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Original Article

Soil organic carbon monitoring to assess agricultural climate change adaptation practices in Navarre, Spain

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Abstract

Climate change adaptation strategies are needed for agriculture, one of the most vulnerable human activities. In Navarre, North of Spain, ongoing adaptive management practices were identified and promoted in the framework of a regional adaptation strategy. Most include practices aiming to increase topsoil organic carbon (SOC) in agricultural land. In this work, the effectiveness of these practices (conservation agriculture, crop rotations, additions of organic matter, irrigation, and controlled grazing management) was assessed by means of monitoring SOC in a network of 159 agricultural fields across the region. These fields were selected across bioclimatic zones, where soil vulnerabilities and land-uses were previously assessed, to represent the most widespread conditions in the region. A sampling protocol designed to compare SOC stocks in plots with equal soil conditions within each zone, and with or without adaptive practices, allowed the determination of their effect size (measured as response ratios, RR). Exogenous organic matter addition was the most effective practice for SOC storage (RR 95% confidence interval (CI) [1.25–1.37]) across the region. Controlled grazing also resulted in net SOC gains (RR CI [1.13–1.42]) in temperate and semiarid grasslands. Conservation agriculture seemed to be more effective in the driest zone (RR CI [1.30–1.53]) than in the more humid ones (RR CI [0.98–1.21]). Irrigation also displayed a net positive effect (RR CI [1.17–1.34]), modulated by irrigated crop management, whereas crop rotations had an overall negative impact vs. monoculture (RR CI [0.84–0.96]), likely by their interaction with irrigation. These results confirm the variability in SOC responses to changes in management, and SOC as an indicator for assessing regional adaptation practices, although other biophysical, agronomic, and socio-economic factors also need to be accounted for.

Keywords

Soil organic carbon
Adaptation
Regional approach
4per1000
Response ratio

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Supplementary Information

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Introduction

Soil appears as a key element in global change. Soils play a crucial role in the biogeochemical cycles of carbon (C) and nitrogen (N), and in particular, in the exchange of these elements between the atmosphere and terrestrial ecosystems (Lal 2020). Soil is of special interest because of its role as a sink of atmospheric C, and therefore in climate change mitigation. The interference of agricultural management in this process has merited attention in policies and mitigation guidelines since long ago (IPCC 2006). In this regard, initiatives such as the well-known "4per1000" (Minasny et al. 2017; Rumpel et al. 2020), use this potential as a basis for promoting management strategies that contribute to an increase in soil organic C (SOC) stocks in agricultural land.

In addition, SOC dynamics has also a role in climate change adaptation (IPCC 2014; Jia et al. 2019), as it is related to soil properties and functions that can reduce the vulnerability of agrosystems to changes in climate, such as water retention, resistance to erosion, or high fertility (Adhikari and Hartemink 2016; FAO 2017).

Because the agricultural sector is particularly vulnerable (Iglesias et al. 2012), there is a growing interest in studying different adaptation strategies in this sector (IPCC 2014; FAO 2018). The most recent IPCC specific report on mitigation and adaptation strategies related to land-use and land-use changes (Jia et al. 2019; Olsson and Barbosa 2020), indicates that increasing SOC should be considered a tool to improve the resilience of agrosystems, and to maintain the ecosystem services provided by soils. According to IPCC, the most relevant management practices affecting SOC stocks in croplands are the management of crop residues, tillage and fertilization (both mineral and organic) and irrigation, the choice of crops and the intensity of cropping management, including mixed systems with crops and pasture (Lasco et al. 2006).

Despite this growing interest, most reports recognize that there are still significant sources of uncertainty about the consequences and efficiency of SOC storage strategies (Jia and Shevliakova 2019). Uncertainties are associated to the high variability observed in SOC responses to the different strategies, and to gaps in our understanding about the relationship between agricultural management and the accumulation of organic matter in soils (Chenu et al. 2019).

In general, the possibility of increasing SOC through agricultural management is related to its capacity to modify the inputs of organic materials into the soil, and/or the sensitivity of organic matter to mineralization (Dignac et al. 2017). The final effect is dependent on time and local conditions. For instance, some meta-analysis and long-term studies have shown that the effect of tillage suppression on SOC can be dependent on the actual change induced by this practice on crop yields, and therefore C inputs to the soil from crop residues (Virto et al. 2012; Mary et al. 2020) , and on climate conditions (Dimassi et al. 2014), which can be inter-related. Net SOC gains following manure applications have also been seen as likely dependent on climate (Maillard and Angers 2014). Another major variable in this sense is soil type. Although the role of soil mineralogy in SOC protection is increasingly acknowledged (Barré et al. 2014; Fernandez-Ugalde et al. 2016; Rowley et al. 2018), and it has been seen to be relevant at regional (Wiesmeier et al. 2013, 2020; Gartzia-Bengoetxea et al. 2020) and national scales (Chen et al. 2019), few studies account for this variable when assessing SOC strategies (Jia and Shevliakova 2019). Francaviglia et al. (2019) recently revised SOC storage rates under different managements in field experiments with Mediterranean climate, and found that results were influenced, among other factors, by the initial SOC content, soil texture, and climate regime. In this sense, it is considered a good practice (Aalde et al. 2006) to run stratified analysis for climate zones and soil types when assessing changes in SOC stocks with management in croplands (Lasco et al. 2006).

Furthermore, there are still technical limitations for the systematic assessment of SOC changes at the regional scale, such as the high spatial variability or the small annual SOC response to management in comparison to background levels (Paustian et al. 2019). Up-scaling from laboratory or experimental field studies to landscape or regional-level evaluations is a major challenge in this sense (FAO 2013; Paustian et al. 2016; Dignac et al. 2017; Chenu et al. 2019). For instance, a study conducted to assess SOC changes with cropland management in Mediterranean conditions observed greater SOC gains in experimental fields than commercial farms (Aguilera et al. 2013). Reducing uncertainty in the evaluation of agricultural management practices for climate change adaptation needs therefore to move toward strategies that consider local and regional characteristics (Chen et al. 2019; Jia and Shevliakova 2019), and take these limitations into account. Adequate sampling designs, including geo-referenced sampling networks, are crucial for adequate regional-scale comparisons in time and space (Tugel et al. 2008; Smith et al. 2019).

In this process, it is important to consider that increasing SOC through agricultural management has not only agronomic and environmental consequences, but also sociological, economic and ethical dimensions (Chenu et al. 2019). Collaboration with land users and the experience of extension agents are major tools for a comprehensive assessment of these practices at the regional scale (Karlen et al. 2014; Altieri et al. 2015; Demenois et al. 2020). In particular, studying the efficiency of those strategies which are already common practice in a region can help to overcome the general problem of implementing new strategies that farmers would be reluctant to adopt (Rumpel et al. 2020).

Within the framework of a regional-scale project (Nadapta) launched in 2017 in the region of Navarra (North of Spain), a vulnerability study of agricultural soils to projected regional climate change was developed. For that, various adaptive management strategies, already implemented by farmers in the region and included in the regional roadmap for climate change adaptation were considered (Gobierno de Navarra 2017).

The main objective of this work was to carry out a quantitative assessment of the effectiveness of these adaptive agricultural practices to achieve an increase in SOC storage at the scale of the region of Navarre. For this purpose, a first objective was to define the baseline of SOC storage under conventional management conditions in zones of the territory with homogeneous conditions for plant growth. Then, we aimed at studying the effect of the most relevant adaptive agricultural practices promoted in the regional roadmap on topsoil SOC storage, in a selection of representative agricultural fields in each homogeneous zone.

