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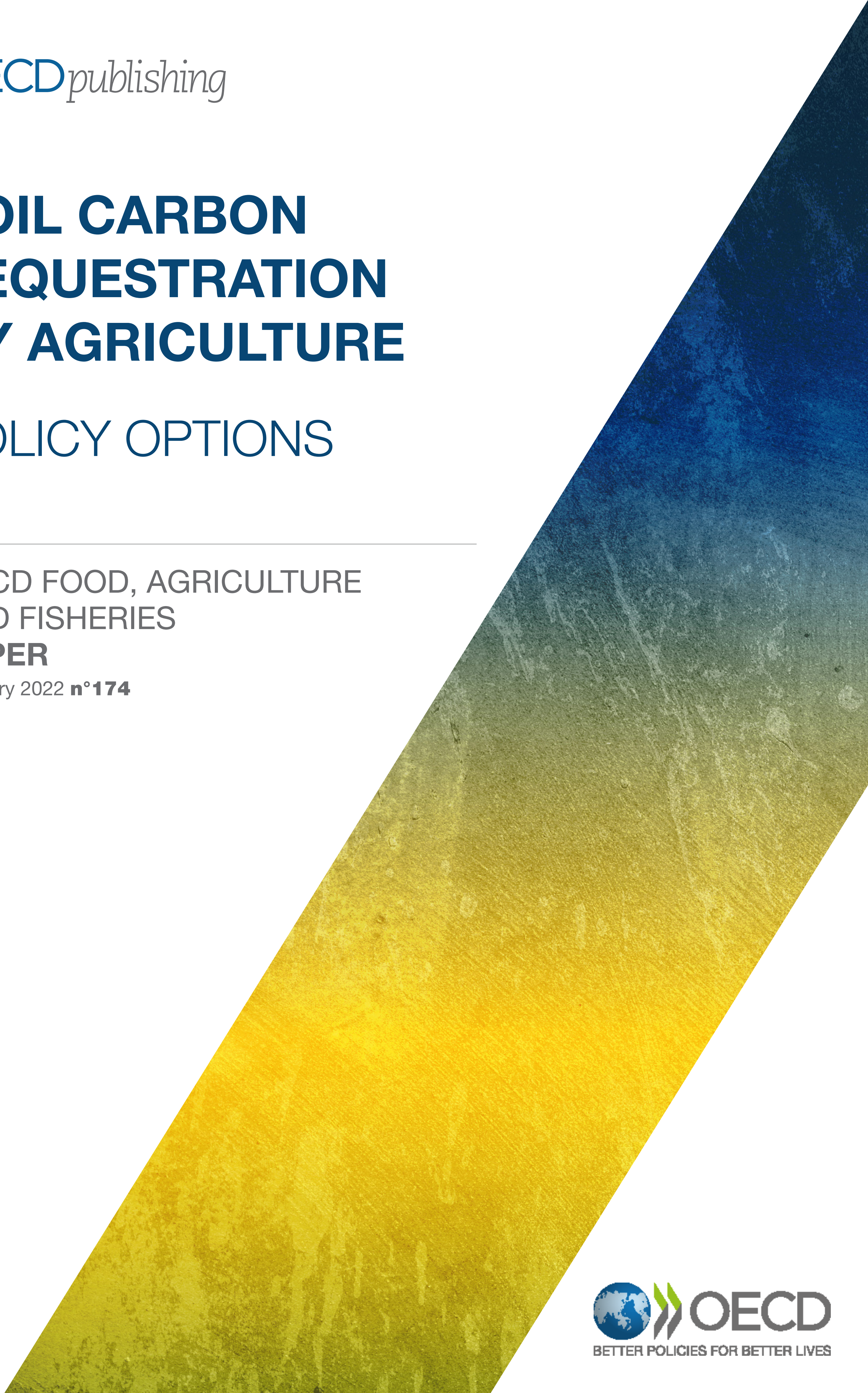
SOIL CARBON SEQUESTRATION BY AGRICULTURE

POLICY OPTIONS



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Soil Carbon Sequestration by Agriculture: Policy Options

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Net soil carbon sequestration on agricultural lands could offset 4% of annual global human-induced GHG emissions over the rest of the century and make an important contribution to meeting the targets of the Paris Agreement. To harness this potential of the agricultural sector to positively contribute to the sustainability agenda, a package of policies is needed to enhance global soil carbon stocks. Such a package would include regulations to prevent the loss of soil carbon, knowledge transfer policies to promote "win-win" solutions, and additional incentives delivered via market-based policies. The latter will need to be supported by innovative contracting solutions to address concerns about the non-permanence of carbon stocks and to reduce transaction costs.

Key words: Climate change, Mitigation, GHG, Sequestration practices

JEL codes: Q1, Q2, Q5, Q18, Q24, Q28, Q54, Q57, Q58

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Key messages

- Taking into account the dynamics of adoption and the finite capacity of soil carbon sinks, net soil carbon sequestration (SCS) could offset 4% of average annual global greenhouse gas emissions over the rest of the century.
- Half of these potential offsets could be achieved at carbon prices consistent with global economy-wide efforts to limit global temperature increase to 2°C. The inclusion of peatland management would further increase this potential.
- A package of policies is needed to enhance global soil carbon stocks, including:
    - Regulations to prevent the loss of soil carbon, particularly from carbon-rich peatland soils;
    - Knowledge transfer policies where agronomic measures can increase carbon stocks and profits for farmers (so called “win-win” solutions);
    - Voluntary incentives delivered via market-based policies and cross-compliance to stimulate additional net SCS.
- Adopting innovative contracting solutions can help address issues related to the non-permanence of carbon stocks, to transaction costs and to the need to ensure additionality, thereby enhancing the feasibility of using market-based policy measures to incentivise net SCS. More research is needed into the design of such contracts.
- More generally, a comprehensive assessment of the costs and benefits of the various market and non-market policies, tailored to either reducing emissions from soils or to protecting soil carbon stocks, would also help policy makers design cost effective policy packages to incentivise net SCS at a large scale.
- Finally, to be efficient, policies supporting the adoption of net SCS practices should also take into account their environmental co-benefits and resolve environmental trade-offs.

Executive summary

Given that soils store substantial quantities of carbon, a small increase in soil carbon stocks could mitigate significant amounts of global greenhouse gas (GHG) emissions. Soils can be a source of CO_2 emissions but they can also remove CO_2 from the atmosphere. Net soil carbon sequestration (SCS) occurs when the difference between CO_2 removals and CO_2 emissions is positive. IPCC scenarios show that limiting global temperature increases to 1.5°C or 2°C by the end of the century will not be possible without significant CO_2 removals from the atmosphere, and net SCS can make an important contribution to this process.

How can this this potential be achieved? To address this question, this report reviews the practices available for enhancing net SCS in agricultural soils, summarises the evidence on the global mitigation potential of these practices, and discusses policy options to stimulate the adoption of these practices.

