Costantini, E.A.C.; Antichi, D.; Almagro, M.; Hedlund, K.; Sarno, G.; Virto, I. 2020. **Local adaptation strategies to increase or maintain soil organic carbon content under arable farming in Europe: Inspirational ideas for setting operational groups within the European innovation partnership.** JOURNAL OF RURAL STUDIES.79. © 2020 Elsevier Ltd. DOI (**10.1016/j.jrurstud.2020.08.005**).

Local adaptation strategies to increase or maintain soil organic carbon content under arable farming in Europe: inspirational ideas for setting Operational Groups within the European Innovation Partnership

Abstract

In the European Union, the setting of Operational Groups (OG) is supported by the European Innovation Partnership to tackle specific problems and favor innovation in agriculture. They constitute an important aspect of the current Common Agricultural Policy. Increasing or maintaining soil organic carbon (SOC) content under arable farming has been acknowledged as a primary target of European agriculture. SOC-preserving agriculture needs its techniques to be tailored to local conditions, namely, the combination of factors related to the environment (climate and soil characteristics), to the farming system (land use type, farm specialization, crop management), but also to the social and cultural context (market and availability of production means, subsidies, farmers' education, propensity for innovation and change)~~, too~~. In this paper we present inspirational ideas and show success examples of local adaptations strategies to increase or maintain SOC content in soils under arable farming in Europe. They include:

- Adoption of soil management strategies to improve SOC storage in irrigated systems.

- Precision farming and other high-tech solutions able to generate local diagnosis and adaptive strategies for increasing SOC and reducing greenhouse gasses emissions.
- Innovative strategies for extending soil cover periods and introducing cover crops in rotations in areas with limited water availability or prone to harsh weather conditions.
- Management of rainfed and low input crops to maintain and increase SOC in dry climates and erosive prone soils.

These case studies could facilitate the setting up of OGs and the application of innovative practices in different European countries.

Keywords: *SOC; soil fertility; sustainable land management; conservation agriculture; cover crops*

Highlights

- Rationale is given for considering local soil and climate in farming strategies
- Limitations to increase SOC in arable land are described
- Case studies illustrate possible references for Operational Groups
- Diversification of cropping system as key factor to increase SOC

1. Introduction

The Common Strategic Framework (EU Regulation 2013/1303) outlines the strategic guidelines and recommendations to be achieved by the European Union by 2020. Among the Primary Objectives (Themes) of the Cohesion Policy there is promoting the adaptation to climate change and the efficient use of resources. To this aim, measures to promote soil organic carbon (SOC) sequestration in agriculture and forestry are supported by the pillars of the Common Agricultural Policy (CAP). However, the Communication on the Future of Food and Farming, recently delivered by the European Commission (COM (2017) 713 final), clearly states that a one-size-fits-all approach to the CAP simply does not work in a Europe where farms and farming conditions are so diverse. Despite intensive mechanization and large supply of other technological inputs, the management of agricultural lands in Europe is still very much differentiated. One of the main reasons for this differentiation is constituted by the presence of large climatic and pedological differences, and varying environmental limiting conditions. The main separations reflect the North-South gradient of moist-cold Boreal, moist-temperate Oceanic, and dry-warm Mediterranean climates, with the corresponding different limitations expressed by the length of plant growing period in the North and the amount and length of plant water deficit in the South. Soil features and constraints instead differ at a more detailed scale and form the basis for the success of adopted strategies to increase or maintain SOC at the farm and ~~field~~[A1] regional levels.

The basic strategy to increase SOC stocks is through restitution of endogenous (e.g., crop residues, wood litter, weeds) or incorporation of exogenous (e.g. animal manure, ~~depuration~~sewage ~~municipal wastes~~sludge, compost) organic matter to the soil. In this context, the recycling of organic wastes from domestic activities and urban areas as organic fertilizers is an opportunity to transfer organic carbon in ways that enhance SOC storage, ameliorate the nutrient content of soils and close nitrogen and phosphorus cycles at regional scales (Rumpel et al., 2019). In addition to exogenous organic amendments such as compost and manure, reduced or no tillage, improved management of crop residues and agro-industry by-products, crop rotation, green manuring, and cover cropping are the most suitable interventions to enhance SOC stocks in agricultural soils (FAO, 2017a). However, few generalizations can be made of findings about sustainable agricultural practices, because their effectiveness is inherently dependent on the local socio-economic, environmental and cultural context (Henry et al., 2018; Rumpel et al., 2019; Sanz et al., 2017; Schoonhoven and Runhaar, 2018). Local limitations due to climate and soil conditions can make standard strategies to be ineffective when applied at these sites, or local growing conditions can interfere with the efficiency of these strategies, suggesting the need of developing locally-adapted innovative strategies ~~of adaptation~~.

In their analysis of the pros and cons of the 4p1000 Initiative, Rumpel et al. (2019) highlighted how local conditions, and above all pedoclimate, land use and management practices, may hamper reaching the targeted SOC stock gain. The same authors also indicated that the levels of SOC inputs, soil-inherent pedologic characteristics and the state of soil development are the major factors affecting the SOC stock potential of each single soil. It is well known that this potential is the result of a new steady state reached by a soil when management practices aimed at increasing SOC stocks are being applied. The level of this new equilibrium conditions varies widely upon different soil and climatic conditions. Normally, this process takes years or even decades, with differences among soils and climates, and implies a decreasing trend of the SOC sequestration rate, meaning that long term observations are needed to substantiate SOC storage potential of each single soil-climate combination (Lal, 2008~~ref~~).

The Agricultural European Innovation Partnership (EIP-AGRI) was launched in 2012 to contribute to the European Union's strategy 'Europe 2020' for smart, sustainable and inclusive growth (https://ec.europa.eu/eip/agriculture/en/about). This strategy sets the strengthening of research and innovation as one of its main objectives and supports a ~~new interactive, multi-actor~~new interactive, multi-actor~~ial~~ approach to innovation. Farmers, advisers, researchers, companies, ~~NGOs~~NGOs, and other stakeholders are supported by the National and Regional Rural Development Programs (RDPs) to form Operational Groups (OGs) aimed to create innovations by tackling specific practical problems or opening new opportunities. The OG approach makes the best use of different types of knowledge (practical, scientific, technical, organizational, etc.), in an interactive and collaborative way.

The objective of this paper is to give the rationale for setting new OGs, present inspirational ideas, and show success examples of local adaptation~~s~~ strategies to increase or maintain SOC content in soils under arable farming in harsh~~difficult~~ conditions. These case studies could facilitate the adoption of innovative practices in other European regions, showing similar environmental constraints.

2. Diversity of environmental and management conditions in Europe

In Table 1 we summarized the results of the literature search performed to address the issue of the importance of adapting strategies to increase SOC storage in peculiar local conditions. Each management practice has been reported with related results in terms of SOC concentration, SOC storage and SOC storage rate.

Table 1 - Results from scientific literature and projects dealing with management practices and soil organic carbon (SOC) concentration (g 100 g^{-1}), stock (Mg C ha^{-1}) and storage rate

(Mg C ha^{-1} y^{-1})~~Examples of successful case-studies on the use of cover crops under limiting pedoclimatic conditions for a possible development into EU Operational Groups.~~

2.1 Land uses, climates, and soils

According to Eurostat (2018), agricultural land use is the most common primary land use category in the EU-28, accounting for 41.1 % of the total area in 2015. Arable land made up 60% of the Utilized Agricultural Area (UAA) in 2013 with 104 million hectares, although the distribution of the main types of agricultural land use types (arable land, permanent grasslands, permanent crops and kitchen gardens) varied widely between Member States. The highest values observed in Finland and Denmark (98% and 91% of the UAA respectively). ~~The lowest share of arable land (21% of the UAA) was observed in Ireland, the United Kingdom, Slovenia and Luxembourg (79%, 63%, 59% and 51% respectively).~~ Close to half of the utilized agricultural area (UAA) was reported in France, Spain, the United Kingdom, and Germany. The lowest share of arable land (21% of the UAA) was observed in Ireland. Within agricultural land, cropland covered, on average, about~~some~~ 22.2% of the total area, although the share of cropland varies greatly among countries and NUT2 territories (from 50.6% in Denmark to 9.5% in Slovenia and 1.2% in Sweden). In most member states, the share of cropland was between 10% and 35% of overall land cover. ~~Arable land made up 60% of the UAA in 2013 with 104 million hectares, although the distribution of the main uses of agricultural land types (arable land, permanent grassland, permanent crops and kitchen gardens) varied widely between Member States. The highest values observed in Finland and Denmark (98% and 91% of the UAA respectively). The lowest share of arable land (21% of the UAA) was observed in Ireland, the United Kingdom, Slovenia and~~

~~Luxembourg (79%, 63%, 59% and 51% respectively).~~ Finally, in relation to the production system, the total area under organic farming in the EU-28 was 11.9 million ha in 2016 and is still expected to grow in the coming years. The increase in organic area between 2012 and 2016 was 18.7%.