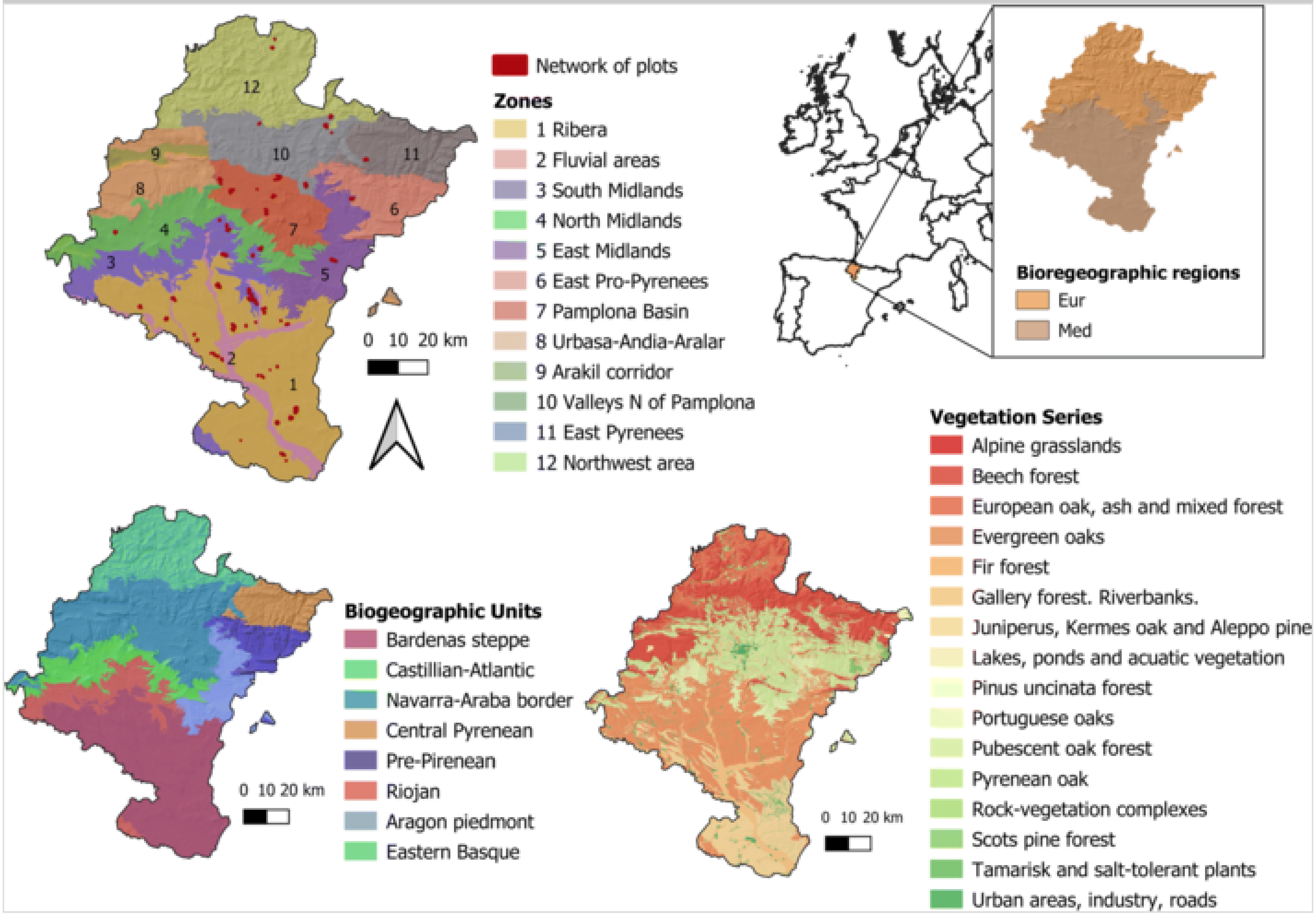
Material and methods

Study area

The region of Navarre, North of Spain (Fig. 1), has a high climatic variability created by the distance to the sea and differences in altitude (from 2434 m.a.s.l. in the Pyrenees to 18 m.a.s.l. at the lowest point). The most significant natural division derives from the gradient in rainfall and evapotranspiration between the North and the South. Annual precipitation ranges between >2500 mm in the North and <350 mm in the South-East (Pejenaute Goñi 2017). Mean annual temperatures vary from 14.5 °C (Buñuel, 41°58′47″N; 1°26′38″W) to 9.3 °C (Irabia, 42°59′07″N; 1°09′28″W) (Gobierno de Navarra 2020). The territory is thus divided into two major biogeographical regions, the Eurosiberian and the Mediterranean (Peralta et al. 2013) (Fig. 1). Limestone massifs in the North and Center of the region, and carbonaceous materials of sedimentary origin in the South, are the most relevant lithologies, as they explain topography soil formation.

Fig. 1

Homogeneous zones and network of plot defined for this study (top left), location of the region of Navarre and biogeographical regions (top right), vegetation series (bottom right) as in Peralta et al. (2013), and biogeographical units (bottom left).



Due to this heterogeneity in terms of climate, topography, and geology, the conditions for the development of plants, and therefore agriculture, differ considerably within the region. At present, 39% of the total area is used as agricultural land (90.7% cropland and 9.3% grassland).

Zoning and zone characterization

In a first step, a study of climate and soil characteristics in zones with homogeneous conditions for plant growth was conducted. To this end, the biogeographic units defined in the region (Peralta et al. 2013) were further divided using information on vegetation series for the identification of ecologically homogeneous territories (Rivas-Martinez 2005). Biogeographical, climate and soil characteristics were obtained from the available cartographic information (IDENA 2020), and a new analysis of the regional soil map 1:50,000 (Iñiguez 1982-1992). This allowed for the determination of the most limiting soil vulnerability traits in each zone. Twelve homogeneous zones were defined (Fig. 1). Their climate and soil characteristics appear in Table 1. Information on soil types (Soil Survey Staff 2014) and vulnerability traits can be found as Supplementary material (Online Resource 1). The most relevant ones were stoniness and limited depth. In the North of the region, acidity and slope were also relevant. In the Central and South zones, low organic matter content, carbonates concentration, water deficit, and, in some cases, salinity were also identified. Papadakis (1952) climate types, corresponded to the regional gradient, from the driest and warmest conditions in the South (zones 1, 2, and 3), to moist temperate conditions in the Central part of the region (zones 4, 5, and 7) and fresher and moister conditions corresponding to maritime climates in zones 8 to 12, with some Mediterranean traits in zones 8, 9, and 10.