Studies have estimated that net SCS practices could sequester up to 2 Gt C per year in the short term. However, when the dynamics of adoption and the finite capacity of soil carbon sinks are taken into account, their global sequestration potential declines to between 0.3 and 0.6 Gt C per year on average over the remainder of this century. This could offset between 2% and 4% of global GHG emissions, respectively.

Recent OECD research found that about half of this potential could be achieved with a SCS subsidy at carbon prices consistent with global economy-wide efforts to limit the global temperature increase to 2ºC. These estimates do not consider peatland management options, which would further enhance CO_2 removals.

Since net SCS is a stock accumulation process, a package of policies is needed to both prevent CO_2 losses, by protecting existing stocks, and to increase CO_2 removals. Three main approaches can be used: knowledge transfer, policies to prevent soil carbon losses, and incentives to enhance carbon stocks. The appropriate policy elements of this package will depend on which avenue for mitigation is being targeted and on the costs and benefits of the associated mitigation practices.

First, in contexts where carbon sinks in agricultural soils are near saturation for a given land use, policy measures to prevent the loss of soil carbon will be more important than policies to promote further sequestration. Policy options to prevent these losses could include regulations to prevent the use of unsustainable practices that cause soil CO_2 losses, including restrictions on the drainage and conversion of peatland soils. In theory, the most appropriate market-based policy in these contexts would be a tax on the CO_2 emissions for which landholders are responsible. However, uncertainties and costs associated with the measurement of these emissions are significant obstacles and there are no examples of such a policy in practice.

Second, 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.

Third, while market-based policies may be the most economically efficient policies available to enhance soil carbon stocks, they are the most challenging to implement at a large scale. This is reflected in the small number of market-based policies that are used to incentivise net SCS in practice. Some of the challenges for these policies arise from the measurement and coordination difficulties of engaging with production units spread over extensive and highly heterogeneous landscapes.

Three additional issues constrain the creation and trade of carbon credits from net SCS practices: 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.

- The non-permanence of soil carbon stocks poses challenges associated with the risk of paying for abatement that is lost at some future point. This uncertainty can undermine the integrity of carbon credits from net SCS. Policy makers have responded to this challenge with a number of design innovations and options for carbon contracts, including comprehensive accounting, whereby credits are provided 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, which improves measurement accuracy, but increases transaction costs associated with the measurement, reporting and verification (MRV) of carbon credits.
- 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 landholders’ willingness to participate in carbon markets. These costs could be lowered through the use of aggregators that pool individual farmer contracts into a larger project to exploit economies of scale and manage risk. Transaction costs should also decrease over time as farmers and policy makers find new ways to minimise the time and resources needed to comply with and administer new policies.

- Non-additionality is an important issue that can affect the environmental integrity of carbon credits generated by net SCS practices. To be additional, policies need to encourage the implementation of practices that go beyond the “business as usual”. 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 accuracy.

Future research into policy design options for contracting solutions to address the issues of non-permanence, lower transaction costs and provide greater assurance of additionality would help to improve the feasibility of using market-based policy measures to incentivise net SCS. This would include options to address the risks of soil carbon losses that are caused by climatic events, such as droughts and floods, to prevent landholders from being penalised for reductions in soil carbon stocks that are beyond their control.

More generally, a comprehensive assessment of the costs and benefits of the various market and non-market policies, tailored to either reducing emissions from soils or to building soil carbon stocks, would also help policy makers design cost effective policy packages to incentivise net SCS at a large scale.

Finally, net SCS practices can create synergies and trade-offs between different GHG sources as well as between GHGs and other environmental impacts, including on biodiversity, air quality and water quality. More than most other mitigation practices in agriculture, net SCS practices tend to positively affect the overall environmental performance of the agriculture sector. To be efficient, policies supporting the adoption of these practices need to take these interactions into account to enhance these environmental co-benefits, and resolve their environmental trade-offs.

1. Introduction

The Paris Agreement, signed in 2015, committed signatories to limiting global temperature increases to well below 2°C, and pursuing efforts to limit the increase to 1.5°C. Estimates of the annual reduction in agricultural emissions that could contribute to meeting the 2°C target range from 14-33% (Wollenberg et al., 2016[1]; IPCC, 2019[2]; Henderson et al., 2021[3]). The Land Use, Land Use Change and Forestry (LULUCF) sector is expected to play an even greater role, as these temperature stabilisation targets are unlikely to be met without significant removals of CO_2 from the atmosphere (Smith, 2016[4]; Wollenberg et al., 2016[1]).

Although much of the attention has gone to carbon sequestration in forests as central to global mitigation efforts, there is scope for agriculture and LULUCF to contribute via carbon sequestration in agricultural soils. The purpose of this report is to evaluate, based on a review of the literature, the extent to which net soil carbon sequestration (SCS) in agricultural soils can offset global greenhouse gas (GHG) emissions, and to identify policy constraints and solutions for unlocking this potential.

Few countries have integrated soil carbon targets into their national climate mitigation policy frameworks and, where they exist, policy incentives that specifically target net SCS have not yet had a large scale impact (Henderson, Frezal and Flynn, 2020[5]). The use of market-based instruments to incentivise net SCS is rare, and other policies have so far achieved more with respect to protecting and enhancing soil carbon stocks, even though they have not been designed directly for these purposes. This includes a blend of R&D and extension led by farmers, government and industry, as well as voluntary incentives and cross-compliance measures to promote conservation agriculture practices in a number of OECD countries (Llewellyn and D’Emdem, 2010[6]; Claassen et al., 2018[7]).

The technical potential for net SCS practices to offset GHG emissions and the various barriers for adopting these practices are outlined in Section 2. First the concept of net SCS and the various practices that are available to deliver it are described in Section 2.1. Then the potential for the wide-scale uptake of these practices to offset global GHG emissions is explored in Section 2.2, while the regional variations in this potential are elaborated in Section 2.3. The main synergies and trade-offs between net SCS and other environmental objectives are then discussed in Section 2.4. The technical and socio-economic barriers to the adoption of net SCS practices are described in Section 2.5.

The policy options and policy implementation considerations for achieving net SCS are outlined in Section 3. First, the main types of policy options available to stimulate the uptake of net SCS practices, along with a snapshot of progress in the implementation of these policies, are outlined in Section 3.1. A number of technical challenges specific to the design and implementation of net SCS policies are then described in Section 3.2, while policy design options for addressing these challenges are discussed in Section 3.3.

