Soil-related ecosystem services trade-off analysis for sustainable biodiesel production

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Soil-related ecosystem services trade-off analysis for sustainable biodiesel production

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Abstract

There have been strong calls globally to improve the sustainability of biodiesel production from oilseeds. Nevertheless, there is a lack of robust methodologies that are able to depict the local impacts of intensive feedstock production on soil properties and functions. The aim of this study is to quantify and map the potential biodiesel production from oilseed (e.g. soybean, sunflower and rapeseed), and understand possible trade-offs with other soil-related Ecosystem Services (ESs) such as i) habitat for soil organisms (supporting service), ii) soil carbon storage (regulating service), iii) groundwater quality protection (regulating service) and iv) food crops (provisioning service). This method is tested on current intensive agricultural areas of the Veneto region plain of Northern Italy. The results suggest that the study area has a sustainable biodiesel production potential of 20.7 dam^3 per year, which is only 52% of the regional target for the year 2020. The areas that are currently under other annual crops (primarily cereals and maize) can also have a significant further contribution that if exploited would greatly exceed the regional target. This finding indicates that achieving the regional target will be impossible without having significant trade-offs with other soil-related ES or causing land use change. The proposed methodology could provide a tool that could be integrated within (and potentially improve the effectiveness of) biofuel certification schemes, strategic environmental assessments of renewable energy pathways, and regional energy plans.

Keywords: biofuels, oilseed, certification schemes, trade-off analysis, strategic environmental assessment

1. Introduction

Soil contributes to the provision of several Ecosystem Services (ESs), such as food, erosion regulation, and carbon storage [1–5]. Soil biodiversity influences multiple ecosystem processes and functions that are necessary for the provision of many ESs [6-7]. As a result, increasing attention has been devoted to soil management practices such as tillage, fertilization and farming practices [7–9].

In Europe, soil is considered as a non-renewable natural resource, and has become the subject of protection according to the Soil Thematic Strategy [10]. Moreover, the Seventh Environment Action Programme, which has been in force since January 17th, 2014, implies that Member States should increase efforts (i) to reduce soil erosion, (ii) to increase soil organic matter, and (iii) to remediate soil quality in contaminated sites.

As a non-renewable resource, soil is increasingly under stress due to multiple drivers such as urbanization, agricultural intensification and climate change among others [4,5,7,11,12]. Biofuel supply chains may have severe negative impacts on soil as for example due to deforestation [15], competition with food production [19], increased greenhouse gas emissions and loss of soil carbon storage [18–20], land use change [13,15,21], soil degradation [22], and biodiversity loss [15,23,24]. Moreover, high water consumption [25] and air/water pollution [13,15] associated with biofuel value chains can have indirect effects on soil characteristics that can collectively affect "the capacity of a soil to function, within ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health" [4,26]. Furthermore, biomass for bioenergy is a provisioning ecosystem service that may compete with the provision of other ESs whose provision depends on soil such as food crops and carbon sequestration to mention just a few [13,14].

However, according to the EU Renewable Energy Directive (EU RED) 2009/28/EC [27] biofuels are a valuable fuel option that can support Member States in meeting the 10% renewable sources target for transport fuels by 2020. With respect to the sustainability of feedstock production, voluntary schemes and bilateral/multilateral agreements are valuable tools to support local feedstock supply and rural development as reported in COM 2010/C 160/02 [28]. Such schemes can enhance biofuel sustainability [29–31], connect feedstock supply to local production, and support the innovation and development of the agro-food industry in Europe [32,33].

Under the EU RED [27], the European Commission has established some minimum requirements with respect to the sustainability of biofuel feedstock production. These include (i) greenhouse gas emission savings from the entire biofuel lifecycle (i.e. from feedstock production to biofuel consumption); (ii) non-conversion of land with high carbon stocks; and (iii) non-conversion of land with high biodiversity [27]. Biofuels and bioliquids used in the EU must conform to these sustainability criteria if they are to count towards the national renewable energy targets established by EU RED [27], and to access supporting policies (and related funds) [31,33].

However, soil quality receives variable recognition among the 19 certification schemes approved by the European Commission (see Table A1, in the Supplementary Electronic

Material). While not all certification schemes have strong regulations for soil, all account for the contribution of soil to GHG emissions, explicitly through compliance with the methodology for GHG emissions that is included in Annex V.C of the EU RED [27], and its follow-ups [28,34]. Similarly, cross-compliance with good agricultural practices is considered in every certification scheme.

However, only two certification schemes requite the detailed monitoring, and the related audit of soil protection and erosion control, soil organic matter, and soil biological, chemical and physical conditions, i.e. the International Sustainability and Carbon Certification (ISCC) and the Roundtable on Sustainable Biomaterials (RSB). In these schemes, a soil management plan is considered as valuable but it is not compulsory. RED CERT and the Round Table on Responsible Soy (RTSR) consider soil quality indicators. Solomon and Bailis [35] acknowledge that, when it comes to soil, the standards of certification schemes vary in scope, ranging from general principles to specifications in land management and tillage practices. They suggest that cross-compliance and certification (as a formal procedure) are the primary approaches to assess the sustainability of feedstock production [35].

In general, certification schemes have to apply common and harmonized standards as a response to local environmental conditions [31,36], while at the same time reconize that it is necessary to consider the effects of these local characteristics [37,38]. For example, the RSB certification scheme foresees a possible adaptation to specific “political, legal, customary and/or technical social, environmental, cultural, ethical and/or economic conditions in a particular geographic region” [33]. As a result by accepting that sustainable bioenergy systems are embedded in unique social, economic, and environmental contexts [39], the effectiveness of certification schemes often depends on local conditions [37,38]. Moreover, cross-compliance with environmental sustainability criteria (exclusively applied to biomass produced in the EU) is accounted for only through the formal verification of meeting pre-established regulations. There is no on-site impact verification for feedstock production [36,40], especially in relation to the preservation, maintenance and enhancement of soil properties and quality. Moreover, certification schemes appoint feedstock producers individually, at farm level [41,42]. In this respects they cannot account for the possible cumulative effects of feedstock production, or even exclude “considerations of indirect land use change and social and environmental impacts above farm or plantation level” [31,36].

Considering the importance of soils for biofuel sustainability, our study applies concepts from the ecosystem services literature to quantify the potential biofuel production in the Veneto Region of Italy, and its expected trade-offs with other soil-related ES. It views feedstock for biodiesel (oilseeds in this case) as a provisioning ecosystem service (as stated by the Common International Classification of Ecosystem Services [43]) that depends on soil and primary productivity. In particular, the main objectives of the study are to:
i) quantify the fraction of current oilseed production that can be considered as environmentally sustainable for biodiesel production, with respect to soil-related ESs;
ii) identify potential areas that might be converted for biofuel feedstock production (oilseeds), while avoiding significant trade-offs with soil-related ES.

Section 2 outlines the methodology used to elicit biofuel potential and ES trade-offs. Section 3 quantifies biodiesel potential and trade-offs with other soil-related ESs namely i) habitat for soil organisms (supporting service), ii) soil carbon storage (regulating service), iii) groundwater quality protection (regulating service) and iv) food crops (provisioning service). Subsequently these results are discussed with respect to existing gaps in biofuel sustainability certification practices and the energy plan for the Veneto region (Section 4).

2. Methodology

2.1 Study site

Italy produced approximately 1.2 x 10^3 dam^3 of biofuels in 2014, of which 99% was biodiesel, and 99.8% was certified as sustainable. This was primarily for domestic consumption, with aproximately 20.7% of the Italian production capacity being located in the Veneto region [50]. Despite substantial domestic production most of the feedstock consumed in 2014 was imported from other European countries (47%), with the rest coming from developing countries outsite of the EU (of which 46% from Indonesia) [51]. Palm oil, largely from Indonesia and Malaysia, is the primary raw material for biodiesel production in Italy (47%), followed by rapeseed oil (27%) and soybean oil (6%) [51].

Considering its importance for the domestic Italian biodiesel production, we chose the Veneto plains region as the study site for this analysis (Fig. 1). It has a surface area of 10,311.91 km^2 (56% of the regional total surface) and is part of the soil region of the “Po plain and moraine hills” [44]. It is characterized by quaternary alluvial and glaciofluvial deposits, with an average slope of 1% and altitude that ranges between sea level at the coast of the Adriatic Sea to 70 m above mean sea level.

