

# Trade-offs among ecosystem services advance the case for improved spatial targeting of agri-environmental measures

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## ABSTRACT

Agri-environmental measures (AEMs) are meant to foster environmentally-friendly farming techniques. The use of AEMs to enhance agroecosystem quality is still under debate due to site-specific spatial mismatches that often occur between adopted AEMs and delivered ecosystem services. Here, a site-specific approach was employed to assess the advantages and disadvantages of AEMs adopted from the Rural Development Programme and applied in the Veneto Region (NE Italy) during 2014–2020. Specifically, a DayCent model-GIS platform compared business-as-usual (BAU) and AEM scenarios. The effect of AEMs on ecosystem services was assessed by integrating high-resolution spatial data from multiple pedo-climates and land managements and combined agronomic and environmental outcomes. Results showed that AEM adoption generally improved ecosystem service delivery, especially by reducing water pollution and increasing soil fertility. Among simulated practices, permanent soil cover and minimum soil disturbance (i.e., conservation agriculture, pasture and meadow maintenance) produced the best results across the Veneto Region, despite compromises in agronomic performance due to AEM-specific commitments (e.g., narrow crop rotation in conservation agriculture, fertilizer use restrictions in pastures and meadows). Other AEMs (e.g., organic farming) appeared highly dependent on their spatial distribution and were influenced by a strong interaction between pedo-climatic characteristics (e.g., soil properties) and management techniques (e.g., type and quantity of nutrients input). The spatial-target approach is highly recommended to identify AEMs that achieve environmental quality objectives and develop indications as to where they should be encouraged to maximize ecosystem services delivery.

## Credit author statement

Longo M.: Conceptualization, Methodology, Investigation, Writing-Original draft, Dal Ferro N.: Conceptualization, Methodology, Investigation, Writing – review & editing, Lazzaro B.: Resources, Funding acquisition, Writing – review & editing, Morari F.: Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Funding acquisition

## 1. Introduction

The EU has introduced agri-environmental schemes in Europe since 1992 to mitigate the environmental harm caused by intensive agriculture, and has funded specific agricultural practices that focus on reducing the intensity of farmland management (Science for

Environment Policy, 2017).

Over the last forty years, investments in sustainable farming practices –agri-environmental measures (AEMs)– have expanded (Riley, 2016) such that they accounted for about 7% of the total CAP budget of the EU Member States for the years 2014–2020 (European Commission, 2013a). However, there is still debate as to whether adopted AEMs efficiently enhance agroecosystem quality (Ekroos et al., 2014).

Indeed, several studies have concluded that the rigor of payout requirements to farmers is insufficient to deliver the desired environmental benefit. For instance, Kaligarić et al. (2019) mapped grassland-focused AEMs in Slovenia, and found that they were all eligible for compensation payments, even those that were sown or very intensively used with poor natural value. In a survey of Dutch agricultural landscapes, nitrogen input reductions prescribed by management agreements turned out to be ineffective in promoting plant diversity

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(Kleijn et al., 2001). AEMs follow an action-based scheme, wherein management activities are prescribed and adopted, as opposed to a result-oriented approach that allows the direct assessment of ecosystem service delivery (Russi et al., 2016). The approach raises several concerns: (i) environmental pressure and agri-environmental payment mismatch caused by poor spatial allocation of highly effective AEMs (Früh-Müller et al., 2018); (ii) ambiguous AEMs that do not address specific objectives and limit quantification of all relevant biogeochemical fluxes and related environmental indicators (Uthes and Matzdorf, 2013); (iii) contrasted/decreased yields that result from the interplay of system property differences and AEM-prescribed restrictions on agricultural managements (e.g., organic farming or conservation agriculture) to deliver other ecosystem services (De Ponti et al., 2012; Huang et al., 2015; Kertész and Madarász, 2014).

Effective AEMs must be targeted through site-specific evaluation of environmental anthropogenic pressures and their underlying causes, so that countermeasures can be tailored to specific locations, and thus ensure the supply of ecosystem services (Albert et al., 2016). By contrast, AEMs assessed at the landscape level can be affected by environmental, management, and sociocultural factors that can confound comparisons between “areas with” and “areas without” agri-environmental scheme agreements (Primdahl et al., 2003). Moreover, AEMs often take years to deliver ecosystem services (Swetnam et al., 2004), requiring long time periods for proper assessment.

GIS-based agroecosystem modeling that integrates ecosystem properties with agricultural management factors are suitable tools for comprehensive and site-specific studies, including the determination of multiple environmental and agronomic indicators (Balković et al., 2013; Huffman et al., 2015; Lugato et al., 2018). In addition, predictions can be scaled to cross regions and nations, overcoming the spatial limitations of local empirical studies (Constantin et al., 2019) and the expense of direct measurement (Bartkowski et al., 2021).

Most past studies have worked to quantify output indicators that are not good proxies for desired outcomes (Pe'er et al., 2019) or have focused only on specific impacts, e.g. water quality (Hérivaux et al., 2013; Kersebaum et al., 2006) or soil erosion (Deumlich et al., 2006), and thereby have left behind the holistic vision needed to integrate different biogeochemical cycles. To this end, we hypothesize in this research that AEMs do not deliver equal ecosystem services under different pedo-climatic and management conditions, and that a fine spatial scale assessment is required to guide land managers toward sustainability.

In Italy, the responsibility for implementing agricultural interventions to support the rural development through their own programming lies with the Regions (NUTS2) (Tocaceli, 2015); therefore, they are required to evaluate the effectiveness of the AEMs adopted under the Rural Development Programs (RDPs) (European Commission, 2015). In light of this, a site-specific modeling approach was employed to quantify agronomic and environmental AEM performances under the current RDP (2014–2020) in the Veneto Region (NE Italy). Our objectives were i) identify AEMs that achieve environmental quality targets (water, air, soil indicators) relative to a baseline; ii) disentangle pedo-climatic and management factors affecting agronomic and environmental AEMs performances; iii) develop indications as to whether and where specific AEMs should be encouraged and adopted for delivery of ecosystem services.

## 2. Materials and methods

### 2.1. Study area

Our case study was of the Veneto Region, an administrative area (NUTS 2) in northeastern Italy that encompasses about 18,400 km<sup>2</sup>. The Veneto Region is not only among the most densely populated and industrialized areas in Italy, but also intensively farmed and highly productive agriculturally. The existence of the two sectors leads to

increasing pressure over natural resources that causes important environmental issues (e.g., water and air pollution, land grabbing, and low soil fertility). Geographically, the elevation of the area varies from sea level (south) to ca. 3200 m a.s.l. (north) in the Dolomites. The plain, which covers 55% of the region and where most of the agriculture is concentrated, is generally flat and rarely in excess of 100 m a.s.l. The area surrounding the Venice Lagoon (1240 km<sup>2</sup>) lies about 2 m below sea level where the reclaimed land has been cultivated since the 1st century BC. Most of the low-lying plain in Veneto is covered by sandy and silty-clay deposits. The Venetian Plain soils are mostly Calcisols and Cambisols (WRB, 2015), characterized by medium natural fertility due to relatively low organic matter (approximately 15 g kg<sup>-1</sup>) and cation exchange capacities ranging from low (sandy) to high (silty-clay). Northern hilly areas at 15–300 m a.s.l. are composed of calcareous, skeletal (25–47%) loam, and clay loam soils (Luvisols and Cambisols). Mountain areas generally contain sandy/clay loam soils of poorly differentiated profiles (Leptosols on slopes) that alternate with deeper Cambisols in the valleys.

### 2.2. Model-GIS platform

A model-Geographic Information System (GIS) platform to integrate geographic and alphanumeric data was created to assess identified environmental benefits resulting from implementing Rural Development Programme AEMs. The coupling of the DayCent v4.5 model (Hartman et al., 1998) and the GIS was well-suited for the research goals: i) to compare cropping systems with/without AEMs; ii) to investigate the effect on environmental targets (soil, water, atmosphere, biota) with an approach that considered all of the main biogeochemical cycles (C, N, P); iii) to generate short- and long-term scenarios. In total, 3049 polygonal units were delineated through map overlay of the soil, climate, land use, digital terrain model, and zones vulnerable to nitrate leaching.