2. Net soil carbon sequestration practices, potential and obstacles to adoption

2.1. Net soil carbon sequestration measures

SCS primarily occurs when atmospheric CO_2 is transferred to soils. Plants absorb CO_2 during growth via photosynthesis. Soil organisms transform plant material (such as crop residues and leaf litter) into soil organic matter, which in turn retains water and nutrients in the soil, promoting plant growth. Depending on how the land is managed, these processes can lead to a net transfer of carbon from the atmosphere to the soil over time. While large quantities of atmospheric carbon dioxide are consumed by plants during the process of photosynthesis each year at the global scale, much of this is returned to the atmosphere within a short time period by the reverse process of respiration. Operationally, net SCS is the difference between the uptake and release of CO_2 from a particular environment (Rees et al., 2005[8]). For convenience, all practices that can increase soil carbon stocks, either by enhancing SCS or by preventing losses of soil carbon, are collectively defined as net SCS practices throughout this report.

Net SCS practices can be implemented on agricultural soils, including on organic soils that are cultivated with crops or that support livestock grazing. Soils contain significant quantities of carbon, storing two to three times as much carbon as the atmosphere at a global scale (Le Quéré et al., 2016[9]; Minasny et al., 2017[10]). However, if soils are disturbed, their carbon content may be lost. Conversion of undisturbed land to agriculture typically reduces the soil organic carbon content of soils. For centuries, agricultural expansion has contributed to the depletion of global stocks of soil organic carbon. The cultivation of soils has led to the decomposition of the organic materials contained within them and the accrual of a substantial carbon debt of an estimated 133 Gt C (Sykes et al., 2020[11]). Some of this lost carbon can be recovered through net SCS practices on agricultural soils. The concept of carbon debt is described in Sanderman, Hengl and Fiske (2017[12]) as the loss of soil organic carbon due to human land use, measured as the difference between historic and current soil organic carbon levels.

Organic soils are a particularly important global carbon store. Peatlands, which are characterised by organic soils with a high organic matter content that often exceeds 90%, account for approximately one-fifth of the total global stock of soil carbon. Peatlands are often drained for agricultural purposes (cropland or pasture), forestry or peat extraction. Between 11% and 15% of global peatlands have been disturbed or drained (Frolking et al., 2011[13]; Leifeld and Menichetti, 2018[14]). When drained, however, peatlands become net carbon sources. The upper layers of peat are exposed to oxygen, resulting in microbial peat oxidation and losses of carbon due to increased levels of leached dissolved organic carbon (Leifeld, 2006[15]; Armstrong et al., 2010[16]). CO_2 emissions from degraded peatlands account for approximately 10% of GHG emissions from AFOLU (Smith et al., 2014[17]). However, some of the carbon emitted from degraded peatlands can be avoided by restoring peatlands.

Net SCS in the AFOLU sector involves measures on agricultural lands, organic soils and in forestry. As mentioned, this paper focuses on net SCS in agricultural soils, including measures implemented on croplands and grasslands, and on organic soils used for agricultural production. As changes in soil carbon stocks depend on the balance of carbon inputs and carbon losses, net SCS measures include those that increase inputs or prevent carbon losses. A selection of the main net SCS measures available are outlined in Table 1.

Table 1. Net soil carbon sequestration measures on agricultural lands

Measure category	Measure	Land type	
		Cropland	Grassland
Carbonation	Mineral carbonation of soil	✓	✓
Erosion control	Prevent / control soil erosion	✓	✓
Fire management	Fire management	✓	✓
Grazing land management	Optimise stocking density		✓
	Pasture renovation		✓
	Sward management, bio nitrogen fixation		✓
Improved rotations	Perennial crops	✓	
	Catch crops	✓	
	Cover cropping	✓	
	Cover cropping with legumes	✓	
	Cultivated crops to increase soil carbon e.g. deep-rooted		✓
Management of organic soils	Restoration of cultivated organic soils	✓	
	Prevent degradation of organic soils	✓	
Nutrient management	Optimise nutrient inputs	✓	✓
Organic resource management	Residue retention	✓	
	Organic amendments	✓	✓
	Biochar	✓	
pH management	Keep pH at optimum for plant growth e.g. liming	✓	✓
Tillage management	Reduced tillage / no till	✓	
Water management	Soil water management	✓	✓

Note: There is some evidence that the integration of crop and livestock production systems, including the introduction of grass leys can increase soil carbon stocks. However, crop-livestock integration measures are not covered in this report.

Measures on croplands include improved rotations involving the incorporation of catch, cover or perennial crops, optimised use of fertiliser and organic amendments, residue retention, and tillage management. Reduced or no-till farming has been regarded as one of the most important net SCS measures on croplands (Lal, Fellett and Kimble, 2003[18]). 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 residue retention and the use of cover crops, and the promotion of crop species diversity (Giller et al., 2015[19]; OECD, 2016[20]). These practices can increase SOC content and prevent losses of SOC from erosion. However, the high potential for no-till farming found in early studies, which focused on top soil, have been debated in the research literature. Several studies have shown reduced tillage methods do not necessarily raise SOC stocks when deeper soil depths are considered (Baker et al., 2007[21]; Du et al., 2017[22]; Dimassi et al., 2014[23]). At the same time, as discussed in Minasny et al. (2017[10]) other studies, including Syswerd et al. (2011[24]), have shown that the carbon gains in topsoil were not offset by changes in carbon at greater depths. Furthermore, Wang et al. (Wang et al., 2020[25]) found that in residue returned tillage systems, no-till methods lowered CO_2 fluxes and increased SOC stocks at 0-60 cm soil depth compared with conventional tillage. Research also shows that no-till methods can significantly reduce SOC losses from erosion when compared to conventional tillage by (Olson, Ebelhar and Lang, 2013[26]).

Grassland measures include sward management, pasture renovation, rotational grazing and related measures to manage stocking densities for the purpose of maximising net primary production. Erosion control, fire management, carbonation, irrigation management and agroforestry measures are applicable to both crop and grasslands.

There are two main options for enhancing net carbon sequestration in peatlands; protecting intact peatlands and restoring degraded peatlands. Peatland restoration involves raising water tables to near-surface levels, thereby halting further degradation and the loss of carbon to the atmosphere. Where soils cannot be rewetted an adaptation of peatland management can be considered to slow down, but not prevent, the degradation of peatlands to minimise carbon losses. Adaptation will be appropriate if, for example, peatlands provide a vital platform for food production or if the opportunity costs of restoration are high. While higher water levels will prevent the use of land for intensive agricultural activities including the cultivation of many crops and intensive livestock grazing, sustainable use of the land under rewetted conditions is possible, in the form of paludiculture (the practice of crop production on wet soils) for example (Joosten et al., 2016[27]).

2.2. Global potential for soil carbon sequestration

The large potential for net SCS to offset global CO_2 emissions has aroused interest at the international level. This enthusiasm is demonstrated in the 4 per mille initiative launched at the twenty-first session of the Conference of the Parties (COP21). By dividing the 8.9 Gt C in annual global emissions from the use of fossil fuels by the 2 400 Gt C estimated to be contained in the world’s soil carbon sink (8.9/2 400 = 0.004), it was shown that a 0.4% annual increase in this sink could achieve carbon neutrality with respect to fossil fuel emissions (Minasny et al., 2017[10]). This simple calculation carried a powerful message about the impact that small increases in the world’s largest terrestrial carbon sink could play in addressing climate change.

