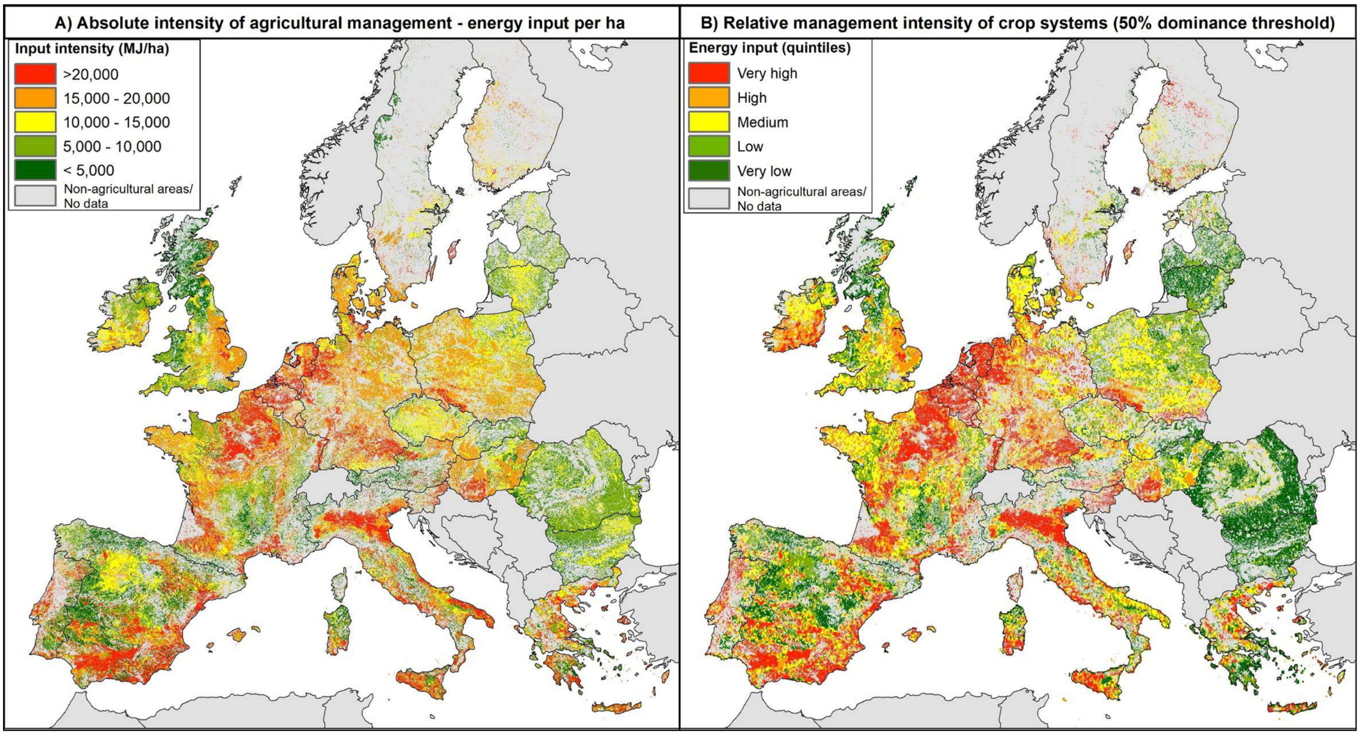

Fig. 3. Left (A): absolute Input intensity in agricultural land. Elaboration based on data in Pérez-Soba et al. (2015). Right (B): Intensity of management relative to crop systems defined using the 50% dominance thresholds. Intensity classes are based on quantiles of the energy input value with in each crop system.

in Valencia and Murcia regions (Spain). High levels of intensity are also associated to specialist vineyard systems in Southern France and Bordeaux, and pasture-dominated areas in the Netherlands.