Table 1

Climate, land-use, management strategies, number of groups, and plots and soil groups for the 12 zones determined for the study. Managements are conservation agriculture (CA), addition of exogenous sources of organic carbon (ExO), rotations (ROT), irrigation (IRR), and controlled grazing and/or rotation in grasslands (GSS)

Zone	Climate	Land-use		Adaptive management strategies and plots			Reference soil groups
	(Papadakis 1952)	Total area (ha)	Agricultural use (%)	Strategies	Groups	Plots	(Staff 2014)
1. Ribera	Mild Steppe (AvM-Ost) and Dry Temperate Mediterranean (AvMMe)	254,140	66.7	CA ExO ROT IRR GSS	5 8 3 4 2	12 26 13 16 6	Fluventic Inceptisols and Entisols, Orthents, Xerepts, Xerolls, Ustolls, Calcids, Gypsids

Zone	Climate	Land-use		Adaptive management strategies and plots			Reference soil groups
	(Papadakis 1952)	Total area (ha)	Agricultural use (%)	Strategies	Groups	Plots	(Staff 2014)
2. Fluvial areas	Dry Temperate Mediterranean (AvMMe)	39,625	81.9	–	–	–	Inceptisols and Entisols
3. South Midlands	Dry Temperate Mediterranean (AvMMe)	79,700	67.7	CA ExO ROT	3 4 4	9 13 12	Fluventic inceptisols and entisols, Other Xerepts, Xerepts with depth limitations, Ustolls
4. North Midlands	Moist Temperate Mediterranean (AvMMe)	95,679	39.3	ExO IRR	1 2	4 4	Xerepts with depth limitations, Other Xerepts
5. East Midlands	Moist Temperate Mediterranean (AvMMe)	64,764	40.1	ExO GSS	1 1	4 5	Orthents, Xerepts with depth limitations
6. East Pre-Pyrenees	Cool Maritime Mediterranean (AvTrME)	56,949	3.4	–	–	–	Entisols
7. Pamplona Basin	Moist Temperate Mediterranean (AvMMe)	67,857	46.5	CA ExO ROT	2 2 2	6 7 6	Xerepts, Orthents, Fluventic inceptisols and entisols
8. Urbasa-Andia-Aralar	Cool Maritime Mediterranean (AvTrME)	69,165	7.5	–	–	–	Inceptisols, Entisols, Spodosols
9. Arakil corridor	Cool Maritime Mediterranean (AvTrME)	13,457	42.8	–	–	–	Inceptisols and Entisols
10. Valleys N of Pamplona	Cool Maritime Mediterranean (AvTrME)	87,669	21.4	GSS	4	10	Orthents, Udepts
11. East Pyrenees	Cool Maritime (AvTrHU)	63,016	7.2	GSS	1	5	Orthent, Fluventic Udepts

Zone	Climate	Land-use		Adaptive management strategies and plots			Reference soil groups
	(Papadakis 1952)	Total area (ha)	Agricultural use (%)	Strategies	Groups	Plots	(Staff 2014)
12. Northwest area	Cool Maritime (AvTrHU) and Warm Maritime ((AvMHU-Hu)	14,4324	9.8	GSS	1	3	Alfisols, Ultisols

Inceptisols and Entisols are widely distributed throughout the region. Those in the Central and South areas (zones 1, 2, 3, 4, 5, and 7) have a *xeric* soil moisture regime. Aridisols appear in zone 1, corresponding to the *aridic* moisture regime. In the Central-Western and North zones (8, 9, 10, 11, and 12), the *udic* soil moisture regime dominates. Entisols with fluventic characteristics are widespread, corresponding to the hydrological network of the region. Entisols and Inceptisols are dominant in mountain areas with frequent high slopes (zones 6, 8, 11, and 12). Some Mediterranean red soils (*Palexeralfs*) exist on relatively old river terraces, especially in zones 4 and 5. Other Alfisols with moister soil water regime conditions, as well and Ultisols, dominate in the more humid zones 10 and 12.

The distribution of the most widespread land uses for the 12 zones varied greatly (Table 1) from zones with very little agricultural use, such as zones 6 and 8 to zones 1, 2, and 3, with more of 65% of their surface used for agriculture. In terms of the type of agricultural uses, zones 1, 2, and 3 represented 94% of the region's irrigated area, with the maximum in zone 1 (60% of the total irrigated area in the region).

Selection of soil management strategies and network of plots

The agricultural managements considered were those included in the regional roadmap for climate change adaptation (Gobierno de Navarra 2017), and most commonly found in the region. They were conservation agriculture (CA), management of exogenous sources of organic C (ExO), and rotations (ROT), as cropping strategies in cultivated plots. Other managements of regional interest, i.e., the implementation of irrigation (IRR), and optimized grassland management

(GSS), were also included. CA included no-till in cultivated plots and permanent grass cover in permanent woody crops. ExO included the regular addition of different sources of organic matter at agronomic doses, ROT included different crops in the regular sequence of cultivation, either on annual basis in rainfed systems, or with several crops per year in irrigated land. IRR was tested in plots under sprinkler irrigation, and GSS included mostly controlled grazing strategies, and in some cases, in combination with lay or lay/crops rotations.

The establishment of a network of agricultural plots representative of these systems was carried out in a procedure that involved extension agents, farmers and researchers (Tugel et al. 2008). First, the most common land uses were identified within those zones representing the highest proportion of agricultural land (1, 3, 4, 5, 7, 10, and 11; Fig. 1). . Then, extension agents and farmers identified, in each zone, plots where at least one of the adaptive managements had been applied for at least 5 years consecutively. Contiguous or close plots with the same crop or type of crop and under conventional management were identified. This enabled the selection of groups of plots with the highest possible physical proximity and contrasting managements, and on the main soil types in each zone, with at least one plot corresponding to the reference adaptive management, and the rest under conventional management. The conventional management implied mineral fertilization in the case of ExO, nonirrigated plots in IRR, annual monoculture for the ROT strategy, and regular mowing and/or no rotation in the case of GSS. In the case of CA, conventional management implied inversion tillage in nonpermanent crops, and frequent tillage to keep the soil free of vegetation in the rows of woody crops, where permanent grass cover was considered. The number of groups of plots per zone was determined considering the extension of agricultural land, and the diversity of strategies adopted, in each zone. The number of plots selected, and the management strategies tested in each zone, are listed in Table 1. Overall, the network comprised 157 agricultural plots, grouped in 48 groups. The description of each group, including soil types, number of plots, strategies tested, and, in the case of groups considered within the ExO strategy, the source of the organic input applied, is provided as Supplementary Material (Online Resource 2). The soil types corresponding to each zone (Table 1) and tested group (Online Resource 2) were defined at the Great Group level in Soil Taxonomy (Soil Survey Staff 2014), and in some cases attending to special characteristics within each group, such as fluventic traits in Inceptisols and Entisols, or depth limitations.

Soil sampling design and analysis

In the next phase, a sampling strategy was developed to ensure that only areas differing in management, but with homogeneous soil conditions, were compared within groups. That for, in each plot a sampling area was determined so that sampled areas in each group of plots corresponded to the same soil unit for all plots within the group, following the methodology described in Antón et al. (2019). The delimitation of these homogeneous soil zones was carried out on the basis of the highest available detail (soil series or phase). The regional soil map at 1:25,000 was used in the areas where it was available (~40% of the territory and ~70% of cultivated land). Where this was not the case, the delimitation was made from soil information available at 1:50,000, geological information and photo-interpretation. In all cases, the process was completed with a field visit, and with extra soil profiles description when necessary. Attention was paid to generate zones that were as homogeneous as possible, considering in addition to soil criteria, others such as slope or orientation (Tugel et al. 2008; Wiesmeier et al. 2013).

For each sampling area, a sampling design was adapted following the one described by Stolbovoy et al. (2007) for comparing SOC stocks changes in croplands. A randomized template was used to define at least three representative sampling squares per sampling zone (i.e., areas with the same type of soil in each plot of the group). The sampling template was suited to the boundaries of each sampling area, so that the size of the squares was always proportional to, and dependent on, the size of the sampling area defined per plot. Based on a 25-point grid defined within each of the squares, a disturbed composite sample of 25 subsamples was collected at 0-20 cm, the most common tillage depth in the region (Lasco et al. 2006). A 100-cm^3 undisturbed core was collected at the center of each area to determine bulk density at 0–20 cm. This sampling design grants random and representative topsoil sampling. All the processing of cartographic information was performed with ArcGIS 10.6 (Redlands, CA: Environmental Systems Research Institute, Inc., 2018).

