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Road4Schemes

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List of acronyms and abbreviations

Administrative and Control Systems (IACS)

Agriculture, Forestry and Other Land Uses (AFOLU)

Agri-environment-climate measures (AECM)

Common agricultural policy (CAP)

Emissions Trading System (ETS)

European Agricultural Fund for Rural Development (EAFRD)

European Agricultural Guarantee Fund (EAGF)

European Union (EU)

Farm accountancy data network (FADN)

Good Agricultural and Environmental Conditions (GAEC)

Greenhouse gas (GHG)

Lad use, land use change and forestry (LULUCF)

Marginal abatement cost curve (MACC)

Member State (MS)

Monitoring, Reporting and Verification (MRV)

Nitrous oxide (N2O)

Rural Development Program (RDP)

Soil carbon sequestration (SCS)

Soil organic carbon (SOC)

Statutory management requirements (SMR)

Utilized agricultural area (UAA)

Voluntary carbon market (VCM)

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1. Introduction

The present report summarizes the analysis carried out for T2.4. Specifically, the report investigates the economic viability of some carbon farming initiatives addressing the improvement of carbon stocks in agricultural soils through a simulation analysis using available data from the literature and considering existing and prospective incentive schemes. Existing incentive schemes encompass area-based subsidies promoting carbon sequestration practices, provided through the European Common Agricultural Policy (CAP) (Reg. UE 1307/2013). Prospective incentive schemes analyzed here are voluntary carbon markets (VCM), which were recently introduced in some European contexts, but which are still largely under development as revealed by D2.4 (Smit and van der Kolk 2023), though they are expected to start functioning soon with the issuance of the European regulation on carbon removals (COM/2022/672 final).

The report is divided into 5 main sections, the first one being this introductory chapter.

Section 2 provides an overview of the carbon sequestration potential of different practices on agricultural land, and it provides an estimation of the costs required to implement them at the farm level.

Section 3 provides an overview of the European policies promoting carbon removal practices, with special reference to the CAP, to the proposal of regulation on the European voluntary carbon market and other facilitating policies (e.g., payment for investments, provision of advisory services, etc.). In addition, section 3 provides some information on the transaction costs to make these policies work and to allow farmers and other land managers to access subsidies/generating credits. Thus, section 3 shed light on how different policy instruments are conceived and how and to which extent they can be combined to promote the application of carbon sequestration practices on the agricultural land.

Section 4 describes a conceptual model aiming at assessing the viability of carbon sequestration practices on an economic perspective under the incentive schemes discussed in section 3. The conceptual model is then implemented using the data provided in sections 2 and 3, where average costs and sequestration potentials of agricultural practices are provided as well as average values for subsidies and carbon credits. The model is used to estimate to which extent it is worth implementing carbon sequestration practices and what should be the minimum size of the land under commitment to make them economically viable.

The report concludes with section 5, providing recommendations on how to best combine different policy instruments and on how to effectively promote carbon sequestration practices.

2. Carbon removal potentials and implementation costs for farmers in Europe

Carbon sequestration practices are agricultural management practices guaranteeing soil carbon sequestration (SCS) that occurs when atmospheric CO_2 is transferred to soils. Operationally, net SCS is the difference between the uptake and the release of CO_2 from a particular soil. For convenience, all practices that can increase soil carbon stocks, either by enhancing SCS or by preventing losses of soil carbon, are all defined as net SCS practices (Henderson et al., 2022). In the present document, net SCS is expressed as t CO_2eq ha^{-1} y^{-1} and therefore include also non-CO_2 GHG emissions variation due to the application of carbon sequestration practices. Most scholars provide essentially equal weight to avoided emissions and increased carbon sequestration since it is the combined implementation and maintenance of these practices that ensure net carbon sequestration over time. But the substantial difference is in the cost incurred by the land manager in their implementation. Indeed, there exists land managers implementing carbon sequestration practices because they find them worth to be implemented even in the absence of incentives and land managers who need to be incentivized to cover the extra costs they face when adopting carbon sequestration practices. In the present report with SCS practices we strictly refer to practices that can increase carbon sequestration if implemented.

2.1 Carbon removal potentials of carbon sequestration practices

SCS practices are addressed to both agricultural and non-agricultural areas. Among non-agricultural areas it is worth mentioning Peatlands and Forests. Peatlands are characterized by organic soils with a high organic matter content that often exceeds 90% (Smith et al., 2014). When drained, however, peatlands become net carbon sources. CO_2 emissions from degraded peatlands account for approximately 10% of greenhouse gas (GHG) emissions from agriculture, forestry and other land uses (AFOLU). However, some of the carbon emitted from degraded peatlands can be avoided by restoring them.

Forests are characterized by soils with significant litter layers and deeply rooted trees and recycling of organic matter and nutrients by wide varieties of soil-dwelling organisms (Cools and De Vos, 2013). A huge variety of forests soils exists because of differences on the parent material, type of bedrock, climate, composition of tree species, and other aspects including natural (e.g., fire) and anthropogenic disturbances (e.g., forest management such as thinning frequencies and intensity).

SCS practices on agricultural areas can be differentiated into measures on croplands and measures on grasslands. Measures on croplands include improved rotations involving the incorporation of catch, cover or perennial crops, optimised use of fertiliser and organic amendments, burial of crop residues or left on field, and tillage management. Reduced or no-till farming has been regarded as one of the most important net SCS measures on croplands (Lal et. al., 2003). This is typically promoted as part of a package of measures known as "*conservation agriculture*", which in addition to no-till farming, includes the maintenance of permanent soil cover, through residues retention and the use of cover crops, and the promotion of crop species diversity.

Grassland measures include sward management, pasture renovation, rotational grazing and measures related to stocking densities for the purpose of maximising net primary production (Henderson et al., 2022).

Erosion control, fire management, carbonation, irrigation management and agroforestry measures are applicable to both croplands and grasslands.

In principle, there are no practices that are better than others. In areas where soil carbon sinks are near saturation, preventing the loss of soil carbon is more important than promoting further sequestration. On soils with low existing soil organic carbon (SOC) content, the choice of net SCS practices is paramount as low soil carbon contents can have adverse impacts on crop production and soil fertility. The following reasoning focuses on addressing measures directed at increasing soil organic content.

Table 1 provides a summary of SCS potentials for different practices considering a common baseline defined by monoculture on arable land (i.e., maize, for irrigated field; wheat, for non-irrigated fields) cultivated with traditional management techniques, such as: inversion tillage, nutrient distribution with conventional spreaders and crop residues removal.

The SCS practices listed in table 1 are grouped with respect to different management aspects: soil management, crop management, crop rotation management and land use-change. Soil management and crop management refers to 'soft' changes related to the practices adopted to grow the single crop; crop rotation management refers to changes related to the cropping sequence, i.e, changes in the type of crops grown (which might involve the use of new equipment); and land use change refers to 'deep' changes involving the farming systems, i.e., the transition might involve also require new equipment and facilities. The data reported in table 1 are essentially static (i.e., they refer to average climate conditions, not affected by the changing weather over time) and provide a snapshot of average values and ranges, being the referenced studies carried out in different contexts. Ranges are here provided to highlight uncertainties associated with CO_2 abatement rates (t CO_2eq ha^{-1} y^{-1}) due to both natural variability and the limited knowledge around the underlying biophysical processes.

Table 1 – Unit abatement potential of different farming practices with respect to a baseline scenario characterized by monoculture on arable land with maize as a reference for irrigated fields and wheat as a reference for non-irrigated fields cultivated with traditional management techniques.

Management issue	Farming practices	Abatement potential (t CO_2eq ha^{-1} y^{-1})[(1)]	Source(s)
Soil management	From traditional tillage to minimum tillage	0.395 [0.11 - 0.68]	Sellars et al., 2021
	From traditional tillage to no-tillage	0.47 [0.23 - 0.71]	Sellars et al., 2021

Crop management	Replacing synthetic fertilizers with manure	0.41 [(-0.03) - 0.85]	Maillard e Angers, 2014; Han et al., 2016
	Improving the efficiency of fertilizers applications	0.2 [0 - 0.4]	Lynch et al., 2021
	Burial of crop residues	0.17 [(-0.52) - 0.86]	Lessman et al., 2022; Ranaivoson et al., 2017
Crop rotation management	Rotation with legumes	0.15 [0.08 - 0.22]	Rios et al., 2022; Singh et al., 2007
	Rotation with permanent grasslands	0.23 [0.1 - 0.36]	Cooper et al., 2009; Schjønning et al., 2012
	Introduction of cover crops	0.275 [0.15 - 0.4]	Kale et Shulz, 1994; Schjoning et al., 2012
Land use change	Management of field borders with hedgerows	0.32 [0.08 - 0.58]	Mayer et al., 2022
	Conversion of arable land to permanent pasture	1.66 [1.44 - 1.88]	Minasny et al., 2017; Lugato et al., 2014
	Conversion of arable land to agroforestry	1.44 [0.7 - 2.2]	Mayer et al., 2022; Drexler et al., 2020
	Afforestation of abandoned agricultural land	2.13 [1.36 - 2.83]	Thibault et al., 2022
	Afforestation of agricultural land	2.53 [1.76 - 3.23]	Thibault et al., 2022; Flessa et al., 2002

Notes: (1) The information provided in the table are average values accompanied with ranges in square brackets. The presence of a (-) is to highlight that the practices sometimes can decrease rather than increase net SCS.