According to the European Soil Data Centre (ESDAC), in Europe there are at least 24 different major types of soil, this variety representing the variability in climatic conditions and pedogenetic factors.

Considering the topsoil (0-30 cm), it has been estimated that 45% of European soils have a low or very low organic carbon concentration (from 0 to 2 g 100 g^{-1}) and 45% have a medium concentration (2 to 6 g 100 g^{-1}) (JRC, 2011). The databases reflect the broad scale influence of climate on SOC, with a manifest decreasing gradient from the Boreal to the Mediterranean climates. In fact, it has been largely demonstrated that drier and hotter climates favor SOC depletion in agricultural lands (Pellegrini et al., 2018; Francaviglia et al., 2019). Lugato et al. (2014b) estimated the content of SOC in European agricultural topsoils under different ~~uses~~ conditions [A2]through a modelling approach, which allowed for upscaling single spot measures of SOC content, taking into account also management practices and official statistics. According to their predictions, arable land was predicted to store~~ck~~ 7.65 Gt of SOC (43% of total) in the first 30 cm of depth. The distribution of this SOC was however seen as rather heterogeneous among territories. Another study on the potential for SOC sequestration in European arable land (Lugato et al., 2014a) illustrated that, among land-~~-~~use~~s~~ changes that do not imply converting arable land into other uses (i.e., grasslands), some strategies (i.e., ley cropping systems and cover crops) seem to have a greater potential to increase SOC stocks than others (i.e., straw incorporation and reduced tillage). The efficiency of these strategies was however found to be highly variable ~~in~~ across different regions (Lugato et al., 2014a).

Besides climate and soil typ~~eology~~e, soil degradation is acknowledged as a main driver of SOC impoverishment (FAO, 2017a; Sanz et al., 2017). A review on major soil degradation problems in Europe issuing from many~~ of these~~ sources can be found in Virto et al. (2015), who concluded that no single soil management strategy to cope with soil degradation is suitable for all regions, soil types and soil uses.

2.2. Organic fertilization strategies

In addition to ~~the ~~returning carbon to the soil~~ return of C from ~~by decomposition of crop residues or cover crops, supplementing the soil with carbon from external sources (i.e., organic fertilizers, manure, composts, slurries, sewage sludge) is another complementary strategy with huge potential to increase SOC in many cropping systems. In a ~~their ~~review of studies conducted under~~produced in~~ Mediterranean conditions, Francaviglia et al. (2019) reported that the application of external C sources to the soil has a great potential in terms of SOC storage rate, with highest results obtained by compost (+334.02•~~-~~10^{-3} M~~kM~~g C ha^{-1} yr^{-1} ~~x 1000~~) and sewage sludge (+101.58•10^{-3} M~~ kM~~g C ha^{-1} yr^{-1} ~~x 1000~~), whilst manure was less effective (+18.70•10^{-3} M~~ kM~~g C ha^{-1} yr^{-1} ~~x 1000~~) and slurry even negative (-0.07•10^{-3} M~~ kM~~g C ha^{-1} yr^{-1} ~~x 1000~~), especially when combined with mineral fertilizers (-7.02 •10^{-3} M~~kM~~g C ha^{-1} yr^{-1} ~~x 1000~~) (Table 1).

The use of organic amendments is normally linked to organizational and economic aspects of farm management and supply chains. The availability of farmyard manures or slurries is obviously connected to the presence of animal husbandry in the farm or in neighbor farms, whilst purchasing these products on broader markets is normally unviable for farmers due to their high volume and consequently high transportation and spreading costs. The choice to include or not animal production in the single farm or in a local network of ~~local ~~farms is normally an option linked to farm diversification strategies, ~~and~~ availability of manpower as well as local markets for animal products.

Nevertheless, given their high potential in terms of SOC storage rate, other external sources of carbon as composts and sewage sludge could be valuable fertilization options for farms not connected to animal production.

2.3. Tillage systems

Reduced tillage is still a limited practice in Europe. In relation to tillage systems used in arable land, inversion tillage (mostly ploughing) was the most wide-spread tillage practice in EU-27 in 2010, being practiced on almost two-third of the arable land in EU, while almost a fifth was tilled with conservation practices, but pure zero tillage was not practiced in most areas. ~~Conservation agriculture in Europe, in particularalthough in increase, is estimated to interest onlyabout 2.04Mha in 2013 (Kassam et al. 2015).~~ ~~In relation to tillage systems used in arable land, inversion tillage (mostly ploughing) was the most wide-spread tillage practice in EU-27 in 2010, being practiced on almost two-third of the arable land in EU, while almost a fifth was tilled with conservation practices, but pure zero tillage was not practiced in most areas.~~ The share of arable land on which conservation tillage, which includes minimum soil disturbance coupled with crop rotation and permanent maintenance of soil mulch cover (http://www.fao.org/conservation-agriculture/en/), is applied also varied greatly among countries within regions, for instance, from 0% in the Azores, Madeira, Malta and Montenegro, to 65% in Thüringen (Germany) and the West Midlands (United Kingdom) in 2010. In a fifth of the regions, conservation tillage was practiced on more than 29.5% of the arable land. ~~In~~More recent estimations (year 2013) report that ~~2013,~~ conservation agriculture in Europe, although in increase, is estimated to ~~interest~~cover [A3]about 2.04 Mha -(Kassam et al. 2015). In most countries, the largest share of arable area on which conservation or zero-tillage is applied was found on farms specialized in cereals, oilseed and protein crops.

2.4. Irrigation

Since the 1990s, recurrent droughts in Europe, along with the increased need to enhance crops economic sustainability, have forced the implementation of additional irrigation, growing the proportion of the total cultivated area that is irrigated. The need of irrigation has become particularly important for the Mediterranean countries. At present, much of the food production (about 40%) in the Mediterranean area is associated with irrigation. The amount of water used accounts for 72% of the current freshwater withdrawals across the Mediterranean area (Antonopoulos et al., 2017).

As described by Eurostat (2018), in 2013 the total irrigable area in EU-28 was 18.7 million ha (11.3% total agricultural area), although only 10.2 million ha (6.2% of total) ~~was~~ were ~~actually~~ really irrigated. These values are in fact the result of an expansive trend, which represents an average increase of 13.4% since 2003 in all countries except Portugal. In particular, Spain and Italy increased their irrigable area by 19.7 and 15.5%, respectively. In the context of climate change, irrigation demand in Southern Europe is projected to further increase (Füssel et al., 2017).

2.5 Precision farming

High Tech Farming can be a useful tool to maintain SOC, using best available technologies to adapt crop and soil management to specific conditions and variability at field scale. Site-specific management through precision agriculture (PA) can lead to optimization of quantity and quality of crop yields, whilst local variability of SOC is detected and corrected by means of fertilization, applied on a detailed soil-by-soil basis. The contribution of PA can be referred to a series of tools sharing an integrated use of Information and Communication Technologies (ICT) to identify and properly manage small areas with homogeneous conditions, for instance in terms of soil fertility.

3. Effect of crop type and management on SOC at the national and regional scale

3.1 The influence of different crop types on SOC

Many authors suggest that changes in land use and crop management might be responsible for the variations in SOC at the country and regional levels (Smith et al., 2012). Comprehensive studies recently published online (FAO, 2017b) indicated marked variations in organic carbon stocks among crop types. In particular, topsoils (0-30 cm) of arable lands at the global scale show mean values of 51.0 ± 0.66 Mg C ha^{-1}, while rice fields and forests ~~stands~~ account for 55.6 ± 3.01 and 71.1 ± 2.10 Mg C ha^{-1} respectively. Most authors agree that, under equal pedoclimatic conditions, SOC content is generally smaller in cropland soils than in forests, grasslands or shrublands (see, for instance, Pellegrini et al., 2018).