### 2.3. DayCent agroecosystem model

DayCent is a daily version of the monthly time-series ecosystem model CENTURY (Parton et al., 1994). DayCent simulates carbon (C), nitrogen (N), phosphorus (P) and sulfur (S) cycling in natural or cultivated systems associated with soil organic carbon (SOC) dynamics. Water balances are also considered. The model has been applied to many agroecosystems worldwide (Campbell et al., 2014; Clemens Scheer et al., 2014; Nocentini et al., 2015). Information about file structure and content needed to perform DayCent runs can be obtained from <https://www2.nrel.colostate.edu/projects/daycent-home.html>.

To establish baseline C–N–P pools and to stabilize SOC content, DayCent was “spun-up” for 20 years to reach equilibrium at the start of each simulation. Some assumptions were made to run the model that arose from incomplete land use and management data for the entire region. In particular, agroecosystems were assumed to have been cultivated historically with maize and permanent meadow crops.

### 2.4. DayCent model validation

DayCent is a robust model whose predictions have been extensively evaluated across Europe (Abdalla et al., 2010; Leip et al., 2011; Nocentini et al., 2015) and approved for simulation use under different pedo-climatic conditions by utilizing previously-calibrated management practices. Nevertheless, a preliminary validation of the model was performed to assess its reliability and sensitivity to the different pedo-climatic and agronomic conditions of the Veneto Region. The model had previously been successfully applied in a long-term Veneto Region study (with CENTURY) under different management practices after extensive parameterization on C dynamics (Lugato et al., 2007; Lugato and Berti, 2008). The DayCent model was also validated for N cycling on a daily time series (Dal Ferro et al., 2016) across the Veneto

Region by comparing predictions of crop yields, nutrient leaching, and greenhouse gas (GHG) emissions to values observed from experimental monitoring at different locations.

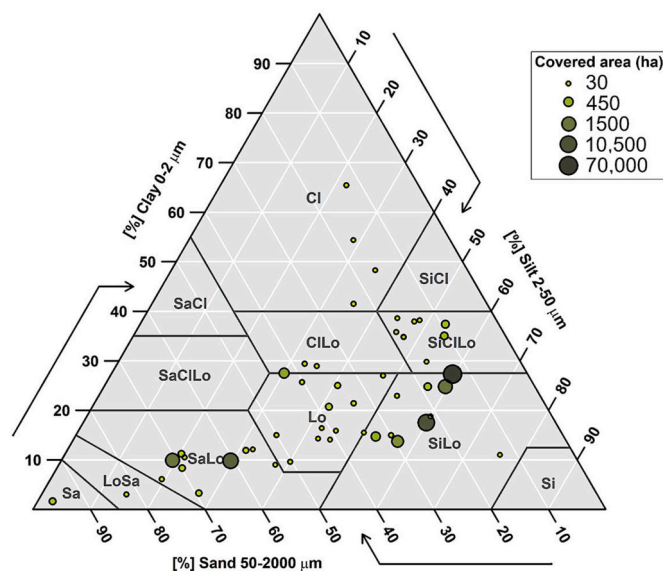
#### 2.4.1. *Pedo-climatic database*

The Veneto Region 1:250,000 soil map (Regione Veneto, 2005) was sourced for soil information in this study. The map contains geographical information relating to 56 homogeneous soil units in total (Fig. 1) and is linked to an alphanumeric database storing physicochemical characteristics (e.g., soil layer depths, bulk densities, gravel contents, pH) and soil profile hydraulic parameters (e.g., saturated hydraulic conductivity, wilting points). A cascade method (Morari et al., 2004) was applied to re-proportion (reduce) each soil horizon by its gravel content as DayCent fails to consider the effect of gravel in soil-water dynamic simulations.

The region was divided into 15 homogeneous meteorological zones by the Veneto Region Environmental Protection Agency (ARPA Veneto). Daily rainfall and temperature data were obtained from a representative meteorological station for each zone (Table 1).

### 2.5. Crop and management database

Municipal level data of the agricultural crops and land use management throughout the region were provided by the [Regione Veneto \(2012\)](#) and totaled 579 polygonal units. Eleven crops, representing more than 60% of the total utilized agricultural area (UAA) were simulated with DayCent: maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), soybean (*Glycine max* L.), sunflower (*Heliantus annuus* L.), rapeseed (*Brassica napus* L.), potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.), and pastures and meadows (permanent grasslands and in succession, i.e. alfalfa – *Medicago sativa* L.). According to the last census ([ISTAT, 2010](#)), the UAA covered about 44% of the region. Mostly concentrated on the plain (78%), the UAA contained mainly cereals (e.g. maize, wheat), soybean, and fodder crops (ca. 70%). Field management information for the municipal units was also extracted from the Veneto Region agricultural administration database ([Regione Veneto, 2012](#)). Tillage practices included soil plowing and standard seedbed preparation operations (e.g., harrowing) at different times according to crops. A fertilization database was created including information on the type (organic or mineral) and quantity ( $\text{kg ha}^{-1} \text{yr}^{-1}$ ) of N and P input for each simulated crop. For arable lands, identical tillage



**Fig. 1.** Soil textural classes of Veneto Region soil profiles used in DayCent simulations.

Table 1

Mean annual temperature, absolute maximum and minimum temperatures, and rainfall for the selected meteorological zones.

N°	E°	Elevation (m)	T <sub>mean</sub> (°C)	T <sub>min</sub> <sup>a</sup> (°C)	T <sub>max</sub> <sup>b</sup> (°C)	Rainfall (mm)
45.929	11.507	1001	6.9	−7.3	19.8	1380
46.565	12.339	850	7.3	−7.5	25.5	1231
45.000	11.503	7	13.7	0.5	31.4	929
45.440	11.479	151	13.7	0.7	30.1	876
45.539	10.696	65	14.0	−2.0	30.6	734
46.404	12.037	966	7.2	−10.2	24.7	1018
45.903	12.117	163	13.2	0.5	28.1	1430
46.041	11.916	325	10.7	−3.6	26.2	1521
45.338	11.938	8	13.7	0.8	29.9	828
45.568	12.253	8	13.8	0.5	30.3	980
45.783	12.841	5	13.3	−0.1	30.1	1084
45.696	11.210	448	8.5	−1.4	21.0	2228
45.613	12.396	8	13.2	−0.7	30.7	1080
45.089	12.297	5	14.0	1.2	27.7	736
45.241	11.028	25	13.8	0.4	31.4	772

<sup>a</sup> Average minima of the coldest month (January).

<sup>b</sup> Average maxima of the warmest month (July).

operations (30 cm deep plowing and seedbed preparation with a spring-tine harrow) were assumed. Simulations included irrigated and non-irrigated areas.

## 2.6. Application of agri-environmental measures

For the purposes of this study, the agroecosystem-impacting AEMs evaluated unto two simulated scenarios included the “agri-environment-climate” (measure M10.1) and “organic agriculture” (M11) commitments (European Commission, 2013b) of the CAP funding period (2014–2020). The first scenario, termed the business-as-usual scenario (BAU), highlighted the impact of traditional farming practices. It encompassed the arable systems of the Veneto Region without adopted AEMs. The second scenario, called the AEMs scenario, focused on the effects of the AEMs adopted through application of RDP 2014–2020 (Regione Veneto, 2015) and European Council Regulation (EC) No 1305/2013. Some AEMs were financed for new adoption (“New”) and adopted during the 2014–2017 period (i.e., conservation agriculture –CA<sub>New</sub>– and organic farming –OF<sub>New</sub>). Others were financed for long term maintenance (“Maint”) over a period of 18 years: BUFFER<sub>Maint</sub> (buffer strips), PAST-MEAD<sub>Maint</sub> (pasture and meadow), OF<sub>Maint</sub> (organic farming) and WOODLAND<sub>Maint</sub> (woodlands). Finally, CA<sub>Maint</sub> (conservation agriculture) was financed for 11 years (Fig. 2).