Soil degradation in the Veneto plain region is mostly related to urbanization and intensive agriculture (Fig. A1, Supplementrary Electronic Material). The main oilseeds produced are soybean (*Glycine max* L.), sunflower (*Helianthus annuus* L.) and rapeseed (*Brassica napus* L.). For our study, yield conversion parameters are calculated for areas that overlap with the administrative boundaries of the Provinces as delineated by ISTAT [45]. These provinces represent areas with the same climatic conditions, which is consistent with the bioenergy potential study of Motola et al. [46].

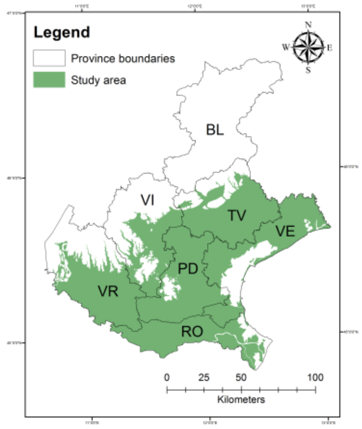

Fig. 1: Location of study area within the Veneto Region. Province boundaries are highlighted: BL = Belluno, TV = Treviso, VI = Vicenza, VR = Verona, VE = Venezia, PD = Padova, RO = Rovigo.

For our study, we consider 76% of the entire Veneto region (i.e. 7,847.35 km^2) (Table 1). Artificial surfaces, natural areas, wetlands and water bodies (i.e., land classes 1, 3, 4, and 5 in the first level of the CORINE Land Cover Classification) are not considered. Thus, the potential trade-offs due to indirect land use change [47–49], are excluded from this study. The areas under oilseeds (i.e. soybeans, sunflowers and rapeseed) and other arable uses are derived from the Land Cover Map provided by Veneto Region. The map outlines the land cover on five levels, adopting the CORINE Land Cover nomenclature, at a scale of 1:10.000.

Table 1: Land use classes and their extent.

Land use	Crop types	Surface (km^2)
Soybean	Soybean	910.15
Sunflower	Sunflower	37.86
Rapeseed	Rapeseed	254.81
Other arable land	Cereals, maize, beetroot, tobacco and other arable land in general	5052.78
Not available	Greenhouses, horticulture, orchards, nurseries, complex cultural systems established by law, perennial crops in general, rice, vegetable gardens	1591.74
Total		7847.35

2.2 Research Approach

This study assesses the impact of biofuel feedstock production from rapeseed, soybeans and sunflowers, on soil-related ESs considering ecological variables such as soil characteristics and soil hydrological conditions. It expands the framework proposed by Gissi et al. [40], that defines the sustainable biodiesel potential as "the fraction of energy potential whose exploitation causes no harms to other ES delivered by the sources of renewable energy" (p. 2). Following the recent acknowledgement of Biomass-Based Energy Sources (BBES) as a provisioning ecosystem service by The Common International Classification of Ecosystem Services (CICES) [43], we interpret oilseed production as part of the BBES and hence a provisioning ecosystem service.

Our analysis starts from the assumption that trade-offs may occur between ecosystem services when the provision of one (or more) service inhibits the provision of others [52,53]. Agro-ecosystems are often multi-functional landscapes that can provide ESs that are synergistic or complementary [54,55]. For example, some agricultural products are essentially raw materials that can be used for food (e.g. food crops) or feedstock for biofuel production (i.e. BBES), that are both derived from primary production in agro-ecosystems [56]. In such systems trade-offs with other ecosystem services can occur through different mechanisms:

i) compete for land, e.g., land diversion from food production and/or other uses to BBES feedstock production;
ii) compete for the end-product, e.g. use of raw materials that are initially devoted for human or livestock consumption;
iii) interfere in ecological processes that provide other ESs, e.g., degradation of soil that acts as habitat to micro-organisms, due to the intensive use of agro-chemicals to support intensive feedstock production or the uptake of residues that are important for the biological cycle of soils [57–59];

iv) indirect effects from the production of biofuel crops, e.g., emission of agrochemicals that degrades groundwater quality in areas with soil that are vulnerable to nitrates.

Finally, we consider that ES trade-offs can have different severities depending on:

i) the previous land use (when there is a land transition to biofuel crops);
ii) the level of crop productivity in the previous land use (when there is a different final use of the end product);
iii) the level of ES provision of the ES negatively affected by conversion (the higher the ES provisioning level of the original land use, the more severe is the trade-off).

2.3 Methodological steps

To assess the amount of biofuel that can be produced from BBES feedstock in the Veneto region that does not affect other soil-related ESs, we follow seven methodological steps (Fig. 2):

Step 1) - identify crop types and areas within the study site to perform the analysis;
Step 2) - calculate the potential biodiesel production from oilseeds (i.e. BBES feedstock) as if it was all used for biodiesel production;
Step 3) - identify and map other soil-related ESs, which can potentially compete with oilseed production;
Step 4) - identify and map pair-wise trade-offs between oilseed production and other soil-related ESs (according to the types of relationship explained in Section 2.2);
Step 5) - analyze tradeoff combinations between oilseeds and the other soil-related ESs according to the combined severity of pair-wise relationships;
Step 6) - calculate the sustainable biodiesel potential from current oilseed production that does not compete, interfere or interact negatively with other soil-related ESs;
Step 7) - identify areas for potential oilseed production (among areas currently devoted to the intensive production of annual crops such as cereals and maize).

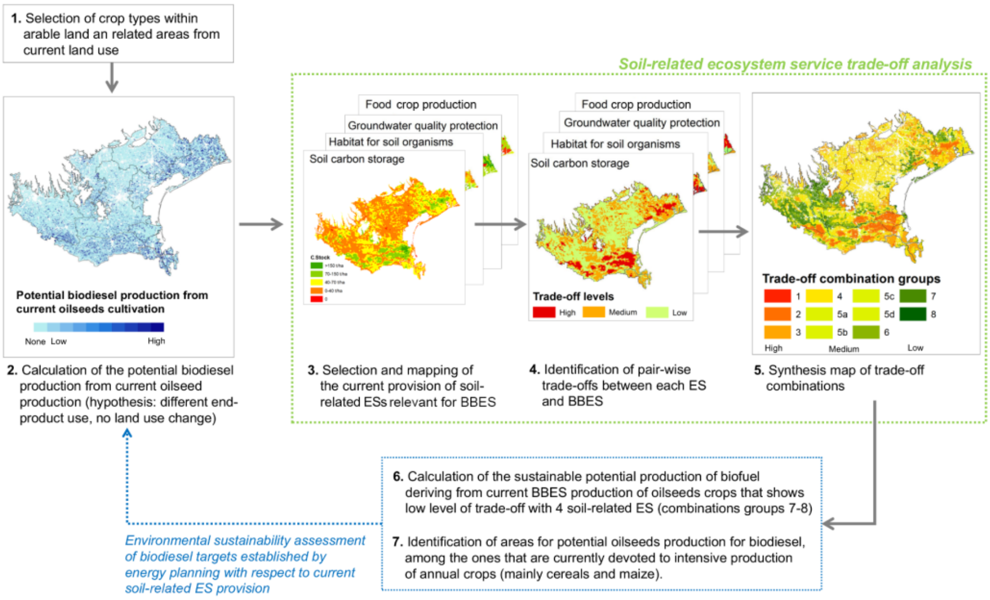

Fig. 2: Conceptual framework of the step-by-step analysis

In this study we consider that the change in the use of the final product (oilseeds) implies a change in agricultural practices to produce oilseed feedstock for biodiesel. “Land cover” is defined as “the observed (bio)physical cover on the earth's surface”, while “land use” is defined “by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it”, in line with the definitions given by United Nations Food and Agriculture Organization (FAO) [60].

Based on the above definitions, for Steps 1-6, we consider that no land cover change occurs. In other words, we assume that there is no change from natural land cover to agriculture, nor any change in crop type. Instead, we consider that only land use change occurrs. This is because we assume that oilseed feedstock production for bioenergy entails an intensification of agricultural practices, when compared to oilseed production for food/feed. This is demonstrated by the fact that oilseed feedstock production for bioenergy implies i) shifting from traditional crop rotations to a continuous oilseed production [61,62] and ii) increasing fertilizer application to boost oilseed yields [63]. Even though farmers attempt to boost yields when growing oilseeds for food, oilseed production for bioenergy requires their continuous and stable production to supply feedstock-processing facilities. This makes crop rotation and organic farming practically impossible, as the intensification of agricultural practices for the production of biofuel feedstock can alter the provision of ESs as studies in several food production systems around the world have shown [64–66]. To calculate the potential oilseed production for biodiesel we only consider areas that are currently devoted to oilseed production for food. However, we assume that agricultural practices in these areas will change in order to allow for the change in the final use of the oilseed (i.e. from food to bioenergy).