Fig. 3B (right) shows management intensity relative to the different crop systems identified in Fig. 2. For each crop-system cell (5 arcminutes resolution), the mean value of the energy input indicator was calculated. As for the previous map, the quantile method was used to define 5 classes of intensity, but quantiles were calculated considering the intensity values' distribution within each of the 10 crop-systems. In this way, differences in management of the different crop systems can be better taken into account and comparisons between the same crop systems in different geographic contexts can be made. Differences in the spatial pattern of intensity between the two maps are evident for example in Ireland, where intensity is high relative to grassland systems, in Denmark, which intensity is high in absolute terms, but medium in relative terms (arable crops prevailing here); in the arable plain in Castilla y León (Central Spain), where the relative intensity is lower than the absolute one, or in Southern Greece. The intensity remains very high even in relation to the crop system in large areas of the Po Plain (North Italy), the Benelux and NW Germany, or large part of Andalusia. The East-West divide identified in Fig. 3A is even more marked in Fig. 3B.

3.3. Identification of crop-management systems

The information provided by the crop systems map and the relative management intensity map is combined into what we term 'crop-management systems'. This is shown in Fig. 4. For visual purposes, in this map we show 3 intensity classes – low, medium and high – to maintain a manageable and readable number of total classes (30 = 10 crop systems × 3 intensity classes).

Intensive cereal systems correspond to the highly productive regions mainly located in western Europe, such as the Po Plain in North Italy, the Atlantic Plain in France, Eastern England, Lower Saxony and North-Rhine Westphalia in Germany. In eastern countries, who joined the EU more recently, intensive cereal system are identified in parts of Hungary and Southern Poland, whilst medium intensity ones prevail in the central Plain of Poland, and low intensity ones in the Danubian Plain (Northern Bulgari/Southern Romani), Wallachian Plane (East Romania) and central Lithuania. The cereal system in Castilla y León and Central Spain is mainly classified as low intensity, and can be seen to largely correspond to the High Nature Value (HNV) farming system of the Iberian cereal steppe (Oppermann, Beaufoy, Jones, 2012). Indeed, other low intensity areas also correspond to HNV systems: among the example that are most visible at the EU scale there are extensive grasslands systems in Bulgaria, hay meadows of the Cantabrian Mountain, North Spain, *dehesas* (traditional agroforesrtey) in Extremadura (Western Spain) (ibid.). Low-intensity mixed systems with a prevalence of arable crops are diffused in the Baltic States and along the Apennine foothills of central Italy, where they largely correspond to HNV systems, whilst medium intensity ones are common e.g. in Southern Italy (Sicily, Sardinia). High-intensive specialist forage systems are identified in Emilia Romagna (Po Plain) where they produce the feed for the dairy herds associated with cheese production, the Southern regions of the Netherlands, Brittany and in Sweden and Finland (here, together with areas classified as medium and low intensity).

Turning to specialist permanent crop systems, high intensive vineyards are mostly located in France, mainly in Roussillon (South France) and partly in the Bordeaux area, in Italy in Veneto (NE) whilst the vineyards dominated landscapes of Langhe and Roero (Southern Piedmont in NW Italy) are low intensity. Low and medium intensity vineyards are found also in Greece, some parts of Provence (SE France), Catalonia and Hungary. Intensive specialist fruit systems are prevalent in the Spanish regions of Valencia and Murcia, medium intensity ones are located in these same regions and in Southern Italy. Specialist vegetables systems have overall a limited extension, but can nevertheless be found in the eastern part of Andalusia and Murcia regions (Southern Spain), the area north of Naples in Italy, and North Holland (intensive), whilst medium-low intensity ones along the Mediterranean coast in Liguria (Italy), Provence (France) and Catalonia (Spain), Southern Sicily and on the Black Sea coast in Bulgaria. The intensive specialist olive systems are located in the Iberian peninsula, particularly in