Source: our elaboration of selected references from the literature.

The information provided in Table 1 stems from a selected literature addressing net SCS and not simply SCS, as this is considered a more cautious and correct estimate about the potential mitigation effect these measures can generate (Minasny et al., 2017; Schulte and Donnellan, 2012).

For example, regarding **non-inversion tillage** techniques, i.e., avoiding as far as possible tillage practices to increase soil carbon storage reducing microbial decomposition, Sellars et al. (2021) accounted for both the increasing carbon storage and the differences in GHG emissions related to fuel consumption and herbicide uses compared with traditional tillage techniques. Reversely, in other studies (Haddaway et al., 2017; Sun et al., 2011), the abatement potential reaches higher values compared to the ones reported in Table 1 (0.68 - 0.81 t CO_2eq $ha^{-1}y^{-1}$), possibly because they only measures the increase in SCS, disregarding of associated GHG emissions changes (e.g., emissions brough by to the increased use of herbicides induced by the practice). the increase in SCS.

This difference is further evident when considering **replacing the use of synthetic fertilizers**

with organic amendments. For example, Han et al. (2016) and Maillard and Angers (2014) (Tab. 1) included in their estimation the increase in fuel consumption and the influence of the distance between the field and the manure storage center. In other studies (Poulton et al., 2018), the abatement potential of manure application exceeded 1.5 t CO_2eq ha^{-1}y^{-1}, but we do not have a clear understanding of whether the authors accounted for associated changes in GHG emissions. Indeed, some scholars argue that manure application to agricultural fields should be considered a practice required to compensate for a negative externality produced by the same agricultural sector and not a practice that can be implemented at the farmer's discretion (McDonald et al., 2021). That's why this practice is not included among the ones listed in the recent communication on sustainable carbon cycles of the European Commission (COM(2021) 800 final). Other typologies of organic amendments, i.e., biochar and municipal composts, can even have negative effects on soil health and biodiversity due to potential contaminants, such as heavy metals and micro-plastics depending on the raw material of origin (McDonald et al., 2021).

The **improvement on the efficiency of fertilizers application** can be achieved through precision farming, which can be beneficial on fields where yield varies according to a predictable pattern due to differences in soil quality, weed infestation, drainage, etc. The most important GHG impact of this management practice is the reduction in nitrogen fertilizers use and a consequent reduction in the nitrous oxide (N_2O) emissions from soils. Because of the high influence of field characteristics on N_2O emissions, and the low number of studies available on this topic, the average estimates provided in Table 1 are very uncertain (Lynch et al. 2021).

The **burial of crop residues** is another important practice that can improve SCS. Alternatively, crop residues can be burned on field because of phytosanitary threats, removed for use in livestock barns, or sold in the market. The abatement potential estimates related to the burial of crop residues provided in Table 1 (0.17 [-0.52 - 0.86 t CO_2eq ha^{-1} y^{-1}] account for both for the amount of carbon sequestered in soils and the emissions due to the extra-field operations this practice requires (Lessmann et al. 2022; Ranaivoson et al. 2017). Other estimates, only focusing on SCS, reached values of 1.3 t CO_2eq ha^{-1} y^{-1} (Poulton et al., 2018; Xu et al., 2019).

Crop rotation is also considered as a practice that can increase net SCS. In table 1 we consider both a 1-year grain legume and a 3-year permanent mixed grassland in a 5-year rotation.

The effect on SCS is less evident when introducing **legume crops** in cereals monocultures (De Los Rios et al., 2022; Singh et al., 2007). The main on-farm mitigation effect of legumes is via reduced or avoided N_2O emissions thanks to the reduced N fertilizer requirement by the subsequent crops. But this effect is highly influenced by the characteristics of the succeeding crop, i.e., higher for maize (Rios et al., 2022) and lower for wheat (; Singh et al., 2007).

Similarly, the introduction of **three-year permanent grasslands** in the rotation contributes to increasing SCS compared to maize monoculture and shows a slightly higher effect compared to annual grain legumes. This happens because of the organic carbon stored thanks to the presence of undisturbed permanent grassland (see the values provided in table 1). Also, other estimates are available in the literature (Poulton et al., 2018), revealing that crop rotation can increase SCS up to 0.84 – 1.53 t CO_2eq $ha^{-1}y^{-1}$. This is highly influenced by the characteristics of the crop sequence and the length of the rotation, that can range between 2-7 years, differing from the reference baseline for crop rotation considered in this study.

The effect on net SCS is particularly evident when introducing **cover crops** in the rotation. Cover crops can mitigate GHG emissions in four main ways: by increasing soil organic carbon content; by decreasing soil carbon losses due to erosion during the fallow period; via a reduction in N leaching (and associated N_2O emissions); and, by reducing the amount of N that needs to be applied to the following crop (Macleod et al., 2015). The influence of cover crops on net SCS increases with the duration of the green cover, but the introduction of cover crops may result in potential loss of production, if they lead to switching from winter to spring cultivation. In addition, the introduction of cover crops requires additional field operations, compared to a standard monoculture scenario, and therefore higher GHG emissions that mitigate the net SCS benefit of cover crops. Accounting for all of these factors brings to the values reported in table 1 (0.275 [0.15 - 0.4] t CO_2eq $ha^{-1}y^{-1}$) (Cooper et al., 2009; Schjønning et al., 2012). These values differ substantially from others available in the literature (Sánchez et al., 2016), where the SCS potential reaches up to 1 t CO_2eq $ha^{-1}y^{-1}$, a value that can be partially explained with the different experimental conditions, but also with the different approach used for SCS estimation.

Regarding **land-use change**, the conversion of field borders in **herbaceous strips or hedgerows** to control erosion and avoid nutrient leaching in rivers and/or canals is also beneficial to net SCS (Mayer et al., 2022). The impact on net SCS is influenced by the degree of fragmentation of the agricultural land. The proportion of land covered by hedgerows increases as field size decreases. The plantation of hedgerows on agricultural land has a similar impact of **afforestation**, but values of abatement potentials are lower because of the smaller surface area impacted by the practice. e.g., the value provided in table 1 (0.32 [0.08 - 0.58] t CO_2eq $ha^{-1}y^{-1}$) is calculated assuming the plantation of hedgerows on a quota of land of around 7% of the utilized agricultural area (UAA). **Agroforestry** allows further improving net SCS (1.44 [0.7 - 2.2] t CO_2eq $ha^{-1}y^{-1}$), as around half of the land is converted to forest (Drexler et al., 2020; Mayer et al., 2022). Net SCS increases even more with the **conversion of arable land to grassland** (1.66 [1.44 - 1.88] t CO_2eq $ha^{-1}y^{-1}$) (Lugato et al., 2014; Minasny et al., 2017), with the **afforestation** of abandoned agricultural land (2.13 [1.36 - 2.83] t CO_2eq $ha^{-1}y^{-1}$) (Thibault et al., 2022) and with afforestation of cropland (2.53 [1.76 - 3.23] t CO_2eq $ha^{-1}y^{-1}$) (Flessa et al., 2002). The afforestation of cropland can mitigate GHG emissions in two main ways: carbon sequestration with increases in above-ground carbon storage; carbon sequestration with an increase in below-ground carbon storage.

Values reported in table 1 consider SCS for below-ground and only partially for above-ground, as also forests are subject to periodic harvesting limiting the potential growth of the vegetation.

2.2 Costs to implement carbon sequestration practices

In this section we estimate the impact on farmers' income of the implementation of a new carbon sequestration practice. To estimate the costs required to implement carbon sequestration practices we followed an approach similar to the one developed by Sánchez et al. (2016): (Sánchez et al. 2016)we calculated the difference in the costs and revenues between the new and the old practice, in an opportunity costs perspective. From this perspective, the cost actually incurred by the farmer is not represented simply by the cost required to implement the new practice but, rather, by the difference in income between the new practice and the current practice.

Net SCS measures can involve high **upfront adoption costs** if, for example, **investment** in machinery is required. For example, water and tillage management measures, and agroforestry practices, require investment in equipment by farmers or investments to introduce perennial crops (Wreford et al., 2017). There are also **maintenance costs**, as net SCS practices must be maintained over the long term to prevent future losses of sequestered carbon. In addition to these financial costs, net SCS measures can also incur **opportunity costs** if their implementation requires farmers to forgo revenue from other sources. For instance, the restoration of cultivated organic soils (e.g., peatlands) will require farmers to forfeit income from agricultural production. Similarly, farmers who retain crop residues could forgo revenue or cost savings from the sale of that residue or from its use as a livestock feed or bedding in the farm. Finally, there are other costs, such as the **transaction and learning costs** of adopting measures, which are difficult to quantify and therefore omitted in this analysis.