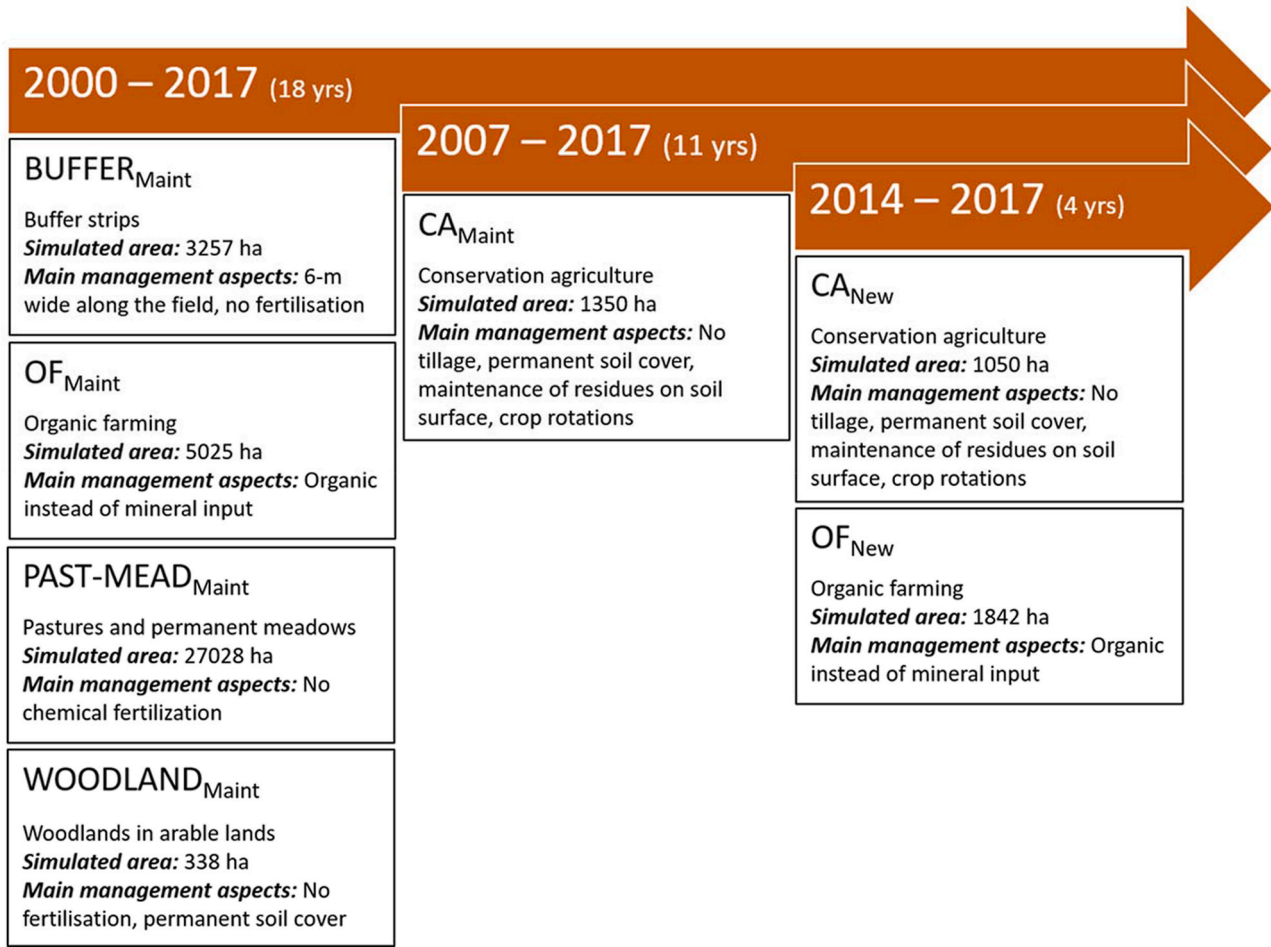
Mixed systems, such as those composed of crops and buffer strips cannot be simulated by DayCent. Therefore, buffer strips were modeled as 6 m wide herbaceous strips per RDP guidelines, whose effect was then weighted by considering a UAA reduction in fields of average size, equal to 200 m  $\times$  30 m on the plain and 75 m  $\times$  30 m in hilly and mountain areas. Moreover, since DayCent does not simulate erosion and P runoff, the Revised Universal Soil Loss Equation (RUSLE) was first applied to predict soil losses and then combined with P soil surface concentration to estimate phosphorus sediment losses (Dal Ferro et al., 2016).

A total of 84,000 unique simulations, distributed over the 3049 unique polygonal units covering the Veneto Region, were performed with the DayCent model resulting from the combination of pedoclimatic and AEM information.

## 2.7. Data analysis

The agronomic and environmental benefits and drawbacks that resulted from the AEMs were evaluated according to several parameters:

- i) yields ( $\text{Mg ha}^{-1} \text{ yr}^{-1}$ ) and nitrogen use efficiency (NUE);



**Fig. 2.** Visualization of the time periods in which each agri-environmental measure (AEM) was adopted and simulated. Subscripts “Maint” or “New” for each AEM refer to maintenance of existing systems or introduction of new systems, respectively.

- ii) soil quality using SOC accumulation ( $\text{Mg ha}^{-1}$ ) and soil erosion (A) ( $\text{Mg ha}^{-1} \text{ yr}^{-1}$ ). Soil water erosion was not estimated for OF measures due to the negligible differences in soil cover between AEM and BAU that DayCent was unable to differentiate;
- iii) water quality using N ( $N_{\text{Leach}}$ ) and P ( $P_{\text{Leach}}$ ) leaching as well as P loss ( $P_{\text{Loss}}$ ) due to erosion ( $\text{kg ha}^{-1} \text{ yr}^{-1}$ ).  $N_{\text{Leach}}$  and  $P_{\text{Leach}}$  for woodlands (WOODLAND<sub>Maint</sub>) were not calculated by DayCent; consequently, they were excluded from the evaluation;
- iv) greenhouse gas emissions of CO<sub>2</sub> (DayCent computes CO<sub>2</sub> flux from heterotrophic soil respiration), CH<sub>4</sub> and N<sub>2</sub>O ( $\text{kg ha}^{-1} \text{ yr}^{-1}$ ),

by considering the absolute and relative yearly average difference between AEM adopted and AEM not adopted in the agroecosystems as follows:

$$\Delta Y = Y_m - Y_o \quad (5)$$

where  $\Delta Y$  is the absolute difference of the evaluated parameter (e.g., N leaching), while  $Y_m$  and  $Y_o$  are the yearly average parameters under evaluation in the AEM and BAU scenarios, respectively. The parameter was also expressed in relative terms as follows:

$$\Delta Y\% = \frac{Y_m - Y_o}{|Y_o|} \times 100 \quad (6)$$

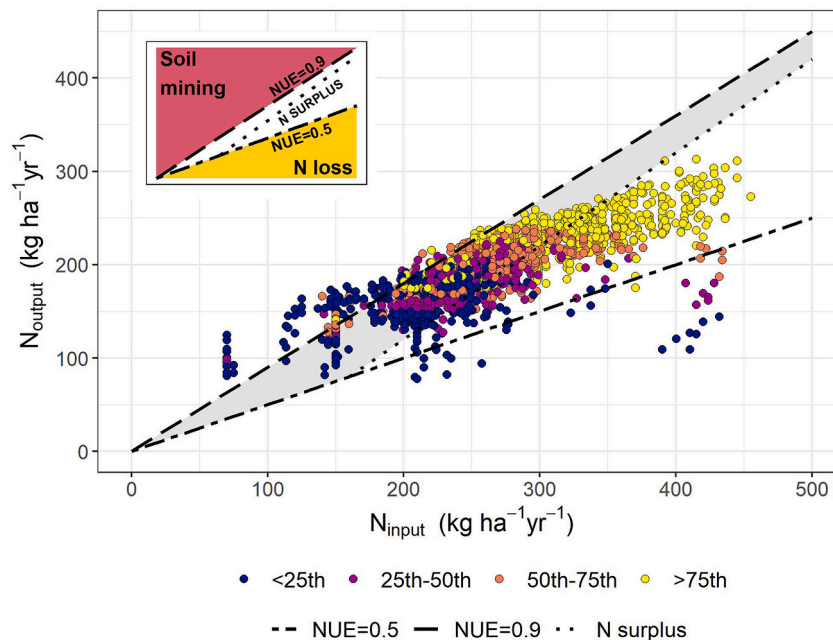
where  $\Delta Y\%$  is the percentage change of the evaluated parameter.