Disturbed samples were air-dried, thoroughly mixed and sieved at 2 mm. Because of the elevated inorganic C content in many samples, organic C was analyzed by wet oxidation (Tiessen and Moir 1993). The stock of SOC for each group of plots was calculated from SOC concentration, bulk density, coarse fragment content and depth, for an equivalent soil mass to that of the sample point with the lowest bulk density in each group (Ellert and Bettany 1995; Poeplau and Don 2013; Meurer et al. 2018; Smith et al. 2019).

Soil organic carbon storage assessment and statistics

Data on SOC stocks were first used to make a comparison at the regional level in the different zones identified, and at a local level in each zone, between different soil typologies. Data are provided as means ± standard deviation, and ANOVA was performed to assess differences between groups based on a probability level of $p < 0.05$.

The study of the effect of each strategy considered on SOC storage was performed for each group of plots according to the natural logarithm of the response ratio (RR), understood as the ratio in SOC between the plots with adaptive management, and those under conventional management within each group:

$$LRR = \ln(\mathrm{RR}) = \ln\left(\frac{\overline{X}_R}{\overline{X}_C}\right) \tag{1}$$

where $\overline{X}_R$ and $\overline{X}_C$ are the mean values in the reference plots with adaptive management, and those under conventional management within each group, respectively. This represents a practical way to quantify and summarize the magnitude and direction of the results, allowing to linearize and normalize the sampling distribution (Hedges et al. 1999). The variance of the LRR for each group was calculated following these authors as

$$\mathrm{var}(LRR) = \frac{(SD_R)^2}{n_R\overline{X}_R^2} + \frac{(SD_C)^2}{n_C\overline{X}_C^2} \tag{2}$$

where *SD* and *n* indicate the standard deviations and the sample size of the reference and conventional plots within each group of plots.

Following the approach commonly applied in meta-analyses comparing results on the same parameters but from different study areas, the overall effects of each strategy were analyzed with an unweighted fixed effects (FE) model. This was done at two different scales: first, in the zones including more than one group of plots, allowing to estimate an overall effect in those zones, and second, at the regional scale, providing an overall effect in the region. This model assumes that the only source of variability in the analysis is that associated to the sampling process within each group, calculated according to

Eq. 2 (Hedges et al. 1999). The unweighted analysis assigns the same weight to each group, avoiding the underestimation of the LRR due to differences in sample sizes.

The LRRs for different strategies at group, zone and regional levels were represented in forest graphs, transformed into RR for simplification. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one ($\alpha = 0.05$) (Hedges et al. 1999). All statistical analyses were carried out with R (R Core Team; 2019). Calculations and model performance for RR analysis were carried out using the *metafor* package (Viechtbauer 2010).

Results

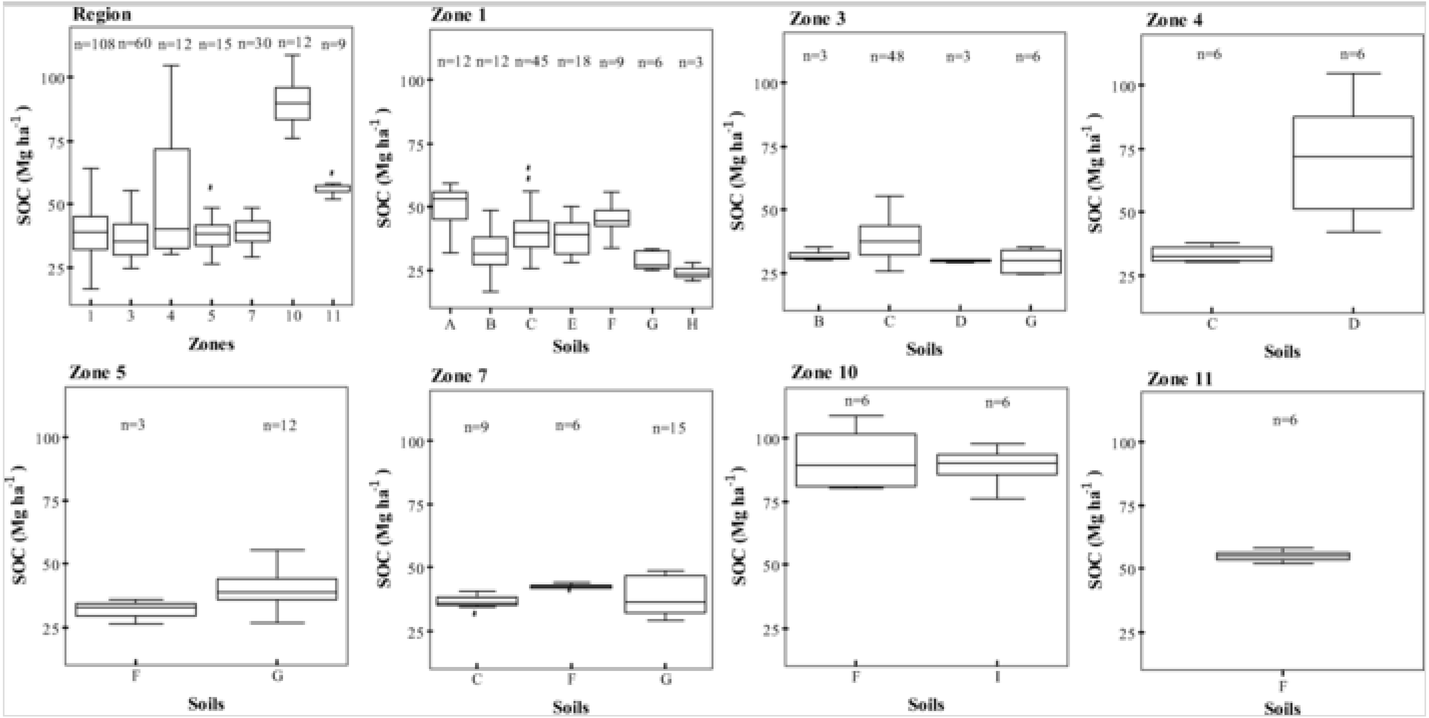
Soil organic carbon storage per agricultural zone and soil type

Figure 2 shows SOC stocks stratified to bioclimatic zones, for plots under conventional management, which can be considered the baseline for agricultural soils in the region. Average values ranged from less than 15 Mg SOC ha^{-1} at some points in zone 1, to more than 100 Mg SOC ha^{-1} in zone 10, for the studied depth (0–20 cm).

Fig. 2

AQ2

Soil organic carbon (SOC) stocks in conventionally managed topsoils (0–20 cm) in the region and in the zones selected for this study, for the different type of soils in each zone. **A** Xerolls, **B** Ustolls, **C** Xerepts, **D** Xerepts with depth limitations, **E** Calcids, **F** Orthents, **G** Fluventic Inceptisols and Entisols, **H** Gypsids, **I** Udepts (Soil Survey Staff 2014)



Among the zones selected for this study, SOC stocks in zones 10 and 11 were significantly higher than in zones 1, 3, 5, and 7 (with no differences between them). Zone 4 had an average stock similar to that in zone 11, but the highest variability by far.

SOC stocks for different soil types within each zone showed differences only in zones 1 and 4. In zone 1, Xerolls displayed the highest observed values, while Gypsids and Fluventic Entisols and Inceptisols the lowest ones. In zone 4, plots on Calcixerepts with a petrocalcic horizon at depth (denoted as Xerepts with depth limitations), had much higher mean values and variability than those on other types of Xerepts.