The range of cost estimates is usually very wide. This largely depends on three elements: the costs of inputs, the size of the farm and the characteristics of the region (Macleod et al. 2015). Thus, a reference scenario is required to substantiate the assessment. To calculate the average costs required to implement SCS practices, we considered as a baseline the representative farming system described in section 1, using available information from the Italian Farm Accountancy Data Network (FADN 2023). The same reference was used to calculate the costs associated with land use change and changes in crop rotation. To calculate changes in the costs associated with specific practices and their impact on yields we took advantage of available information from recent assessment carried out in western countries (Macleod et al. 2015; Sánchez et al. 2016; Schulte and Donnellan 2012)[1]. The assessment of opportunity costs can be summarized as follows:

$$\Delta GM_a = GM_a - GM_b \quad (1)$$

Where, GM_p is the gross margin of the field after the implementation of the new carbon sequestration practice, a. Its value is influenced by the impact of the practice on the yield and by the implementation costs, including annual costs of additional equipment, if needed, and the management costs; while GM_b is the typical gross margin for the crop without the new carbon sequestration practice implementation.

Table 2 provides an estimation of the costs associated with the practices already analyzed in

[1] We didn't make any explicit reference to farm size for this exercise as this is a very controversial issue. Indeed, in one hand increasing farm size lower the impact of fixed cost, on a financial perspective, facilitating the adoption of SCS practices requiring specialized equipment. In the other hand, on a opportunity cost perspective, what large farms give-up changing practices is greater than what small farms lose, since the former have notably higher unit margins.

section 2.1. The estimates provided in table 2 differ substantially from the ones provided by Sánchez et al. (2016) for crop rotation management. The estimates provided by Sánchez et al. (2016) are far lower than the estimates provided in this table, which combine both estimates from Sánchez et al. (2016) and FADN (2023). Sánchez et al. (2016) provide a 'win-win' impact, as these practices can potentially provide net economic benefits together with carbon sequestration. However, they accounted for impacts on single crops, missing to assess the economic impact of introducing new crops in the rotation, implying income losses of the substituted crops, that can be captured by widening the assessment horizon to the time-length of the rotation. Taking this into account makes it apparent why it is still hard to spread crop rotation practices in Europe (Galioto and Nino, 2023).

Table 2 – Average unit cost estimates of different farming practices with respect to a baseline scenario characterized by monoculture on arable land with maize as a reference for irrigated fields and wheat as a reference for non-irrigated fields cultivated with traditional management techniques for the period 2017-2021.

Management issue	**Mitigation actions**	**Net costs €/ha (range)**	**Source(s)**
Soil management	From traditional tillage to minimum tillage	27 [(-18) - 73]	Sanchez et al., 2016 (1)
	From traditional tillage to no tillage	60 [40 - 80]	Sellars et al., 2021 (2)
Crop management	Replacing synthetic fertilizers with manure	28 [(-20) - 75]	Maillard e Angers, 2014; Han et al., 2016
	Improving the efficiency of fertilizers applications	146 [(-40) - 332]	Lynch et al., 2021
	Burial of crop residues	192 [170 - 215]	Sanchez et al., 2016; FADN, 2023
Crop rotation management	Rotation with legumes	147 [(-56) - 172]	Sanchez et al., 2016; FADN, 2023 (3)
	Rotation with permanent grasslands	350 [300 - 400]	Sanchez et al., 2016; FADN, 2023
	Introduction of cover crops	149.5 [121 - 178]	Lynch et al., 2021; FADN, 2023
Land use change	Management of field borders with herbaceous strips	36.8 [11 - 62.6]	Sanchez et al., 2016; FADN, 2023
	Conversion of arable land to permanent pasture	444 [362 - 526]	Sanchez et al., 2016; FADN, 2023

	Conversion of arable land to agroforestry	330 [206 - 305]	Sanchez et al., 2016; FADN, 2023
	Afforestation of abandoned agricultural land	461 [211 - 672]	Sanchez et al., 2016; FADN, 2023
	Afforestation of agricultural land	991.5 [511 - 1472]	Thibault et al., 2022; Flessa et al., 2002

Note: (1) Data from Sanchez et al. (2016) are adjusted using direct costs to define max values and the difference between direct costs and expected benefits to define min values. (2) Data from Sellars et al. (2022) are adjusted converting the currency and the reference size units in EU standards. (3) Costs on land use change were estimated with reference to the FADN standard output estimates of Italy using the 2017-2021 average Maize and Wheat outputs for the baseline (FADN, 2023).

Source: elaboration of the authors of selected references from the literature.

It is worth highlighting here that the values provided in table 2 refer to estimates from western countries and that these are strongly influenced by labor and input costs as well as by different pedological and climate conditions, which might significantly change from region to region and from time to time. Thus, the provided information should be interpreted purely from a qualitative perspective, helping to understand which practices more expensive and which ones are are less. The negative values between the square brackets refer to practices that were found to have greater potential to deliver net private benefits.

Despite the potential of some practices to improve farm profitability, the high upfront costs may prevent farmers from their adoption in the absence of sufficient savings and/or the perceived lack of benefits. These barriers can be mitigated with support for investments and extension services. Also, structural conditions, relating to land tenure and farm size, influence farmers' propensity to adopt net SCS methods. In the absence of property rights, difficulties may arise in establishing improved management practices. Finally, generational renewal and farmers' age are thought to play a role in conditioning investments decisions (Henderson et al., 2022).

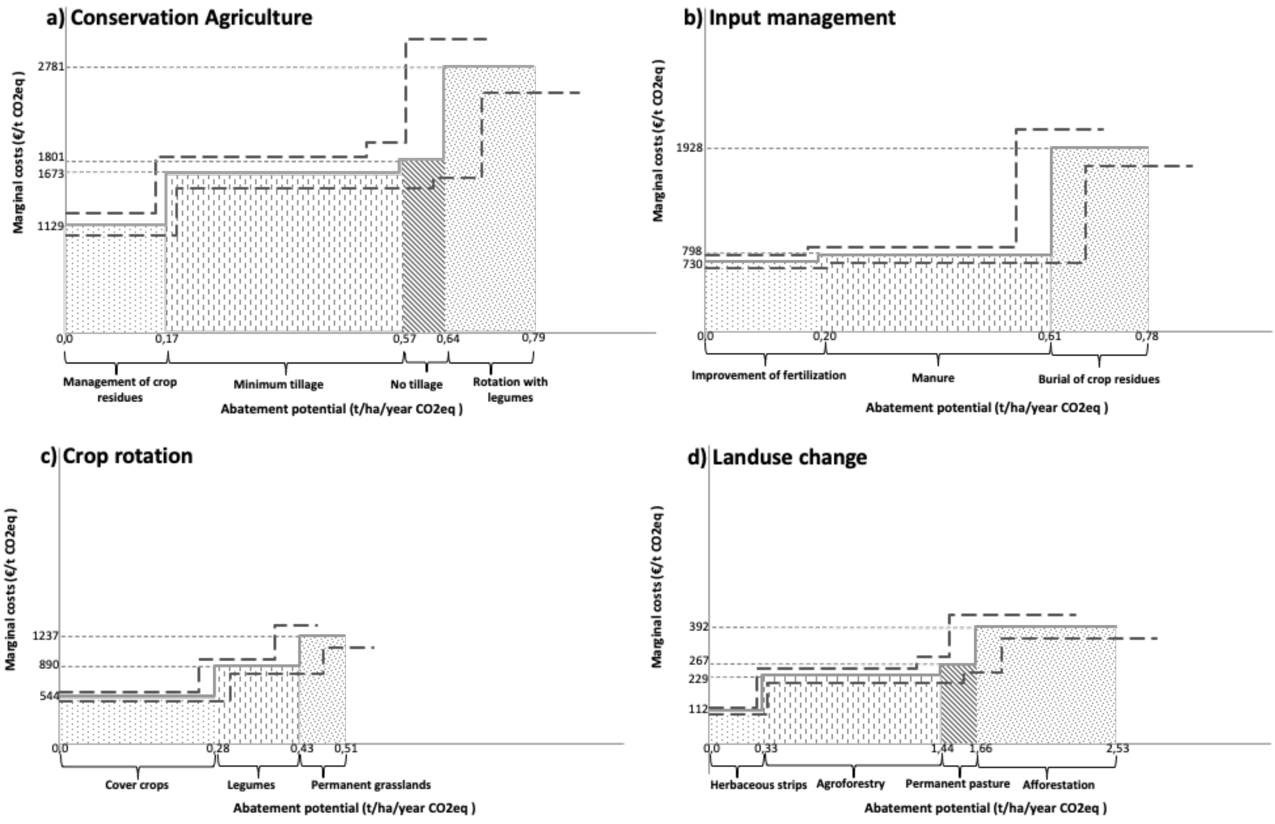
By combining the information provided in table 1 and 2 we obtain the **cost-effectiveness ratio** that can be expressed as the ratio between the changes in the costs (inputs costs and income losses) of the new practice compared to the old one ΔGM_a (see equation 1), to the changes in net SCS of the new practice compared to the old one, ΔSCS_a. The cost-effectiveness, C, for each practice, a,can be formulated as follows:

$$C_a = \frac{\Delta GM_a}{\Delta SCS_a} \qquad (2)$$

By ordering the cost-effectiveness values of each SCS practice, C_a, from the least cost-effective to the most cost-effective it is possible to derive a marginal abatement cost curve (MACC), defining the changes in costs brought by unit variation in SCS. MACCs are essentially static and tend to provide a high-level snapshot of the average or typical performance of a set of mitigation measures at a point in time. Here, both biophysical and economic uncertainties are combined, further amplifying the overall variability (Macleod et al., 2015).