Step 1 extracts from the CORINE land cover map (an arable land class at the first level of the CORINE Land Cover classification) the crop types and related production areas within the case study site. This analysis is performed for current land uses related to annual oilseed crops (i.e. rapeseed, sunflowers, soybeans) and other annual crops (e.g. maize, cereals), but excludes perennial crops and other types of cultivation. These agricultural areas are classified into five land use groups (Table 1). Artificial surfaces, natural areas, wetlands and water bodies (i.e., land classes 1 and 3-5 at the first level of the CORINE Land Cover Classification) are not considered. This excludes potential land cover transitions from this study due to the competition between land uses.

Step 2 quantifies the potential biodiesel production in the study site. This potential feedstock production is defined as the fraction of the gross energy that can be harvested by the energy conversion system, assuming that all suitable crops are destined for oilseed production in accordance with legal and technological limitations [40,67]. Thus, the potential biodiesel production is calculated only from the current land use destined to oilseeds. The algorithm for calculating the potential biodiesel production (Eq. 1) is modified from [68] as follows:

$$BP_{ij} = Y_{ij} \cdot A_{ij} \cdot E_i \qquad \text{(Eq.1)}$$

where, BP_{ij} is the average energy production per hectare that can be achieved for each oilseed crop type (i) (i.e. rapeseed, soybeans, sunflowers) within province j, Y_{ij} is the average yield of each crop type in each province (see Table A2 in Supplmentary Electronic Material), A_{ij} is the area of each crop type in each province as obtained by the Land Cover map (Veneto Region

2013) and E_i is the specific energy provision capacity, which is considered as the biodiesel yield, with specific values for each crop type (see Table A3 in Supplementary Electronic Material). Average yields for each crop type have been calculated using the ISTAT database for the time period between 2006 and 2015 [69]. Unlike Gissi et al. [40], this paper maintains the administrative domains of provinces to calculate the yields, and as a result crop yields vary between provinces (Table A2 in Supplementary Electronic Material).

Step 3 maps the main soil-related ESs in the study area. Initially, we identify through a literature review those soil-related ESs that are most affected by the cultivation of biofuel feedstock (Table 2). In total four ESs are selected and mapped individually for the case study area, namely carbon storage (a regulating service), habitat for soil organisms (a supporting service), groundwater quality protection (a regulating service), and food production (a provisioning service).

Table 2: Relationship between oilseed production for biofuel (BBES) and other soil-related ESs.

ES class	Ecosystem functions and processes	Ecosystem services	Trade-off type	Mechanism	Map resolution	Map sources	References
Supporting	Habitat provision	Habitat for soil organisms	Interference	Cropping systems affect soil biota communities	500m	[79] for Organic Carbon fraction, [80] for Bulk Density	[57-59]
Regulating	Soil buffering	Groundwater quality protection	Indirect impact	Increased tillage and agro-chemical application affect the quality of water bodies by increasing nitrogen leaching	1:250,000 (scale)	[94]	[89,90]
Regulating	Organic matter accumulation	Soil carbon storage	Interference	Annual crop production decrease the accumulation of soil organic carbon, particularly when crop residues are not retained in fields	1 km	[71]	[87,88]
Provisioning	Primary production	Food crop production	Competition in end-product use	Trade-offs between biofuel and food provision occur both through land conversion and competition for the use of final products	1:250,000 (scale)	[105]	[99] [102-104]

The indicators selected for mapping the soil-related ESs reflect the context of the study site and the geographical scale of policy questions. In more detail biofuel production (and its related targets) are managed at the regional scale (through the Regional Energy Plan of Veneto Region [70]), and operationally implemented at the provincial administrative level. Soil-related ESs are mapped in the case study area by considering the climatic and environmental characteristics of each province. The selected indicators for each soil-related ES are explained in Section 2.4.

Step 4 analyzes the potential conflicts between ESs and BBES across three trade-off levels (i.e. low, medium and high) for each area. To rank trade-offs across these three levels, appropriate thresholds are defined (Table 3). These thresholds distinguish among a positive (low), medium (medium) or negative (high) trade-off relationship between the oilseed production and each soil-related ES.

Table 3: Thresholds for trade-off levels for each soil-related ES.

	Trade-off levels

Ecosystem Services	High	Medium	Low	References
Habitat for soil organisms	>0.235	0.188-0.235	<0.188	[4]
Carbon storage	> 70 t ha^{-1}	40-70 t ha^{-1}	< 40 t ha^{-1}	[71]
Groundwater quality protection	“Low”	“Moderatly low” “Moderatly high”	“High”	[94,97]
Food crop production	“Intensive”, “Intensive/Moderate”	“Moderate”	“Limited” and “Moderate/Limited”	[4,40,105,107]

Table 3 summarises the thresholds for the levels of ES provision. In a nutshell, we relate ES provision to the current state of the soil in each area, according to current land use (obtained from Step 1) and other characteristics such as soil texture and organic matter content. Then, according to the capacity of each area to provide soil-related ESs (i.e. high, medium and low capacity), we identify the actual trade-off levels with oilseed production. For example, according to the Regional Agency for Environmental Protection of the Veneto Region (ARPAV) [71], areas that have soil carbon contents of >70 t ha^{-1} have a high capacity to deliver carbon storage ES. If such areas are used to produce biodiesel feedstock, then the loss of regulating ESs related to carbon storage will be more severe when compared to areas with lower soil carbon content (e.g. 40 t ha^{-1}).

The underlying hypothesis here is that soils can either deliver directly or contribute to the delivery of some ES such as habitat for soil organisms, carbon storage, and food production. They should be conserved or utilized sustainably, because once this capacity is lost, it is difficult and costly to be restored artificially [72]. On the other hand, the trade-off mechanism for groundwater quality protection is a bit different. Trade-offs between feedstock production and water regulating ES are expected to be low in areas with soils that have a high capacity to buffer nitrate. This is because the increased fertilizer application for the production of oilseeds for bioenergy at an industrial scale is expected to be mitigated by the natural filtering capacity of the soil. Conversely, trade-offs with potential feedstock production are expected to be high in areas of low groundwater quality regulation potential.

Table 3 summarises the thresholds related to the current capacity of soil to provide ES under prevailing environmental and agricultural management conditions (e.g. fertilizer use, tillage). These tresholds were identified according to a literature review of peer-reviewed papers and policy documents that define acceptable trade-off levels for maintaining ES provision. Thresholds for indicators that were not already ranked in classes in the background literature were determined by ranking values into three quantiles, with the higher quantile associated with a high trade-off level with feedstock production.

Step 5 obtains various combinations of trade-off levels by overlapping ES maps with ArcGis 10.3 (ESRI). These combinations were classified into eleven groups (Table 4) according to the severity of pair-wise trade-offs. In essence this ranking represents a progressively more severe scale of trade-offs between potential BBES feedstock production and other soil-related ES. The correlation between BBES feedstock production and other soil-related ESs was statistically tested with a Spearman's Rank Coefficient test, both at the regional and the provincial level. The ranking scores were used as input values, as the different soil-related ESs are originally measured through different variables.

Table 4: Trade-off groups ranked from the most severe (Group 1) to the least severe (Group 8).

Trade-off group description	**No.**
High trade-off levels for all 4 ESs	Group 1
High trade-off levels for 3 ESs	Group 2
High trade-off levels for 2 ESs	Group 3
High trade-off levels for 1 ES plus at least one ES at medium trade-off level	Group 4
High trade-off level for Habitat for soil organisms, and low trade-off level for the other ESs	Group 5a
High trade-off level for Soil Carbon Storage, low trade-off levels for other ESs	Group 5b
High trade-off level for Groundwater Quality Protection, low trade-off level for other ESs	Group 5c
High trade-off level for Food Crop Production, low trade-off level for other ESs	Group 5d
Medium trade-off level for at least 3 ESs, no High trade-off level for other ESs	Group 6
Medium trade-off level for at least 1 ES, no High trade-off levels for others ESs	Group 7
Low trade-off levels for all ESs	Group 8

Step 6 calculates the distribution of potential oilseed production from BBES feedstock within different trade-off combination groups. The aim here is to assess both the amount of oilseed production that can be produced sustainably and its spatial distribution, when considering the current availability of rapeseed, soybeans and sunflowers.