However, under closer inspection this potential for net SCS appears to be overly optimistic. As Minasny et al. (2017[10]) show, sequestering 8.9 Gt C each year would require a sequestration rate of 0.6 tonnes of C per hectare per year over the world’s entire 149 million km^2 land area. This vast area of land is covered by deserts with low sequestration potential or which are expected to lose soil carbon as a result of climate change, leaving the land that is suited or available for net SCS to approximately half of the world’s land surface (Schlesinger and Amundson, 2019[28]). By restricting the 0.4% increase to the 480 to 790 Gt of soil C stocks that are estimated to be in the top 1 m of the 3 900 to 4 900 Mha of global agricultural land, Minasny et al. (2017[10]) calculate that 1.9-3.1 Gt C (an average of 2.5 Gt C) would be sequestered in agricultural lands each year. This would only offset 20-35% of global GHG emissions from fossil fuel consumption.

According to other global studies, the average sequestration rate of 2.5 Gt C per year needed to raise soil carbon stocks in agricultural lands by 0.4% would be difficult to achieve without innovation. For instance, Smith et al. (2014[29]) estimate that global average of 1.4 Gt C could be achieved with currently available practices and without considering economic constraints. According to Paustian et al. (2016[30]), this could be increased to 2.2 Gt C per through plant breeding measures to select and use crops with higher root biomass and root architectures that store more carbon.

To achieve the annual average of 2.5 Gt C and raise soil carbon stocks by 0.4% on agricultural soils, would imply a global average net SCS rate of 0.5-0.6 t C $ha^{-1} y^{-1}$. In practice, net SCS potential is dependent on a number of factors, including the sequestration rate and applicability of each measure across regions. These rates vary markedly across net SCS practices, and are often low in cultivated agricultural soils. Sequestration typically vary from 0.1 to 1 t CO_2 $ha^{-1} y^{-1}$ (or 0.03 to 0.4 t C $ha^{-1} y^{-1}$) for agronomy measures (e.g. using cover crops or optimising soil pH), tillage/residue management, and grazing land management (Smith et al., 2008[31]). Minasny et al. (2017[10]) indicate that sequestration rates of 0.2 to 0.5 t C $ha^{-1} y^{-1}$ are possible with adoption of net SCS practices such as reduced tillage and the use of legume cover crops. By comparison, abatement rates are highest for the management of organic soils (predominantly from avoided emissions), ranging from 5.5 to 10.4 t C $ha^{-1} y^{-1}$ (or 20 to 38 t CO_2 $ha^{-1} y^{-1}$) (Smith et al., 2008[31]).

However, the abatement rate is not the sole determinant of total mitigation potential. To convert area-based estimates of sequestration into estimates of regional and global mitigation potential, it is necessary to account for differences in the regional applicability of net SCS measures, by multiplying values by the land areas for which these measures can be applied. The land area that is used as cropland and grazing land is much larger than the area of degraded organic soils that are suitable for restoration. Consequently, as shown in the following paragraph, cropland and grazing land management could make a larger contribution to total global sequestration than the restoration of cultivated organic soils (Smith et al., 2008[31]).

The total global mitigation potentials from different net SCS measures varies according to different land types, with estimates ranging from 0.25–6.78 Gt CO_2eq y^{-1} (or 0.07–1.85 Gt C y^{-1}) in croplands, from 0.13–2.56 Gt CO_2eq y^{-1} (or 0.04–0.7 Gt C y^{-1}) in grasslands and 0.15-0.81 Gt CO_2eq y^{-1} (or 0.04–0.22 Gt C y^{-1}) for peatland restoration. Preventing further drainage or conversion of peatlands could reduce emissions by 0.45–1.22 Gt CO_2eq y^{-1} (or 0.12–0.33 Gt C y^{-1}) (Shukla et al., 2019[32]).

These ranges in mitigation potential are useful, but they tend to provide a static sense of the global mitigation potential from net SCS measures. A more helpful interpretation of their potential can be gained from considering important dynamic processes of adoption and saturation. Firstly, the widespread adoption of measures, above current levels, is a gradual process. Secondly, since soil carbon sinks are finite, global net SCS rates may increase as the adoption of net SCS measures increases, but this rate would eventually decline as soil C stocks approach a new equilibrium level of storage. Sommer and Bossio (2014[33]) take these dynamic considerations into account by assuming plausible rates of enrolling agricultural land into a global net SCS programme, under a range of net SCS rates. They calculate that the gradual adoption of practices to turn agricultural soils into carbon sinks could sequester between 31 and 64 Gt of C between 2014 and 2100. This could offset 2% to 4% (0.36 to 0.73 Gt C y^{-1}) of projected global anthropogenic GHG emissions accumulated over this period. Sequestration was assumed to peak in 2032-33, at which time it would offset up to 9% of annual global emissions, with sequestration rates assumed to taper off considerably after 20 to 40 years. This simple assessment provides a useful dynamic perspective, which demonstrates how the mitigation potential of a concerted global net SCS plan could help to partially offset global anthropogenic GHG emissions over a finite timespan.

Comparable annual mitigation rates of 0.19 Gt C y^{-1} in 2050 (0.17 Gt C y^{-1} in 2030) for net SCS measures are reported in recent OECD research (Henderson et al., 2021[3]). This study uses a global economic model to evaluate the mitigation potential of market-based policy packages applied to the entire AFOLU sector, based on carbon prices consistent with global economy-wide efforts to limit global temperature increase to 2^oC. The mitigation potential for net SCS measures calculated in (Henderson et al., 2021[3]) do not explicitly consider the dynamics of soil carbon storage, but instead use average marginal abatement cost estimates from (Smith et al., 2008[31]). Nevertheless, the limits to adoption that are imposed by considering these costs keeps the mitigation rates under the plausible annual rates that are calculated by Sommer and Bossio (2014[33]).

That said, Sommer and Bossio (2014[33]) does not consider either the mitigation potential associated with avoided drainage and conversion of peatlands for agricultural uses or the restoration of degraded peatlands. This potential should also be considered alongside net SCS practices on crop and grasslands as part of a comprehensive package of mitigation efforts on agricultural lands. According to (Leifeld and Menichetti, 2018[14]) up to 80.8 Gt of the carbon currently stored in drained peatlands could be lost over time if mitigation measures are not put in place, which could prevent agricultural soils a whole from ever becoming a net carbon sink.