The nitrogen use efficiency (NUE) was estimated as the ratio between N removed by crop yields ( $\text{kg N ha}^{-1} \text{ yr}^{-1}$ ) and the total yearly input of N

fertilizer (mineral and organic,  $\text{kg N ha}^{-1} \text{ yr}^{-1}$ ). According to the EU Nitrogen Expert Panel (EU Nitrogen Expert Panel, 2015), the proposed NUE indicator is informative in many ways and embeds information on both agronomic (i.e., productivity) and environmental (i.e., N surplus) results in a unique conceptual framework (Fig. 3) as follows: i) a desired NUE between 0.5 and 0.9 (diagonal dash-dotted lines) implies lower values exacerbating N pollution and higher values suggesting the risk of mining soil N stocks), and ii) a required N surplus lower than  $80 \text{ kg ha}^{-1} \text{ yr}^{-1}$  to avoid substantial pollution losses (diagonal dotted line). NUE was calculated only for N-fertilized crops. Therefore, soybean and alfalfa were excluded from the analysis as was the pasture measure, which was not fertilized according to AEM commitments.

Agronomic and environmental outcomes in each polygonal unit were expressed per unit area (ha) per year, by weight averaging each simulated crop on the basis of its invested surface therein.

Finally, to compare overall AEM effectiveness, an integrated ecosystem service index ( $I_{\text{ES}}$ ) was calculated. It includes the percentage change in yields and environmental indicators (SOC, A,  $P_{\text{Loss}}$ ,  $N_{\text{Leach}}$ ,  $P_{\text{Leach}}$ , N<sub>2</sub>O, CH<sub>4</sub>), as compared to the BAU scenario. Each  $i$ -th agronomic and environmental outcome ( $\Delta Y\%$ ) was arbitrarily classified for every geographic unit as slightly ( $0-25\% = 1$ ;  $-25-0\% = -1$ ), moderately ( $25-75\% = 2$ ;  $-75 \text{ to } -25\% = -2$ ), or highly ( $>75\% = 3$ ;  $<-75\% = -3$ ) capable of delivering (positive value) or undermining (negative value) ecosystem services. The  $I_{\text{ES}}$  was expressed as a ratio between the sum of the classification values (C) for each  $i$ -th agronomic and environmental outcome, and the sum of maximum achievable values ( $C_{i \text{ Max}}$ ), as



**Fig. 3.** Nitrogen use efficiency (NUE) of BAU (business as usual) scenario. Colors represent percentiles within homogeneous meteorological areas. The desirable N balance between input and output that minimizes N mining and N loss is shown in grey (EU Nitrogen Expert Panel, 2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

follows:

$$I_{ES} = \frac{\sum_{i=1}^n C_i}{\sum_{i=1}^n C_{i \text{ Max}}} \times 100 \quad (7)$$

The  $I_{ES}$  index integrated several indicators into a single number and represented an overall increase or decrease of ecosystem services by weighting for the range of values of each indicator.

Finally, possible linear relationships among agronomic indicators ( $\Delta N_{UE}$ ,  $\Delta N_{Surplus}$ ,  $\Delta N_{Input}$ ,  $\Delta N_{Output}$ ), environmental indicators for water and soil quality, and GHG emissions and soil properties were estimated through Pearson correlation coefficients using the 'corrplot' package (Wei et al., 2017) of R software (R Development Core Team, Vienna, Austria).

### 3. Results

#### 3.1. Business-as-usual (BAU) scenario

The best yield performances resulted in simulations of maize in the central-northern plain, where it was the main cultivated crop (>60%). Yields peaked at 18 Mg ha<sup>-1</sup> yr<sup>-1</sup> in highly fertilized and irrigated areas absent adverse weather conditions, such as low temperatures. The comparatively small area cultivated with sugar beet crop (covering 2.9% of arable areas) exhibited its greatest simulated yield (up to 25 Mg ha<sup>-1</sup> yr<sup>-1</sup>) in the low-lying plain. Winter crops, cultivated in the mountainous and hilly polygonal units, produced less (<4 Mg ha<sup>-1</sup> yr<sup>-1</sup>) but covered an average of 74% of the agricultural area. In the southern Nitrate Vulnerable Zones, the combination of reduced nitrogen input and less-favorable pedo-climatic conditions led to 21% lower yields as compared to the central plain.

The amount of N removed by cropping systems equaled 195 kg N ha<sup>-1</sup> yr<sup>-1</sup> (242 kg N ha<sup>-1</sup> yr<sup>-1</sup> including leguminous crops). More than 140 kg N ha<sup>-1</sup> yr<sup>-1</sup> were removed regardless of fertilization dose in all cropping systems except for 2.5% or 9256 ha across Veneto UAA (Fig. 3). In a few scattered areas of the central and northern plain (ca. 847 ha across Veneto or 0.2% of the UAA),  $N_{Output} > 280$  kg N ha<sup>-1</sup> yr<sup>-1</sup> (excluding pulse crops) was simulated with mixed mineral and organic fertilization inputs above 370 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The  $N_{Output}$  rate trended

with the temperature gradient, as it was higher in the central and northern plain areas and lower in the colder, northernmost hilly and mountainous areas of the region. The average nitrogen use efficiency (NUE) was 0.77, with 98.2% of the simulated UAA within the limits of the optimal 0.50–0.90 interval. Moreover, 75.9% exhibited a N surplus of <80 kg N ha<sup>-1</sup> yr<sup>-1</sup>, providing proof of generally good agronomic performances (Fig. 3). NUE values outside the threshold limits were mainly found in hilly and mountainous areas.

DayCent predicted contrasting results for SOC stocks in the topsoil layer (20 cm) during 2014–2017 (Table 2). SOC accumulation (up to 3.4 Mg ha<sup>-1</sup>) resulted in highly productive arable crops (e.g., maize) fertilized with organic inputs, while mineral fertilizers led to general SOC depletion (as low as 3.0 Mg ha<sup>-1</sup>).

The BAU simulation microbial soil respiration rate ranged from 2996 to 6144 kg C–CO<sub>2</sub> kg ha<sup>-1</sup> yr<sup>-1</sup>. An increase in CO<sub>2</sub> emissions was found in the mountainous areas, where high SOC content likely boosted C mineralization. Higher methane emissions were also concentrated in these areas, with values as high as 2.8 kg C–CH<sub>4</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Table 2). Nitrous oxide (N<sub>2</sub>O) emissions averaged 3.50 kg N–N<sub>2</sub>O ha<sup>-1</sup> yr<sup>-1</sup>, with maximum values of 7.45 kg ha<sup>-1</sup> yr<sup>-1</sup> found in high water-retention capacity soils, such as clay-loam. Nutrient leaching was affected by the interaction between pedo-climatic and management conditions. Total nitrogen leaching ( $N_{Leach}$ ) varied between 1.3 and 69.8 kg N ha<sup>-1</sup> yr<sup>-1</sup>, with larger values in sandy soils and smaller ones in the highly-productive central plain. Phosphorous leaching ( $P_{Leach}$ ) was observed only in its organic form and never exceeded 0.10 kg P ha<sup>-1</sup> yr<sup>-1</sup>. Phosphorous losses ( $P_{Loss}$ ) trended with erosion (range of 0.2–5.9 kg P ha<sup>-1</sup> yr<sup>-1</sup>) (Table 2).