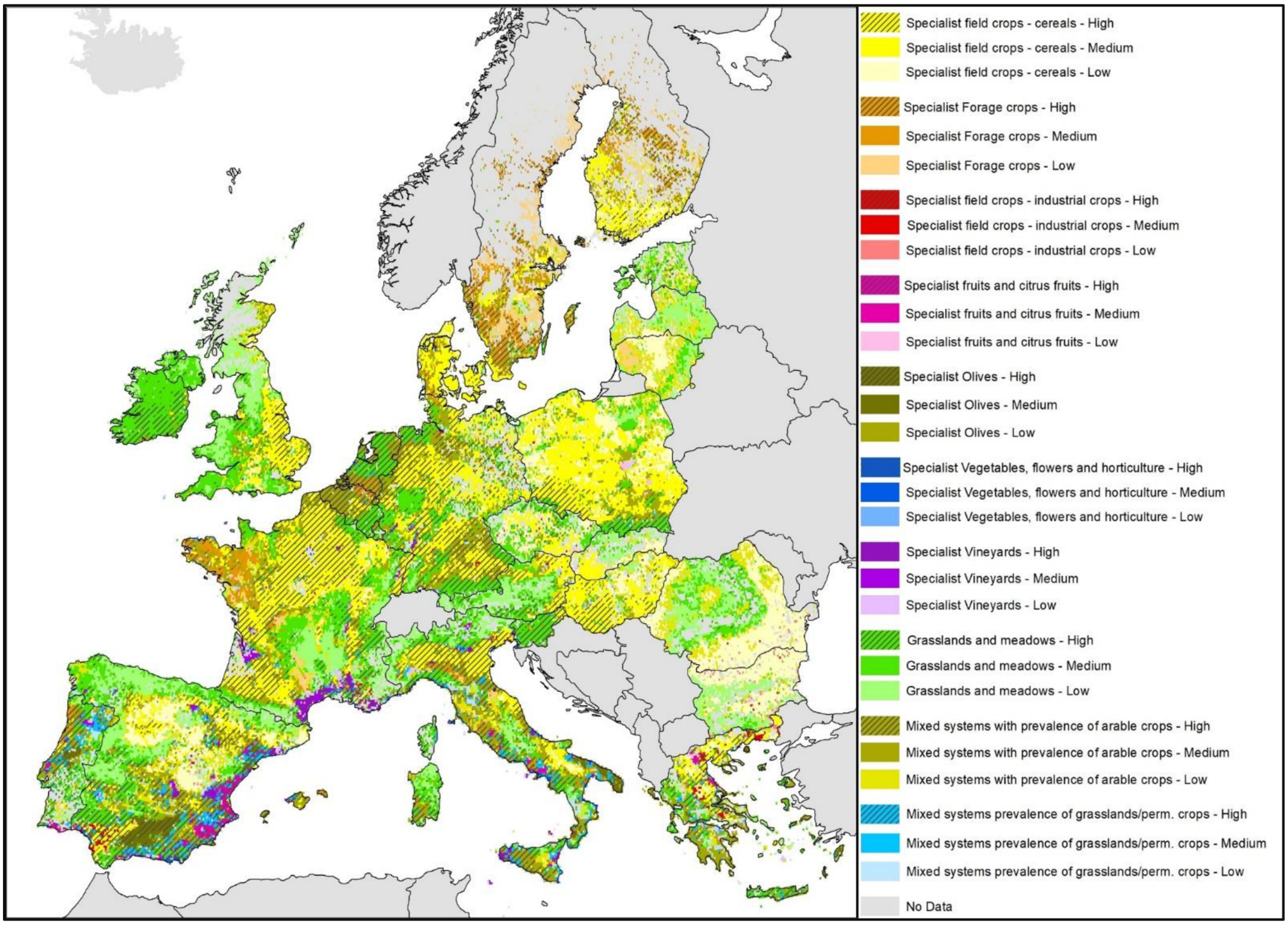

Fig. 4. Crop-management systems in the European Union. 30 classes derived from the combination of 10 crops systems (50% dominance threshold) and three level of management intensity.

Andalusia (Southern Spain), central Portugal and in some part of Southern Italy (Puglia, Calabria) and the Southern part of Catalonia (Spain). Medium intensive ones are diffused in Southern Italy, mainly in Puglia, Calabria and Sicily, in some parts of Greece, where, however, the largest share of this system is in the lower intensity class.

Specialist industrial crops system with high management intensity are mainly located in Greece (cotton), Eastern Andalusia (sun flower), Friuli-Venezia-Giulia (NE Italy, soybean), and Provence (aromatic plants). Medium-intensity ones are concentrated in Greece but also occur in scattered areas of Hungary and Czech Republic (sunflower), whilst low-intensity ones occur in Romania and Bulgaria (again, sunflower cultivation is present here).