Step 7 identifies and maps other potential suitable areas for sustainable feedstock production. With respect to "other arable land" (mainly under maize and other cereals) we only analyze its capacity to provide soil-related ESs other than feedstock, and capture the potential trade-offs with BBES. Subsequently, we identify areas that can have low trade-off combinations with other soil-related ESs, and we designate them as areas of potential land use change (i.e. from maize and other cereals, to oilseeds for bioenergy). In particular the potentially available areas for feedstock expansion were extracted from the land use category "other arable land" in Table 1, and especially those areas that have low expected trade-offs with soil-related ESs. This calculation is only meant to verify how much area would be needed to achieve the Energy Plan targets in the Veneto Region (and if this amount is actually available in the region). The estimated gap is then calculated in relation to the potential conversion of land among the different provinces.

2.4. Assessment of Soil-related ES

2.4.1. Habitat for soil organisms

Soil organisms can sustain several ecosystem processes and maintain above and below-ground ecological functions [73,74]. Soil organisms are crucial for nutrient [75] and carbon cycling [76], pathogen control [77], and the degradation of synthetic pesticides or industrial contaminants [78]. However, the cultivation of biofuel feedstock can strongly alter soil biota communities [57,58], for example, by decreasing the microbial processing potential [61] and arthropod abundance [11,59].

To map the capacity of soils to offer habitat to biodiversity (a supporting ecosystem service), we apply the indicator proposed by Calzolari et al. [4] as follows (Eq. 2):

$$BIO_{0-1} = (\log OC_{0-1} - \log BD_{0-1}) + QBS_{ar\,0-1} \quad \text{(Eq. 2)}$$

where BIO is the potential of soil to offer habitat to biodiversity, OC is the organic mass fraction of the soil (%) in the first 30 cm of soil (derived from [79]), BD is the bulk density (t m^{-3}) (derived from [80]), and QBSar is an index for assessing the biological quality of the soil based on the abundance of microarthropod groups (ar) [81,82]. We set the QBSar at a low level (=0.25) for the entire study [4], given the lack of spatially-explicit information on agricultural practices and intensive management for the entire Veneto plain. All variables were standardized between 0 and 1.

2.4.2 Soil carbon storage

Soil organic carbon (SOC) plays a crucial role in agro-ecosystems related to soil structure, water cycling, and nutrient availability, among others [83]. Moreover, the soil is the most important terrestrial carbon pool [84,85] so it provides important regulating ecosystem services related to carbon sequestration and climate change regulation [86]. However the cultivation of annual crops such as oilseeds can cause the decrease of SOC if conventional intensive agricultural practices are adopted [22,87,88]. This can create trade-offs between SOC preservation (and the climate regulation services it offers) and the cultivation of bioenergy feedstock [68].

The SOC content was mapped in the study area based on the regional carbon stock map developed by the Regional Agency for the Environment of Veneto [71]. The indicator used in our study is the amount of SOC (in t ha^{-1}) in the first 30 cm of soil. The map is developed at a 1 km-pixel resolution by cross-mapping the Veneto region map of soil types with data from field measurements. However, it should be mentioned that this indicator does not account for the superficial humic layer, which is an important component of soil in mountains of the region [89]. However, as the study area includes only the Veneto region plains, this effect is expected to be negligible.

2.4.3 Groundwater quality protection

Soil is a natural filter that can protect groundwater from the leaching of chemicals, such as fertilizers and pesticides. The soil attenuation capacity depends on the vertical retention of water-soluble pollutants, which, in turn, depends on soil characteristics, climatic/hydrological conditions, and agronomic practices [90–92]. However, as discussed in Section 2.3 in the case of biofuel crops, agricultural management practices are strongly oriented towards intensive tillage and the massive application of agro-chemicals [63,93]. This means that the extensive use of agrochemicals, combined with soil disturbances from tillage, could negatively affect the provision of the ecosystem services related to water quality protection (a regulating ecosystem service).

The Regional Agency for Environmental Protection of the Veneto Region (Agenzia Regionale per la Protezione Ambientale Regione Veneto - ARPAV) mapped nitrogen retention capacity [94], by applying the MACRO model for the simulation of the hydrological balance [95], and the SOIL-N model for the simulation of the nitrogen balance [96]. The MACRO model is applied for 31 different soil-climate-aquifer conditions, considering the same cropping system (maize monoculture) for a period of 10 years (1993-2002). Agricultural practices are considered to be the same in all areas within the Veneto plain, with the exception of irrigation. The SOIL-N model is applied to simulate the relation between hydrological fluxes and nutrient leaching.

The output of the above analysis is divided into four categories that represent the protective capacity of the soil according to leaching fluxes and nitric oxide loss. As the index represents the potential nitrate leaching, we use inverse values to denote the soil-related groundwater quality protection potential (i.e., the nitrogen retention capacity), see [97]. In other words, the higher the soil capacity to buffer nutrient leaching is, the lower the threat to groundwater quality, and the higher the level of the water quality protection ESs provided by the soil.

2.4.4 Food crop production

The direct use of crops and/or agricultural land for feedstock production has raised important concerns as exemplified with the "fuel vs food" controversy, e.g. [98]. The actual trade-off between feedstock and food crop production mainly relates to the final end-use of the crop [99] (i.e. energy conversion vs food consumption) and the direct and indirect land use change effects [100]. Such trade-offs can have important ramifications for food security [13], but there is conflicting evidence about their actual effect on food prices [101–104].

In our study, potential food crop production was mapped in the study area using the Land Capability Classification (LCC) index [105]. The LCC index has already been applied for ES mapping [4,40], based on the principle that the most productive agricultural land should not be targeted for bioenergy production [40,106]. The LCC map is available at a 1:50,000 scale for the Veneto region [107], and classifies land according to its potential to support agricultural production considering 13 characteristics related to soil, water, erosion risk and climate.

3. Results

3.1 Potential biodiesel production and provision of soil-related ESs

Table 5 shows the maximum potential biodiesel production that is achievable under the hypothesis that all current oilseed feedstock will be used for biodiesel production. Total biodiesel potential in the region was estimated at approximately 97.6 dam^3. At the regional scale, the potential biodiesel production from current land use is primarily attributed to soybeans (65.8%), followed by rapeseed (29.3%) and sunflowers (4.9%). Sunflower production is slightly more efficient in terms of the potential biodiesel production per unit area (120.3 m^3 km^{-2}), followed by rapeseed (110.1 m^3 km^{-2}). Soybean, on the other contrary, is a largely inefficient biofuel feedstock (71.4 m^3 km^{-2}).

Table 5: Annual potential biodiesel production from current levels of feedstock production.

			Not available	Other arable land	Rapeseed	Soybean	Sunflower	Tot
Belluno	Area	km^2	260.00	60.00	0.00	0.00	0.00	320.00
		%	82.10%	17.69%	0.00%	0.00%	0.00%	100.00%
	Biodiesel Potential	m^3	0.00	0.00	0.00	0.00	0.00	0.00
		%	0.00	0.00	0.00	0.00	0.00	0.00
Padova	Area	km^2	228.31	1 124.10	34.50	122.52	1.91	1 511.34
		%	15.11%	74.38%	2.28%	8.11%	0.13%	100.00%
	Biodiesel Potential	m^3	0.00	0.00	3 563.16	7 903.85	213.16	11 680.17
		%	0.00%	0.00%	30.91%	67.19%	1.90%	100.00%
Rovigo	Area	km^2	136.68	904.57	57.60	245.53	9.03	1 353.42
		%	10.10%	66.84%	4.26%	18.14%	0.67%	100.00%
	Biodiesel Potential	m^3	0.00	0.00	6 463.29	17 784.69	991.33	25 239.31
		%	0.00%	0.00%	25.64%	70.25%	4.11%	100.00%
Treviso	Area	km^2	382.09	746.40	46.35	119.59	0.00	1 294.43
		%	29.52%	57.66%	3.58%	9.24%	0.00%	100.00%
	Biodiesel Potential	m^3	0.00	0.00	5 061.88	8 919.89	0.00	13 981.78
		%	0.00%	0.00%	37.32%	62.68%	0.00%	100.00%
Venezia	Area	km^2	216.18	958.07	23.97	282.51	2.15	1 482.88
		%	14.58%	64.61%	1.62%	19.05%	0.15%	100.00%
	Biodiesel Potential	m^3	0.00	0.00	2 881.27	20 625.44	282.79	23 789.50
		%	0.00%	0.00%	12.65%	86.06%	1.29%	100.00%
Vicenza	Area	km^2	168.32	496.89	55.95	43.55	0.73	765.44
		%	21.99%	64.92%	7.31%	5.69%	0.09%	100.00%
	Biodiesel Potential	m^3	0.00	0.00	5 812.39	3 038.30	87.23	8 937.91
		%	0.00%	0.00%	64.75%	34.21%	1.04%	100.00%
Verona	Area	km^2	459.89	822.70	36.44	96.46	24.04	1 439.53
		%	31.95%	57.15%	2.53%	6.70%	1.67%	100.00%
	Biodiesel Potential	m^3	0.00	0.00	4 261.17	6 746.09	2 979.93	13 987.19
		%	0.00%	0.00%	31.30%	46.72%	21.99%	100.00%
Veneto Region	Area	km^2	1 591.74	5 052.78	254.81	910.16	37.86	7 847.35
		%	20.28%	64.39%	3.25%	11.60%	0.48%	100.00%
	Biodiesel Potential	dam^3	0.00	0.00	28.04	65.02	4.55	97.62
		%	0.00%	0.00%	29.26%	65.85%	4.89%	100.00%
Regional conversion parameter	BP/A	m^3 km^{-2}	0.00	0.00	110.06	71.44	120.30	81.16