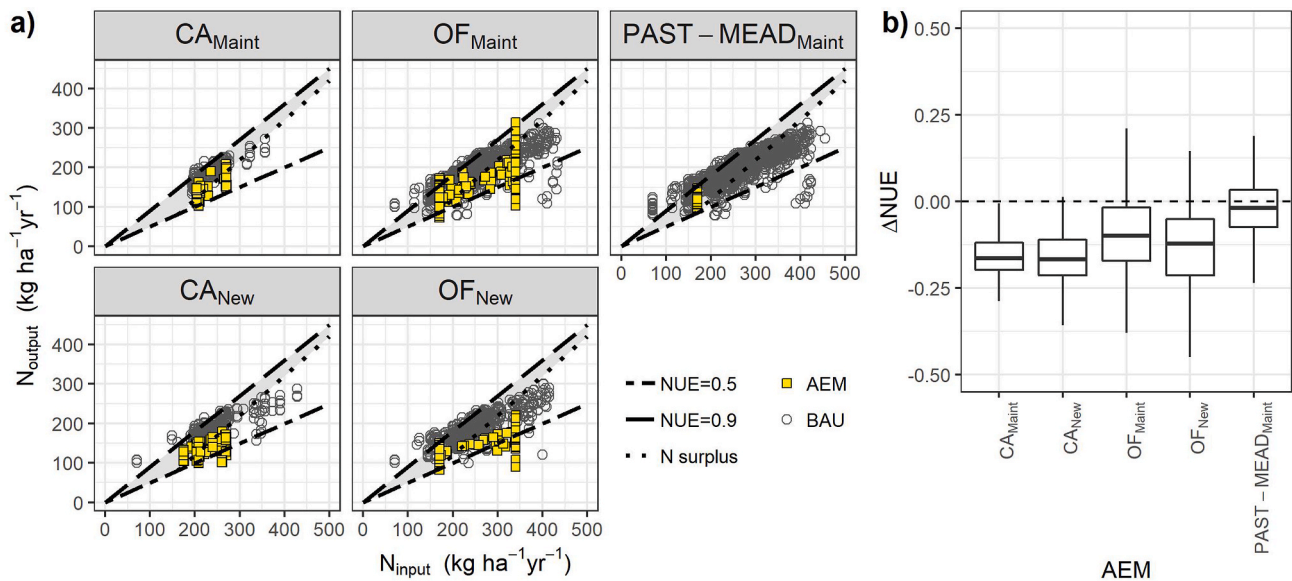
#### 3.2. Application of AEMs: agronomic performances

AEMs strongly influenced agronomic performances (Fig. 4a). For instance, crop rotations and cover crops in CA reduced total N fertilizations, being  $\Delta N_{Input} = -17.7$  kg N ha<sup>-1</sup> yr<sup>-1</sup> (–7.7%). The results approximated those in OF where manure rates were capped at 170 in vulnerable and 340 kg N ha<sup>-1</sup> yr<sup>-1</sup> in non-vulnerable zones by the Nitrate Directive. Some differences in  $N_{Output}$  were also observed between the OF short- and long-term scenarios, where values averaged 186 and

**Table 2**

Results from simulations of the business-as-usual (BAU) scenario.

	N <sub>In</sub>	Yield	N <sub>Output</sub> <sup>a</sup>	N <sub>Output</sub> <sup>b</sup>	C-CO <sub>2</sub>	N-N <sub>2</sub> O	C-CH <sub>4</sub>	SOC <sup>c</sup>	A	N <sub>Leach</sub>	P <sub>Leach</sub>	P <sub>Loss</sub>
	kg ha <sup>-1</sup> yr <sup>-1</sup>	Mg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>	Mg ha <sup>-1</sup>	Mg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>	kg ha <sup>-1</sup> yr <sup>-1</sup>
25th	172.8	7.8	171.5	196.2	4174.0	2.03	1.15	-0.8	3.5	22.0	2.3E-02	1.5
50th	211.3	9.4	194.8	241.5	4574.4	3.50	1.42	0.3	4.3	30.0	3.2E-02	2.1
75th	249.4	11.0	218.1	294.6	4975.1	4.26	1.87	1.0	5.7	41.4	5.3E-02	3.3

<sup>a</sup> N uptake without considering N-fixing crops.<sup>b</sup> N uptake considering N-fixing crops.<sup>c</sup> Difference between the end and the beginning of the BAU simulations.**Fig. 4.** Nitrogen use efficiency (NUE) of agri-environmental measures (AEMs) scenarios (a). Box-plots of changes in NUE between AEMs and BAU scenarios (b).

167 kg N ha<sup>-1</sup> yr<sup>-1</sup>, respectively (Fig. 4a).

Compared to BAU, CA and OF simulations resulted in lower NUEs (Fig. 4b), with short-term values in OF<sub>New</sub> slightly worse than those for the long term (OF<sub>Maint</sub>). Despite these reduced efficiencies, 94.0% of AEMs produced NUEs within the desired range (0.5–0.9), which suggests that most adopted practices did not result in excessive soil N mining or N loss. Moreover, in some simulated areas, using organic fertilizers only increased NUE in OF<sub>Maint</sub>, being ΔNUE +0.27 (Fig. 4b).

### 3.3. Application of AEMs: soil quality

The SOC content in the topsoil (20 cm) was affected by the adoption of AEMs (Fig. 5a). The highest topsoil SOC accumulations occurred in scenarios that were long term, had AEMs that minimized soil disturbance, and contained permanent soil cover with herbaceous crops, such as PAST-MEAD<sub>Maint</sub> or CA<sub>Maint</sub>. In contrast, topsoil SOC depletion was always found after 18-year simulations under continuous tree cultivation (WOODLAND<sub>Maint</sub>). The ΔSOC loss averaged -14.9 Mg C ha<sup>-1</sup>, with peaks of -20.9 Mg C ha<sup>-1</sup>, regardless of the pedoclimatic conditions. Contrasting results also emerged in OF, where SOC ranged from depletion to accumulation in the long term (OF<sub>Maint</sub>; ΔSOC varied from -13.5 to 13.2 Mg C ha<sup>-1</sup>) and short term (OF<sub>New</sub>; from -2.4 to 4.9 Mg C ha<sup>-1</sup>) (Fig. 5a). The highest SOC accumulation value was observed in the northwestern zone, especially under PAST-MEAD<sub>Maint</sub>, where favorable pedo-climatic conditions (e.g., high clay content and rainfall) limited C mineralization. Naturally SOC-poor soils (<0.9%) in the southern area also were found to have benefited from the adoption of AEMs; their topsoil accumulations rose as much as 12 Mg C ha<sup>-1</sup>. In contrast, SOC losses were spatially scattered across Veneto, emphasizing that some