A revision of the values given for SOC concentration in the first 30 cm of Spanish soils showed a high variability in the medians, from 0.82 g SOC 100 g $soil^{-1}$ in fallow areas to 1.24 and 1.29 g SOC 100 g^{-1} in horticultural land (mostly under irrigation) and grain legumes, respectively (González-Sánchez et al., 2018) (Table 1). The comprehensive study of the potential of different management strategies to increase SOC in Spain (González-Sánchez et al., 2018) also showed a great influence of crop types, farming systems and/or crop rotation.

The information stored in the Italian soil database confirms the influence of land use type on ~~soil carbon~~SOC stocks (Costantini and Lorenzetti, 2013). Recently updated studies for the Italian map of soil organic carbon, published in the framework of the FAO global assessment (FAO, 2017b), indicate mean SOC concentration values (0-30 cm) in paddies and other arable lands (urban soils included) between 1.16 and 1.33 g 100 g^{-1}, between 1.74 and 2.26 g

100 g^{-1} in meadows and other less intensively or not cultivated areas, whereas in different kinds of woodlands and natural areas they can reach hig1her values up to 3.48 g SOC 100 g^{-1} (Table 1). Though, the large values of standard deviation indicate that variations of land management and local conditions play a great role in regulating SOC.

In NW Portugal, in temperate areas with adequate rainfall for winter cereal cultivation, recent trials on the introduction of legume crops in a rotation of winter cereals have resulted in no gains in SOC after three years (Oliveira et al., 2019), very likely because of soil conditions including low clay contents, and low-reactive minerals in the clay fraction.

3.2 The influence of tillage on SOC

In some cases, strategies widely adopted and recognized to increase SOC content in arable land, such as no-till adoption or the diversification of rotations by including legume crops, seem not to get the expected responses (Dimassi et al., 2014; Oliveira et al., 2019). Within no-till systems, it has been observed that the gain in crop productivity associated to the adoption of no-till is the major driver of SOC gains, explaining more than 30% of the observed increment in a worldwide meta-analysis (Virto et al., 2012). Recent research for the Mediterranean region (Francaviglia et al., 2019) supports this view. Crops ~~sensitive to this change~~benefiting from shifting from conventional tillage to conservation tillage in terms of productivity seem therefore more effective for SOC enhancement under no-tillage systems. Usually, these crops are represented by summer crops (e.g. maize, soybean) when grown in areas prone to drought stress. Compared to inversion tillage, the application of no-till through the direct sowing of these crops in dry conditions can result then in earlier and better crop establishment, higher nutrient availability (mediated by faster mineralization of organic matter in the hottest season) and then also higher yields if sufficient water availability is also ensured across the season (Pareja-Sánchez et al., 2019). Nevertheless, besides increasing plant biomass-derived C inputs (i.e. crop residues returning to the soil), reducing SOC mineralization rates (i.e. the major SOC output) by tillage operations can also play a major role, especially in Mediterranean areas prone to high oxidative conditions (Mazzoncini et al., 2011). Reduced or nil response to no-till adoption in the long-term has been also verified in loam soils in temperate areas of Europe with extensive wheat and maize cropping (e.g. Dimassi et al., 2014). This result has been associated to the lack of response of crop productivity to tillage strategies, as well as to the existence of a climate with a positive water balance inducing mineralization of crop residues left at the soil surface. As crop productivity is also the result of a successful crop protection, low or null increase in crop yields observed in no-till and minimum tillage systems under different pedoclimatic conditions should be related to difficulties in controlling weeds, especially perennial species, pests and diseases (Chinseu et al., 2019). Spatial and temporal variability in soil and climatic conditions clearly plays a key role in the selection of target noxious organisms in each specific case.

Other technical barriers actually hindering a wider adoption of no-till among farmers in Europe could be identified in peculiar combinations of soil characteristics and unavailability of proper machinery (i.e. direct drilling machines or machinery to manage crop residues or cover crops) (Sanz et al., 2017). For instance, it is well known that soils prone to crust and heavy compaction in topsoil (e.g. soils rich in silt, or with low ability of the soil structure to regenerate naturally because of a high content of illite-type clay, which has low shrinkage-swelling capacity) are not well adapted to the direct sowing of many crops, above all small seeds crops (Sasal et al., 2017). Due to their weight, direct drilling machines may cause soil compaction themselves, hampering seeds to germinate and plantlets to establish well (Chinseu et al., 2019), and need to be adapted to specific soil conditions to reduce soil compaction (e.g. by mounting shanks in front of the furrower), but then increasing purchase costs. Also clay soils on hillslopes can be difficult to manage under no-tillage, due to difficulties in field operations (e.g. powerful tractors are needed due to high traction forces, the high clay content make narrower the windows where the soils can be seeded) which translate into frequent poor crop establishment and yield.

Besides these technical constraints, there is a number of other barriers faced by farmers willing to adopt conservation agriculture practices. First of all, the absence in specific regions of financial incentives or subsidies to motivate or compensate farmers for possible yield losses. No till normally encompasses the use of agrochemicals (pesticides but also mineral ~~fertilisers~~fertilizers), which makes its environmental impact less positive and sometimes farmers cannot afford the costs because crop yields ~~also~~ are also reduced or maintained in the short term, which makes the economic balance negative, at least in the short run (Sanz et al., 2017; Ingram et al., 2014).

From a socio-cultural point of view, in some areas no-till conflicts with an important cultural symbol for hard work, as tillage is generally believed to ~~symbolise~~symbolize a hard worker, and with the social recognition that a field properly ploughed is “clean” (Chinseu et al., 2019; Schoonhoven & Runhaar, 2018).

Uncertainty about the weather, policy and market developments in addition to internal farm factors (such as debt, tenure, and family status) are other important barriers to overcome.

3.3 SOC in irrigated and non-irrigated arable lands

In relation to soils and organic C storage, the adoption of irrigation has different potential effects, including alterations of the organic C cycle (Entry et al., 2002; Denef et al., 2008), as it can increase the amount of organic C entering the soil through a greater plant productivity, but can also favor mineralization by providing moisture and thus stimulating microbial activity. Irrigation is also associated to some intensive cropping systems such as vegetables, which need intensive and frequent tillage operations and high fertilization inputs, which can concur to alter the carbon cycle.

The consequences of these practices have been reported to affect the soil chemical fertility (McDowell et al., 2011), its physical condition and biological indicators (Manono and Moller, 2015), which can indirectly affect the stabilization of SOC. Soil quality indicators sensitive to management can also therefore change when dryland is converted to irrigation (Apesteguía et al., 2017). As pointed out by Chenu et al. (2019), different observations suggest that these alterations are site- and management-dependent, as the changes observed in SOC stocks are not always directly related to the increment observed in crop yields (Follett et al., 2013).

The effect of irrigation on SOC has been indeed observed to vary according to local conditions and specific water and soil management. In Mediterranean Europe, soil C losses associated to the implementation of irrigation have been reported in Portugal (Nunes et al., 2007) as well as in Italy (Costantini and Lorenzetti, 2013). The negative effect of irrigation might be related to the consequent intensification of agricultural management and it is particularly evident under warm and dry climates. The data stored in the Italian soil database indicate for the regions of central and southern Italy lower SOC values for all irrigated crops, particularly for vegetables, row-crops, and orchards (Costantini and Lorenzetti, 2013).

Modeling scenarios also point out the possibility of C losses upon a wider irrigation adoption in the long term in terms of acreage (Álvaro-Fuentes and Paustian, 2011; Muñoz-Rojas et al., 2017). A study conducted in Navarre (NE Spain) showed that the turn-over rates of organic C can be accelerated in the short-term, very likely because of changes induced in the shoot-to-root ratios of some crops, and the less limiting conditions for soil C mineralization (Apesteguía et al., 2015) when irrigation is adopted.

Some other studies have shown a positive effect of irrigation on SOC. Aguilera et al. (2013b), when comparing organic and conventional cropping systems in Mediterranean conditions, observed that SOC stock increment in organic systems was greater under irrigation than under rainfed conditions (25% vs. 13% increase over conventional, respectively).

In summary, we can conclude that

the overall consequence of the described~~As a summary,~~ interactions between soil, climate, crop type, and agricultural management,~~ make~~ is that ~~that ~~strategies to ensure SOC stabilization in arable land need for~~a~~ local assessments.