2.3. Regional variation in potential for net SCS

The mitigation potential associated with net SCS measures varies across world regions, with different practices better suited to different areas. The potential from cropland management is highest in Asia, followed by the OECD-1990[1] and LAM, while most of the potential for the restoration of cultivated organic soils is concentrated in East Asia and Southeast Asia (40%), Western Europe (26%) and the Russian Federation (11%) (Smith et al., 2014[17]).

Although degraded peatlands are concentrated in relatively small land areas, the high abatement rates associated with their restoration provide significant mitigation potential, globally. Estimates of degraded peatland area reveal several hotspots of abatement potential. Among OECD members this includes the United States, a range of European countries (Finland, Sweden, Germany, Poland, Iceland, Norway, Estonia, the United Kingdom, Ireland, the Netherlands, Denmark, and France), Japan, and Canada. The area of degraded peatland in selected non-OECD countries (Indonesia, the Russian Federation, the People’s Republic of China, Malaysia, Belarus, Mongolia, Uganda, Papua New Guinea, Brazil and DR Congo) is approximately double that of the aforementioned OECD countries. Furthermore, peatlands in some non-OECD countries are located in tropical areas where sequestration rates and therefore their mitigation potential is higher (Joosten, 2010[34]).

In addition to differences in abatement rates and land areas, there are other factors that influence the mitigation potential of net SCS across regions. The mitigation potential of the combined net SCS measures at different carbon prices, also known as the economic mitigation potential, is a particularly important consideration for policy makers. This is because it indicates the amount of mitigation that could be achieved using policies that create financial incentives for net SCS.

The potential for net SCS also depends on the existing stock of carbon in soils. Soils that have heavily depleted carbon stocks as a consequence of conversion of land for agricultural cultivation, are generally those with the greatest potential for net SCS. By restoring these degraded soils to their original condition, much of the lost carbon can be recovered (Paustian et al., 2019[35]).

As discussed, the timeframe over which SOC increases is finite, ceasing once a new SOC equilibrium is reached. Thus, where SOC content is already high, the role for net SCS measures will be limited. Paustian et al. (2019[35]) note that abatement rates will likely be sustained for two or three decades before decreasing as soil carbon levels approach a new equilibrium.

Soils with the largest carbon stocks are typically located in the high latitudes. In many OECD countries in the northern hemisphere, soils are at or close to a maximum carbon content, limiting the scope for GHG removal via net SCS. This is also the case in other OECD countries, such as in New Zealand

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[1] This grouping used in Smith et al. (2014[17]) corresponds to the countries in Europe, North America and Oceania that were part of the OECD in 1990.

where the conversion of native forests to long-standing pastures for dairy cattle and sheep production, has tended to increase soil carbon stocks (Schipper et al., 2017[36]; Parfitt et al., 2014[37]; McNeill, Golubiewski and Barringer, 2014[38]). In areas where soil carbon sinks are near saturation, policy measures to prevent the loss of soil carbon will be more important than policies to promote further sequestration, from the perspective of increasing global net SCS. This includes the restoration of degraded soils and peatlands in relatively small areas of the landscape (Minasny et al., 2017[10]).

Minasny et al. (2017[10]) describe the variation in SOC with location, with higher stocks at higher latitudes (i.e. above 45 degrees north and below 35 degrees south) and also in humid tropical areas. They noted that while there should be greater scope for increasing carbon stocks in low latitude areas with low inherent SOC (such as Australia), the high temperatures and farming practices in some of low latitude areas could pose challenges.

Inventory records for land use change show significant above and below ground carbon losses across the American continent, sub-Saharan Africa and South-East Asia, attributable in many cases to the conversion of forests and natural grasslands for agricultural production. There will be significant opportunities to increase carbon stocks through improved management in these regions. For example, nutrient management, soil management and the cultivation of leguminous plants offer an effective low-cost method for net SCS in Brazil’s Cerrado region (Cerri et al., 2007[39]; de Oliveira Silva et al., 2017[40]). Grazing management will also be important particularly in warm and dry regions, which can be particularly susceptible to carbon loss from soils due to overgrazing (Abdalla et al., 2018[41]).

On soils with low existing SOC content, the choice of net SCS measure is paramount as low soil carbon contents can have adverse impacts on crop production and soil fertility. This is the case in sub-Saharan Africa. Strategies to increase soil carbon in the region should focus on those measures that will simultaneously increase carbon stocks and productivity, such as nutrient and water management, and the avoidance of land use change (Vågen, Lal and Singh, 2005[42]; Minasny et al., 2017[10]; Burgess et al., 2019[43]). Fire management is often used for the regeneration of pastures in sub-Saharan Africa. Such regeneration can help improve productivity and provide additional carbon inputs to soil. However, where fires burn at high temperatures the soil carbon itself could be burned and carbon stocks reduced (Furley et al., 2008[44]).

Historical land use patterns also influence the applicability of net SCS measures in a region and, therefore, their regional potential. Where land use patterns have long been established, scope to introduce new practices may be limited. This is the case in countries where land use patterns tend to be stable with relatively constant management. In these areas, opportunities for carbon sequestration may be limited to those practices that can be undertaken under existing conditions, such as changes in tillage operations, improved nutrient management, the use of cover crops or improved grazing (Smith, 2004[45]; Conant et al., 2017[46]; Abdalla et al., 2018[41]).

2.4. Environmental synergies and trade-offs associated with net SCS measures on agricultural lands

Since many net SCS measures have profound effects on land management practices, they also have environmental impacts beyond those on greenhouse gases, including on biodiversity, air quality and water quality. The majority of net SCS measures will positively affect overall environmental performance. It is necessary to take these co-effects into account so that policies supporting net SCS can be designed to efficiently manage these synergies and trade-offs.

With respect to their environmental impacts, net SCS practices can generate synergies and trade-offs between different GHG sources as well as between GHGs and other environmental impacts. For example, the restoration of degraded organic soils can reduce CO_2 and N_2O emissions, but it can cause moderate increases in CH_4 emissions, although there is considerable uncertainty about the magnitude of these CH_4 emission fluxes (Baird, Holden and Chapman, 2009[47]). However, the avoided losses of CO_2 from restoring organic soils, particularly heavily degraded peatlands, including those under intensive lowland cultivation, should easily outweigh the moderate increases in CH_4 from restoration (Evans et al., 2017[48]). The restoration of organic soils can also create co-benefits by improving biodiversity and resilience to floods and fires (Eory et al., 2017[49]; Griscom et al., 2017[50]).

The use of legume crops also involves interactions among different GHGs. In addition to building soil carbon stocks they can fix nitrogen from the atmosphere thereby reducing N_2O emissions from fertiliser application (and the GHG emissions associated with the production of synthetic N fertilisers). These measures, along with the optimisation of synthetic nitrogen fertiliser use, can also improve air and water quality (Eory et al., 2017[49]).