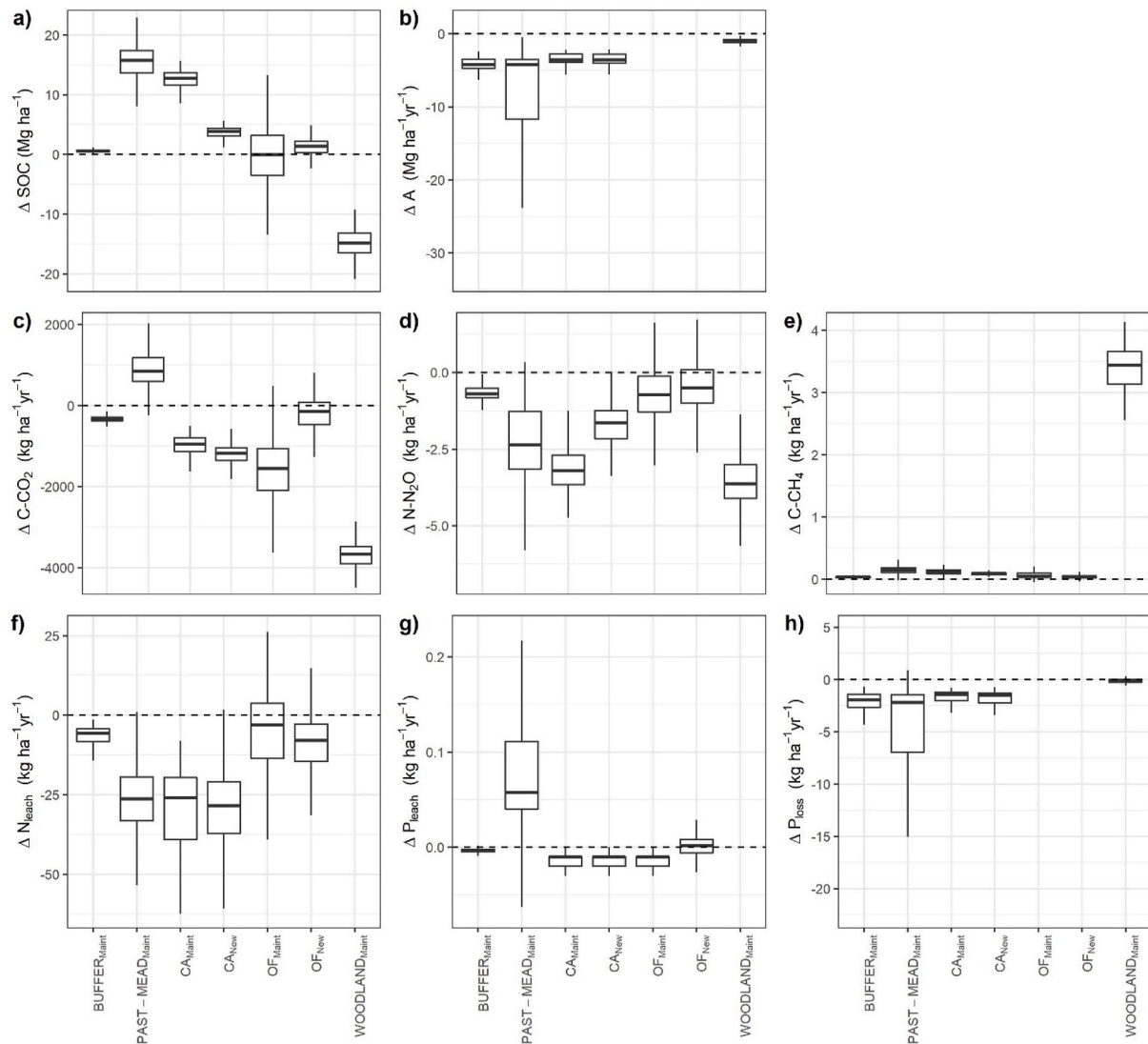
negative interactions between site-specific conditions and AEMs may exist, especially for OF and WOODLAND<sub>Maint</sub>. Indeed, correlation analyses showed a positive relationship between clay and ΔSOC in both OF<sub>Maint</sub> and CA<sub>Maint</sub> (Table S1).

The adopted AEM scenarios compared favorably to BAU (ΔA, Fig. 5b) in that the former produced a general mitigation of soil water erosion as predicted by RUSLE. In hilly and mountainous areas, PAST-MEAD<sub>Maint</sub> sustained less erosion (ΔA = -4.2 Mg ha<sup>-1</sup> yr<sup>-1</sup>) compared to arable lands. In rank order, buffer strips proved to be most effective at decreasing soil loss (99.8%), followed by PAST-MEAD<sub>Maint</sub> (95.0% and 90.2%, respectively) (Fig. S1b).

### 3.4. Application of AEMs: GHG emissions

Adopted AEM simulations resulted in a general decrease of heterotrophic CO<sub>2</sub> emissions (Fig. 5c). WOODLAND<sub>Maint</sub> produced the most relevant results by decreasing emissions between 3674 kg C-CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> and 4502 kg C-CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Fig. 5c). Similarly, but to a lower extent, reductions were observed in both the long term (957 kg C-CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>) and short term (1182 kg C-CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>) under CA conditions. In OF<sub>New</sub>, the results contrasted to those of CA; emissions dropped by 152 kg C-CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>. Spatially, the ΔCO<sub>2</sub> pattern reflected the ΔSOC distribution across the region. The increased CO<sub>2</sub> in the northwestern mountainous areas of the region highlighted the effect of the prevailing measure (PAST-MEAD<sub>Maint</sub>), while the lowest CO<sub>2</sub> emissions were found in soils of the low plain.

Modeling results suggested that remarkable effects came from regulating N<sub>2</sub>O emissions, as a reduction of 1.0 kg N-N<sub>2</sub>O ha<sup>-1</sup> yr<sup>-1</sup> was produced compared to the BAU scenario (Fig. 5d). In some cases, AEM



**Fig. 5.** Box-plots of changes in soil (soil organic carbon,  $\Delta$ SOC; soil water erosion,  $\Delta$ A), air (carbon dioxide,  $\Delta$ CO<sub>2</sub>; nitrous oxide,  $\Delta$ N<sub>2</sub>O, methane,  $\Delta$ CH<sub>4</sub>) and water (nitrogen leaching,  $\Delta$ N<sub>Leach</sub>; organic phosphorus leaching,  $\Delta$ P<sub>Leach</sub>; phosphorus loss  $\Delta$ P<sub>Loss</sub>) quality parameters.  $\Delta$ SOC was the difference between the end and beginning of the agri-environmental measure (AEMs) simulations, thereby varying between new (subscript “New”) adoption and maintenance (subscript “Maint”) measures. Please refer to Fig. 2 for comprehensive AEMs explanation.

commitments that capped N fertilizations (e.g., WOODLAND<sub>Maint</sub>, PAST-MEAD<sub>Maint</sub>) favored strong N<sub>2</sub>O reductions ( $\Delta$ N<sub>2</sub>O equaled 3.6 and 2.4 kg N-N<sub>2</sub>O ha<sup>-1</sup> yr<sup>-1</sup>, respectively). In other instances, AEMs imposed permanent soil coverage measures, such as in CA, which allowed N<sub>2</sub>O emissions to be reduced by more than 80% and 45% in the long and short terms, respectively (Fig. S1d). Likewise, AEMs that required conversion from mineral to organic fertilizers, or those that generally improved N use efficiency, resulted in N<sub>2</sub>O emission mitigation. Spatially, sharp decreases were observed primarily in hilly areas and in some areas at the southern end of the region.

For methane (CH<sub>4</sub>) emissions, the maximum  $\Delta$ CH<sub>4</sub> was predicted to reach 0.2 kg C-CH<sub>4</sub> ha<sup>-1</sup> yr<sup>-1</sup>, except in WOODLAND<sub>Maint</sub> that exhibited increased emissions of 3.4 kg C-CH<sub>4</sub> ha<sup>-1</sup> yr<sup>-1</sup>. Often, climatic conditions emphasized soil methanogenesis as rainfall correlated significantly with  $\Delta$ CH<sub>4</sub> (Table S1).

### 3.5. Application of AEMs: water quality

Agri-environmental measures improved water quality by limiting

nutrient losses to water resources. In particular, permanent soil cover resulted in N loss reductions that were demonstrated by high performance predictions under CA ( $\Delta$ N<sub>Leach</sub> was -29 for new adoption and -26 kg N ha<sup>-1</sup> yr<sup>-1</sup> for maintenance) and -26 kg N ha<sup>-1</sup> yr<sup>-1</sup> for PAST-MEAD<sub>Maint</sub>. On the other hand, OF values fluctuated above and below zero ( $\Delta$ N<sub>Leach</sub> was as high as 29 and as low as -39 kg N ha<sup>-1</sup> yr<sup>-1</sup>) compared to BAU. AEMs were also shown to be very effective in areas most vulnerable to N leaching as evidenced by their strong effect on N<sub>Leach</sub> when hydraulic conductivity values were high (Table S1).