4. Needs for adaptation at the local scale: problematic soil, climate, and management conditions

~~In Table 1 we summarized the results of the literature search performed to address the issue of the importance of adapting strategies to increase SOC storage in peculiar local conditions. Each management practices has been reported with its ownrelated results in terms of SOC concentration, SOC storage and SOC storage rate.~~

4.1 C management in soils subjected to wind erosion

Wind erosion affects both the semi-arid areas of the Mediterranean region as well as the temperate climate areas of the northern European countries (Borrelli et al., 2018).
The North-West parts of Europe are the most vulnerable to wind erosion and almost 40% of the agricultural area in Denmark is deemed to be affected (Riksen & De Graaff, 2001). This depends on the combination of wind trades, light soil texture, and intensity of the farming

practice. As most of the carbon is lost with the shallowest eroded soil (Borrelli et al., 2016), ~~The soil lost through~~ wind erosion can counteract ~~the mitigation of~~ soil carbon sequestration ~~,~~ if ~~the~~ management is not ~~also~~ adapted to limit erosion problems~~, as most of the carbon is lost with the shallowest eroded soil (Borrelli et al., 2016)~~. To mitigate wind erosion, the soil surface needs to be covered throughout the year and it is suggested to use ~~-~~conservation tillage for promoting aggregate stability of the soils. This will at the same time increase the carbon sequestration of the soils, thanks to the inputs of C from plant residues and roots. Also organic amendments would contribute a lot to improve structure stability and to increase SOC conservation. Unfortunately, we are not aware of any case study reporting success stories combining agricultural practices aimed at reducing wind erosion and at the same time increasing SOC in arable lands. Setting Operational Groups to address this issue in representative lands, especially of Northern Europe, would be highly recommended.

4.2 C management in water eroded soils

Enhancement of soil organic carbon in water eroded soils ~~could~~ can be effective ~~also~~ to increment soil water infiltration and storage capacity ~~and~~ as well as to reduce soil and water losses by erosion (FAO, 2017a). However, halting soil erosion in sloping lands is a fundamental prerequisite. Actually, it must be considered that the topsoil keeps the major part of SOC. For instance, a soil loss of 10 Mg ha^{-1} y^{-1} in a soil with a bulk density of 1.4 g cm^{-3} corresponds to an annual loss of about 0.5% of the carbon stock of the first 30 cm, and the map of soil erosion of Europe shows many parts having erosion rates far larger than 10 Mg ha^{-1} y^{-1} (https://esdac.jrc.ec.europa.eu/themes/erosion). The visual comparison of the maps of soil erosion rates and SOC contents in Europe reveals a strong inverse relationship, especially in the Mediterranean countries (https://esdac.jrc.ec.europa.eu/themes). Many experimental data confirm the relationship between high soil erosion rate and low SOC content in different arable and tree crops, and the importance of preventing soil erosion to improve the ability of the agro-ecosystems to incorporate SOC (Le Bissonnais et al., 2002; Cerdan et al., 2010; Costantini et al., 2018; Chenu et al., 2019).

The success of the wide variety of soil conservation practices to be adopted will depend on local combinations of soil type, climate, and management practices, together with the socio-economic context. In a comprehensive overview on different soil and water conservation techniques in Europe and the Mediterranean, it was found that crop and vegetation management (i.e., cover crops, mulching, grass buffer strips) and mechanical techniques (i.e., terraces, contour bounds, geotextiles) were more effective in reducing annual runoff and soil loss rates than soil management (i.e., no tillage, reduced tillage, contour tillage, deep tillage, soil amendment) (Maetens et al., 2012). Regarding soil management techniques, it was also found that no tillage and conservation tillage become less effective in reducing annual runoff – but not annual soil loss – over time. A conclusion drawn from this meta-analysis was that the more erosion-prone conditions are (i.e., erodible soils, steeper slopes, areas with high-intensity low-frequency rainfall events occurrence), the most effective in reducing runoff and soil erosion rates these soil and water conservation techniques are. Arable cropland can be considered among the most erodible land uses, so that any management ensuring a permanent soil cover could result in a dramatic reduction of actual soil loss rates (Panagos et al., 2015)[A4][A5]. On the other hand, due to their usual low SOC content, eroded soils can ~~be considered as~~ show higher SOC sequestration rates in the short term, ~~potential new C sinks for C~~ as C incorporation is potentially ~~quicker~~ faster ~~just~~ in soils ~~where SOC values are lower~~poorer in SOC (Francaviglia et al., 2019).

4.3 C management in soils with shallow groundwater and limited drainage

Some agronomic strategies to increase SOC content in arable soils, such as the adoption of no-till, have been observed to be unsuitable to poorly drained soils (Soane et al., 2012), as well as in soils with shallow groundwater (Costantini and Dazzi, 2013). In poorly drained soils, reasons for this unsuitability are related to the difficulty of soil management when the seeding dates coincide with the rainiest season. Areas with poor drainage also result in low productivity, as water excess in topsoil limits the presence of oxygen in soil pores, hampering soil microbial activity, nutrient availability (e.g., the inhibited activity of nitrifying bacteria can reduce nitrate concentration in the soil) and root functioning. A reduced crop productivity will also result ~~also~~ in reduced C return to the soil. Areas of winter cereals grown on soils with high content of clay and/or silt in Mediterranean climates, with the highest precipitation peaks in fall, are good examples of soils of that kind. If winter crops follow a spring crop harvested in the fall, problems of poor drainage may become extremely severe, thus preventing the adoption of reduced tillage.

Gleysols (soils affected by groundwater) share the same lowland environment of Histosols (organic soils) and are still rich of organic carbon. Many Gleysols, in particular, are just degradation forms of Histosols caused by reclamation activities, in particular, drainage, addition of mineral material, and repeated ploughing, which mineralized the most elaborated parts of the organic matter. Therefore, the management of organic matter in Gleysols goes along with that of groundwater (Costantini and Dazzi, 2013) as drainage can at the same time facilitate the adoption of cropping strategies increasing crop productivity, but also SOC losses through mineralization.

Some soil management strategies have been developed in these areas to improve drainage and allow for higher productivity. Surface drains are common in many of these areas and have to be done every year before seeding. Subsurface de-compaction can be done with different types of subsoilers, and subsurface drainage can also be improved by mole-ploughs.

Some experiences in NE Spain (Pérez de Ciriza, personal communication) have shown that these techniques can efficiently improve soil conditions at seeding, and therefore allow for increased productivity and the adoption of some strategies of conservation agriculture. A group of arable farmers from NE Italy (Life HelpSoil, http://www.lifehelpsoil.eu/) ~~)~~ even demonstrated to be able to apply continuous no-till for several years in clay soils thanks to occasional subsoiling.

4.4 C management in stony soils

Rock fragments are frequently found as a part of the soil volume in many areas. Soils with rock fragments are usually less productive than other soils in the same conditions of texture. Their presence at the soil surface can limit both crop development and soil management by impeding tillage. Direct seeding can be impossible in stony soils.

In arid and semi-arid land, the reduced water-holding capacity has led stony soils to be considered marginal soils for agriculture since long ago (Arias et al., 2017). In terms of SOC stock, their limitations arise from their reduced primary productivity when rock fragments occupy a significant part of the soil volume, and also from their reduced proportion of fine soil able to effectively protect organic C from mineralization.

Different management strategies can be adopted on these soils to overcome these limitations, especially in semi-arid and arid lands. However, the interaction between conservation agriculture and soils with rock fragments has been seldom addressed, and its adoption can be challenging in this context (e.g., Schwilch et al., 2015).

A recent study on the effect of the simultaneous adoption of irrigation and no-till in a stony soil in NE Spain (Arias et al., 20174) [A6]has shown that these soils can be reactive to the improved carbon inputs from crop residues resulting from the combination of irrigation with no-till in the very short-term~~ (2 years)~~. In particular, an increment of 10 Mg SOC ha^{-1}

(from 37.9 ± 0.7 to 47.9 ± 1.1 Mg SOC ha^{-1}) in the upper 30 cm (after correction for stone content using the hybrid method for bulk density described by Throop et al., 2012) was observed after ~~3~~ 2 years (Table 1).

4.5 C management in saline, gypsiferous and alkaline soils

Many soils in arid and semi-arid areas display significant accumulations of soluble salts in the upper horizons. Although these soils are generally not common in arable land, some are cultivated in marginal areas of Southern Europe. More frequently, salinization occurs as a result of agricultural management (especially irrigation). These soils are naturally not suited for SOC stabilization. For instance, Solonchaks displayed the lowest values of SOC (11.1 Mg SOC ha^{-1}) in the upper 25 cm among all arable soil types in Andalusia (Muñoz-Rojas et al., 2012).