Effect of management on soil organic carbon stocks

The results of the strategies effect on SOC storage are shown in Figs. 3 and 4 as RR for each group of plots, together with the overall effect per zone, and in the whole region. Across the region, CA, ExO, IRR, and GSS had a net positive effect, and a negative effect was observed for ROT.

Fig. 3

Response ratio (RR) of soil organic carbon (SOC) stocks (0–20 cm) for adaptive management strategies (rotations (*ROT*), irrigation (*IRR*), and controlled grazing and/or rotation in grasslands (*GSS*)). Zones correspond to those in Fig 1. The effect was considered significant when the 95% confidence interval (CI) of the RR did not overlap one (α = 0.05)

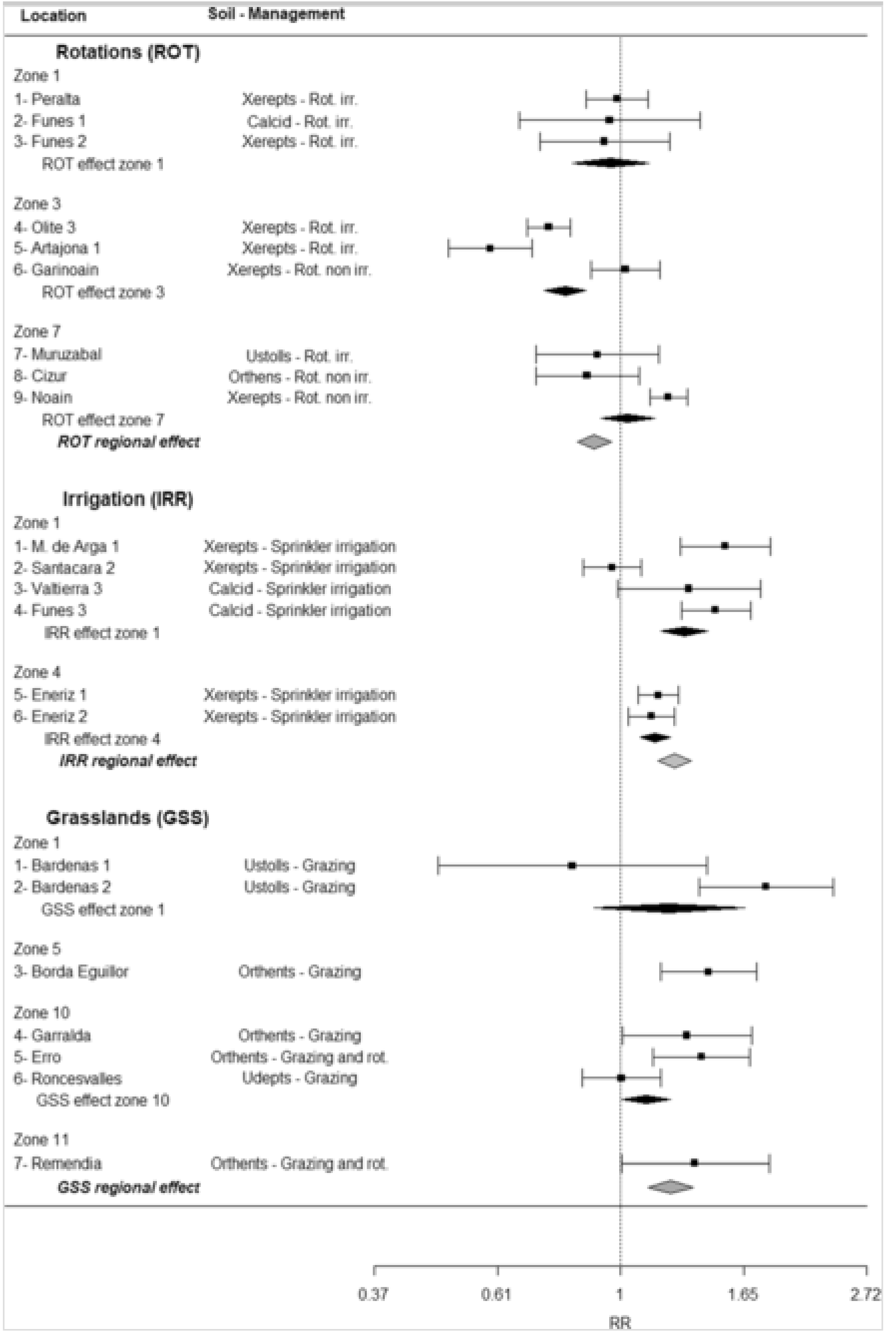
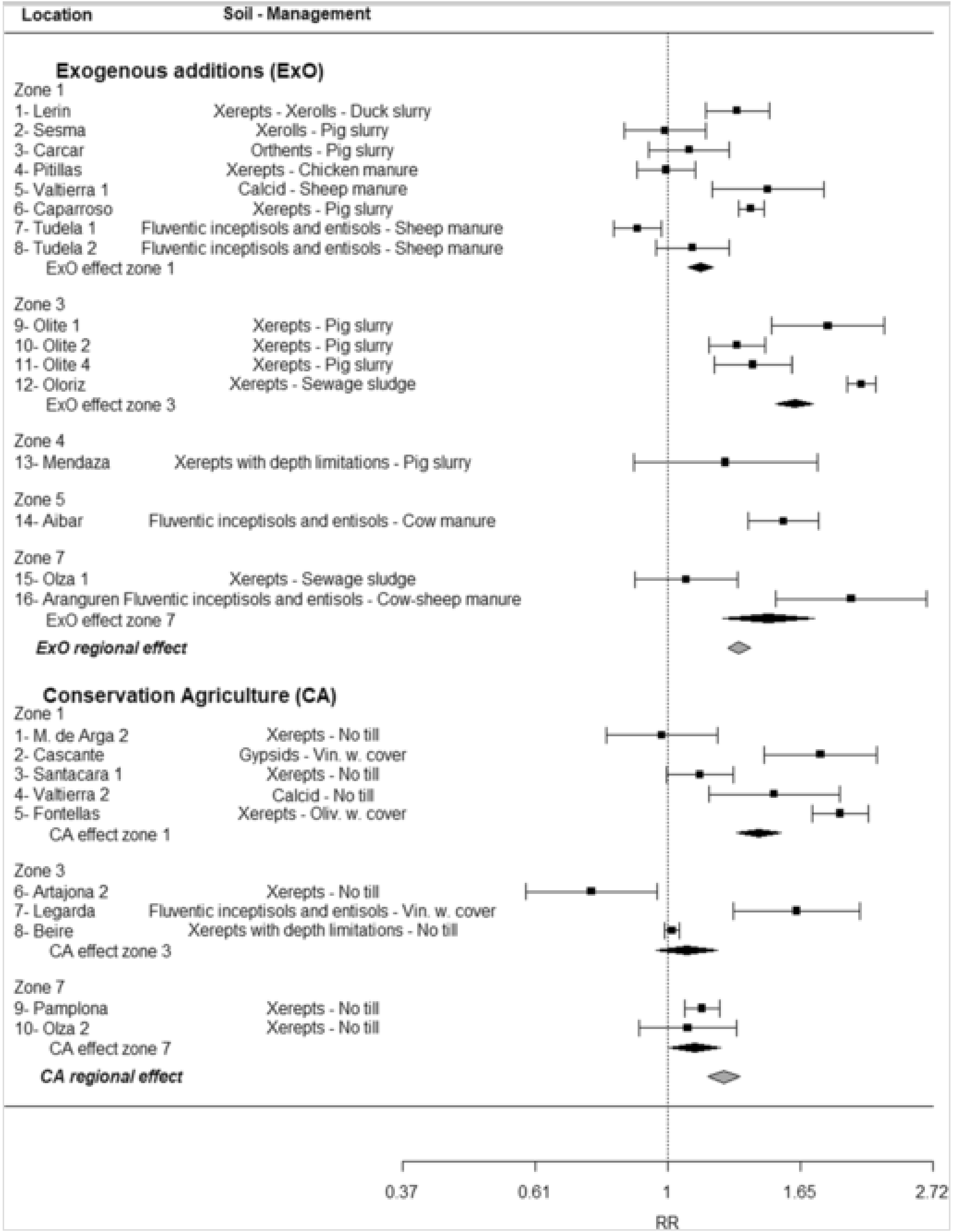