On the other hand, some of the main methods available to increase soil organic matter could result in emissions of other GHGs (Schlesinger and Amundson, 2019[28]). For instance, Van Groenigen et al. (2017[51]) note that the scale of carbon sequestration proposed would require additional nitrogen fertilisation to increase biomass production, which could increase nitrous oxide emissions, and offset the emission reductions achieved via carbon sequestration.

For reduced till and no-till practices there are important interactions between different GHGs and between these emissions and other environmental impacts (OECD, 2016[52]). With respect to GHG emissions, these practices reduce emissions from fossil fuels used in tillage operations, in addition to sequestering soil C. Reduced or zero tillage practices usually decrease soil erosion, nitrogen runoff, and particulate phosphorus runoff, but may increase dissolved phosphorus runoff and herbicide runoff (due to increased use of herbicides to control perennial weeds) (Lankoski, Ollikainen and Uusitalo, 2006[53]). Furthermore, reduced or zero tillage practices can, for instance, inhibit incorporation of nutrients and manures in soil, leading to a potential increase in nitrogen leaching. Pest and weed build-up may also occur under no till practices (Soane et al., 2012[54]; Sykes et al., 2020[11]). At the same time, reduced tillage can improve soil health by increasing the quality of organic matter, microbial diversity and structural stability (Minasny et al., 2017[10]).

While the application of organic amendments on croplands generally improves soil fertility and biodiversity, Gravuer, Gennet and Throop (2019[55]) identify both positive and negative environmental impacts of their application on grazing lands. Possible adverse impacts include increased nitrogen and phosphorous runoff as well as increased soil CO_2 emissions.

The introduction of more productive pastures can also introduce trade-offs. While it can increase carbon stocks in the short run, it may also encourage higher stocking densities of grazing animals in the longer run. In this case, the increased emissions from livestock may in fact offset the benefits from net SCS over the long term.

Although adverse impacts of specific net SCS measures have been identified, net SCS is generally recognised for its role in delivering improved environmental performance. For example, Pattanayek et al. (2005[56]) and Feng et al. (2007[57]) find that the water quality benefits of carbon sequestration practices (through reduced erosion and nutrient runoff) are very significant. Furthermore, net SCS is one component of a portfolio of land stewardship practices known as nature-based solutions that work with and enhance natural and managed ecosystems to produce a diverse range of services (Bossio et al., 2020[58]; Fargione et al., 2018[59])

The variety of both the available net SCS measures and the geographical locations to which they can be applied means that there is huge diversity in the co-effects and the natural, agronomic and technological drivers of these effects. Enhancing the synergies and reducing the trade-offs of carbon sequestration with other goals, be it food availability, accessibility, GHG mitigation or other environmental outcomes, is an important aspect of policy formulation. 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. Tailored policies that can account for these impacts are required.

The implications of environmental co-benefits, which result from the jointness between a given net SCS practice and multiple environmental outputs, for policy design are discussed in Section 3.3.4.

2.5. Technical and socio-economic barriers to landholder adoption of net SCS measures

Despite the significant technical mitigation potential for net SCS in agricultural soils there are often barriers to their uptake. In this section, some of the main barriers preventing the adoption of net SCS measures by landholders are described. Barriers and costs associated with the design of the policies themselves are dealt with in Section 3.

2.5.1. Economic barriers

A significant barrier to the uptake of net SCS practices at the farm level is the financial cost associated with these practices. 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. Among the practices that do not require capital investments, establishment costs may still exist, such as those associated with planting cover crops or introducing perennial crops (Wreford, Ignaciuk and Gruère, 2017[60]). 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 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 beddings on farm.

On the other hand, net SCS measures can generate benefits by increasing productivity and profitability, particularly over the longer term. Whether farmers adopt net SCS practices in the absence of policy incentives will largely depend on whether the returns from these practices can offset their costs. Table 2 provides a summary of the costs and benefits associated with agricultural net SCS measures, adapted from Sykes (2020[11]). The results of the meta-analysis undertaken in this study reveals considerable variation in the net costs and benefits of net SCS methods.[2] Of the 19 measures examined, cover cropping, no till practices, catch cropping and residue return were found to generate net private costs in most cases. Though closely related, cover cropping with legumes, optimised fertilisation, organic amendments and reduced till have greater potential to deliver net private benefits. Based on these findings, these latter measures can be considered as “win-win” options.

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[2] 195 estimates of mitigation cost-effectiveness were extracted from 15 sources. Nineteen SCS measures were characterised with sufficient detail to extract cost-effectiveness estimates. Data was grouped by country and aggregated into FAO Global Administrative Unit Layer (GAUL) regions.

Table 2. Summary of the costs and benefits of net SCS measures on agricultural lands

Measure	Costs		Benefits
	One-off costs	Recurring costs	Recurring benefits
Mineral carbonation of soil		Purchase of crushed rock Time costs to spread	Offset of other agrochemicals
Prevent/control soil erosion	Implementation of support measures	Maintenance of support measures	Yield gap closure System resilience to weather Reduction in input requirements
Fire management	Construction of firebreaks/ barriers	System maintenance time increased Possible yield penalty	May result in higher grazing capacity
Optimise stocking density		Short-term yield losses if stocking density is reduced Higher time costs for system if complexity increased	Sustainable yield Increased system health/resilience
Pasture renovation	Equipment for renovation	Input costs for renovated pastures Time to renovate and maintain pastures	Increased yield and carrying capacity Increased system health/resilience
Grassland sward management, biological nitrogen fixation		Input costs for managed swards Time to maintain sward	Increased yield and carrying capacity Increased system health/resilience Offset of nitrogen inputs with biological fixation
Introduction of perennial crops		Input costs for perennial establishment and maintenance Increased time to maintain system	Increased yield/ha possible By-products from perennial crop
Catch/cover crops and reduction of bare fallow		Input costs for cover crop maintenance Increased time to maintain system	Potential to increase main crop yield or reduce yield variability By-products from cover crop Increased system resilience to erosion
Optimise nutrient input		Increase in input costs if nutrient rates increased	Yield gap closure Increased system resilience Decrease in input costs if nutrients over applied
Organic amendments		Time costs for application Forgone sale revenue/purchase of replacement	Increased system resilience to erosion/extreme weather Offset of purchased synthetic inputs
Crop residue retention	Equipment for residue incorporation	Purchase of crop residue replacement/forgone revenue from sale of crop residue	Reduction in nutrient purchase
Biochar	Purchase of equipment if biochar made on-site	Purchase of CR replacement/loss of sale revenue if residues used for biochar Purchase of biochar Time cost for incorporating	Increased system resilience to erosion/extreme weather Offset synthetic nutrients
pH management		Cost of lime purchase	Potential yield gap closure Offset of other agrochemical inputs
Reduced tillage/ no till	No-till equipment	Purchase of additional inputs (e.g. herbicide)	Potential yield increase Increased resilience to erosion/extreme weather Reduced time costs for cultivation Reduced irrigation requirements (if used)

Measure	Costs		Benefits
Water management	Investment in irrigation/ drainage	Maintenance of irrigation/drainage systems Possible water abstraction cost	Potential for yield gap closure
Management of organic soils		Forgone revenue from output where soils were drained for cultivation Forgone forage yield for grazing	

Source: Adapted from Sykes et al. (2020[11]).