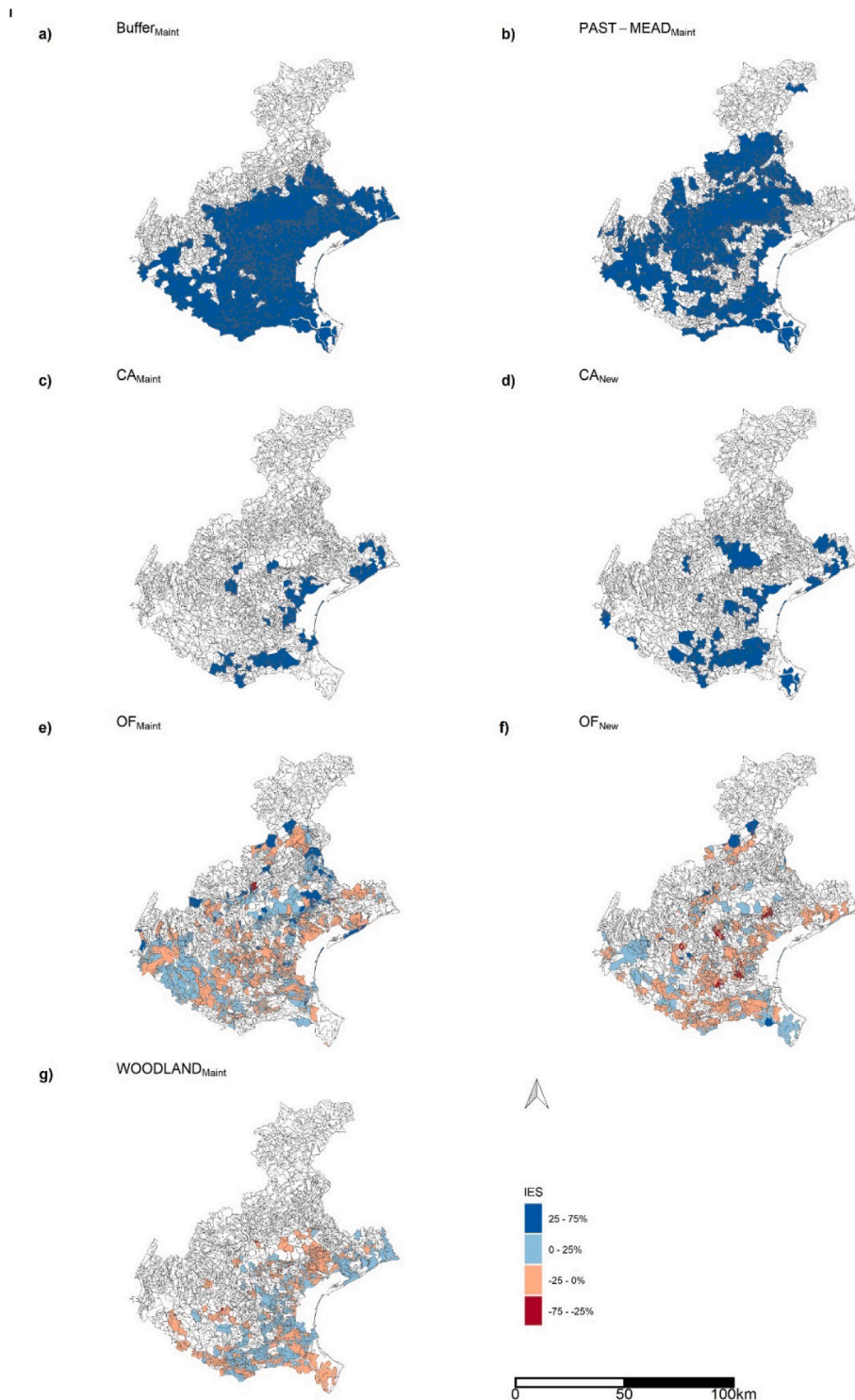
Spatial measures in hilly and mountainous areas underscored the effect AEMs have in reducing nutrient water pollution as exhibited in the sizeable reductions in N leaching when croplands were replaced with grasslands. Large reductions also occurred in the south of the region, especially in loose soils with high sand content. In such areas, AEM adoption led to a decrease of 68 kg N ha<sup>-1</sup> yr<sup>-1</sup> (99.5%) (Fig. S1f).

The dynamics of P leaching to groundwater ( $\Delta$ P<sub>Leach</sub>) behaved differently (Fig. 5g). Averages changed only slightly compared to BAU. Values were negative in BUFFER<sub>Maint</sub> ( $\Delta$ P<sub>Leach</sub> = -0.003 kg P ha<sup>-1</sup> yr<sup>-1</sup>), CA<sub>Maint</sub> (-0.1 kg P ha<sup>-1</sup> yr<sup>-1</sup>), CA<sub>New</sub> (-0.1 kg P ha<sup>-1</sup> yr<sup>-1</sup>), and OF<sub>Maint</sub>

( $-0.1 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ ) and positive in  $\text{OF}_{\text{New}}$  ( $0.001 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ ). Only  $\text{PAST-MEAD}_{\text{Maint}}$  showed more homogeneous values in P leaching ( $\Delta \text{P}_{\text{Leach}} = 0.057 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ ) with peaks up to  $0.47 \text{ kg P ha}^{-1} \text{ yr}^{-1}$  in the hills and mountains where soils were rich in SOC. P loss was mostly mitigated with decreases in soil erosion. In fact, agri-environmental measures that implemented permanent soil cover performed best, as shown with a  $\Delta \text{P}_{\text{Loss}}$  of  $-1.4$ ,  $-1.5$ , and  $-2.2 \text{ kg P ha}^{-1} \text{ yr}^{-1}$ , in  $\text{PAST-MEAD}_{\text{Maint}}$ ,  $\text{CA}_{\text{New}}$ , and  $\text{CA}_{\text{Maint}}$ , respectively (Fig. 5h). In relative terms,  $\text{BUFFER}_{\text{Maint}}$  performed best; it reduced  $\text{P}_{\text{Loss}}$  by 99.8% across the Veneto Region.

### 3.6. AEM provisioning of ecosystem services

The ability of AEMs to deliver ecosystem services was evaluated at the site-specific level by integrating agronomic and environmental indicators. Overall, the  $I_{\text{ES}}$  index (Eq. 7) revealed that ecosystem services were substantially enhanced relative to those delivered in the BAU scenario (Fig. 6). In particular, AEM commitments to minimize soil disturbance and to maintain a permanent soil cover ( $\text{PAST-MEAD}_{\text{Maint}}$ ,  $\text{CA}_{\text{Maint}}$ , and  $\text{CA}_{\text{New}}$ ) proved most effective and provided moderate increases in ecosystem services, regardless of the area of application across



**Fig. 6.** Spatial visualization of the integrated index of ecosystem services ( $I_{\text{ES}}$ ) incorporating agronomic and environmental outcomes for agri-environmental measures (AEMs) simulated with DayCent. Blue and red gradients indicate the ecosystem benefit or drawback by adopting AEMs, respectively. Subscripts “New” and “Maint” refer to new adoption or maintenance measures, respectively. Please refer to Fig. 2 for comprehensive AEMs explanation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the Veneto Region. In contrast, OF resulted in both increased and decreased values due to fluctuations in biomass production, SOC content, or water quality that served to offset other benefits. Similarly, ecosystem service results varied between slight decreases and increases for WOODLAND<sub>Maint</sub>. It is noteworthy that no modeled AEMs were shown to enhance ecosystem service delivery to a strong degree.

#### 4. Discussion

During 2014–2017, AEMs were maintained in 7.7% (ca. 37,000 ha) and replaced conventional practices in another <1% (4242 ha) of the total simulated Veneto Region UAA. Evaluation of their impact revealed contrasting agronomic and environmental outcomes in the various regional agroecosystems. Overall, the adoption of organic farming (OF) fared poorer than did conservation agriculture (CA) adoption.

From an agronomic perspective, some OF findings require discussion. First, under organic farming, a reduction of N input imposed by OF commitments caused the provisioning of biomass to be generally reduced, even in highly productive cropping systems. Second, it is important to recall that the DayCent model excluded the effect of pest and disease management in the simulated scenarios, which if not controlled might have widened yield differences *versus* BAU (Stockdale et al., 2001). Third, exclusive use of organic fertilizers led to lower nutrient use efficiency compared to scenarios in which mineral fertilizers were applied, likely due to mismatches in timing between N availability and crop N requirements. Evidence from field experiments conducted in the same region (Dal Ferro et al., 2017; Morari et al., 2012) have already indicated that some adopted OF areas may suffer from high N leaching. In fact, OF applied over the long term increased NUE slightly compared to short-term scenarios. The slow mineralization of organic fertilizers probably enhanced a legacy effect on nutrients availability (Aguilera et al., 2013) (Table S1). Moreover, no clear evidence of a generalized topsoil SOC increase was observed under OF, which agrees with other studies (Kirchmann et al., 2007; Leifeld et al., 2009). It was hypothesized that some areas suffered from low residue and root carbon inputs, which may have offset the positive effect of adding external organic material. In contrast, topsoil SOC accumulation was more pronounced in some other areas, especially when new OF systems were adopted in the naturally-low-in-SOC sandy soils of the low plain, which aligns with previous findings (Dal Ferro et al., 2020b; Francaviglia et al., 2019). However, the more labile SOC that was more frequently found in sandy soils than that accumulated in clay-rich soils suggests that long-term practice maintenance is prerequisite in order to continue reaping soil ecosystem benefits.