Location
Soil - Management
Rotations (ROT)
Zone 1
1- Peralta
Xerepts - Rot. irr.
2- Funes 1
Calcid - Rot. irr.
3- Funes 2
Xerepts - Rot. irr.
ROT effect zone 1
Zone 3
4- Olite 3
Xerepts - Rot. irr.
5- Artajona 1
Xerepts - Rot. irr.
6- Garinoain
Xerepts - Rot. non irr.
ROT effect zone 3
Zone 7
7- Muruzabal
Ustolls - Rot. irr.
8- Cizur
Orthens - Rot. non irr.
9- Noain
Xerepts - Rot. non irr.
ROT effect zone 7
ROT regional effect
Irrigation (IRR)
Zone 1
1- M. de Arga 1
Xerepts - Sprinkler irrigation
2- Santacara 2
Xerepts - Sprinkler irrigation
3- Valtierra 3
Calcid - Sprinkler irrigation
4- Funes 3
Calcid - Sprinkler irrigation
IRR effect zone 1
Zone 4
5- Eneriz 1
Xerepts - Sprinkler irrigation
6- Eneriz 2
Xerepts - Sprinkler irrigation
IRR effect zone 4
IRR regional effect
Grasslands (GSS)
Zone 1
1- Bardenas 1
Ustolls - Grazing
2- Bardenas 2
Ustolls - Grazing
GSS effect zone 1
Zone 5
3- Borda Eguillor
Orthents - Grazing
Zone 10
4- Garralda
Orthents - Grazing
5- Erro
Orthents - Grazing and rot.
6- Roncesvalles
Udepts - Grazing
GSS effect zone 10
Zone 11
7- Remendia
Orthents - Grazing and rot.
GSS regional effect
0.37
0.61
1
1.65
2.72
RR

Fig. 4

Response ratio (*RR*) of soil organic carbon (*SOC*) stocks (0–20 cm) for adaptive management strategies (addition of exogenous sources of organic C (*ExO*) and conservation agriculture (*CA*)). Zones correspond to those in Fig 1. The effect was considered significant when the 95% confidence interval (*CI*) of the RR did not overlap one ($\alpha = 0.05$)


Location
Soil - Management
Exogenous additions (ExO)
Zone 1
1- Lerin
Xerepts - Xerolls - Duck slurry
2- Sesma
Xerolls - Pig slurry
3- Carcar
Orthents - Pig slurry
4- Pitillas
Xerepts - Chicken manure
5- Valtierra 1
Calcid - Sheep manure
6- Caparroso
Xerepts - Pig slurry
7- Tudela 1
Fluventic inceptisols and entisols - Sheep manure
8- Tudela 2
Fluventic inceptisols and entisols - Sheep manure
ExO effect zone 1
Zone 3
9- Olite 1
Xerepts - Pig slurry
10- Olite 2
Xerepts - Pig slurry
11- Olite 4
Xerepts - Pig slurry
12- Oloriz
Xerepts - Sewage sludge
ExO effect zone 3
Zone 4
13- Mendaza
Xerepts with depth limitations - Pig slurry
Zone 5
14- Aibar
Fluventic inceptisols and entisols - Cow manure
Zone 7
15- Olza 1
Xerepts - Sewage sludge
16- Aranguren
Fluventic inceptisols and entisols - Cow-sheep manure
ExO effect zone 7
ExO regional effect
Conservation Agriculture (CA)
Zone 1
1- M. de Arga 2
Xerepts - No till
2- Cascante
Gypsids - Vin. w. cover
3- Santacara 1
Xerepts - No till
4- Valtierra 2
Calcid - No till
5- Fontellas
Xerepts - Oliv. w. cover
CA effect zone 1
Zone 3
6- Artajona 2
Xerepts - No till
7- Legarda
Fluventic inceptisols and entisols - Vin. w. cover
8- Beire
Xerepts with depth limitations - No till
CA effect zone 3
Zone 7
9- Pamplona
Xerepts - No till
10- Olza 2
Xerepts - No till
CA effect zone 7
CA regional effect
0.37
0.61
1
1.65
2.72
RR

The RR for each individual strategy was different among zones and groups of plots. Variability within each group was rather heterogeneous. For CA, 4 out of the 10 groups of plots tested displayed a net positive effect, and only one (in zone 3) had a net negative effect. The effect was overall positive in zone 1, and nill in zones 3 and 7. ExO resulted in net SOC gains in 9 out of 16 groups tested, with only one (in zone 1) displaying net SOC losses. Only zone 4 showed no overall positive zonal values. IRR had a positive effect in 4 out of the 6 groups tested, with a greater response in zone 1 than zone in zone 4. ROT showed a positive effect in one group (in zone 7) of the 9 tested, and no effect on 6 of them. The net effect was negative in zone 3, and nill in zones 1 and 7. Finally, improved grassland management with GSS had a significant positive effect in 4 out of 7 groups of plots, spread across 4zones (1, 5, 10, and 11).

Discussion

Regional characteristics and soil organic carbon

The climate and soil characteristics defined for the 12 zones in the study corresponded to the expected ranges considering the regional biophysical traits (Online Resource 1, Supplementary Material). This includes climates from warm maritime in the North-West, to dry temperate Mediterranean and dry Steppe in the South-East (Papadakis 1952) and soils in the orders of Alfisols, Ultisols, Entisols, Inceptisols, and Aridisols (Soil Survey Staff 2014). This heterogeneity of pedoclimatic conditions in the region supports the need for a stratified study for accurate assessment of SOC stocks (Lasco et al. 2006; Tugel et al. 2008; Smith et al. 2019). The analysis of SOC storage in conventionally-managed soils (Fig. 2) revealed that the more humid zones, situated at the North of the region (zones 10 and 11 in Fig. 2), where the most common agricultural use is grasslands, had the highest SOC stocks. This is in agreement with general observations in Europe (de Brogniez et al. 2015) and Spain (Rodríguez Martín et al. 2016, 2019), and usually explained by a more favorable water balance allowing for greater primary productivity, and better SOC preservation in grasslands (usually not tilled and without plant residues removal with harvest) than croplands (Wiesmeier et al. 2013). In this study, such effect cannot be determined overall, as no croplands were present in zones 10 and 11 (Table 1). However, comparing croplands and grasslands present at the South of the region in the most arid zone 1 (Table 1), the former were observed to have significantly higher stocks (40.0 ± 9.5 Mg C ha^{-1}) than the later (31.8 ± 9.4 Mg C ha^{-1}), again supporting the interest of stratified studies at the regional scale.

In relation to SOC storage in croplands in zones 1, 3, 4, 5, and 7, the observed values were within the average national range (45.3 ± 28.5 Mg C ha^{-1} in annual crops and 38.09 ± 11.9 Mg C ha^{-1} in permanent woody crops at 0–30 cm, Rodríguez Martín et al. 2016), and in previous studies conducted in these zones (Fernández-Ugalde et al. 2009; Imaz et al. 2010; Antón et al. 2019). The highest values observed in zone 4, in the West-Central area of the region, corresponded to one particular group of plots on Xerepts with depth limitations (Fig. 2), which provides an example of natural heterogeneity and the relevance of considering areas with homogeneous soil characteristics for comparisons among managements.