The provinces with the highest biodiesel potential from soybeans were Padova (67.2%), Rovigo (70.2%), Treviso (62.6%) and Venezia (86.1%). Rapeseed was the most dominant in Vicenza (64.7%), while the potential for the three feedstocks was more balanced in Verona (31.3% from rapeseed, 46.7% from soybeans, and 22% from sunflowers). Fig. 3 shows the spatial distribution of the potential biodiesel feedstock production according to the current land use and in relation to different conversion parameters, which are specific for each feedstock and province (see Table A2 in Supplementary Electronic Material).

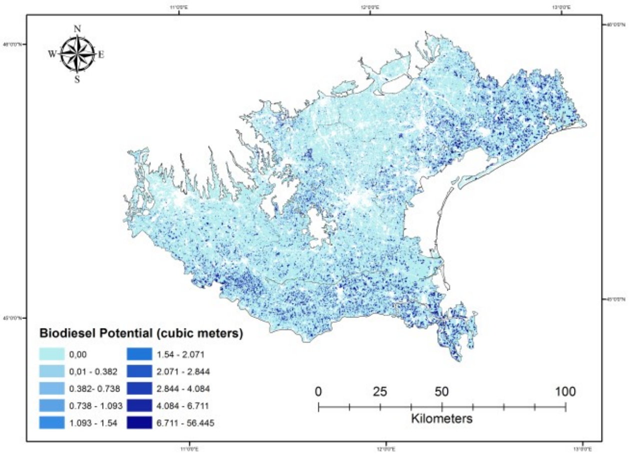

Fig. 3: Spatial distribution of the annual potential biodiesel production in the Veneto plain region.

Fig. 4-5 map individually the different soil-related ESs such as carbon storage, habitat for soil organisms, groundwater quality protection, and food production for the plains of the Veneto Region. The distribution of these ES varies between provinces according to their distinct environmental characteristics and soil properties. For example, as the indicator for "habitat for soil orgasisms" is a function of bulk density (Eq. 2), we found higher values close to rivers where soils with coarser texture are prevalent. Similarly, groundwater quality protection is low in areas of the southern part of the region (where the higher concentration of soil organic matter is responsible for nitrogen mineralization), and on higher plains (where soil classes with coarser texture are more prevalent).

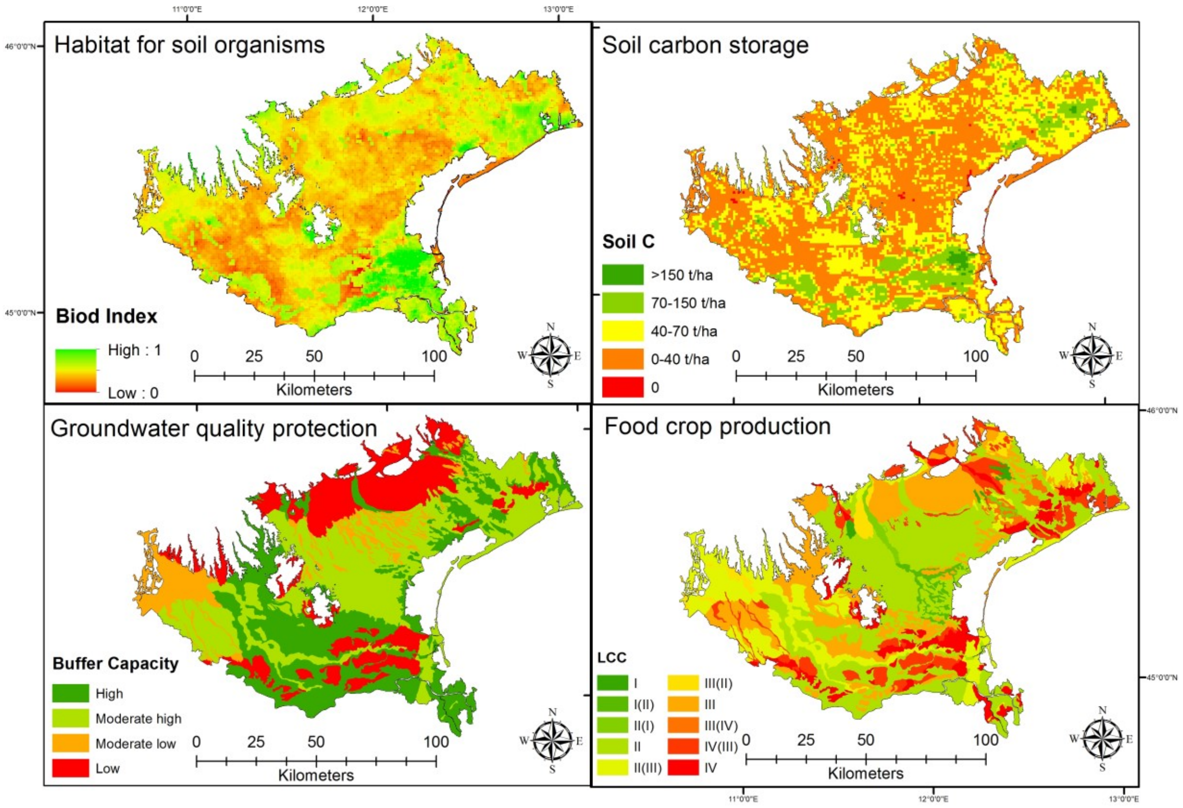

Fig. 4: Spatial distribution of the four soil-related ESs

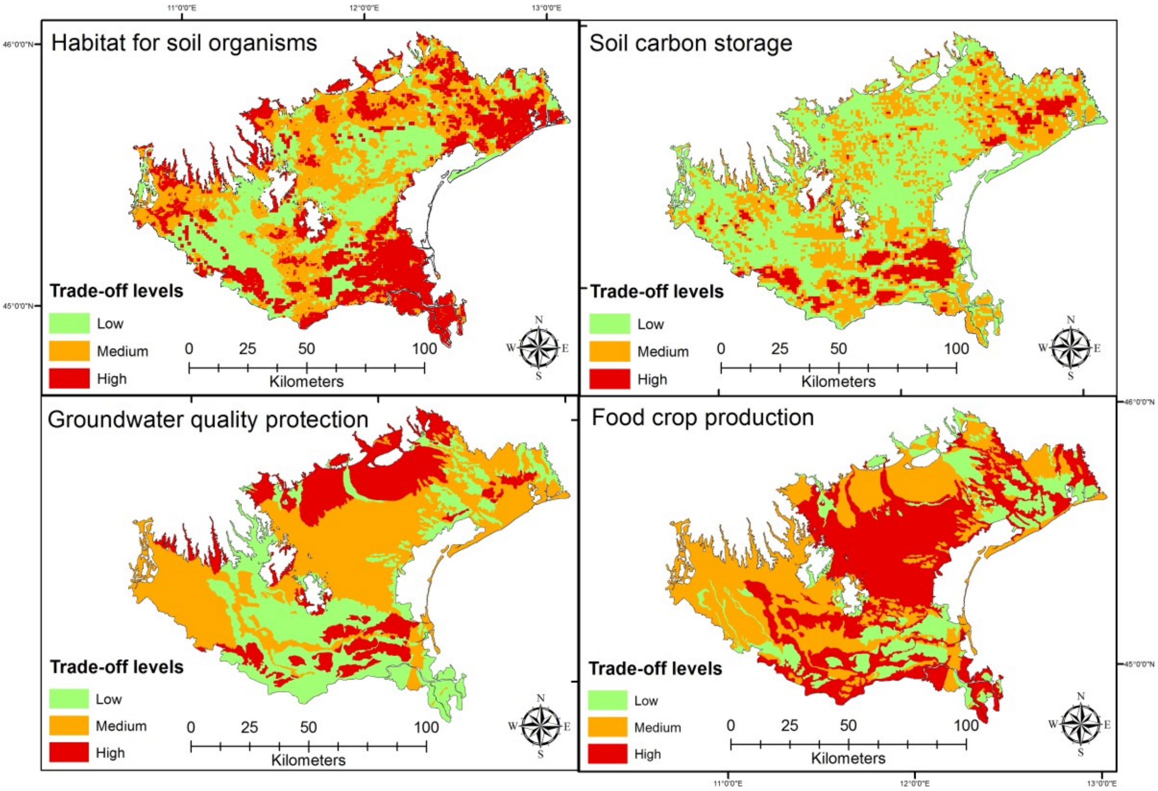

Fig. 5: Spatial distribution of the trade-off levels of the four soil-related ESs with BBES.