It is important to remember that this study did not consider the soil microbiological functions associated with the use of organic fertilizers. Indeed, a long-term experiment carried out on silty-loam soils on the Venetian Plain (Nardi et al., 2004) proved that farmyard manure can improve biochemical and hormone-like (e.g., auxin and gibberellin-like) activities, as well as the production of humus with a high degree of polycondensation, a fraction usually linked to soil fertility. Moreover, if agro-chemical restrictions were included as a topic in this study, then additional ecosystem benefits would require consideration in the ecosystem service trade-off analyses.

The permanent soil cover and no tillage applied in conservation agriculture, adopted mainly in areas of the plain, enhanced ecosystem services. Soil functions were improved by minimizing its degradation from soil water erosion. Moreover, topsoil SOC content increased by as much as 15 Mg C ha<sup>-1</sup> at mean annual rates of 1.1 Mg C ha<sup>-1</sup> yr<sup>-1</sup> under CAMaint. While SOC in CANew increased only 3.7 C Mg ha<sup>-1</sup>, it did so at similar rates (0.9 Mg C ha<sup>-1</sup> yr<sup>-1</sup>). Camarotto et al. (2020) found lower rates (0.25 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) in the top 0–30 cm layer in three Venetian Plain farms managed for six years under CA. As a cautionary note, the evaluation of SOC sequestration potential could have been biased in this study for two reasons. The first reason is that C balance information was limited to the 0–20 cm layer, which failed to consider SOC redistribution

below the arable layer (Camarotto et al., 2020). Second, DayCent excluded pivotal soil physical changes, such as bulk density and aggregate stability (Lugato et al., 2014) that both drive SOC stock dynamics.

Conservation agriculture adoption produced benefits to water (less loss of N and P) and air (low N<sub>2</sub>O emissions) quality. Several authors (e.g., Camarotto et al., 2018) have reported that the combination of no tillage and permanent soil cover, as opposed to conventional practices, reduce nutrient concentrations in groundwater. The improved water quality may have come from less soil erosion in CA, although some northern region arable hilly areas that typically suffer from soil and P losses (representing 77% of the UAA or ca. 25,000 ha) were also maintained without the adoption of erosion-regulating strategies (CA and BUFFER<sub>Maint</sub>). However, regardless of soil management, the effect was not as noticeable on the less-erosion-prone plain as associated with low rainfall erosivity.

In regard to N<sub>2</sub>O, DayCent predicted greater reductions with CA in pedo-climatic conditions generally favorable for emission production (e.g., clay soils with high water retention capacity), which underscored the benefits that AEMs may exert in intensive farming areas. Nevertheless, the effect of CA on N<sub>2</sub>O emission is still debated. Some authors (e.g., Guenet et al., 2020) have purported that CA can enhance N<sub>2</sub>O by boosting SOC content and local anoxic conditions of no-till topsoil. Additional uncertainty on ecosystem service delivery was due to a lack of estimates about ammonia volatilization (DayCent does not simulate it), which could be considerable especially in some alkali soils with inadequate N fertilizer burial (Mencaroni et al., 2021).

Despite improving environmental conditions, CA often fell short in agronomic performance compared to BAU, albeit for reasons other than those for OF. In addition to no-till and permanent soil cover practices, CA involved narrow crop rotations from the introduction of winter crops. As opposed to the yields produced from widely-adopted maize under BAU conditions (64.8% of total simulated UAA), winter crop yields were smaller and had lower NUE values (Piccoli et al., 2020). Tight cultivation system rules and worse agronomic performances might explain some of the unwillingness by farmers to adopt CA (2400 ha in total and <1% of the total arable land in Veneto (Dal Ferro et al., 2020a)). It follows that adoption of each AEM force policy-makers select and apply appraising tools suited to weigh agricultural income and environmental conditions in each agroecosystem (Okpara et al., 2020), overcoming the lack of sensitivity to local conditions (Kleijn et al., 2001).

BUFFER<sub>Maint</sub> and WOODLAND<sub>Maint</sub> were being supported as non-productive agricultural sector investments that generate insignificant financial returns to its beneficiary (i.e., the farmer). In both hilly areas and on the plain, farmers preferred to implement buffer strips (3257 ha) instead of woodlands (338 ha) because the latter leads to a loss of crop profitability. Commitments for BUFFER<sub>Maint</sub> and WOODLAND<sub>Maint</sub> were motivated by reductions in agroecosystem inputs (e.g., nutrients) and soil disturbance, which generally enhanced soil, water, and air quality. In some cases, DayCent predicted negative impacts, such as a substantial topsoil SOC reduction in WOODLAND<sub>Maint</sub>. In fact, high topsoil SOC losses were commonly observed in afforested soils (Kirschbaum et al., 2008). It is likely that decreased litter inputs from the herbaceous understory highlighted the effect of labile SOC fraction mineralization (Pérez-Cruzado et al., 2012). Some authors have observed that new equilibrium may be expected under very long periods (>30 years) (Laganière et al., 2010). Others have highlighted that afforestation did not lead to SOC accumulation even after 50 years (Tau Strand et al., 2021) and suggest that C stock in tree plantation was mainly due to uncut aboveground vegetation. Conversely, PAST-MEAD<sub>Maint</sub> was widely adopted in the Veneto Region (61437 ha) despite commitments using organic fertilizers only at maximum doses of 170 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The long history of pastures and meadows not only in hilly and mountainous areas where arable crops are barely cultivated, but also in the plain where more intensive cultivation takes place have helped to maintain existing cattle and dairy farms (Mantovi et al., 2015).

Throughout the region, PAST-MEAD<sub>Maint</sub> have helped to increase a broad range of ecosystem services (Fig. 6); in particular, those related to clean water provisioning (less N leaching and P loss), soil structure and fertility (more SOC, less A) regulation, and climate change (less N<sub>2</sub>O).

In the case of GHG emissions, a broader assessment (e.g., life cycle assessment) is needed and should include the potential for emissions along the entire animal husbandry chain.

Finally, the high biomass productivity modeled for PAST-MEAD<sub>Maint</sub> was a poor indicator of farmer propensity to consider different crops for specific agroecosystems, which failed to explain any possible trade-off between ecosystem services and profitability (Schipanski et al., 2014).

## 5. Conclusions

The model-GIS platform was demonstrated to be a suitable tool to evaluate implementation of AEMs using a results-based direct assessment of ecosystem services. The platform proved capable of providing information as to whether or not –and where– the adoption of specific measures should be encouraged, which could improve European agri-environmental policy cost effectiveness.

In general, a positive picture emerged on the effectiveness of AEMs to deliver essential ecosystem services in the Veneto Region. Most of the positive effects were observed when commitments included a combination of permanent soil cover and minimal soil disturbance, such as pasture and meadow maintenance and conservation agriculture management. Nevertheless, these results were insufficient to ensure wide implementation of innovative measures (e.g., conservation agriculture) because of their negative effects on yields, or for reasons other than economics and technology. Other practices exhibited contrasting results across the Veneto Region and indicated that AEM outcomes were highly dependent on local conditions. The results confirmed the starting hypothesis that AEMs do not deliver equal ecosystem services under different pedo-climatic and management conditions. It is imperative to advance the modeling tools for evaluating agri-environmental schemes at fine spatial scales in order to inform future European policies and to develop more reliable monitoring schemes to properly assess their effects.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2021.112131>.

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