When assessing the difference between zones and soil types, it has to be noted that SOC storage values shown in Fig. 2 corresponded to topsoils of conventionally managed soils. It is known that agricultural management tends to homogenize topsoil properties (Kuzyakov and Zamanian 2019), blurring natural differences. Despite of this fact, differences observed in zone 1 are an example on the potential natural conditions and limitations imposed by soil type on SOC storage. The soils with the highest SOC content in this zone were those described as Xerolls, i.e., with a Mollic organic-matter rich upper horizon within a *xeric* moisture regime area, corresponding to more or less freely drained Mollisols of regions with Mediterranean climates developed on grasses or oak species (Soil Survey Staff 2014). On the other hand, the soils containing gypsum (Gypsids, Fig. 2), were those with the lowest SOC reference values. The limitations of high gypsum contents for SOC are known (Virto et al. 2006; Casby-Horton et al. 2015).

Adaptive management and topsoil organic carbon

A first observation in terms of the effectiveness of the strategies assessed in this work is that their net effect was uneven, both among them, and within each strategy in different zones. Overall, CA, ExO, and GSS seemed to be efficient at the regional level in promoting SOC storage, in agreement with the general perspective worldwide (Jia and Shevliakova 2019). However, ROT, did not perform as expected from the general knowledge associated to the effect of crop diversification on SOC. (Kremen and Miles 2012; McDaniel et al. 2014; Autret et al. 2016).

Conservation agriculture has been widely promoted as an efficient SOC storage technique (Pittelkow et al. 2014; Gonzalez-Sanchez et al. 2015). Its effect seems to be however highly context-specific (Virto et al. 2015; Jia and Shevliakova 2019). In Spain, for example, no-till has been attributed a potential capacity for fixing atmospheric C of 2 Gg $year^{-1}$, compared to conventional management, but with different rates in time and space (González-Sánchez et al. 2012). In Mediterranean land, contradictory results have been reported, from net gains (Aguilera et al. 2013) to lower sequestration rates than conventional tillage (Francaviglia et al. 2019). This has been related to local conditions, especially those related to the soil water balance and its interaction with crop yields (Virto et al. 2012; Dimassi et al. 2014; Shekhar and Shapiro 2019). In our study, it was observed that, although the effect at the regional level was positive, it was smaller and with a RR close to 1 in zones 3 and 7 in comparison to zone 1 (Fig. 4). These zones differ mostly in their moisture regimes (Table 1), which is drier in zone 1 than in zones 3 and 7. Although no data were recorded for yields in the plots considered in this study, these results agree with the general observation of more frequent yield gains with CA in arid and semiarid land (Pittelkow et al. 2015). This can be related to the greater effect of improved soil moisture conditions associated to CA (Bescansa et al. 2006). Indeed, CA plots with permanent woody crops and grass cover, where there is no removal of grass biomass with harvest, and organic C inputs from grass are higher than in harvested plots, displayed the most positive RR (Fig. 4). In this sense, CA can be an effective technique in the promotion of SOC storage in the topsoil in the South of Navarre. It has to be noted, however, that data in our study refer only to the uppermost soil layer (0−20 cm). It is known that the accumulation of SOC when tillage is reduced can be limited to the upper soil layers (Angers and Eriksen-Hamel 2008; Meurer et al. 2018). This has to be undoubtedly considered when assessing the role of CA in climate change mitigation *via* soil C sequestration. Nevertheless, from an adaptive perspective, gains in topsoil SOC, which can reduce or control soil erodibility and increase infiltration, can be of high interest in a region subjected to increasing extreme rainfall events and scarce precipitation.

AQ3

In relation to ExO, our results confirmed the general observation at the scale of the Mediterranean (Aguilera et al. 2013; Francaviglia et al. 2019) that increased C inputs associated to exogenous additions of organic C are the most effective systems for increasing SOC in agricultural soils. The variability of our results (which was high between and within zones, Fig. 4) can be related to both soil characteristics and to different types of amendments and doses. The goal of the addition of exogenous organic materials to soil was not to gain SOC *per se*, but to manage soil fertility. As a consequence, the doses and types of amendments varied among plots, depending on crops needs and on the availability of economically viable sources. The relevance of the origin and type of organic amendments for exogenous SOC stabilization has been widely reported (Bhattacharya et al. 2016). No direct relationship was found between one particular type of organic amendment and SOC gains, which suggests that the net effect depended on a combination of factors. In addition to the amount (Francaviglia et al. 2019), the time of application and the fractionation of doses, for instance, has been observed to be determinant in final SOC gains when pig slurry is used in similar climate conditions than those in the South of Navarre (Domingo-Olivé et al. 2016).

The actual benefit of importing organic C to increase SOC storage in agricultural soils is under debate, as it can imply loosing C in other systems, depending on the alternative fate of the C in the materials used (Powlson et al. 2011). In the plots included in the study, which represented real agricultural plots using organic amendments and/or fertilization in the region, the most common sources were of animal origin. In this sense, the regional scale can be an adequate framework to redistribute C from surplus systems such as intensive animal production farms to SOC-depleted agricultural soils. Integrating crop and livestock systems can be a good adaptation option (Jia and Shevliakova replace by Jia et al 2019).

AQ4

Some variability was observed in our results when studying IRR (Fig. 3) in zones 1 and 4. The effect of irrigation on SOC storage is not clear. Zhou et al. (2016) observed, in a global meta-analysis, that in all the studied biomes, irrigation induced an increase in SOC of 1.27%, for an increase in C stock in plants of 34.4%. This difference was explained by the fact that irrigation increased both primary production and microbial biomass responsible for mineralization. Trost et al. (2013) found that 8 out of 14 long-term field experiments resulted in SOC gains with irrigation. The effect was observed to be related to climate conditions, with aridity increasing SOC gains. In fact, plots in zone 4 (with a less dry climate than zone 1, Table 1) displayed a smaller effect than those in zone 1. However, unlike in other regional-scale studies (Nunes et al. 2007; Da Gama et al. 2019; Rodríguez Martín et al. 2019), irrigated systems were seen here as able to contribute to SOC storage at a regional scale, when adequate management conditions accompanied irrigation.

Crop diversification cannot be separated from irrigation to understand the net negative impact of ROT in SOC in this study (Fig. 3). None of the groups of plots considered in zones 1 and 3 displayed a positive effect of ROT. The only group of plots with a positive effect of ROT was in zone 7, where irrigation is not used. This has a regional explanation, as these zones differ mainly in their humidity regime (Table 1), making irrigation very rarely used in the more humid zone 7, and widely used in the drier zones 1 and 3. In arid and semiarid areas, fallow and monoculture (or rotations with low diversity) are frequent as a strategy to cope with natural water scarcity (Liu et al. 2016). The advantages of including rotations in cropping systems, and the reduction of fallow periods, have been established for temperate and moist areas (Poeplau and Don 2015). In semiarid areas, only when irrigation is introduced, more complex crop rotations can be adopted. When this happens, however, irrigation is associated to an intensification of tillage and increased fertilization, which in turn may increase SOC losses (Six et al. 1999; Meurer et al. 2018). As such, ROT cannot be considered a win-win strategy for increasing SOC in irrigated areas. Even so, the neutral effect observed in zone 1, indicates the possible viability of this measure that, although did not increase SOC, can increase yield through intensification. Thus, considering climate change projections, and the undeniable adaptive potential of irrigation, adequate combinations of ROT and IRR could be explored in context-specific assessments, including both biophysical and socio-economic aspects.