3.2 Relationship between soil-related ESs and potential biodiesel production

Table 6 summarises for the entire study area (i.e., the regional level) the trade-offs between potential biodiesel production and individual soil-related ES. There is a higher potential conflict between rapeseed production and food production, as about 43.7% of rapeseed biodiesel potential is located in areas of high food production. The lowest potential trade-offs of rapeseed production were with soil carbon storage, as only 6.8% of rapeseed biodiesel potential is located in areas with high levels of soil carbon storage. On the other hand extensive areas of soybean biodiesel potential have a high possible trade-offs with habitat for soil organisms (46.9%) and food production (43.4%). Trade-offs with sunflower biodiesel potential were the highest with carbon storage (49.4%) and habitat for soil organisms (40%).

Table 6: Distribution of potential Biodiesel Production (BP) and Areas (A) per land use class, with respect to the trade-off levels of the four soil-related ESs.

	Soil-related ESs							
	Carbon storage		Habitat for soil organisms		Groundwater quality protection		Food crop production	
Trade-off level	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)
Other arable land								
High	-	13.22	-	34.92	-	22.03	-	42.64
Medium	-	41.88	-	32.26	-	44.60	-	37.54
Low	-	44.90	-	32.81	-	33.36	-	19.81
Tot		100.00		100.00		100.00		100.00

Rapeseed								
High	6.82	6.63	36.69	36.45	22.59	23.02	43.66	44.43
Medium	43.88	44.01	36.04	36.44	45.08	44.50	38.36	37.78
Low	49.30	49.36	27.27	27.11	32.32	32.48	17.98	17.80
Tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Soybean								
High	31.46	20.23	46.86	46.55	18.98	18.89	43.37	43.35
Medium	48.25	48.17	26.14	26.21	40.97	41.14	26.33	26.51
Low	20.29	31.60	27.00	27.23	40.05	39.97	30.30	30.15
Tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Sunflower								
High	49.44	48.86	39.99	40.45	16.08	16.39	24.74	25.39
Medium	32.41	32.85	12.29	12.55	56.38	54.90	51.74	51.00
Low	18.15	18.29	47.72	47.00	27.54	28.71	23.52	23.60
Tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Veneto region								
High	16.24	14.01	43.55	36.71	19.90	21.58	42.55	42.71
Medium	46.20	42.82	28.36	31.44	42.93	44.16	31.09	36.03
Low	37.56	43.17	28.09	31.85	37.18	34.26	26.36	21.26
Tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 7 outlines trade-off distributions between provinces. Higher trade-off levels are found with habitat for soil organisms in Rovigo (for 70.5% of the potential biodiesel production in the region) and with food production in Padova (60.4%). Spearman's correlation values (r_s) are shown in Table 8, with some ES relationships being statistically significant (p-value<0.05) in some provinces, and not significant at the regional level (or vice versa).

Table 7: Distribution of potential Biodiesel Production (BP) and Areas (A) per province, with respect to the trade-off levels of the four soil-related ESs.

	Soil-based ESs							
	Soil carbon storage		Habitat for soil organisms		Grounwater quality protection		Food crop production	
Trade-off level	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)
Belluno								
High	0.00	0.00	0.00	44.72	0.00	100.00	0.00	0.00
Medium	0.00	59.95	0.00	0.90	0.00	0.00	0.00	0.00
Low	0.00	40.05	0.00	54.38	0.00	0.00	0.00	100.00
tot	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00
Padova								
High	9.79	8.10	21.91	21.12	12.76	14.71	60.45	59.86
Medium	47.65	45.12	41.05	41.04	49.86	49.17	27.63	30.16
Low	42.56	46.78	37.04	37.83	37.38	36.12	11.91	9.98
tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Rovigo								
High	22.20	21.61	70.53	59.44	23.96	23.24	52.22	52.38
Medium	51.22	45.94	14.44	20.19	6.90	10.24	15.17	18.95
Low	26.58	32.45	15.03	20.37	69.14	66.52	32.61	28.68

tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Treviso								
High	6.13	4.77	29.16	30.95	31.25	48.39	38.79	32.38
Medium	52.23	49.35	45.80	46.63	46.55	33.94	38.58	45.17
Low	41.64	45.88	25.05	22.42	22.20	17.67	22.63	22.45
tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Venezia								
High	23.98	24.44	51.46	49.85	14.20	15.45	39.20	41.22
Medium	47.95	42.55	23.45	21.42	58.24	58.54	22.64	22.82
Low	28.06	33.02	25.09	28.74	27.56	26.01	38.16	35.97
tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Verona								
High	16.13	7.89	29.15	22.28	13.64	9.59	14.57	14.26
Medium	28.42	33.72	20.06	28.77	67.57	67.71	63.56	75.18
Low	55.45	58.39	50.79	48.95	18.79	22.70	21.88	10.56
tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Vicenza								
High	3.79	2.83	20.83	22.04	25.05	29.19	50.01	40.77
Medium	44.18	41.82	49.47	45.69	50.95	44.25	39.74	50.50
Low	52.03	55.35	29.70	32.27	24.00	26.56	10.25	8.73
tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Veneto region								
High	16.24	12.42	43.55	35.08	19.90	22.35	42.55	40.28
Medium	46.20	43.06	28.36	32.86	42.93	44.63	31.09	39.56
Low	37.56	44.53	28.09	32.06	37.18	33.01	26.36	20.16
tot	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

For example, habitat for soil organisms, soil carbon storage and groundwater quality protection showed significant correlation with potential biodiesel production at the regional scale, while they were not significant in 4 out of the 6 provinces. Conversely, the trade-off between potential biodiesel production and food production was significant in 3 out of the 6 provinces, while it was not significant at the regional scale. When significant, the r_s ranged between -0.408 and +0.3705.

Overall, negative correlations were observed for trade-offs with soil carbon storage and groundwater quality protection, and positive with habitat for soil organisms and food production. This means that oilseed crops that are suitable for biofuel production are currently distributed on areas that already have low levels of soil carbon storage and a poor capacity to buffer nutrient leaching to groundwater. On the other hand, these areas are highly productive for food crops and have a high capacity to support soil biodiversity.

Table 8: Statistical correlations between biodiesel potential and soil-related ESs at regional (Veneto) and at provincial level.

	Region	Provinces					
Ecosystem services	Veneto	Rovigo	Padova	Treviso	Venezia	Vicenza	Verona
Habitat for soil organisms							
r_s	0.222	0.3705	0.0708	0.1455	0.31	-0.0108	0.0634
n°	80	42	74	71	63	65	51

p-value	**0.0484**	**0.0177**	0.5452	0.2234	**0.0146**	0.9309	0.6538
Soil carbon storage							
r_s	-0.3349	-0.2438	-0.2207	-0.3997	-0.1711	-0.408	-0.2725
n°	80	42	74	71	63	65	51
p-value	**0.0029**	0.1185	0.0593	**0.0008**	0.178	**0.0011**	0.054
Groundwater quality protection							
r_s	-0.3299	-0.2657	-0.2368	0.1252	-0.0929	-0.2761	-0.1526
n°	80	42	74	71	63	65	51
p-value	**0.0034**	0.0889	**0.0431**	0.2948	0.4646	**0.0272**	0.2806
Food crop production							
r_s	0.0308	0.3489	0.3538	0.1229	0.306	0.0495	-0.0551
n°	80	42	74	71	63	65	51
p-value	0.7846	**0.0255**	**0.0025**	0.3037	**0.016**	0.6923	0.6967

Note: r_s = Spearman's rank correlation; n° = number of trade-off combinations. Significant correlations (p-value < 0.05) are highlighted in bold.