Figure 1 provides the MACCs for the 4 management scenarios analyzed in the present work: A) conservation agriculture, B) input management, C) crop rotation management, D) land use change. A mitigation measure can be applied alone, or in combination with other measures. The scenarios A and B involve practices that can be combined to achieve higher SCS levels, while the scenarios C and D involve alternative practices. When applied in combination, the measures can interact, meaning that the "stand alone" abatement rate and cost-effectiveness can be quite different from the "combined" cost-effectiveness. For example, if a farmer plants legumes and decreases the amount of N fertilizer applied, then the extent to which emissions can be further reduced by improving the efficiency of N application will diminish, making N efficiency measures less cost-effective. The SCS achievements provided in figure 1 A and B do not account for these interactions, with the risk of overestimating the combined abatement potential. Overestimations can occur also for figure 2 C and D due to possible production displacement (*leakage*) effects, i.e., decreasing production in one location associated with temporary or permanent land use change can lead to displacement of production (and associated emissions) to other regions or countries. Finally, misestimation can also occur because of the use of average values not accounting for inputs and outputs price variability across years and between countries, i.e., the cost of growing more maize and less grass for animal feed might be very different for different farmers. Thus, the information provided in figure 1 must be read and used in light of the discussed limitations.

Figure 1 - MACCs for different management scenarios: A) conservation agriculture, B) input management, C) crop rotation management, D) land use change. Marginal costs are drawn on the y-axis (€ t CO_2eq^{-1}) and CO_2 abatement potential of the different SCS practices on the x-axis (t CO_2eq ha^{-1}y^{-1}).



Source: elaboration of the authors of selected references from the literature.

In the face of such limitations, the following consideration can be drawn from the analysis carried out so far:

- Land use change strategies have higher abatement potentials at lower costs, followed by crop rotations, input substitution and conservation agriculture.
- The combination of conservation agriculture and input substitution practices, needed to achieve higher abatement potentials, amplify the inherent uncertainty, making such practices less sustainable, on an economic perspective, than the others SCS strategies here investigated.

3. Policy instruments to promote carbon sequestration in agriculture

The policy options available to stimulate the uptake of SCS practices include regulatory or command and control measures, public incentives, market-based instruments, facilitating policies (e.g., the promotion of investments, the provision of advisory services), carbon taxes, pricing policies etc. In the following section we will provide a snapshot of the key regulatory instruments influencing the adoption of SCS practices with a focus on the two main financial instruments: the **CAP**, which is already existing and consolidated, and the voluntary carbon market (**VCM**), a financial instrument recently introduced but not yet regulated in the European Union (EU). A specific section is then dedicated to discussing transaction costs and their role in influencing the uptake of SCS practices in the framework of the CAP and the VCM. Finally, facilitating policies are also discussed highlighting their paramount role in promoting the uptake of SCS practices.

3.1 Regulatory framework

Any form of market-based and public-based incentive and facilitating policy operate under an overarching regulatory framework. There are two key regulatory frameworks influencing the uptake of SCS practices: the EU climate and energy policy and the biodiversity strategy. The EU climate and energy policy framework plays a crucial role as it sets the overall climate ambitions and prescribes obligations of emissions reductions to certain sectors of the economy, including agriculture. The EU Biodiversity Strategy sets out the EU's planned actions to halt the decline of biodiversity in Europe.

With respect to the **EU climate and energy policy framework**, agricultural emissions, together with emissions from other sectors outside the scope of the EU's Emission Trading System, are covered by the **Effort Sharing Regulation** (Reg. EU 2018/842). The ESR sets binding targets for Member States, with flexibility on the potential contribution of individual ESR sectors. Targets range from 0% to 40% reduction by 2030 (compared to 2005 levels), reflecting the relative wealth of Member States, and they were meant to collectively deliver a 30% emissions cut by 2030, then revised at 40% by the **Fit for 55 package** (McDonald et al., 2021).

The accounting of agricultural CO_2 emissions (or removals) linked to changes in carbon stored in soils and biomass, due to cropland and grassland management practices, are on the other hand covered by the Land use, land use change and forestry (**LULUCF**) **Regulation** (Reg. EU 2018/841). In addition, the same regulation requires Member States to set binding emission reduction targets such as to ensure that emissions from the LULUCF do not exceed removals in the periods 2021-2025 and in the period 2026-2030. Member States with net removals beyond their national emission reduction targets can use them for compliance with the ESR (first capped at 280 Mt of CO_2eq emissions in the period 2021-2030 and then at 310 Mt of CO_2eq with the Fit for 55 package), for example using forestry and agriculture credits or allowances from a European carbon market. But a European carbon market is still missing.

Here it is the current **proposal for a regulation on carbon removals (COM(2022) 672 final)**, establishing the rules for a European voluntary carbon credit market, by making it possible to trade credits from agriculture to the other non-ETS sectors, to facilitate meeting the ESR climate targets of each Member State by 2030. Such a proposal comes just after the recent ban on international offsets to meet emission reduction efforts by the ETS sectors imposed by the European Commission in phase 4 of the ETS regulation (**Directive 2003/87/EC**)[2], allowing to meet targeted reductions more cheaply, although with more uncertain impacts than direct reduction efforts (CMW 2014). Further arguments on this point are provided in section 3.4.

A financial instrument to offset emissions from non-ETS sectors can be identified in the voluntary carbon market, further investigated in section 3.3, while the main financial instrument to reduce emissions from agriculture is the **CAP**, further investigated in section 3.2.

The CAP is also the key EU financial instrument to meet other environmental targets defined in the **EU Biodiversity Strategy**. This strategy aims to strengthening the implementation of existing biodiversity policies, such as the Habitat Directive (Directive 92/43/EEC), the Bird Directive (Directive 2009/147/EC), the Nitrate Directive (Directive 91/676/EEC), the Water Framework Directive (Directive 2000/60/EC), and introduces new initiatives, such as an EU Nature Restoration Law (COM(2022) 304 final). The Nature Restoration Law includes a proposal for legally binding nature restoration targets which should prioritize the restoration of ecosystems with the highest potential to capture carbon, with consequent benefits on hazard risk mitigation, soil health and pollination. The other existing directives above mentioned provide both rules to define common monitoring plans to detect pressures on the environment and their causes, and rules to define management plans to reduce pressures. These management plans define sensitive areas within which farmers are obliged to comply with different type of restrictions (e.g., limitations in the use of fertilizes, plantation and maintenance of buffer strips along field borders with rivers and canals, etc.). Most of the corrective actions adopted by farmers are addressed to primarily solve environmental issues but often they have important positive implication on climate mitigation.

3.2 Overview of existing CAP instruments

The CAP provides rules and subsidies to implement measures that can influence the adoption of conservation agriculture practices and prevent the degradation of sensitive areas, including organic soils. Rules are in the form of Good Agricultural and Environmental Conditions (GAECs) and in the form of Statutory Management Requirements (SMRs). The first set of rules define the minimum commitments farmers must comply with to access subsidies.

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[2] Until 2020, ETS sectors had the chance to compensate part of their emissions by purchasing international credits generated through the Clean Development and/or the Joint Program Mechanisms. The EU does not currently envisage continuing the use of international credits after 2020 to compensate for domestic reduction targets of 2030 (https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/use-international-credits_it).

The second set of rules define the minimum commitments farmers must comply with to be allowed to practice farming.

Box 1 provides a description of the GAECs farmers must comply with to access CAP fundings. Most of these conditions refers to practices that can contribute to improve soil health: maintenance of permanent grasslands, avoiding burning crop residues, contour farming with hedges, trees, etc. and drainage management to counter soil erosion in fields with slopes higher than 10%, soil cover management during rainy seasons, and crop rotation management. Apparently, these are very ambitious and stringent conditions. In reality, only farms with specific characteristics and located in sensitive areas are required to fully meet these conditions.

Box 1 – 2023-2027 CAP Good Agricultural and Environmental Conditions (GAEC)

Water pollution

- GAEC 2: *On designated wetland and peatland areas, certain management requirements have to be met;* GAEC 4: *Establishment of buffer strips along polluted water courses;* GAEC 10: *Compliance with the recommendations for appropriate fertilisation*

Soil conservation

- GAEC 1: *Maintenance of permanent grassland ration on national level;* GAEC 3: *Ban on burning arable stubble;* GAEC 5: *Erosion-reducing measures from a gradient of 10 % on arable land and permanent cropland;* GAEC 6: *Minimum soil cover on arable land and permanent cropland between January 1 and February 15;* GAEC 7: *Requirements concerning crop diversification and crop rotation*

Biodiveristy protection

- GAEC 8: *4 % minimum share of fallow land, protection of landscape;* GAEC 9: *Ban on converting or ploughing permanent grassland designated in Natura 2000 sites*

Source: elaboration of the authors on the Italian 2023-2027 CAP National Strategic Plan.

Box 2 provides a description of the SMRs farmers must comply with to practice farming. Most of these rules are related to food safety and animal welfare, but also to environmental sustainability. Here we have a clear link to the EU Biodiversity strategy, i.e., SMRs oblige farmers to comply with the rules provided in the environmental management plans set by Member States to accomplish with the backbone directives of the EU Biodiversity strategy.