Despite their potential to improve farm profitability, the high upfront costs, associated with some net SCS practices may prevent farmers without sufficient savings or access to affordable credit from adopting these practices. Due to the time lags between when these costs are incurred and when the benefits from productivity improvements are obtained, it may also be some time before these investments yield a return.

The high costs of certain net SCS practices mean that there is considerable variation in mitigation potential at different carbon prices. At a price of USD 20/tCO$_2$e, the restoration of cultivated organic soils could deliver emission reductions of 248 MtCO$_2$e/year (Smith et al., 2014[17]). The estimated mitigation potential rises to 1 250 MtCO$_2$e/year at a price of USD 100/tCO$_2$e, due to the high costs of restoration. In general, cropland measures are relatively more important at lower carbon prices. At prices below USD 20/tCO$_2$eq, the mitigation potential associated with cropland management exceeds that for the restoration of organic soils in OECD countries. However, at prices above USD 20/tCO$_2$eq forestry and the restoration of organic soils become more important (Smith et al., 2014[17]).

2.5.2. Insufficient information and awareness about net private benefits to landholders

The perceived lack of benefits of net SCS practices has been identified as a significant barrier to their uptake. This is one factor that can explain the slow adoption of these practices, despite their apparent profitability in many contexts. A lack of information about available net SCS options and how to effectively select and implement them has also been identified as a barrier to implementation (Mills et al., 2019[61]). As the applicability of measures depends on regional conditions, choosing an appropriate carbon sequestration technique requires knowledge of local environmental conditions, which farmers may lack (Burgess et al., 2019[43]; Sykes et al., 2020[11]). This does not apply to all measures in all farming systems and locations. For example, no-till practices are widely adopted in some parts of the world where soils are fragile and organic content is low, such as in much of Australia's croplands, where the benefits these practices confer in terms of increasing soil moisture retention and resilience to dry conditions is well understood. In fact around 80-90% of Australia's 23.5 million hectares of winter crops are produced using conservation agriculture methods including no-till (Bellotti and Rochecouste, 2014[62]; Llewellyn and D'Emdem, 2010[6]). Nevertheless, there are still likely to be significant information gaps about other net SCS practices and about the benefits of conservation agriculture in many other regions.

2.5.3. Structural barriers

Structural conditions, relating to land tenure and farm size, also influence farmers' propensity to adopt net SCS methods. In the absence of property rights, difficulties may arise in establishing improved management practices, determining the ownership of soil carbon assets and the monitoring of soil carbon stocks (Gerber et al., 2013[63]). This issue is most pronounced in developing countries.

Furthermore, if farmers do not have long-term security in their land, they may be less likely to adopt practices that have longer timeframes or involve investment in physical infrastructure. As net SCS occurs at a slow pace, implementation requires a long-term commitment by farmers, which may not be compatible with the short term outlook of farmers who rent farmland. Equally, farmers who do not own the land they operate may be less likely to make large capital investments (Mills et al., 2019[61]).

Factors such as a farmer's age or farm size can also prevent the adoption of net SCS measures. Older famers may be less willing to adopt new technologies and practices, particularly those that require a long-term investment (Amundson and Biardeau, 2018[64]). Incentives for adoption may also be weaker for small farm owners, given the relatively low abatement rates associated with many agricultural net SCS practices.

2.5.4. Social and cultural barriers

Social and behavioural factors can also discourage the adoption of net SCS measures. Farmers may be reluctant to implement net SCS practices that require them to alter habitual practices. Such resistance is common on small farms and those owned by older farmers where farming practices have been long established. This resistance to change, however, is not unique to net SCS and has been identified as a barrier to the uptake of sustainable land management practices more broadly (Wreford, Ignaciuk and Gruère, 2017[60]).

The importance of each of these barriers will differ across regions. Farm-level decisions to implement net SCS practices will be affected by a unique combination of these factors. Furthermore, different net SCS practices may be associated with different barriers and these barriers may evolve over time (Wreford, Ignaciuk and Gruère, 2017[60]).

3. Policy options, challenges and remedies, to enhance net SCS

3.1. Policy instruments for promoting net SCS

The policy options available to stimulate the uptake of net SCS practices include market-based instruments, regulatory or command and control approaches, self-regulation, and information schemes. Market-based instruments (MBIs) comprise a wide range of policy measures, including instruments that directly or indirectly create a carbon price, grants and access to credit.

Given that stored SOC can easily be lost through unsustainable practices, policies to protect SOC stocks are an important part of the package of policies that are required to turn agricultural land into a net carbon sink.

3.1.1. Market-based instruments

MBIs involve either making producers pay for emissions, through a carbon tax or emissions trading scheme or paying for abatement, through subsidies or the provision of offset credits in compliance and voluntary carbon markets.

To be economically efficient, the marginal abatement incentives of an MBI should reflect the economic value of the environmental benefits that these practices generate. If the objective of the policy is to mitigate GHG emissions, then the financial incentive provided by the policy should ideally be set equal to the social damage costs of GHG emissions.

In most country settings, however, the most practical approach is to set the value of each unit of sequestered carbon equal to the prevailing carbon price found in national market-based policies for mitigating GHG emissions, if available. In this case, the MBI would not achieve the economically optimal level of mitigation, but it would reduce emissions more cost effectively than other policy instruments. It is indeed well-established in economic theory that MBIs are the most cost-effective policies for delivering environmental benefits such as GHG emission reductions (Baumol and Oates, 1988[65]).

Given that net SCS measures can also deliver additional environmental benefits, there is a case to be made for monetising these benefits and including them as part of the financial incentive offered to landholders for adopting net SCS measures (Lankoski et al., 2015[66]). This is often very challenging to do in practice, because non-GHG environmental benefits are typically highly localised and difficult to monetise. As with all payments for environmental services, paying for net SCS can also raise issues related to equity, because such policies could provide greater income generating opportunities for farmers that have depleted their SOC stocks, and ignore the past efforts to raise SOC stocks by farmers through the use of more sustainable production methods.

Importantly, different types of MBIs can have varying distributional impacts on producers, consumers and government budgets and they can also differ in terms of their cost effectiveness (OECD, 2019[67]). Considering soil CO_2 emissions and SCS as two sides of the same coin, an appropriate MBI is one that penalises net emissions and rewards net sequestration for each landholder over time. This could involve pricing CO_2 emissions with a carbon tax or ETS and rewarding net SCS with carbon price-based payment. The latter could be delivered directly via a subsidy or via an offset mechanism that is linked to an ETS or carbon tax. Since agricultural emissions are not typically included in ETS or carbon tax schemes, subsidy or offset schemes can create an opportunity to leverage voluntary participation from landholders. In practice, there are presently no examples of policy instruments that tax soil CO_2 (or non-CO_2 emissions) from agriculture, but there are a handful of countries that use policy instruments that provide payments to landholders for SCS (Henderson, Frezal and Flynn, 2020[5]).