3.3 Sustainable potential biodiesel production

The sustainable potential biodiesel production was calculated through a trade-off analysis for different trade-off groups that are defined and listed in Table 4. These trade-off groups range between those that have very severe trade-offs (Group 1, i.e. all trade-offs are at a high level) to those that have the least severe trade-offs (Group 8, i.e. all trade-offs are at a low level).

We consider as sustainable the biodiesel potential that comes from areas where trade-offs fall under trade-off Groups 6-8 (i.e., the groups that are not involved in trade-offs at a high level) (Section 2.2). The sustainable biodiesel potential corresponds to 20.7 dam^3 per year, which is equal to 21.2% of the total current biodiesel potential in the Veneto plain (Table 9). The rest of the biodiesel potential falls into groups with at least one trade-off at a high level, but we could identify no areas with a Group 1 type of trade-off. This means that there are no areas where all four soil-related ESs simoultaneously have high trade-offs with potential BBES feedstock production.

Table 9: Distribution of potential Biodiesel Production (BP) and Areas (A) among trade-off groups.

	Belluno		Padova		Rovigo		Treviso		Venezia		Verona		Vicenza		Veneto R		
Trade-off Group	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)	BP (%)	A (%)	BP (dam^3)	BP (%)	
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
2	0.00	0.00	7.60	5.97	20.64	19.14	1.48	1.30	15.02	15.88	11.74	3.92	2.88	1.96	11.77	12.06	
3	0.00	44.72	8.47	9.62	36.28	29.93	19.59	23.71	19.50	17.83	6.83	6.36	12.75	15.36	19.62	20.10	1,
4	0.00	44.01	60.16	61.61	26.02	27.05	59.20	62.45	43.58	44.55	19.46	22.32	62.70	56.01	40.56	41.55	3,
5a	0.00	0.00	0.05	0.04	0.56	0.86	0.13	0.10	0.25	0.38	0.00	0.00	0.00	0.00	0.22	0.23	
5b	0.00	0.00	0.00	0.01	0.00	0.00	0.24	0.05	0.06	0.07	0.00	0.00	0.00	0.00	0.05	0.05	
5c	0.00	11.27	0.01	0.04	0.02	0.05	1.22	2.19	0.00	0.00	0.15	0.04	1.11	0.92	0.30	0.31	
5d	0.00	0.00	5.11	4.95	7.88	11.43	0.44	0.41	2.18	2.67	7.57	7.17	1.43	1.31	4.35	4.46	
6	0.00	0.00	12.21	10.99	5.06	6.95	7.18	4.33	9.24	7.48	21.95	28.13	8.00	8.96	9.69	9.93	
7	0.00	0.00	6.37	6.74	2.93	4.21	10.26	5.37	10.00	10.85	32.30	32.06	11.12	15.48	10.81	11.08	
8	0.00	0.00	0.02	0.03	0.61	0.37	0.27	0.11	0.18	0.30	0.00	0.00	0.00	0.00	0.24	0.24	
Tot	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	97.62	100%	7,
Sust. BP (dam^3)	0.00		2.17		2.17		2.48		4.62		7.59		1.71		20.74		
Sust. BP (%)	0.00		10.48		10.48		11.94		22.27		36.59		8.24		100.00		

Note: Sustainable BP is given by the sum of groups 6,7 and 8.

If we constrain the definition of sustainabile biodiesel only to areas that have a Group 8 type of trade-off, then the sustainable potential biodiesel production from the Veneto Region would only be 0.24 dam^3 per year (0.24% of the total potential). The highest biodiesel potential (41.5%) is in areas that have one hig- level ES trade-off and at least one medium ES trade-off (Group 4). Fig. 6 visualises in a spatially explicit manner the distribution of trade-off groups, essentially mapping those areas where sustainable oilseed production is possible. Table 9 also highlights the contribution of each province to the regional biodiesel potential, with Verona having the highest (37% of the total) and Rovigo the lowest (8.6% of the total).

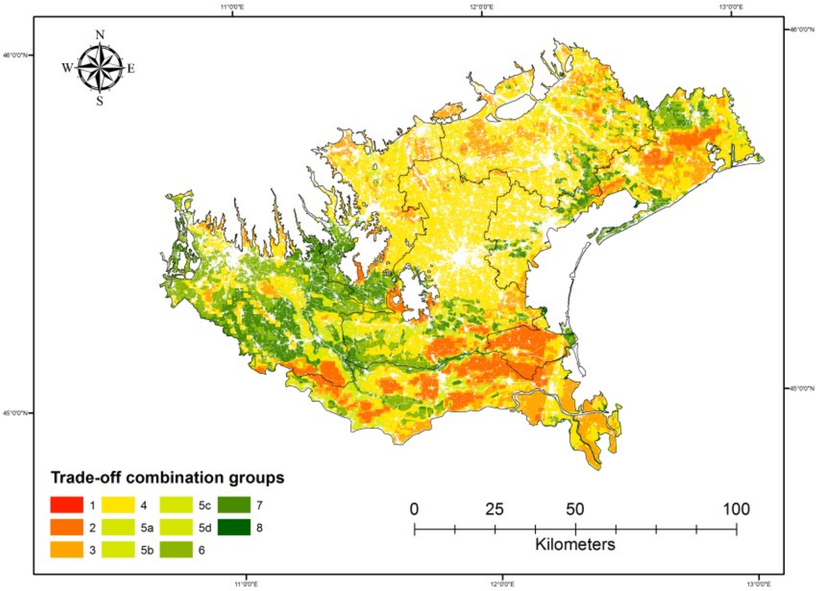

Fig. 6: Spatial distribution of trade-off combination groups.

3.4 Conversion of other arable land to increase sustainable biodiesel potential

"Other arable land" in the Veneto plain spans 5,052.78 km^2 (Table 10). If this arable land that falls into trade-off Groups 6-8 (1,131.33 km^2) is converted into sunflower (the most efficient oilseed crop in the region, Section 3.1), then the sustainable biodiesel potential would increase by 133.8 dam^3 per year. The province of Verona would contain 61.6% of the total area with these characteristics in the Venero Region, further confirming its capacity to produce a significant amount of oilseed without affecting the provisioning of other soil-related ESs.

Table 10: Area distribution of trade-off groups for "Other arable land".

	Area distribution among provinces								
	Belluno	Padova	Rovigo	Treviso	Venezia	Verona	Vicenza	Veneto region	
Trade-off Group	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2	%
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00%
2	0.00	66.18	179.79	8.10	175.32	31.38	10.00	470.78	12.01%
3	0.03	106.54	262.45	178.29	174.04	42.06	74.36	837.77	21.36%
4	0.01	698.39	246.09	484.85	433.00	174.02	277.10	2,313.46	58.99%
5a	0.00	0.41	7.11	0.68	3.68	0.00	0.00	11.88	0.30%
5b	0.00	0.18	0.00	0.20	0.73	0.00	0.00	1.11	0.03%
5c	0.02	0.35	0.60	13.44	0.00	0.18	3.84	18.44	0.47%
5d	0.00	56.90	107.91	3.18	26.25	68.29	5.49	268.02	6.83%
6	0.00	123.15	63.94	24.51	52.02	223.33	49.44	536.38	13.68%

7	0.00	71.72	34.46	32.37	90.11	283.44	76.67	588.76	15.01%
8	0.00	0.28	2.22	0.78	2.92	0.00	0.00	6.20	0.16%
Tot other arable land	0.06	1,124.10	904.57	746.40	958.07	822.70	496.89	5,052.78	100%
Unsustainable	0.06	928.96	803.96	688.74	813.02	315.93	370.78	3 921.45	
Sustainable	0.00	195.14	100.61	57.65	145.04	506.77	126.11	1 131.33	

Note: Sustainable biodiesel potential area is given by the sum of trade-off group 6,7 and 8.

4. Discussion

4.1. Relevance of trade-off analysis for biofuel sustainability

The present study outlines and tests a methodology to evaluate the trade-offs of potential biodiesel production from oilseeds, with soil-related ESs. The Regional Energy Plan of the Veneto Region (REP) [70] proposed a biodiesel production target for the year 2020 in which the annual regional biodiesel production from oilseeds should be 39.6 dam^3 per year. When comparing the potential sustainable biodiesel production that was quantified through our analysis (Section 3.3) and the REP target, it becomes obvious that only 52% of the REP target could be achieved without leading to a high-level trade-off with at least one soil-related ES. This means that achieving the REP target by 2020 would be impossible without having a significant impact on soil-related ESs, or without causing indirect land use change.