Finally, the variety of practices considered as improved grassland management (GSS), was wide, as the zones studied comprised the widest climate gradient in the region (Fig. 3). However, a general trend was observed toward more SOC under GSS management. In all cases, the conventional management implied the exclusion of animals and biomass exportation from the fields. Including controlled grazing, and/or changing land-use to include crop-lay rotations, which very likely improve the net C balance in the systems, was observed to be efficient in SOC storage. Average and low intensity grazing has been seen to lead to SOC gains in moist and dry temperate areas (Abdalla et al. 2018). This was the case also in most groups of plots in zones 10 and 11, where the baseline was the highest in the region (Fig. 2).

Regional assessment

The objective of this study was to assess, at a regional scale, the effectiveness of different strategies expected to have an adaptive potential. Although most of them had positive effects overall, these were not straightforward nor uniform across the region. The reasons for this variability seem different for the different strategies. While for CA climate seemed to induce differences in net SOC gains, ExO effect seemed more dependent on the combination of management factors, such as the source, doses, and frequency of application, as explained above.

One singular observation is that, although some differences were observed in the SOC storage baseline of different soil types under conventional management, this factor was not able to detect differences in all cases within each of the studied zones (see for instance zones 1 and 3 in Fig. 2). A number of reasons can explain this observation. First, although soil types were selected on the basis of their taxonomic characteristics in Soil Taxonomy (Soil Survey Staff 2014), only the upper 20 cm of the profile were considered for this study. Some profiles differing in their taxonomic classification, may have similar characteristics (such as clay content or mineralogy) in this part of the profile. For instance, all soils in zones 1, 3, 4, and 5 contained more than 20% carbonates in their upper horizon, which is a known factor of SOC stabilization (Rowley et al. 2018). Second, all soils studied here corresponded to agricultural soils, most of which have been managed for decades. As explained above, this implies a homogenization of their surface properties compared to their natural standards, which are managed to progressively approach the most favorable conditions for crops (Kuzyakov and Zamanian 2019).

In relation to the role of soil type as a factor in the effectiveness of the strategies, none of the soil types considered was systematically observed to result in gains or losses of SOC among the different strategies. Although the scope and extension of this work does not allow for a detailed study of this factor, an example is the case of Xerepts (the most frequently found soil type, Figs. 3 and 4). In addition to the reasons outlined above to explain this lack of correlation, this suggests that the study of the influence of soil type on SOC storage at a regional scale may require criteria other than the soil genetic classification.

Regardless of soil type, the results observed allow for a regional assessment of SOC gains under different systems in relation to established objectives, such as the 4per1000 initiative. Although more an encouraging figure than a target (Soussana et al. 2019; Rumpel et al. 2020), this figure can be contrasted to the observed quantitative changes to provide a perspective for comparison with other studies. Data in this study came from plots with at least 5 years under the same management. Most ranged between 5 and 20 years of relatively continuous management. Translating an annual gain of 4‰ in this time lapse would correspond to net gains from 2% to 8% (RR of 1.02 to 1.08). Data in Figs. 3 and 4 indicate that this range is well below or below the average gain observed for CA, ExO, IRR, and GSS overall, but within the range of some changes observed in some cases, such as CA in zones 3 and 7.

In the European context it has been observed that adaptive strategies can be effective to improve SOC storage in arable lands, although they are modulated at local level by pedoclimatic conditions (Costantini et al. 2020). For instance, a study developed in Bavaria based on C sequestration scenarios including promising management practices revealed that the 4p1000 target is not feasible for this region (Wiesmeier et al. 2020). For Hamidov et al. (2018) adaptation strategies under climate change scenarios reduced SOC losses in 75% of 20 agricultural adaptation case-studies across Europe, and SOC levels were expected to decrease in only two of them (10%). Our study highlights this site-dependence, as different responses to the same strategy were observed depending on local conditions. Zone 1 (with the highest agricultural surface) seems in this sense strategically interesting, as the one with most diverse agricultural systems (Table 1), in addition to a high proportion of groups showing a positive response. Some of the soils in this zone had the lowest observed baseline SOC contents (Fig. 2).

Another important aspect at the regional scale, is that our approach assessed management strategies already in practice in Navarre. This implies that some farmers are already familiar with them, and that they can be used in the region in conventional farms within the average profitability thresholds. This can be a relevant factor in favor of their expansion across the region, in contrast with the problems associated to the introduction of new techniques (White et al. 2018). Although the farmers’ reasons for adopting adaptive strategies are diverse (Prokopy et al. 2019; Demenois et al. 2020), the existence of successful pioneer farmers in the local environment is a known factor of effective adoption of alternative managements (Altieri et al. 2015).

Finally, and in relation to climate change adaptability, major climate change threats identified for this region are related to changes in temperatures (average increase and heat waves) and rainfall (scarcity and extreme events). In this context, an increase of SOC stocks may have a positive impact on several soil properties such as water storage and infiltration, soil erosion, biodiversity, and soil fertility, crucial for adaptation. However, the relationship between SOC and these properties is not straightforward, and is also known to be soil and climate-dependent (Johannes et al. 2017). Future research is needed to assess the relationship of SOC to soil vulnerability. Also, some of the changes that might have a positive effect in adaptation, might not correspond to increased climate change mitigation, if for instance SOC sequestration rates at depth are not as clear as at the topsoil (CA), their energetic cost overpasses their benefits in SOC (IRR), or they hinder mitigation in other sectors (ExO). Following the criteria established by the 4per1000 initiative (Rumpel et al. 2020), these aspects need to be revised for a general assessment of each strategy. Greenhouse gasses emissions associated to each strategy (such as N_2O) should also be considered to this respect.

In addition, it has to be noted that SOC accumulation related to the agricultural systems studied here is not endless nor irreversible. Soils are a finite carbon sink implying that sequestration rates tend to decline to negligible within decades or years (Chenu et al. 2019). Also, new changes in management, or the mere effects of changes in climate can revert SOC gains in very short time lapses (Álvaro-Fuentes et al. 2012; Jebari et al. 2018).

Conclusions

In this study, the relevance of climate and, to a lesser extent, soil type, on baseline SOC storage in conventionally-managed soils was confirmed in the region of Navarre.

The regional approach also allowed observing relevant differences in SOC associated to the managements tested. As expected, management of exogenous sources of organic carbon (ExO) was the most efficient strategy to increase SOC stocks in croplands across the region. Optimized grassland management strategy (GSS) also resulted in net SOC gains in all the zones tested. This confirms the importance of organic matter management in croplands and livestock farms. The potential benefits of conservation agriculture (CA), and the implementation of irrigation (IRR) and crop rotations (ROT) need to be evaluated with care, as they were observed to be uneven in the region: less efficient with decreasing aridity in CA, management-dependent for IRR, and overall negative in ROT, likely related to the use of irrigation and the intensification of cropping sequences with it. Therefore, although the final benefits of topsoil SOC gains need to be assessed considering other aspects such as their climate neutrality or economic viability, these results support the inclusion of ExO, GSS, and to some extent, CA in regional adaptation programs, and highlight the need of regional approaches and adequate segmentation for site-specific assessment of the efficiency of commonly adopted agricultural practices.

Publisher’s note

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Supplementary Information

ESM 1	**ESM 2**
(PDF 374 kb)	(PDF 232 kb)

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