Box 2 – 2023-2027 CAP Statutory Management Requirements

Environmental sustainability

- SMR 1: Water Framework Directive (*Directive 2000/60/EC); * SMR 2: Nitrates Directive *(Directive 91/676/EEC);* SMR 3: Birds Directive *(Directive 2009/147/EC);* SMR 4: Fauna, Flora, Habitats Directive *(Directive 92/43/EEC)*

Food safety

- SMR 5: Food Safety Regulation (*Regulation (EC) No 178/2002)*; SMR 7 *Regulation (EC) no 1107/2009)* concerning the placing of plant protection products on the market; SMR 8: *Directive 2009/128/EC* extablishing a framework for Community action to achieve the sustainable use of pesticides

Animal welfare

- SMR 6: *Directive 96/22/EC* concerning the prohibition on the use in stockfarming of certain substances having a hormonal or thyrostatic action and of ß-agonists; SMR 9: Minimum standards for the protection of calves *(Directive 2008/119/EC)*; SMR 10: Minimum standards for the protection of pigs *(Directive 2008/120/EC)*; SMR 11: Minimum standards for the protection of animals kept for farming purposes *(Directive 98/58/EC)*

Source: our elaboration on the Italian 2023-2027 CAP National Strategic Plan.

Subsidies are, instead, provided for voluntary measures entailing commitments beyond conditionality. Subsidies are both in the form of ECO-schemes and agri-environment-climate measures (AECM). ECO-schemes and AECM differ ineach other in their design (usually, AECM are more ambitious than ECO-schemes), in their financing method (AECM are co-financed by the Member State (2nd pillar) and ECO-schemes are entirely financed by the EU (1st pillar)), in their duration (ECO-schemes require compliance for a 1-2 year period length, AEC-measure require compliance for a 5 year period).

The 2023-2027 CAP reform requires Member States (MS) of the EU to allocate at least 25% of Direct Payments to ECO-schemes and at least 30% of the Rural Development Program (RDP) budget to voluntary measures that are beneficial for the environment. Among these measures, 20% must have cross-cutting impacts that, amongst others, address climate change Priority 5 of the RDP, i.e., "*Resource efficiency and shift to low carbon and climate resilient economy in the AFOLU and food sectors*". The sub-priority 5E (i.e., carbon conservation and sequestration) is particularly relevant for net SCS.

There is no specific minimum amount of budget (ringfencing) that Member States must put towards climate or carbon farming schemes, given that the ringfencing for eco-schemes in the European Agricultural Guarantee Fund (EAGF) and for environmental payments in the European Agricultural Fund for Rural Development (EAFRD) cover both environment and climate spending. So, much discretion is left to Member States in allocating funds for SCS practices through the CAP. However, the choice of how to allocate resources among practices by Member States is always conditioned by the climate and environmental commitments that they negotiated at the EU level. Among the key SCS practices financed through the CAP it is worth mentioning here: non-inversion tillage, burial of organic matter, Interrow green cover of tree crops, inclusion of cover crops in the rotation (in addition to GAEC 6 it requires soil cover for a longer period and not by spontaneous vegetation), land use change from arable land to permanent grassland, pastures management, management of ecological infrastructures, precision farming, management of crop residues (in addition to GAEC 3 it requires the incorporation of crop residues, sometimes after composting), organic and low-input farming.

3.3 Overview of voluntary carbon market initiatives

In the last decade the EU witnessed the growth of many voluntary carbon schemes initiatives, some of which are in the form of:

- voluntary carbon market, known also as offsetting schemes, where polluting sectors buy carbon credits from non-polluting sectors to offset their emissions,
- voluntary company-led initiatives, known also as insetting schemes, where clients/consumers fund carbon sequestration projects, promoted by the polluting company, to compensate for the emissions they contributed to generate .

The reasoning behind offsetting mechanisms is that polluting companies pay others to compensate emissions instead of reducing them directly for example through the adoption of sustainable technologies. The reasoning behind insetting mechanisms is that consumers pay others to compensate the emissions due to the choice of consuming goods and services with high environmental impact. These are complementary motives, that's why very often hybrid schemes exist, combining market and co-financing, by virtue of the co-responsibilities between polluting companies and consumers (Smit and van der Kolk 2023).

The voluntary carbon market is thought to be a more powerful form of voluntary carbon scheme as it is found to be a lever also for company-led initiatives. But for its functioning, the voluntary carbon market requires regulations from outside the polluting company. That's why most of the voluntary carbon market in the EU are still in a pilot stage due the absence of a common EU regulation on carbon removals and most of the initiatives that are already implemented rely on international exchange platforms (Smit and van der Kolk 2023). The only exception is Label Bas Carbone, a national voluntary carbon market ruled by the French government (Ministère de la transition énergétique 2023). The government certifies credits and records transactions to prevent any risk of double accounting. There is no price control and credit prices are the results of private negotiations. The very fact of certifying projects on the national territory is sufficient to guarantee higher prices than the international market. The greater reputation that companies obtain by supporting national projects more than compensates for the higher prices of the credit. The French VCM encompasses:

afforestation projects, blue carbon projects (e.g., to restore costal ecosystems), and livestock management projects. Projects about the management of agricultural fields are still not supported by this mechanism. The reason behind it might be that net SCS practices are too costly and have lower performances. Nevertheless, there exists some national voluntary carbon markets outside Europe, which include the production of credits from SCS projects. For instance, the Alberta Emission Offset System allows farmers to earn carbon offsets by adopting SCS practices, including the use of no-till practices to increase soil carbon.

Australia's Emission Reduction Fund is another voluntary market-based mechanism targeting GHG abatement in agriculture and other land use. The scheme allows projects to generate Australian Carbon Credit Units, which can be sold on the private market or to the government through a reverse auction process and covers a broad range of eligible activities, including those that enhance soil carbon stocks. As of October 2022, 184 soil carbon projects have been registered under the Emission Reduction Fund (Demenois, Dayet, and Karsenty 2022).

Both European and extra-European regulatory initiatives accompanying the establishment of VCMs made it possible to better control transactions compared to international VCMs, creating more reliable Monitoring, Reporting and Verification (MRV) schemes, although they still need to be improved (Criscuoli et al. 2023).

This fact, together with the changing European climate strategy which opens up a space for domestic carbon credit markets for non-ETS sectors and ceases using international credits for the ETS sector, justify the current proposal for a regulation on carbon removals (COM(2022) 672 final), defining common rules for the creation of a European voluntary carbon credits market.

Nevertheless, the effectiveness of existing regulations providing the possibility to generate credits from the agricultural sector is questioned for several reasons (Demenois et al., 2022), among which: the non-permanence of soil carbon stocks; transaction costs; and additionality. These constraints could each be partially addressed by improvements in the design of payment contracts (Henderson et al., 2022). The following considerations can be made on the abovementioned issues:

- Transaction costs in general, including financial transaction expenses (such as legal and brokerage fees) and MRV, can raise the costs of contracting carbon credits (from 3% to 85% of total credit value) and reduce land managers' willingness to participate in carbon markets. These costs could be lowered by the mean of:
    - Aggregators, that pool individual farmer contracts into a larger project to exploit economies of scale and manage risk,
    - involving existing public governance bodies in the regulation of transactions and issuances of credits from carbon sequestration projects (e.g., Information Administrative and Control Systems (IACS) currently managing CAP payments).
- The non-permanence of soil carbon stocks poses challenges associated with the risk of paying for abatement that is lost at some future point. Credits are issued as carbon is stored in soils and are debited as carbon is returned to the atmosphere. This requires measurements to be carried out at regular intervals over time, but in the face of higher transaction costs. In the inability to monitor the project beyond the committed period, it might be appropriate to differentiate:
    - carbon sequestration projects:projects bound to actions that require

significant costs to restore initial conditions (i.e., projects involving land use change)

  - emission reduction projects: projects accounting for reduced emissions during the committed periods (i.e., projects involving changes in practices).

These considerations are supported by the fact that where maintenance is costly, the risk of reversal is likely to be high (Demenois et al., 2022).

- Non-additionality is an important issue that can affect the environmental integrity of carbon credits generated by net SCS practices. To guarantee additionality, policies need to encourage the implementation of practices that go beyond the "business as usual". Assessing the additionality of a project is complex, as it is an uncertain concept based on an unobservable counterfactual, i.e. on what would have happened in the absence of a policy intervention (Henderson et al., 2022). In practice, simplified baselines are used to approximate the "business as usual" situation, and the approach used to construct these baselines can have a fundamental impact on the supply of carbon credits and their accountability. A solution might be to foresee at least a direct inspection before the beginning of the project, to ascertain initial conditions and a direct inspection at the time the project is implemented, followed by indirect inspections throughout the duration of the project (i.e., using images and remote sensing techniques to check anomalies on the field under commitment and other administrative checks to verify ownership conditions, etc.).

Finally, net SCS practices can create synergies and trade-offs between different GHG sources as well as between GHGs and other environmental impacts, including impacts on biodiversity, and air and water quality. To be efficient, policies supporting the adoption of carbon sequestration practices need to account these interactions to enhance environmental co-benefits and resolve environmental trade-offs.