3.4. Results of the expert-based evaluation

The results of the evaluation exercise show a fairly good degree of agreement between modelled values of intensity and expert judgements. Significantly, in no case do the experts' judgements rest at odds with modelled results. The maximum distance between the scores is 1.55. We defined the match between expert scores and modelled scores as "very good", "good" and "medium" if the difference between the two scores is lower than 0.5, 1, and 1.5 respectively. If the difference is > 1.5 we classified the match as "poor". Using this scale, 8 out of 17 predictions are very good, 5 are good, 3 are medium and one is poor (more details on the assessment for individual CS areas are given in SM). The absolute difference is below 1 in 13 of the 17 areas.

There is no evident bias in the modelled values compared to expert scores, i.e. the experts do not systematically over or under assess the intensity compared to modelled values (see SM). Sensitivity analysis carried out on the expert-based evaluation showed that no significant differences in the results are obtained if more weight is given to case study areas with more respondents. Therefore, although this cannot be considered an expert validation due to the limited sample size and non-random choice of areas, we suggest that these results are encouraging and add further support to the validity of the whole approach.

3.5. Comparison with previous maps

In order to evaluate the impact of our approach, we carried out a visual assessment of the main differences between our results and previous classifications, as mentioned in the introduction, to evaluate similarities and differences. Overall, our results are similar to previous ones as far as arable land is considered. For example, there is a good agreement between our intensive specialist cereals category and the 'high-intensive arable cropland' cluster identified by Levers et al. (2018). This is visible for instance in Northern Italy, Northern France, Eastern England, Germany. The same holds true for low intensity cereal specialist, which both studies mainly identify in Romania and Bulgaria. Both maps identify the cereal region of Castilla (Spain) as less intensive than the previous ones, but our study classified them mostly (though not exclusively) as low intensity whilst Levers et al. (2018) as medium intensity. Good correspondence is also identifiable with medium intensity arable specialist in Poland and in general for grassland systems corresponding to 'livestock farming' in Levers et al. (2018). A full comparison with the map produced by Van der Zanden et al. (2016) is hindered by the fact that these authors also included field size in their characterization. However, there is an overall good match between their intensity classes for arable land and grasslands and ours. Nitrogen input is the most important factor in terms of equivalent energy consumption in both arable and grassland systems, so there is a good correlation between total energy input and total Nitrogen input.

One significant difference in arable land visible at the EU scale can be found in Denmark. This allows us to point out a potential improvement of the presented approach, i.e. that the total energy input takes into account the substitution effects (i.e. changing one input for another, like manure instead of mineral fertilizer), a key aspect when assessing management intensity (Niedertscheider et al., 2016; Erb et al., 2013). In Denmark, intensity of management in arable land is generally classified as high or very high when Nitrogen input (Levers et al., 2018, Van der Zanden et al., 2016) or economic output (Andersen, 2017) is considered. In our classification, intensity there is medium, because a significant share of total Nitrogen input is provided by manure (Pérez-Soba et al., 2015), which entails a lower amount of consumed energy and raw material compared to manufactured mineral fertilizer. The use of economic output as an intensity indicator by Andersen (2017) leads to concordant assessments with ours for e.g. in Central Spain (low intensity), whilst most of intensive arable land identified by our and other studies appears as "medium" in the latter study. Interestingly, in Andersen (2017) the most intensive area is Denmark. This reflects the fact that whilst economic output correlates with input intensity in many cases, it cannot grasp substitution effects.

Irrigation plays a significant role in the Mediterranean Region as it requires water and energy (Malek & Verburg, 2017) and accounts for some differences and similarities between different classifications. For example, irrigated annual crops in Malek and Verburg (2017) has a fairly good correspondence with intensive specialist cereals of our map e.g. in central Greece, intensive industrial/cereal specialist in the Guadalquivir mouth area (eastern Andalusia), and mixed system with prevalence of arable crops in South Sardinia. These areas are mainly classified as not high-intensive by the other mentioned studies.

Another key difference is the classification of permanent crops: in these systems Nitrogen is not the main input, instead irrigation, mechanization and, in particular, pesticide use can be relevant factors. In Van der Zanden et al. (2016) permanent crops are classified according to the field size and not to intensity and in Andersen (2017) permanent crop systems per se are not mapped. High-intensity permanent crops systems from our maps are in many cases within the areas identified by Levers et al. (2018) as 'large scale permanent crop' (e.g. in Andalusia, Murcia, Valencia, Southern France) but the latter includes also areas that we classify as medium intensity (e.g. olive orchards in Puglia and Greece) and the latter study does not identify a specific 'low-intensity' permanent crop cluster.