As a result of high sodium percentage on the cation exchange complex ~~lets~~ the clay particles lose their tendency to stick together when wet. Soils became impermeable in depth to both water and roots, and geomorphologically unstable. Therefore, SOC management in these soils must be accompanied by important measures to prevent soil water erosion.

Gypsisols are not frequent in Europe, being the dominant soil type in less than 0.1 % of the total area, mostly concentrated in the Ebro Basin and other areas of Spain, as well as in Sicily. They are limited for SOC concentration (between 0.4 and 1 g 100 g^{-1} for Ap horizons) because of the low reactivity of its mineral fraction, their low water-holding capacity and other physical limitations. Their location in arid areas makes them~~n~~ unsuitable for agriculture without irrigation (Herrero, 2017). Otherwise, they are mostly not used, or used for extensive grazing. Fertilization needs to be used at higher rates than usually calculated from crop needs. With irrigation, drainage and heavy fertilization, satisfactory yields of gypsum-tolerant crops can be obtained. Increasing SOC in these soils can be particularly challenging, as their physico~~al~~-chemical properties~~, which~~ can impose limitation on water retention (Moret-Fernández and Herrero, 2015), and their mineralogical compositions do not favor the development of stable soil structure or organic matter complexation.

4.6 A stock to be protected: SOC in black soils and peats

Peat lands are common in Northern Europe, due to wet and cold climate, while are marginal but still present in Mediterranean countries. In both cases peatlands have been drained for a long time to get agricultural land and by that they are prone to mineralisation at a rate leading to a loss ~~of~~ from 0.5 to 4 cm of peat soil per year (Regina et al., 2016). This means that the 10-20% of peatlands drained for agriculture and forestry are currently ~~is now~~ losing carbon and producing net greenhouse gas (GHG) emissions such as CO_2 and N_2O, whilst CH_4 decreases with drainage (Berglund and Berglund, 2010; Regina et al., 2016).

In most peat lands, the agricultural exploitation is limited to the most marginal lands, which in some cases are converted to forestry, but still large areas in the Nordic countries are cultivated and will lose carbon if they are not managed properly (Regina et al., 2016).

Suggestions on how to keep the carbon in these soils are either to keep the soil covered with grasslands, perennial crops instead of annual cropping, but also by rewetting, so that the decomposition of the peat slows down (FAO, 2012; Rumpel et al., 2019).

Black soils, or highly base-saturated mineral soils, rich in organic carbon (Phaeozems, Chernozems, Kastanozems) are frequent in eastern Europe but are also present in Mediterranean countries, where soil erosion is not intense and summer drought limits the mineralization of the soil organic matter (i.e., the so-called “Mediterranean steppe”). A common relevant feature of black soils is the relatively high organic carbon content of the topsoil, but also of the subsoil, ~~, reaching values of~~where values of SOC concentration of

0.5% ~~in weight~~w/w even ~~until~~ at 1 m deep are very frequent~~and more~~, which confirms the great potential~~ity~~ for carbon sequestration of this kind of soils. Actually, the SOC concentration in topsoil of modal Italian Phaeozem, Chernozems and Kastanozems is 1.75, 1.34 and 1.29 ~~da~~g ~~kg~~100 g^{-1}, respectively, while ~~density~~[A7] SOC storage in the first meter is ~~respectively 12.69~~126.90, 127.60~~.76~~ and 12~~.14~~1.40 ~~kg~~ Mg C ~~m~~ha^{-}~~^{2}~~^{1} ~~in the first meter~~, respectively, and reaches 17~~.18~~1.80, 12~~.9~~9.00 and 13~~.6~~6.90 ~~kg~~ Mg ~~m~~ha^{-}~~^{2}~~-^{1} in the whole profile (Costantini and Dazzi, 2013). As shown by the results obtained in China by Liu et al. (2003), the SOC of black soils can be restored by adopting the right crop rotation and an intensive return of organic material to the soil through amendments. To the best of our knowledge, we are not aware of any study produced in European black soils.

4.7 Organic soil amendment ~~and organic farming conditions~~

Although the relationship between the application of exogenous organic matter to soil and the gains in SOC is very clear in the reviewed literature (e.g., Dignac et al., 2017), attention must be paid on associated GHG emissions from soils (Aguilera et al., 2013a). In their review, Aguilera et al. (2013a) clearly showed how, for instance, ~~that~~ the typology of organic amendment itself can have a strong effect on the level of N_2O emissions. Liquid organic amendments (i.e., slurry), for instance, were reported to lead to N_2O emissions comparable to those produced by mineral ~~fertilisers~~fertilizers, whilst the application of solid forms of organic amendments, especially when coupled with use of cover crops, resulted in significantly lower N_2O emissions and higher SOC stocks (Aguilera et al., 2013b).

In addition, the interplay between increasing SOC content without substantially increasing the emission of GHGs becomes a challenge and depends on the crop and soil types and management option.

-In this context, fine textured and poorly drained soils are particularly prone to, respectively, limited SOC incorporation and high GHG emissions.

-Sandy soils have limited capacity to store SOC due to usually low organic matter return, on one hand, and high SOC mineralization rates, on the other hand. Low return of organic matter is normally typical of sandy soils due to their lower chemical fertility and lower productivity compared to loam or clay soils, which normally ~~implies also~~also implies a lower return of crop residues into the soil. High aeration and fast mineralization of organic matter normally contribute to keep low the content of SOC in sandy soils, but ~~also~~similarly increase the risk of high GHG emissions.

-Poorly drained soils (e.g. soils with high silt content and prone to shallow crust or clay soils with low permeability) are ~~also~~ well known to have limited capacity of SOC ~~stock~~ storage due to typically poor establishment of the crops and consequently low crop residue return. On the other hand, N_2O and ~~methane~~ CH_4 emissions from these soils can be high due to low aeration (Krichels et al, 2019). To overcome these limitations, the improvement of soil drainage (Kumar et al., 2014) is of paramount importance. Furthermore, ~~poorly drained soils can be managed through~~ liming practices aimed to increase soil nutrient availability for plants and to enhance soil microbial activity and N_2O reductase, which counteracts the emission of N_2O from the soil, can contribute to reduce GHG emissions from poorly drained soils (García-Marco et al., 2016)~~ or drainage (Kumar et al., 2014)~~.

Apart from all the above mentioned environmental limiting conditions for applying organic fertilizers, there are other important barriers such as the lack of access to manure or organic wastes and the lack of technical know-how for proper processing of manure before applying it to the field, causing weed infestation and pest occurrence and/or increasing labour demand and costs of implementing it (Chinseu et al., 2018).

4.8 Organic farming

As for the management options, organic farming can reach a good trade-off between the instances of high SOC increase and reduced GHG emissions and is increasingly adopted by European farmers. Organic farming, as defined by the latest EU Regulation 2018/848, is “an overall system of farm management and food production that combines best environmental and climate action practices, a high level of biodiversity, the preservation of natural resources and the application of high animal welfare standards and high production standards in line with the demand of a growing number of consumers for products produced using natural substances and processes”. Reduced use of synthetic external inputs (mainly mineral ~~fertilisers~~fertilizers and pesticides) and augmented return of organic matter to the soil (through organic amendments and ~~fertilisers~~fertilizers, green manures, and crop residues) are the most relevant farming practices with respect to the objectives of increasing SOC ~~increase~~ and ~~reduced~~ reducing GHG emissions (Aguilera et al., 2015). Nevertheless, the magnitude of SOC increase and GHG reduction that organic farming management can achieve strongly depends on other variables, such as crop type and management intensity. Despite organic inputs are on average higher in organic than in conventional agriculture, often in this type of soil management there is ~~the~~a need to till the soil frequently in order to avoid the use of chemical herbicides to control weeds ~~without chemical herbicides~~, and this can cause significant SOC losses by erosion and mineralization processes (Stavi et al., 2016).

~~For example, d~~Data from Spain revised by Aguilera et al. (2015) showed how in rainfed cereals (wheat, barley), business as usual conventional management led to higher N_2O emissions (mostly due to the exclusive use of mineral ~~fertilisers~~fertilizers) compared to organic management, while soil carbon sequestration rates were similar between both types of management practices (Aguilera et al., 2013b). However, the low use of synthetic inputs under conventional legume management leads to similar GHGs balance when comparing with organic management. On the contrary, although SOC content could be increased by means of incorporating rice straw and manures to the soil in rice fields, the increase in CH_4 emissions derived from these practices could not be overcome by the enhancement of SOC stock (Aguilera et al., 2015). As horticulture requires high input management in terms of irrigation, fertilizers and pesticides, there is a potential for increasing SOC stocks and mitigate GHGs emissions when conversion to organic management is adopted. According to Aguilera et al. (2015) estimations, a decrease of 59% of GHGs emission while a three-fold increase in ~~carbon~~ SOC stock can be reached per ha when passing from conventional to organic management in horticultural cropping systems~~e~~.