3.4 Transaction costs

Transaction costs occur across all stages of the policy cycle (from policy planning to enforcement), and include normal financial transaction expenses (i.e., costs to get support to apply for CAP payments, legal and broker fees to register carbon credits and to access the exchange platform), and costs associated with contracting (i.e., administrative adjustments required by the beneficiary to facilitate access to funds and/or generate credits).

In addition, the peculiar inherent spatial and temporal variability of soil carbon sequestration can raise transaction costs related to measuring sequestration outcomes, monitoring compliance with contract terms over large and heterogeneous geographical areas and setting correct baselines. Uncertainty regarding the permanence of carbon stocks, including the risk of farmers abandoning net SCS practices, can raise additional monitoring and enforcement costs and may also lead to litigation costs.

A significant proportion of the discussed transaction costs are fixed and invariant to farm size. Thus, there are associated economies of scale from spreading the fixed costs over a larger farm area. Table 3 provides some estimates of the transactions costs land managers face to access CAP subsidies and carbon markets.

Table 3 – Estimation of the transaction costs borne by land managers to access CAP payments and existing international carbon markets.

Policy instruments	Item	Fixed costs €/ha (range)	Variable costs % of carbon credits (range)
CAP	Costs to apply to the CAP schemes	130 [128 - 196]	-
Carbon Market	Registry costs	30 [20 - 40]	-
	Project development	360 [200 - 500]	-
	Verification	2,000 [1,500 - 2,500]	-
	Trade	-	15 [10 - 20]

Note: Costs from carbon markets are adapted from VERRA (2023), Gold Standard (2023) and Pearson et al. (2014). Cost from the CAP are adapted from the Commission (2007).

Source: elaboration of the authors of selected references from the literature.

Besides the information reported in table 3, there are few estimates of the transaction costs associated with generating and trading carbon credits, and those that are available vary significantly. For example, for agriculture, these transaction costs are estimated to be almost irrelevant for projects in Latin America, accounting for only 3% of credits' value (Mooney et al., 2004). However, more substantial transaction costs, accounting for up to 65-85% of total credits have been reported in Western Canada (Fulton et al., 2005). This variability is not much attributable to differences in transaction costs between different carbon credit schemes but rather to the different average size of the projects funded under the investigated schemes.

Besides project size, market and biophysical factors can affect the extent to which transaction costs act as a barrier to adoption in the framework of VCMs. Antle et al. (2007) revealed that transaction costs are likely to be particularly important when C prices are low and in regions where C sequestration rates are low.

Nevertheless, while transaction costs can be significant, they should decrease over time as farmers and policy makers find new ways to minimize the time and resources needed to comply with and administer new policies (OECD, 2019).

3.2 Overview of other European facilitating policies

With “facilitating policies”, we mean policies not directly incentivizing carbon sequestration initiatives, but policies that can facilitate overcoming adoption barriers. Both financial and information barriers were found to be the most relevant in discouraging the implementation of SCS practices (Henderson et al., 2022). These barriers can be smoothed by supporting investments and advisory services (McDonald et al., 2021).

There is also a role for R&D in encouraging the adoption of net SCS practices. R&D efforts can help build up the evidence base for mitigation practices and technologies and assure farmers of their effectiveness. R&D can also help refine existing technologies to improve their applicability and affordability. Pilot projects to test the viability and effectiveness of new technologies in different agroecological and socio-economic contexts are essential in investigating the practicality of SCS initiatives and the governance arrangements supporting the trade of carbon credits. In this regard, the EU financed many carbon sequestration projects through the CAP Operational Groups, LIFE and INTERREG, and HORIZON2020 projects. Projects that led to the development of several initiatives investigated by Road4Schemes in D2.4 (Smit and van der Kolk 2023), among which, Label Bas Carbone is thought to be the most successful one since it is operational in the French territory and it successfully supported a consistent number of carbon sequestration projects.

4. Preliminary assessment of carbon removal policy instruments in Europe

4.1 Conceptual framework

In this section we provide a generic assessment framework to evaluate the influence of the existing CAP and a hypothetical VCM in facilitating the adoption of SCS practices. The key underlying assumption of the modelling approach offered here is that land managers are thought to act as profit maximizers agents, i.e., the preferences of land managers are driven by the economic incentive guaranteeing higher profits, as follows:

$$\max \pi_p = r_p - c \qquad \forall\, p = \{p^{CAP}, p^{VCM}\} \tag{3}$$

where:

$$r = v_p x S \tag{4}$$

$$c = \phi(C_a) = f_p + exS \tag{5}$$

$$e = a + bx \tag{6}$$

Here, π in equation (1) is a generic profit function for the individual farm addressing carbon removals and defined by the difference between revenues, r, and costs, c. Revenues are, in turn, defined by the price of carbon removals, v_p, which is assumed to change with the pricing policy, the unit amount of carbon removals, x, and the size of the agricultural area under commitment, S. Costs are the primitive function of C_a on base p, drawn from eq. 2. This primitive function is characterized by a fixed and a variable component. The fixed component is defined by transaction costs, f_p, not influenced by the amount of the committed carbon removals, and variable costs, e, assumed being influenced by carbon removals. Transaction costs and here represented as the costs faced by the land manager to access payments and that change with the incentive scheme under evaluation, *p*. The coefficient e represents the variable cost component, varying with the amount of carbon sequestered and addressing both the direct costs required to remove carbon from the atmosphere and the indirect costs represented by the lost income determined by the reduced production. Finally, the payment of carbon removal is assumed being exogenously determined and influenced by the characteristics of the demand, representing climate claims of the society when the payment is in the form of CAP subsidies, and representing climate claims by private and public enterprises to accomplish with given environmental commitments when the payment is in the form of carbon credits.

In the short term, farmers are assumed to decide how much carbon they would sequester, given the size of the agricultural area they can commit. Based on the above problem this can be done in two steps. In the first step, by maximizing eq. 3 with respect to x it is possible to determine the unit amount of carbon removals that allow maximizing profits. In the second step, the optimal level of unit carbon removal, ${x^*}_p$, is substituted into eq. 3 to calculate profits. It is worth implementing carbon removal initiatives in the case the profit is positive, otherwise it would be better to keep maintaining existing practices.

In light of the above problem, the optimal carbon removal unit amount is as follows:

$$x^*_p = \frac{v_p - g}{2h} \quad (7)$$

Worth noting that x^* takes positive values when $v_p > g$. However, this circumstance does not suffice to deem the intervention worthwhile.

Finally, by replacing the optimal carbon removal unit amount of eq. 7 into eq. 3 and equalizing it to zero yields the size threshold, $\bar{S}$:

$$\bar{S} = \frac{f_p}{x^*_p(v_p - e)} \quad (8)$$

Eq. 8 represents the minimum size guaranteeing positive profits, i.e., the minimum size that enable the implementation of SCS practices on an economic perspective. Worth noting that the size threshold increases with increasing transaction costs and unit costs, and it decreases with increasing unit payments and unit amount of carbon removals.

4.2 Data collection and assessment procedure

Table 4 provides the data used to run the model described in section 4.1. These data steam from the cost-effectiveness analysis provided in section 2 and the transaction cost analysis and payments values provided in section 3.

Table 4 – Model parameter estimates for different scenarios of SCS strategies.

Estimation item	Parameters	Scenarios			
		Conservation agriculture (A)	Input management (B)	Crop rotation (C)	Landuse change (D)
Marginal costs (e) (1)	a	401.74	243.16	283.93	60.79
	b	3,490.6	1,714.8	2,922.5	126.99
Transaction costs (f_p)	$f_p{}^{CAP}$	130	130	130	130
	$f_p{}^{VCM}$	2,390	2,390	2,390	2,390
Marginal revenues (v_p)	$v_p{}^{CAP}$	316.46	341.88	1,251.91	391.72
	$v_p{}^{VCM}$	45	45	45	45

Notes: (1) Marginal costs are estimated from the MACCs provided in figure 1 through a linear regression. For the different parameter estimates provided in the table we obtained the following R^2 values: 0.90 for scenario A, 0.58 for scenario B, 0.97 for scenario C, 0.99 for scenario D.

Source: our elaboration of collected and estimated data from different sources.

The marginal costs parameters provided in table 4 are estimated through a linear regression analysis of the MACCs of figure 1, section 2. Transaction costs are here only represented by the costs land managers need to face to access payments. These costs differ substantially among the alternative payment schemes analyzed in this report. These costs somehow reflect the different complexity of the governance required to ensure the operability of the alternative payment schemes. For instance, both VCMs and CAP governances require facilities to monitor compliance during the period under commitment and this implies costs that are borne by the land managers themselves. The differences in the costs could depend on the fact that the governance of the CAP takes advantage of existing public services while VCMs currently rely on new governance facilities. In addition, the logic of VCMs requires land managers to freely develop their own carbon sequestration project while CAP payments require farmers to participate in a call where the commitments are pre-defined by the public authority. So, while, in principles, VCMs offer more freedom of action, they also require more effort by the land manger, being the one to write the project. Although not monetizable, this also represent an important entry barrier.