4. Discussion

In this section we first discuss the strengths and limitation of the presented approach, by pointing out what we deem are the most relevant aspects, in particular: 1) use of detailed crop information, 2) spatial resolution of the obtained results; 3) the use of an energy based indicator to describe input intensity 4) the use of other characteristics of crop-management systems not present in this study (field size, landscape element); the accuracy of input data, 5) the threshold of classes used for farming system classification, and 6) the time lag of data sources (section 4.1). In section 4.2 we discuss use and potential applications of our results in policy.

4.1. Novelties of the approach, strengths and limitations.

One main novelty of the approach presented in this paper is the more detailed geo-spatialized classification of the crop-management systems, which allows recombining the original data into different classes tailored to specific research needs or geographic contexts. Compared to the broadly used CLC and previous works, this classification allows a more refined identification of agricultural land cover. For example, it allows to distinguish specialist foragers, specialist industrial crops and specialist vegetables/horticulture within the broad "arable" class (Fig. 2). Each of these may require different types of policy measures. This enhanced distinction of crop types came at the cost of spatial resolution, which is coarser than CLC and of many of the studies cited in the introduction (see SM for details). However, the resolution is still adequate for identifying a relatively limited number of agricultural systems at the Pan-European scale, which is the purpose and coverage of this study. The approach would remain suitable for studies at National and Regional (NUTS2) level, but would probably not always hold at more local scales. In this case, the overall framework could be maintained and be fed with more detailed data, if available.

The second innovation is a more comprehensive account of the different elements that contribute to input intensity in agriculture. We have included a plurality of indicators directly measuring input intensity. The conversion of these diverse indicators into a single metric, energy, allows us to integrate several datasets into the study, as called for by previous researchers (Erb et al., 2013; Niedertscheider et al., 2016; Turner and Doolittle, 1978; Van der Zanden et al., 2016). In this way, patterns of intensity across Europe can be grasped in a more detailed way, and account for substitution effects, a key aspect when assessing management intensity. The results of the expert-based evaluation show that the information on intensity is sensible even at relatively small scales, although, again, for local studies it should be complemented with more detailed data. As already mentioned, input intensity is, however, only one of the three dimensions of intensity identified by Erb et al. (2013), and in this study we did not consider output intensity and changes in system properties. There are however some intrinsic limitations associated to the measurement of these two dimensions. Conceptually, the nexus between intensity and output cannot be taken for granted, as yield levels are affected by a variety of factors such as climate, soil, pest outbreaks or types of cultivars. Pérez-Soba et al (2015) also demonstrated that the relationship between input and output is not linear, and that at high level of intensity further gains in output are achieved at the cost of very high increases of inputs. Furthermore, outputs shall be related to full production cycles to account for land left fallow and crop rotation (Erb et al., 2013), but such data are seldom available and highly uncertain (Kuemmerle et al., 2013).

This study does not address directly the third dimension of intensity identified by Erb et al. (2013), namely changes in system properties, such as biodiversity level. These changes, however, are highly context and time-dependent, and assessing them requires field surveys and measurement campaigns that are costly and time-consuming. For these reasons we deem that measuring input level is the best option, given the scope of the present exercise. In other circumstances, however, output intensity or changes in system properties may be necessary to complement the analysis. The presented approach does not require the use of automatized algorithm such as self-organizing maps[3], which are useful to visualise multi-dimensional data and reduce complexity, but may require interpretation, sometimes needing verification through expert judgement (Van der Zanden et al., 2016). On the other hand, using more sophisticated clustering techniques would allow integration in the present framework of other dimensions characterising agricultural landscapes, such as presence of seminatural vegetation and/or field size, which is not included here. This could be a useful future development of the present study.