~~Apart from all the above mentioned environmental limiting conditions for applying organic fertilizers, there are other important barriers such as the lack of access to manure or organic wastes and lack of technical know-how for proper processing of manure before applying it to the field, causing weed infestation and pest occurrence and/or increasing labour demand and costs of implementing it (Chinseu et al., 2018). despite organic inputs are on average higher than in conventional agriculture, often in this type of soil management is needed to till the soil frequently to control weeds without chemical herbicides, and this can cause significant SOC losses.~~

5. Case studies and potential EIP-AGRI operational groups

Table 2 summarizes the results achieved by selected good practices tested in ~~Hereby we identify interesting~~ case studies concerning local adaptation ~~of~~ strategies ~~intended for~~aimed to ~~SOC~~ increase SOC in different pedoclimatic and agronomic conditions. For each case study, the most relevant research gaps are identified. As EIP-AGRI OGs could actively contribute to complement research activities by implementing the most promising practices~~,~~ and collecting and ~~through~~ validating ~~on and~~ data ~~collection~~ at ~~field scale~~farm level, also ideas for potential OGs are illustrated.

Table 2 - Management practices and SOC: state of the art, identified good practices, research gaps, ideas for EIP-AGRI Operational Groups (OGs)

5.1 Management of irrigated crops to increase SOC in dry climates

In irrigated systems, the combination between irrigation and cultivation strategies can have contrasting effects on SOC stocks, in comparison with dryland management (Chenu et al., 2018). Information is needed on the influence of the alteration of the soil water regime on SOC cycling and ~~stock~~storage. This includes research to fill the gaps in understanding SOC dynamics and its determinants at all scales from basic soil processes to landscape- and regional scale. EIP-AGRI OGs could supply consistent[A8] models for irrigation applied to different cropping systems, suitable to be disseminated in similar conditions (e.g. EIP-AGRI, 2019).

An example of project aimed at demonstrating how strategies for climate change mitigation in irrigated agriculture can be developed in drylands was conducted in Navarre (NE Spain), between 2013 and 2016 in the regional-scale project Life Regadiox (http://life-regadiox.es/en/), led by a regional farmers association (Fundagro, https://uagn.es/fundagro/). As part of the work was to quantify climate change mitigation, an inventory of SOC stocks in the most representative cultivated soil types under dryland and irrigated agriculture was conducted.

The results of this project can be summarized as follows:

- Overall, compared to rainfed conditions, irrigation resulted in a greater SOC storage in the tilled layer (0-30 cm). The extent of SOC gain upon irrigation varied among sites, ranging from ~~+19.2~~+10.9 ± 1.4 Mg SOC ha^{-1} in one site more recently transformed to irrigation (9 years)~~4 ± 2.5 Mg SOC ha^{-1} in the site most recently transformed to irrigation~~, to +42.3 ± 2.8 Mg SOC ha^{-1} in the site with 20 years of irrigation and NT corn under irrigation, both on a Haplic Calcisols (Antón et al., 2019) (Table 1);

- Within irrigated systems in arable crops, great differences were observed, mostly related to the intensity of cultivation. For instance, within one site, the soil under horticultural crops with two crops per year and little residue restitution stocked 68.3 ± 2.7 Mg SOC ha^{-1} in the upper 30 cm after 20 years of irrigation, whereas no-till corn stocked 99.6 ± 5.6 Mg SOC ha^{-1}, and rainfed organic wheat 74.5 ± 5.5 Mg SOC ha^{-1}. In this sense, it is noteworthy that the introduction of no-till in irrigated land is less frequent than in rainfed semi-arid areas, where one of the main reasons for introducing no-till is the optimization of water retention. Also, alfalfa stocked 63.1 ± 4.0 Mg SOC ha^{-1} after 6 years of continuous cropping with irrigation in an area where rainfed cereals on the same soil had 43.9 ± 2.3 Mg SOC ha^{-1}. In a previous study (Virto et al., 2006), the effect of irrigation with wastewater from vegetable canning industry, which contained moderated amounts of organic C mostly in the form of particulate organic C, was observed to be inexistent or very low on SOC, compared with that of the implementation of a permanent alfalfa crop.

In arid and semi-arid conditions, inclusion of permanent crops, less intensive crop rotations and tillage strategies seems therefore the major driving variables determining the possibilities to increase SOC stock in soils when transformed from dryland to irrigated. Nevertheless, it must be highlighted that in dry conditions permanent non-woody crops, and especially pastures and forage crops, can be profitably grown only if irrigation is implemented. In this case other crops may result more profitable, hindering their wider adoption by farmers. OGs should consider ways to make irrigated permanent crops more profitable and appealing for farmers, e.g. by opening new market opportunities (e.g. alfalfa protein concentrate), estimating the amount of subsidies to be paid under RDPs, or testing cultivation techniques oriented to increase the yield of such crops in rainfed conditions.

Making irrigated systems more effective in terms of SOC stock increase may also imply a redesign of the proper irrigation system, aiming at reaching the best tradeoff between production-related targets and soil conservation. For instance, the combination between no-till and sub-irrigation seems very promising in overcoming some technical constraints typical of no-till (e.g. limited deepening of crop roots, with consequently scarce water uptake due to lower water infiltration compared to tilled soils, high weed competition for water supplied on topsoil).

On top of that, environmental and socio-economic barriers need to be assessed to evaluate the expected net effects associated to SOC increments in comparison to non-irrigated systems or previous condition under irrigation (Antón et al., 2019). In addition to the profitability issues described above, the net balance in GHG emissions and other possible outcomes of irrigation (soil loss, nutrients leaching, salinization, etc.) are to be considered. While some basic consequences on SOC cycling as affected by irrigation adoption are still unclear and need more research (Chenu et al., 2019; Rumpel et al., 2019), the technical strategies to overcome these limitations (such as erosion control or fertilization management) are promising topics for OGs, in addition to those described above.

5.2 Management of rainfed and low input crops in dry climates and erosion prone soils

In dry climates and poor soils, the enhancement of SOC in rainfed, low input cropping systems is constrained by severe limiting (water and nutrient availability) conditions and thus very low SOC sequestration rates are normally observed. Therefore, reducing the SOC losses caused by water erosion and mineralization processes is of utmost importance. In order to adapt semiarid rainfed systems and increase their resilience against climate change, several sustainable agricultural management practices to control soil erosion and promote SOC sequestration and water harvesting are being implemented in South-eastern Spain. Reducing tillage, ~~intercropping,~~ green manuring, crop diversification, the selection of new and local varieties better adapted to dry climates, crop residue retention, as well as the implementation of vegetative buffer strips, ~~application of~~ swales and ponds for soil and water conservation~~, as well as the selection of new and local varieties better adapted to dry climates,~~ can be promising options to make agro-ecosystems more resilient against climate change and market price fluctuations in the long-term. However, the success of these sustainable agricultural ~~land~~ management practices will depend on the local conditions (soil, climate, and management) together with the socio-economic context. In this regard, monitoring programs and integrated assessments are needed to demonstrate the long-term beneficial effects of such practices from farm ~~hillslope~~ to ~~landscape~~ regional scale and could be the target of OGs.

A good example of ~~carbon~~ SOC management in semiarid rainfed low input systems under eroded soils is that implemented in Southeastern Europe as an outcome of the DESIRE European project (Ritsema and Stroosnidjer, 2008[A9][A10]), in which different sustainable agricultural practices such as reduced tillage, green manuring during fallow periods, straw mulch, and traditional water harvesting techniques (e.g., swales) were successfully implemented to increase SOC and reduce soil and water loss through runoff in cereal fields (de Vente et al., 2012). Specifically, passing from conventional moldboard ploughing at 4~~3~~0 cm depth (5-7 passes yr^{-1}) to minimum tillage at 20 cm depth (2 passes yr^{-1}) has reduced carbon losses by soil erosion and runoff by 56% and increased the SOC stocks at 30 cm depth by 11% (15 and 16.7 Mg SOC ha^{-1} in the former and in the latter, respectively) since 2010~~08~~ to 2016~~1~~ (Martínez-Mena et al., 2020) (Table 2). [A11]Given the outcomes of these experimental plots, these agricultural practices are being currently implemented in other similar areas in SE Spain as part of a monitoring programme in collaboration with the local farmer association Alvelal (www.alvelal.net) and the Commonland Foundation (www.commonland.com).