The differences in the payments can also be explained by the different logic behind its genesis. While CAP payments are based on the average costs and missing revenues farmers face to comply with given commitments, the value of carbon credits steams from the demand-supply interaction and it is both influenced by the costs land managers face to generate the credit and the price polluting enterprises are wishing to pay. The CAP payment expresses the value society attach to a given practices, and the carbon credits express the value polluters attach to a given practice. Society expresses a value that considers all the environmental benefits that flow from a given practice; polluters express a value that considers the cost they would otherwise have to incur to comply with legal limits related to given pollutants. This consideration partly explains the reason behind the significant difference in value between the comparing payment schemes.

Table 5 provide further insights addressing the differences in the per hectare unit values of the comparing payment schemes for each of the SCS practices here investigated.

Table 5 – Per hectare unit values of the CAP and carbon credits payment schemes for a set of SCS practices.

Management issue	Mitigation actions	CAP subsidies by governments (€/ha)	Carbon credits by polluting enterprises (€/ha)
Soil management	From traditional tillage to minimum tillage	250 [160 - 600]	24.675 [10.35 - 42.6]
	From traditional tillage to no tillage	300 [180 - 600]	35.7 [19.35 - 48.6]
Crop management	Replacing synthetic fertilizers with manure	200 [150 - 300]	90.3 [69.3 - 114]
	Improving the efficiency of fertilizers applications	150 [70 - 270]	4.725 [1.485 - 9.54]
	Burial of crop residues	450 [360 - 540]	68.25 [63 - 90]

Crop rotation management	Rotation with legumes	500 [250 - 940]	44.1 [3.6 - 96]
	Rotation with permanent grasslands	120 [110 - 130]	78.75 [18 - 156]
	Introduction of cover crops	200 [150 - 300]	22.05 [-12.6 - 63]
Land use change	Management of field borders with herbaceous strips	157 [114 - 214]	56.7 [24.75 - 99.6]
	Conversion of arable land to permanent pasture	200 [150 - 430]	87.15 [64.8 - 112.8]
	Conversion of arable land to agroforestry	255 [206 - 305]	75.6 [31.5 - 132]
	Afforestation of agricultural land	514 [328 - 698]	111.825 [61.2 - 169.8]

Notes: Marginal Unit carbon credit values are adapted from official data banks (CarbonCredit 2023). Area-based subsidies are adapted from the Italian National Strategic Plan of the 2023-2027 CAP reform (Masaf 2022).

Source: our elaboration of collected and estimated data from different sources

Worth noting that the differences in payments are lower for those practices characterized by higher abatement potentials and low co-effects, such as the replacement of synthetic fertilizers with manure application. Conversely, higher differences in payments are recorded for those practices capable of generating additional benefits, such as biodiversity improvements brought by afforestation.

4.2 Influence of different policy options on addressing SCS practices

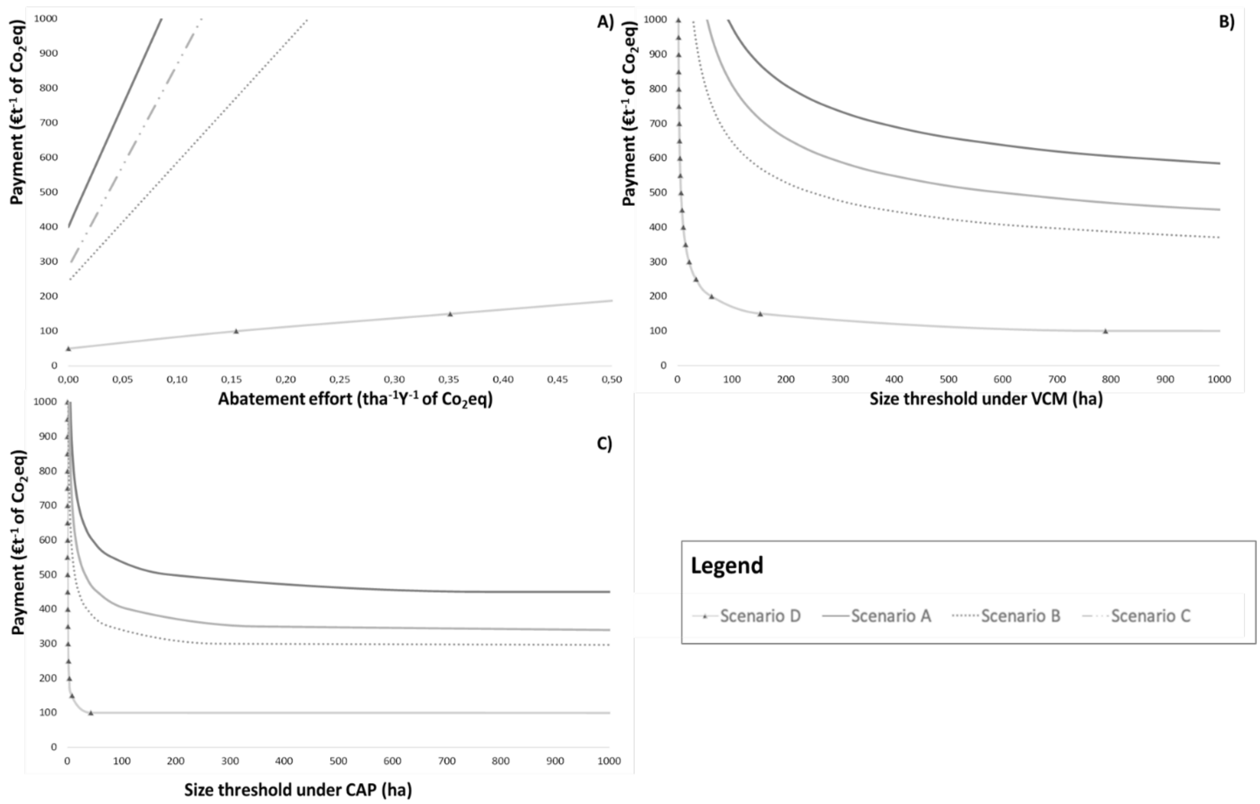
In this final section we provide the results we obtained from our interpretative model and the data used to estimate model parameters. The results here provide are strongly influenced by the way MACCs were estimated. In fact, average values from single practices from the literature were used and based on very different references. Thus, the thresholds here estimated both with respect to the level of commitments land managers are wishing to face and the minimum size of the carbon sequestration project can vary significantly from place to place and time to time. Nevertheless, the substantial difference between the two incentive models remains valid as does the difference in carbon sequestration potential between the different scenarios, reflecting different SCS strategies.

Figures 2 and 3 provide a sensitivity analysis to slightly generalize our impact analysis to different transaction costs and payment levels. Specifically, figure 2 addresses how the intensity of carbon sequestration and the minimum size of the agricultural land for which it is worth implementing carbon sequestration practices vary with payment values.

Figure 2a reveals that land use change strategies have a higher abatement potential, at equal costs, followed by input management strategies, crop rotation and conservation agriculture strategies. Land use change strategies reveal having higher elasticities than others (i.e., lower slopes of the curve in figure 2a), meaning that higher abatements are obtained for increasing payment levels.

Figures 2b and 2c reveal that the minimum size to grantee positive profits is far lower for land use change strategies than others and that, at current transaction costs level, the minimum size of the committed land under CAP payments is far lower than the minimum size of the committed land under VCMs.

Figure 2 – Optimal carbon removal unit amount for increasing unit payment values for carbon sequestration (figure 2a) and size thresholds for different pricing options, Carbon credits (figure 2b) and CAP payment (figure 2c), and different management scenarios: A) conservation agriculture, B) input management, C) crop rotation, D) land use change.