Overall, based on the comparison with previous studies (Section

[3] Self organizing maps are computer-based algorithms used to creates maps that transform high-dimensional data into low-dimensional (usually two-dimensional) space in such a way that the topological relations of the input patterns are preserved. In this case of agricultural systems, the input data would be a set of management parameters and land cover classes and the output data a two dimensional classification (crop system and intensity)

3.5), we suggest that our approach offers a better description of management intensity and a finer classification of crop systems within generic arable/grassland/permanent crops classes, allowing to distinguish systems that may require different management strategies and policy measures. The drawbacks of our approach are that the landscape structure component, considered in other studies, is not accounted for. The use of a specific classification system will depend on the specific needs of users: when landscape structure and resolution are the most relevant factors, other classifications may work better, or different classifications can be used in a complementary way. Another limit of this study is that it captures only one point in time, namely the situation in 2008-2009, whilst other studies (e.g. Levers et al., 2018) used temporally varying data to infer system changes. Whilst intensity data and census crop data are well aligned in time, the produced maps may miss some recent developments. The intensity indicator for example may underestimate possible processes of intensification in Eastern Europe occurred after 2009, an issued raised also by other authors (Estel et al., 2016). However, the information does provide a baseline against which subsequent change can be compared. The problem appears less relevant in Western Europe, where the literature reports strong temporal stability in agricultural management (Levers et al., 2018).

Another caveat, in this case common to all these types of studies, concerns the reliability and accuracy of the input data used. As pointed out by Malek and Verburg (2017), combining different data sets derived from diverse sources can result in aggregating their inaccuracies, but "as fully harmonized data on the different aspects are not available, the possible bias from inconsistencies between the different data layers is unavoidable" (*Ibid.* pag. 113).

The establishment of thresholds to identify discrete classes is always arbitrary to some degree (Malek & Verburg, 2017); in section 3.1 we showed maps based on the 50% threshold to determine crop systems. We have carried out a sensitivity analysis and produced maps with different threshold values (see SM): we maintain that for general purposes, the 50% threshold may be the preferred one given that is straightforward to interpret. Again, depending on specific needs, users may prefer systems based on the different values shown in the SM. Even the number of classes and systems to display in the maps is arbitrary and can influence the interpretation of results: here we aimed at achieving a balance between completeness, manageability of the number of classes and readability of the visual outputs. However, once the framework is established, the methodology put forward allows the elaboration of more focused maps tailored to specific research or policy needs. In a more circumscribed study region, not all cropping systems will occur, so that some systems can be furtherly disaggregated to single out specific crops or crop groups within certain classes.

4.2. Use and applications for policy support

Several scholars have highlighted the need to produce spatial knowledge to support more targeted, context-specific policy making in the field of agriculture and territorial policies in general (Dwyer, 2013; Levers, Butsic, Verburg, Müller, & Kuemmerle, 2016; 2018; Short & Dwyer, 2012). The first use of these maps would be the identification, at European scale, of areas with similar characteristics that can be the target of specific policies. The presented classification can also be used to identify areas for investigation in comparative studies or field surveys, as a basis for selecting case study areas or to compare different regions in Europe with similar features or needs. A major benefit of these maps is the possibility to overlay them with spatially explicit indicators of ecosystem services to perform geostatistical analyses on the relationship between crop systems, intensity of management and the supply of ecosystem services. Mapping and assessment of ecosystem services in agricultural land has made significant advancements in the last years, and spatially explicit indicators are increasingly available across Europe (Burkhard and Maes, 2017; Maes et al., 2018; Paracchini et al., 2014; Rega et al., 2018; Zulian, Maes, & Paracchini, 2013). Combining this increasing amount of information with the maps presented here could improve our understanding of the drivers of ecosystem service supply in Europe. This would also allow the consideration of the third dimension of intensity discussed above.

Results presented here may be used in the context of the ongoing discussion on the CAP post 2020, which, in the proposal of the Commission, should devolve more discretionary power to Member States in selecting and designing their specific agricultural measures within a common EU framework. As currently proposed, the new CAP due in 2021 will also aim to increase the contribution of agriculture to tackling climate change, protecting the environment and preserving landscapes and biodiversity, as stated in the new European Green Deal (EC, 2019). To meet such goals, spatially-explicit information on patterns of agricultural systems and management intensity will be increasingly important. Member States will have to elaborate 'CAP strategic plans' setting specific objectives and measures, which will require extensive analysis of the needs, strengths and weaknesses of the agricultural sector, and to identify potential trade-offs. The EC will be in charge of the approval of such plans and the definition of common monitoring schemes: the information presented here, in combination with other data, can inform both the elaboration and the assessment of these plans, which will need to be based as much as possible on common datasets across Europe. The possibility to disentangle, and consider separately, the different inputs is an important point in this context, as it would add specific information relevant to the improvement of the environmental performance of agriculture.