Soil and crop management strategies intended to increase SOC in low input rainfed systems need to be adapted to the local conditions, being aware of the high variability of pedoclimatic conditions, which may constrain their potential to effectively increase SOC in a specific year, so a long-term perspective is encouraged. For example, in areas more prone to water erosion, because of erodible soils with significant slopes, the incorporation of plant residues through minimum tillage together with the implementation of swales are recommended (Figure 1-2). However, in flat areas with soils less prone to compaction, the implementation of ponds together with no tillage can be a suitable option (Figure 3). Also, demonstration farms in which different mixed cropping systems are tested before being implemented at larger scales are mandatory.

Figure 1 – Keyline opened in an arable field to reduce water erosion in flat land in Spain. Source: Maria Almagro

Figure 2 – Swale opened in a hilly land to reduce the speed of water runoff in Spain. Source: Maria Almagro

Figure 3 – Pond realized in flat soil less prone to soil compaction in Spain. Source: Maria Almagro

5.3 High Tech and Precision Farming to maintain SOC on farm and reduce GHG emissions

Some research/demonstration projects combined PA and conservation agriculture (CA) techniques by means of ICT in Northern Italy (Veneto Region), and in Southern Spain

(Andalusia). The project Agricare (Furlan, 2017) proposed a wheat/canola/maize/soybean rotation at large field scale near Venice, comparing minimum tillage (MT), strip tillage (ST) and no-till (NT) against conventional tillage (CT), under uniform and variable rate application (VRA) of inputs. The project Agricarbon (González-Sánchez et al., 2012) compared 3 farms in Andalusia region applying, on large plots, conventional soil management against the combination of direct drill+PA (GNSS-assisted machinery, sensor-assisted maps, VRA for fertilizers and herbicides by prescription maps, etc.), on a wheat/sunflower/broad bean rotation.

The project Agricare obtained the best results where NT+VRA was applied, with emissions savings of 0.5 t CO_2eq ha^{-1} and the same gross income than CT. SOC content was assessed through time and type of management, to model its mid-term (15-yrs) dynamics, resulting in relevant emission savings by CA+PA techniques (lower direct and indirect energy consumption, reduced losses of SOC due to oxidation, higher fertilization efficiency).

The project Agricarbon showed specific~~-, for each~~ crop~~,~~ reductions of energy consumption per product unit of 12, 26 and 18%, and production cost~~s~~ savings of 10, 21 and 15%, ~~;~~ ~~respectively~~ for wheat, sunflower and broad bean, respectively. On a 4-yr average, CA+PA resulted in a 30% increase of SOC stock, as compared with conventional management (Table 2).

The combination between PA, organic fertilizer~~s~~ application and soil conservation techniques (Pezzuolo et al., 2017), could achieve the best results in terms of both direct and indirect reduction of GHGs emissions, and eventually increase ~~in~~ SOC storage. In this case, more information is needed about the mineralization rate of organic ~~fertilisers~~ fertilizers under different combinations of soil, climate, crop type and management to make VRA applications suitable also for farming systems based on organic ~~fertilisation~~ fertilization as organic farming systems.

PA techniques have the potential to support the ~~decision making~~decision-making process of also organic farmers dealing with spatial variability in their soil conditions, triggering fine-tuning and adaptation of crop technique to small-scale soil fertility level. This could be included in specific EIP’s OGs at different sites.

Digitization of farming and conservation practices need to be adapted anyway at farm level to obtain tailor-made solutions, through the coordination of experts aimed at enhancing environmental and economic performance. Another important challenge is to make PA technologies accessible also to smallholders. The engagement of contractors managing large pieces of land and networking activities specifically aimed to connect small holdings in an information hub exploring also the issue of SOC will be key actions in that sense.

5.4 Using cover crops to increase SOC under limiting pedoclimatic conditions.

Although widely recognized as effective tools to increase SOC stocks, the use of cover crops and mulches may be limited in practice by several reasons, above-all limiting pedoclimatic conditions and socio-economic constraints. For instance, in Mediterranean dry areas of Europe, dry summers can hinder the adoption of strategies including double cropping or summer cover crops. In sub-humid areas, where rainfall normally occurs also in summertime, spring/summer cover crops can be profitably grown even in rainfed conditions, instead, but normally they are not, because of farmers’ attitudes and economic reasons (e.g., farmers prefer to grow cash crops as maize or soybean instead of cover crops, determining intensive soil exploitation). To enhance the adoption of cover crops among farmers, financial instruments (e.g. specific subsidies included among the agri-environmental measures of the RDPs of several Countries/Regions of Europe) can play an important role, but only at an initial stage. Farmers should be rather convinced about the importance of cover crops in sustaining the fertility of their soils and the yield of their most important cash crops in the long run, in a context of market uncertainty and climatic fluctuations triggering farming unprofitability. Adequate levels of financial support and effective education efforts should be tailored to each specific pedoclimatic and socio-economic context through OGs involving all the target stakeholders.

In this framework, peer-to-peer knowledge transfer among farmers can be crucial. Several innovative strategies developed by local farmers with a wide knowledge of their soils and climate conditions have resulted in a win-win strategy allowing for a continuous soil cover and an optimization of the storage of soil C under rainfed conditions. Some ~~particular~~ examples of these strategies are summarized in Table 2~~1~~. They represent different case studies developed in Italy and Spain under reduced tillage systems, aiming to maximize soil cover and reduce as much as possible the period without living plants on the soil, without any detrimental effect on farm profitability (Figures 4-5). Agronomic solutions included the use of spontaneous weeds or cover crop mixtures inter-sown in double crops or after main crop harvest and terminated mechanically or chemically immediately before the following cash crop, ensuring a continuous soil cover all year around and diversifying the quality of the residues returned to the soil. These experiences constitute good examples to be replicated at a broader scale in the same or in other regions, with similar environmental conditions, possibly involving other farmers and stakeholders to form OGs.

Figure 4 – Mechanical termination of a hairy vetch (*Vicia villosa* Roth.) cover crop by roller crimper and simultaneous sod-seeding of sunflower (*Helianthus annuus* L.). Source: Daniele Antichi

Figure 5 – Dead mulch provided by hairy vetch (*Vicia villosa* Roth.) cover crop terminated by roller crimper and reducing weed pressure in sunflower (*Helianthus annuus* L.). Source: Daniele Antichi

An observation arising from the examples in Table 2~~1~~ is that adoption of diversified crop rotations and inclusion of cover crops are essential tools in CA systems to achieve a continuous soil cover and, consequently, an increase in SOC content. Anyway, the entire crop rotation and all the related agronomic strategies must be designed with a holistic approach. This needs to consider the specific climatic and soil conditions, as well as the economic targets of the farm, to path the way for an agronomically and economically efficient application of CA principles. Although with some extra efforts when starting to use them, cover crops can be efficiently introduced in many kinds of crop rotations also in spring or summer time, also in water-limiting conditions. In extreme cases, also keeping growing spontaneous weed species might be a win-win strategy both from biomass production and economic viability points of view. The key factor of success is a proper technical guidance about best solutions for each specific local context in terms of choice of cover crop species and establishment/termination technique and timing, made according to a specific and realistic soil water balance. Finally, it is also recommended that OGs would envisage a support of machinery builders, advisors and plant breeders in providing the best solutions for each specific local context, ~~targeting also~~also targeting a significant reduction in herbicide and fertilizer use to benefit GHG mitigation and prevent on- and off-site soil and water pollution. Selecting and t~~T~~esting ~~and selection of~~ improved genotypes of cover crops, adapted to the local conditions and targeted to increase their potential to supply high C inputs to the soil and to grow in limited water availability are also important steps further to increase the adoption rate of cover crops among farmers.

Furthermore, increasing the awareness among farmers about the benefits of avoiding bare soil during fallow periods would be a likely effective action. This could be pursued, for example, by running an economic assessment to quantify the negative economic impacts of losing a significant amount of soil, and associated carbon and nutrients, after extreme erosion events when the soil is unprotected by vegetation.