Expanding oilseed production for biodiesel may be possible by converting “other arable land” (i.e. land under other annual crops). This added oilseed production could be significant even if it is only confined to areas with low-level trade-offs with soil-related ESs (Section 3.4). However, this type of conversion might not be desirable, as it could cause the loss of landscape diversity (i.e., due to monoculture expansion) [108,109]. This can possibly have significant impacts to supporting and cultural ecosystem services [40,110–114] that are not quantified in this paper.

The trade-off analysis between soil-related ESs and biodiesel feedstock demonstrates the complex spatial nature of the relationships between ESs. First, our analysis shows that the sustainability and the trade-off levels of potential biodiesel production vary across the case study area. This is largely due to the differences in soil characteristics and land cover.

Second, the statistical correlation between soil-related ESs and potential feedstock production varies significantly in the study region, both between the entire study region and the individual provinces, as well as between the provinces (Table 8). This can have important implications for energy planning. As energy policies require the adoption and implementation of both regional and provincial plans, the differences in trade-off patterns as quantified by the present analysis should be considered. For instance, trade-offs with food production are not significant at the regional level, while they are significant for the provinces of Rovigo, Padova and Venezia. In other words, in these provinces, there is a considerable biodiesel feedstock potential located in zones that have high food productivity. However, the spatial conflict between these two ecosystem services could not be detected in regional energy plans as shown by our analysis at the regional level (Section 3.2). This means that regional energy plans for the Veneto Region need to take into consideration such variations between provinces.

4.2. Implications for certification schemes

As already discussed, our methodology can identify areas characterized by high trade-offs between bioenergy feedstock production and other soil-related ESs. Such spatially-disaggregated information is essential for assessing the territorial and cumulative effects of feedstock production when considering local environmental conditions, as well as to model the effects of large-scale feedstock introduction in specific contexts [115,116].

While ecosystem services have not been properly integrated into biofuel-related certifications schemes [42], the ecosystem services discourse has started featuring in some certification schemes such as Bonsucro and the Roundtable for Sustainable Biomaterials (RSB) [117,118]. Besides the conceptual issues of integrating meaningfully ecosystem services in such schemes (e.g. [13]), there proper guidelines for on-field impact assessment are lacking in existing certifications schemes [37,38].

However the trade-offs of biofuel/feedstock production with other ESs can be a key focus of certification standards and can be included in feedstock certification schemes. In particular, tools that can develop ES trade-off maps can be very useful to decision-makers and certification agencies as this can allow the visualization of the impact/trade-offs rather than simply focus on compliance with good agricultural practice.

Our methodological approach can also improve the set of indicators under the principle of "protection of soil, water and air and the application of Good Agricultural Practices" of the EU-RED [27]. Furthermore, the analysis of trade-offs between soil-related ESs can help improve soil management plans, which are actually required only by two certification schemes, ISCC and RSB (see Table A1 in Supplementary Electronic Material).

However, the current implementation of soil management plans at the farm level still remains a major barrier for achieving feedstock sustainability through certification schemes in the EU. In the UK, for example, DEFRA [119] has proposed guidelines for compiling soil management plans, as a means of cross-compliance with Good Agricultural and Environmental Conditions (GAEC) for environmental stewardship. However, these guidelines require farmers to be supported by experts during the preparation of soil management plans.

Considering the above, the integration of an ES trade-off analysis would add further complexity to the current bussiness practices of farmers in the EU if not appropriately implemented. For this reason it would be necessary to reflect seriously on these constraints and find the most effective way to frame ESs in certification schemes in order to support the proper operationalisation of the ES approach within such schemes.

4.3. Implications for Strategic Environmental Assessment

ES trade-off maps could become integral parts of the knowledge frameworks developed for regional energy plans in the EU. Such energy plans usually identify strategic objectives and other related targets with respect to the implementation of EU RED at the national level, and then attribute them to the regional level through burden-sharing. Energy plans are subjected to sustainability compliance assessments under the provisions of the Strategic Environmental Assessment (SEA) Directive 2001/42/EC [120]. Recently, many scholars have suggested that integrating the ES approach into SEAs could add value [121–125]. However, Baker et al. [125] note that this would require "a pragmatic, context specific consideration of how ecosystem services can be used to help addressing some of the common problems with current environmental assessment practice" (p. 3). Among others, a key limitation of SEAs is their lack of a proper analytical orientation [111], especially when dealing with renewable energy pathways [121] and when considering "genuine, reasonable alternatives" [125].

Among the full range of environmental issues addressed in SEAs [126], our methodology can allow the identification of suitable areas for the cultivation of energy crops in order to achieve biofuel targets. In particular, the methodology discussed in this paper can be used to evaluate the sustainability of feedstock production for the Veneto region, especially related to soil-related impacts.

Considering the results outlined in Section 3.3, the biodiesel production targets on the Veneto region can only be met by i) producing oilseed in areas with low trade-offs, ii) affecting other soil-related ES, iii) inducing land use change, or iv) importing feedstock or vegetable oil from outside the study area (which can potentially shift environmental burdens to other areas of energy crop production in Italy or elsewhere). All these solutions imply different possible impacts on soil and can involve other environmental receptors as identified in the SEA Directive [120].

Moreover, the proposed methodology can be used to develop different scenarios to explore development alternatives that can meet the objectives of regional energy plans. For example, the different outcomes/results of our analysis such as biodiesel production potential (Section 3.1), biodiesel potential not competing with soil-related ES (Section 3.2), and sustainable biodiesel potential (Section 3.3-3.4) can represent the baseline information for evaluating different energy pathways to achieve the targets of the Energy Plan of Veneto Region.

Finally, as already discussed our methodology can identify areas of high trade-offs between oilseed production for energy purposes and soil-related ESs. Areas with high expected trade-off levels can be devoted to other agricultural activities in order to minimize impacts on soil-related ES. Alternatively if feedstock production is located in areas of high trade-offs then these impacts can be detected and monitored. In fact, the SEA Directive implies the monitoring of significant environmental effects, while the energy plan is implemented to identify adverse effects and then remediate them [121].

4.4. Challenges and limitations

One of the main limitations of this study is that we have assumed that no land cover change effects take place (Section 2.3). However, land cover change can be one of the most important impacts of bioenergy cropping [11,16,17]. This means that our study provides a rather static analysis of biofuel potential and the impacts of biofuel expansion, which does not take into account effects related to land cover change. However, by quantifying and locating the "sustainable biofuel potential" our approach can be a suitable tool to be integrated in initiatives that aim to both mitigate ES trade-offs and prevent land cover change from biofuel expansion.

Another limitation of this study stems from the selection of the studied ES. For instance, while erosion regulation is an important soil-related ES that might be affected by agricultural intensification for BBES feedstock production [22,35], it has not been included in this analysis as the case study area is a plain with low rates of soil erosion [127]. Furthermore, although biofuel crops can have important impacts to freshwater ecosystem services [100], we have not assessed the effects of oilseed production on such services in this study. This is because the Veneto plain is characterized by well-managed irrigation systems, so water availability is unlikely to be a limiting factor. Finally, as we have not assumed any land cover change in the case study area (as required by [27][128]), cultural ESs were not considered. Trade-offs between BBES and cultural ESs were been linked to the loss of landscape diversity and landscape simplification, following the adoption of intensive mono-cultural practices [40,129,130].

Land use and cover change effects and further ecosystem services need to be integrated to the analytical package outlined in this paper. Such functionality can offer valuable information that can improve the effectiveness of certification schemes, SEAs and regional energy plans related to biofuels (Section 4.2-4.3).

5. Conclusions

The Veneto plain has a significant biodiesel potential from oilseeds such as soybeans, rapeseed and sunflower. However, only a limited fraction of this potential (about half of the REP target for the year 2020) can be tapped without affecting the provision of other soil-related ESs. While by converting other arable areas substantial amounts of oilseeds could be sustainably produced without significanly affecting soil-related ESs, there is a strong risk of fragmenting the landscape and possibly affecting the provision of other supporting, regulating and cultural ecosystem services not considered in the present paper.

The methodology outlined in this study can be used to effectively assess key trade-offs associated with the expansion of biofuel feedstock production. While this paper focuses on soil-related ESs the overall conceptual framework can be used to assess and/or consider trade-offs with other ecosystem services. As such it can provide a tool to assist the planning of biofuel projects (and particularly of the feedstock production stage), thus helping mitigate some of the controversial impacts of biofuels. Thus this methodology can relevant to certification schemes, SEAs and regional energy plans.

While our ES trade-off analysis focused on trade-offs assessment at the local scale, possibly it could be more effectively used at the regional scale. In fact, we observed that our provincial-level analysis was the most appropriate scale for an analysis of the trade-off related to RES planning.

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