For example, reduced or no-tillage systems are considered beneficial to increase soil organic matter and water functions (Skaalsveen, Ingram, & Clarke, 2019) and require less use of machinery, but often need additional use of herbicides to manage weeds: by combining soil organic matter, use of machinery and pesticide use, different measures can be prioritized, e.g. conservation agriculture compared to organic farming. In Nitrate Vulnerable Zones, nitrogen input might be the most important factor to consider, whereas in dry areas irrigation can result in significant pressure on ecosystem services. In other areas with problems of soil erosion, the use of machinery might instead represent the most pressing issue; in biodiversity-rich areas the threat could be represented by pesticides. Therefore, knowing the internal composition of the different factors at the local and regional level, which contribute to management intensity is a key part of the decision-making process.

As pointed out by other authors (e.g. Malek & Verburg, 2017), there is a need to produce spatially explicit knowledge to inform the EU agricultural policy at a scale that falls in between global assessments - not able to grasp the diverse regional characteristics and not always linked to local systems and nomenclatures - and detailed analyses at farm level, which ignore the broader landscape context and are too detailed to be upscaled at the EU level. Previous studies have also highlighted the need to reduce the complexity in agricultural systems to manageable units for policymaking and to improve our understanding of their high spatial heterogeneity (Van der Zanden et al., 2016). This study aims at making a contribution to this discussion.

A better knowledge of intensity patterns and crop systems may also inform the identification of areas suited for sustainable intensification, possibly in combination with other information, such as ecosystem condition, habitat integrity and flows/stock of ecosystem service, as well as socio economic variables. Agriculture is not the only policy area that can benefit from this analysis, there is potential for this approach to assist in the development of conservation policies and biodiversity enhancement. For example by providing evidence of where agriculture management is exerting pressure on ecosystems, in the context of the ongoing elaboration (and future implementation) of the new EU Biodiversity Strategy.

5. Conclusions

In this study we have presented a new approach to map EU crop systems and their management intensity that allows a more detailed description of agricultural land *cover* and *management* intensity. An improved representation of these two dimensions enables a more comprehensive understanding of the resulting systems to inform policy-making, which can be combined with other information to carry out more detailed analysis in the domain of land use science. The energy-based approach used enabled us to account for the substitution effect and to integrate different sources of data, which then permits us to cover a broad spectrum of factors contributing to intensity. Data presented here can be used to complement information provided by previous classification systems, depending on the specific needs of the users such as studying possible relationships between agriculture intensity and other relevant ecological or socio-economic geospatial information.

A natural follow-up of this study is the investigation of the relationships between cropping systems, management intensity and supply of ecosystem services in agricultural land. Another desirable development is the consideration of livestock in the analysis. Although data on livestock presence was included in the original EUROSTAT dataset we used, we did not combine crop management intensity and livestock intensity into a single indicator, nor did we aim at identifying combined crop-livestock systems due to uncertainties in how livestock management is distributed across Europe. Indeed, it is challenging to link livestock to land, since it is not known to what extent the livestock graze on pastures or are fed with imported feedstuff that can be produced far away. Moreover, in mountain regions, transhumance and movement of livestock throughout the year, such as on common land, is practiced throughout Europe. This further complicates the identification of systems at grid level, which was the purpose of the present exercise. Future research will need to address these issues to see if such extensive systems are of ultra-low management intensity.

Our results show that by considering multiple dimensions of intensity, some areas that are usually classified as low-medium intensive (e.g. some permanent crops systems or irrigated arable land) appear in fact to be highly intensive. The present finer classification can be used for better design and targeting of agricultural and nature-conservation policies by providing a more comprehensive picture of cropping and management intensity patterns across Europe.

CRediT authorship contribution statement

Carlo Rega: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Chris Short:** Methodology, Validation, Writing - review & editing. **Marta Pérez-Soba:** Conceptualization, Validation, Writing - review & editing. **Maria Luisa Paracchini:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing - review & editing.

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The layers with information on input intensity, the crop systems maps and the crop-management system maps are available upon request and are accessible and downloadable for free from the following link under the condition that this paper is referenced: https://data.jrc.ec.europa.eu/collection/agri4cast.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2020.103793.

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