~~Table 1 - Examples of successful case-studies on the use of cover crops under limiting pedoclimatic conditions for a possible development into EU Operational Groups.~~

5.~~4~~ 5 Management adaptation in areas subjected to water bombs and hail risk

Dry lands that experience extreme thunderstorms, even if infrequent, are the most susceptible to the negative effects of both rainfall and hail in terms of soil compaction, erosion and loss of the C-richest layer, i.e. the topsoil. In Europe, many areas are frequently affected by such events. Among these, the Mediterranean region has the highest risk of erosive ~~events~~ and flooding events, yet, at the same time, water scarcity — because of the low infiltration of very intense local rainstorms- and loss of soil fertility. This is because of frequent thunderstorms associated with water-bombs and hailstorms that typically occur in fall after long dry conditions in spring-summer. Farmers are more and more often experiencing severe crop damages due to late summer-early fall thunderstorms, but also, their soils are reported to be degraded.

In field vegetable cropping systems, soil structure could be better protected, and SOC maintained or increased, by the so called “permanent raised bed" technique, i.e. the combination of reduced tillage and permanent soil cover achieved through mulching (plastic films or organic material) (Sayre and Moreno, 1997) (Figure 6). In this technique, the soil is tilled only once at the beginning of cultivation to establish high macro-porosity and then is covered by plastic or biodegradable films, or even organic material as cereal straw, wood chips, etc. This mulching material will stay on top of the soil until the end of its lifecycle, which is normally about one year for the plastic mulch, or a single season for the biodegradable film and the organic materials. Organic fertilizers are usually incorporated into the soil at the time of the initial tillage. Each crop is manually transplanted into the mulch and the raised bed is never trampled by field workers/machines, in order to protect soil structure. Once the first crop has been harvested manually, also its residues are removed from the fields and used for composting. Then, the second crop can be transplanted in the same positions or in new ones, without any replacement of the mulch. ~~As long as~~If the mulch material is sufficiently covering the soil, it could be kept on place and the next crop transplanted.

Figure 6 – Permanent seedbed implemented in Veneto, North-East of Italy. Source: Daniele Antichi

A group of farmers practicing this technique in Veneto (NE Italy) reports that with this management they could improve their soils in terms of organic C content and biological and physical fertility (Luca Conte, personal communication). As a proof of that, the spade test, usually performed to evaluate visually soil fertility, always gave excellent results (Figure 7). Soil structure was dramatically improved, soil depth reached at least 30 cm, earthworms were abundant and organic materials were well decomposed. This promising technique can be applied not only in small farms but also in larger ones and practiced with business as usual machinery (e.g. standard transplanting machines) and the use of organic material instead of films. For large vegetable farms willing to use films instead of organic mulch material, the use of PA technologies for detection of transplant patterns can make it possible to perform the transplant of vegetables into permanent raised beds also mechanically, with huge advantages in terms of costs saving.

Figure 7 – Soil structure improved after one year of implementation of permanent seedbed on plastic film in Veneto, North-East of Italy. Source: Daniele Antichi

Although the use of organic mulch materials (e.g. biodegradable films, wood chips, straw, etc.~~…~~) should be preferred to plastic mulch to reduce the environmental impact of non-renewable materials, it is not clear yet whether this could be more profitable for farmers from an economic point of view, due to the short lifetime of organic materials. This aspect needs further investigation both at scientific and demonstration levels.

Another technical issue to be carefully considered is the management of the space between the raised beds. This space is much prone to soil compaction (and then to water logging) due to the huge traffic by field workers and/or machines. Some benefits in terms of water infiltration, but also of weed suppression, may come from sowing perennial living mulch (e.g. white clover, black medic) on this space when establishing the raised beds. Clearly, this might imply the development of proper machines adapted to these conditions for sowing and management of the living mulch~~,~~ that is currently not included in research projects. Following this development, OGs could be focused in developing adequate strategies for the implementation of the technique described above in different farm typologies and pedoclimatic conditions.

6. Conclusions and perspectives

We have identified a series of l~~L~~ocal climatic and soil ~~limitations ~~conditions as~~can be~~ limiting factors for the adoption of some strategies to increase SOC in European arable lands~~.~~

~~They are~~: i) water scarcity or seasonal imbalances, which need the tailoring of strategies under irrigation, ii) high risk of wind or water soil erosion, reducing SOC in the surface soil layers, iii) presence of a shallow groundwater and limited drainage, which pose specific management problems and lower crop productivity, iv) high stoniness, limiting the use of certain machinery, v) saline, gypsiferous and alkaline soils, where SOC is naturally more difficult to be stabilized, and vi) manure fertilization, increasing GHG emissions in Mediterranean climate and fine textured soils.

To overcome some of this limiting factors we have illustrated ~~Some~~five case studies ~~illustrate~~ together with potential proposals~~ssible references~~ for Operational Groups to support a successful local adaptation of ~~measures~~ agronomic practices to improve ~~carbon~~ SOC storage in arable lands~~. They include~~: i)

~~•~~ Adoption of soil management strategies to improve SOC storage in irrigated systems, ii) ~~.~~

~~•~~ . Management of rainfed and low input crops to maintain and increase SOC in dry climates and erosive prone soils, iii)

~~•~~ Precision farming and other high-tech solutions able to generate local diagnosis and adaptive strategies for increasing SOC and reducing GHG emissions, iv) ~~.~~

~~•~~ Innovative strategies for extending soil cover periods and introducing cover crops in rotations in areas with limited water availability or prone to harsh weather conditions, and v) ~~.~~

~~•~~ Adaptation of soil management to cope with water bombs and hail risk.

~~Other~~ Additional possible OGs ~~could~~ should deal with no-till based cropping systems of heavy soils, in order to find affordable ways to improve the ~~soil~~ structure ~~in~~ of surface soil ~~surface~~ horizons ~~soil~~ (i.e. the first 10 cm-layer, the most prone to compaction in the transition to no-till), which is crucial for a good early establishment of the crops and for improving water infiltration and drainage. Furthermore, effective combinations of no-till/reduced tillage with other components of cropping systems ~~-~~(e.g. crop rotation, fertilization, irrigation strategy and technique, cover cropping, mechanical weed control) have to be identified, aiming at maximizing the return to the soil of large amounts of C, on the one hand, and at modulating soil organic matter mineralization rates~~,~~ in order to synchronize them with crop nutrient demands, on the other hand.

In general, increasing no-till crop productivity in areas with limiting pedoclimatic ~~characteristics~~ conditions requests an additional knowledge effort on the climate-soil-crop interactions, ~~andpermitting~~which can lead to ~~could be achieved through~~ the ~~tuning of~~ intensive application of specific agro-ecological strategies, like in the case study of the permanent raised bed technique applied in small holding vegetable production.

Acknowledgements

The work was initiated in the framework of the EIP-AGRI Focus Group on Moving from source to sink in arable farming (https://ec.europa.eu/eip/agriculture/en/focus-groups/moving-source-sink-arable-farming).

One author was supported by the Juan de la Cierva Program (Grant IJCI-2015-23500).

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Table 1 - Results from scientific literature and projects dealing with management practices and soil organic carbon (SOC) concentration (g 100 g^{-1}), stock (Mg C ha^{-1}) and storage rate (Mg C ha^{-1} y^{-1})~~Examples of successful case-studies on the use of cover crops under limiting pedoclimatic conditions for a possible development into EU Operational Groups.~~

~~Table 1 - Case-studies for a possible development into EU Operational Groups~~Table 2 - Management practices and SOC: state of the art, identified good practices, research gaps, ideas for EIP-AGRI Operational Groups (OGs)

Figure 1 – Keyline opened in an arable field to reduce water erosion in flat land in Spain. Source: Maria Almagro

Figure 2 – Swale opened in a hilly land to reduce the speed of water runoff in Spain. Source: Maria Almagro

Figure 3 – Pond realized in flat soil less prone to soil compaction in Spain. Source: Maria Almagro

Figure 4 – Mechanical termination of a hairy vetch (*Vicia villosa* Roth.) cover crop by roller crimper and simultaneous sod-seeding of sunflower (*Helianthus annuus* L.). Source: Daniele Antichi

Figure 5 – Dead mulch provided by hairy vetch (*Vicia villosa* Roth.) cover crop terminated by roller crimper and reducing weed pressure in sunflower (*Helianthus annuus* L.). Source: Daniele Antichi

Figure 6 – Permanent seedbed implemented in Veneto, North-East of Italy. Source: Daniele Antichi

Figure 7 – Soil structure improved after one year of implementation of permanent seedbed on plastic film in Veneto, North-East of Italy. Source: Daniele Antichi