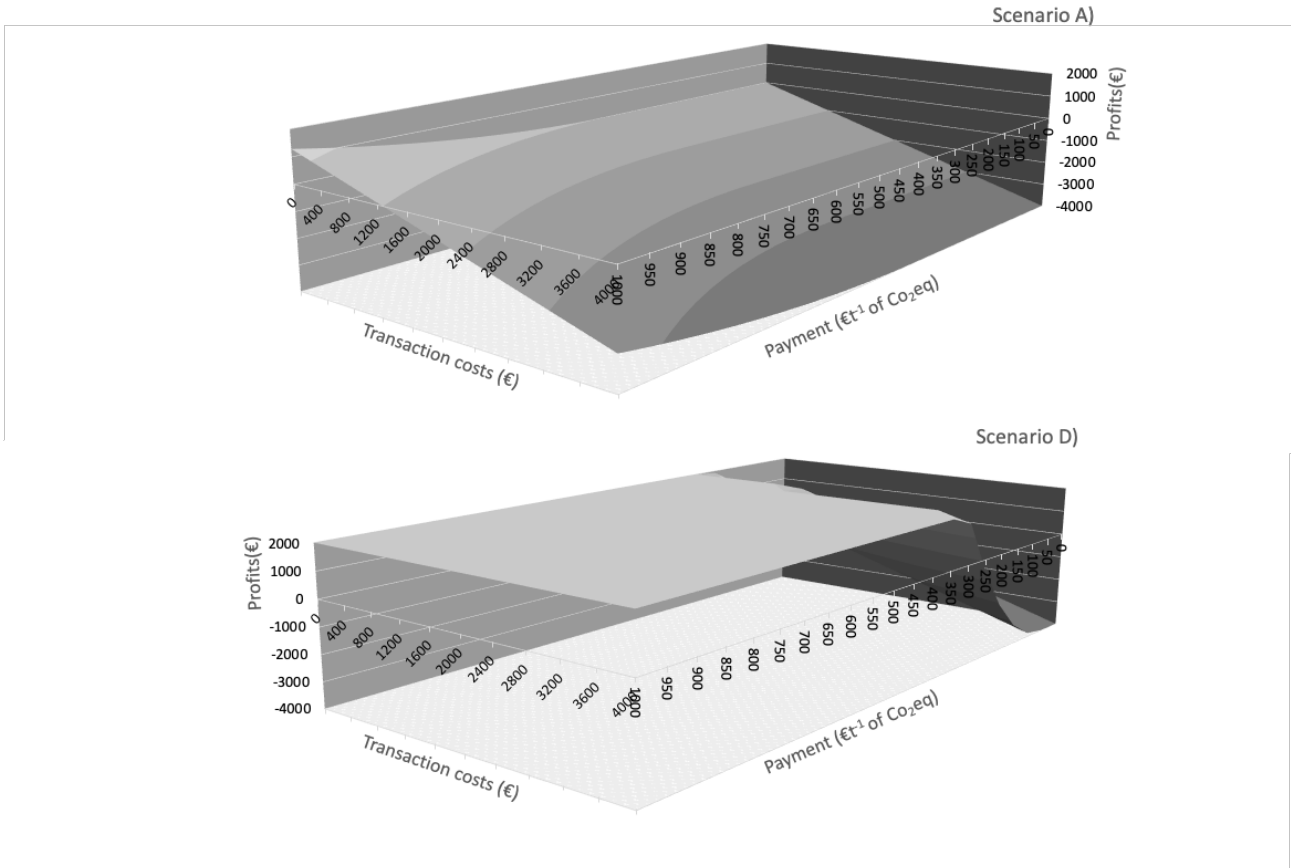
Source: our elaboration on model parameters.

Figures 3a and 3b, provide indication on how profits change with changing payment values and transaction costs for both conservation farming and land use change. The Figure shows what combination of values allows positive profits, making SCS affordable under the comparing strategic configurations.

Below a payment of 450 €/t of CO_2 eq and above 1,200 € of transaction costs it is not worth implementing conservation agriculture for a committed field below 50 ha. Conversely, it is worth implementing land use change practices for a payment above 300 €/t of CO_2 eq, even in the presence of very high transaction costs, and above 100 € /t of CO_2 eq in the absence of transaction costs. Worth noting that, at global scale, according to Soussana et al. (2019), less than two-thirds of croplands could be converted to SOC sequestration-enhancing practices with a CO_2 price below 80 € per tCO_2 (equivalent to 300 €/t of CO_2 eq).

So far, the analysis here provided reveal that on average conservation agriculture is prohibitive under both the comparing financial scenarios, while the payment provided under that CAP are close to cover the extra costs (mainly in the form of foregone revenues) accompanying land use changes. However, the generalities of the information used in this report does not allow us to draw firm conclusions, especially with respect to the CAP payments, the value of which varies consistently form place to place, and the characteristics of the farms, with special reference to their size and their cropping systems.

Figure 3 – Profit values of an average field area of 50 ha under commitment, implementing conservation agriculture practices (figure 3a), and land use change practices (figure 3b) with increasing transaction costs and increasing payment values.



Source: our elaboration on model parameters.

5. Discussions and conclusion

Throughout this report we investigated soil carbon sequestration potentials of different agricultural practices, the characteristics of two key financial instruments adopted in and outside the EU to promote soil carbon sequestration on agricultural lands, and the influence of these instruments in accompanying the adoption carbon sequestration practices in the EU. The existence of different forms of incentives to promote carbon sequestration in agriculture are motivate by the fact worldwide the agricultural sector is a net emitter and emissions from agriculture are increasing. In the EU agricultural emissions decreased, but they decreased the least in the period of 2005-2018 among non-ETS sectors. Agriculture remains the sector where projections foresee only limited changes in emissions in the period up to 2030 in the EU (EEA, 2020).

The most important financial instrument addressing sustainable agricultural practices in the EU is the CAP. Various analyses have concluded that the CAP climate spending is not justified due to requirements being too weak, with special reference to GAEC conditionality requirements aimed at raising baseline standards for carbon farming and the additional requirements to get payments from voluntary measures (McDonald et al., 2021). In addition, there are no special requests by the EU on the allocation of payments to enhance climate mitigation, leaving Member States to freely choose whether and how much incentivizing carbon farming. Furthermore, agricultural lands are not entirely covered by the CAP.

Taken together, these considerations suggest investigating funding mechanisms complementary to the CAP to further incentivize the adoption of climate mitigation measures in agriculture. With good reason, in this report we gave special emphasis to voluntary carbon markets as climate mitigation actions in agricultural lands could potentially support the achievement of climate commitments by other non-ETS sectors, offsetting their emissions. Hence the importance of European regulation on carbon removal that facilitates the trading of carbon credits within the union, a common framework for estimating carbon sequestration by the means of agricultural practices, robust verification reporting, and monitoring mechanisms, and consistency with other forms of financing (i.e., CAP subsidies).

However, from the experiences accrued from the VCMs of Australia, Canada, the United States of America and other international private companies challenges related with transaction costs, additionality and permanence issues strongly limited the efficacy of this instruments (Demenois et al., 2022). Addressing these issues is challenging and will generally increase policy-related transaction costs.

In this report, we have shown how at present both CAP and VCMs are only partially able to adequately offset the costs required to put in place actions that can have some climate mitigation impacts.

The following recommendations can be deducted from the analysis carried out so far:

- Recommendations addressed to the CAP

- Eligibility criteria to access payments – Sometimes public agencies and other ownership arrangements responsible for the management of peatlands, forested areas and other areas with great carbon sequestration potentials have not the rights to access CAP payments. Their inclusion, although narrowed to few strategic actions could help addressing climate mitigation targets.

- Selection criteria to access payments – Appropriate selection criteria should be implemented to better target agricultural and forest areas with higher potentials compare with the measure targets, i.e., by prioritizing the conversion from arable land to grassland in those areas where grasses and other herbaceous forage are traditionally not predominant or absent.

- Eco-schemes and AECM – Tie a fixed portion of CAP funds to climate mitigation and adaptation measures with higher impact on the climate in all Member States.

- Recommendations addressed to the VCM:

- Transaction costs – These costs could be lowered by the mean of aggregators that pool individual farmer contracts into a larger project to exploit economies of scale and manage risk and involving existing public governance bodies to regulate transaction and regulate the issuance of credits from carbon sequestration projects.

- Permanence – In the inability to monitor the project beyond the committed period, it might be appropriate to differentiate carbon sequestration projects to climate mitigation projects and where the first are projects bind to actions that require significant costs to restore initial conditions (i.e., project involving land use change), the others are projects accounting for the credits generated for the reduced emissions during the committed periods (i.e., projects involving changes in practices).

- Additionality – Foresee at least a direct inspection before the beginning of the project, to ascertain initial conditions and a direct inspection at the time the project is implemented, followed by indirect inspections throughout the duration of the project.

- Common recommendations:

- Interoperability - Exploiting existing Information Administrative and Control Systems (IACS) to manage both CAP payments and the issuance of Carbon credits to reduce transaction costs (i.e., by using existing governance infrastructures), to avoid any risk of double funding (i.e., by the control of applications for similar actions under different funding initiatives), to facilitate monitoring (i.e., using images and remote sensing techniques to check anomalies on the field under commitment and other administrative checks to verify ownership conditions, etc.);

- CAP aids for investments – To cover investments for the equipment and other initial costs to switch to carbon farming (e.g., blocking drains to rewet peatland, restoration of low-intensity traditional agroforestry systems under threat and creation of new agroforestry systems, converting arable land to permanent grassland);

- CAP aids for knowledge creation – Support for the creation of a more specialised advice and training services on carbon farming and other climate mitigation and adaptation initiatives (public and private). Support for innovative and pilot projects for carbon farming, bringing together farmers, advisors, researchers, enterprises or non-governmental organisations in European Innovation Partnership Operational Groups and/or LEADER initiatives.

As a corollary to the above recommendations, where agronomic measures can raise carbon stocks and profits for farmers (so called “win- win” solutions), knowledge transfer policies may be sufficient to stimulate their uptake. Experience in some OECD countries has shown that a blend of R&D and extension led by farmers, government and industry have achieved high adoption rates for conservation agriculture practices. In other OECD countries, voluntary incentives and cross-compliance measures have been added to this mix of policies, which can stimulate further mitigation in contexts where the adoption of net SCS practices is costly for farmers (McDonald et al., 2021).

A further consideration is that usually carbon markets are design to allow sectors with low CO_2 abatement cost offsetting emissions of other sectors with high abatement costs. No additional co-effects are valued through this mechanism, also because non-GHG environmental benefits are typically highly localised and difficult to monetise (Henderson et al., 2022). Thus, if society values these co- effects, a carbon market or carbon sequestration policy that does not address these co-effects will not maximize social welfare. Hence, policy design issues related to co-effects are important for the efficient design of GHG mitigation policies, including net SCS measures in agriculture. Thus, tailored policies that can account for these impacts are required.

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