3.1.2. Regulations

Regulations could also be used to encourage net SCS in agriculture, such as prohibiting certain activities, imposing standards or specifying technologies or products to use in production (Gupta et al., 2007[68]). However, given the particularly high degree of heterogeneity in the agriculture sector, it is generally accepted that direct regulation in the form of uniform standards is unlikely to be a cost-effective option for reducing emissions from the sector (Gupta et al., 2007[68]; Grosjean et al., 2016[69]).

While there may not be regulations that directly target the net sequestration of SOC in agricultural soils, some OECD countries have regulatory measures in place to increase the use of conservation agriculture practices and prevent cultivation of organic soils, which can increase soil carbon stocks. The Conservation Compliance provisions in the Farm Bill legislation in the United States is one such example, which farmers must comply with in order to receive certain US Department of Agriculture (USDA) programme benefits. These provisions include the Highly Erodible Land Conservation (HELC) compliance programme, which requires the use of soil conservation systems on croplands, and the Wetland Conservation compliance programme, which requires participants to refrain from draining wetlands (Stubbs, 2016[70]). The provisions have been regarded as a policy success. For example, the HELC provisions have helped to significantly lower soil erosion from cropland in the United States (Claassen et al., 2017[71]).

3.1.3. Facilitating policies

There are a number of policy measures that do not provide strong incentives on their own, but can facilitate the performance of other stronger policies and encourage the uptake of profitable net SCS practices (i.e. “win-win” or negative cost practices).

For example, the provision of affordable lines of credit dedicated to net SCS and other abatement practices can be used to leverage abatement through investments rather than payments (Burgess et al., 2019[43]). This can be particularly helpful in cases where high upfront costs prevent the uptake of profitable net SCS measures.

Information provision is another important facilitating policy measure, as missing or inadequate information can act as a barrier to uptake of net SCS practices. Policy measures include government advisory services such as that provided by *Farming for a better climate* in Scotland (Smith et al., 2014[29]).

There is also a role for R&D in encouraging the adoption of net SCS practices. R&D efforts can help build 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 agro-ecological and socio-economic contexts will be an important part of research efforts (Gerber et al., 2013[63]).

Also government certification schemes can facilitate adoption of net SCS practices. For example, the *Label Bas Carbone* in France, is a certification scheme, whereby criteria to get certified have been approved by the French government and this certification can be used as a reference for carbon credit buyers (CARBON AGRI, 2019[72]). Another example is CARBOCERT in Spain, which establishes methodologies for the standardised quantification of net SCS on croplands that can be certified by National Certification Bodies, and also provides farmers with the opportunity to access government subsidies to support the adoption of SCS practices (UNE, 2022[73]).

The development of affordable and accurate MRV practices and technologies is another important measure to facilitate the application of net SCS policies, particularly MBIs. However, as MRV approaches and tools are not policy instruments in their own right, they are discussed in the following section on policy design options to address barriers specific to the adoption of net SCS practices and policies.

3.1.4. Examples of policy progress in support of net SCS in agriculture

Where they have been developed, national GHG mitigation policy frameworks sometimes include specific targets for agriculture, although legally binding mitigation targets in agriculture are rare (Henderson, Frezal and Flynn, 2020[5]). Net SCS has been recognised as part of some of these frameworks. For example, Ireland identifies better management of peatlands and agricultural soils in its climate action plan (Government of Ireland, 2019[74]). The Pan-Canadian Framework on Clean Growth and Climate Change (PCF) identifies a range of actions to enhance carbon sinks including on agricultural soils (Government of Canada, 2018[75])

However, concrete policy incentives to either prevent CO_2 emissions from soils or enhance net SCS are still relatively rare, and currently cover a tiny fraction of the world’s agricultural soils. The snapshot in this section focuses on policies which provide strong financial incentives.

The small number of market-based measures that exist focus on paying farmers for net SCS rather than applying taxes on soil CO_2 emissions. For example, the Alberta Emission Offset System, allows farmers to earn carbon offsets by adopting abatement practices, including the use of no-till practices to increase soil carbon (Government of Alberta, 2020[76]). 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 broad range of eligible activities, including those that enhance soil carbon stocks. As of October 2021, 180 soil carbon projects have been registered under the Emission Reduction Fund (Clean Energy Regulator, 2021[77]). Spain's Carbon Footprint Registration, Offsetting and Carbon Dioxide Absorption Projects (Registro de huella de carbono, compensación y proyectos de absorción de dióxido de carbon) scheme is another voluntary scheme that provides options for landholders, business and other organisations to generate emission reduction credits, including through practices that enhance net SCS (Government of Spain, 2022[78]).

Due to uncertainties in the MRV of net SCS and concerns about non-permanence, activities that enhance net SCS have not been eligible for the generation of credits in carbon markets that are typically termed compliance markets (because they are compliant with national and international laws and protocols) such as the EU ETS, the NZL ETS and Clean Development Mechanism. Instead, carbon credits generated from SCS measures tend to be traded in low volumes in smaller voluntary carbon markets, mainly from independent crediting mechanisms, which offer lower credit prices. Credit creation in these voluntary markets is supported by programs for verifying credits such as the Verified Carbon Standard and the Gold Standard (World Bank, 2020[79]).

Given the challenges associated with the using MBIs, grants and investments are also often used to encourage the adoption of net SCS practices. In Scotland, restoration grants are provided to support the target of restoring 40% of Scotland's peatland by 2030, as set out in its Climate Change Plan (Scottish Government, 2018[80]). In California, the Healthy Soils programme invests in the adoption of conservation management practices that improve soil health, sequester carbon and reduce GHG emissions. Eligible practices include cover cropping, reduced tillage, and planting windbreaks, riparian buffers and hedgerows (California Department of Food and Agriculture, 2020[81]). In the European Union's Rural Development Programme, investment funding is provided to support carbon conservation and sequestration in agriculture and forestry under priority 5E. Carbon sequestration is expected to play an even greater role under the post-2020 CAP (European Commission, 2020[82]).

There has also been widespread adoption of conservation agriculture practices in OECD countries (OECD, 2016[20]). These practices include no-till farming, residue retention and the use of cover crops which, as discussed, can increase SOC content and prevent losses of SOC from erosion. Surveys show that more than 70% of grain growers in Australia are using no-till cropping practices (Llewellyn and D'Emdem, 2010[6]). This widespread adoption has been attributed to a combination of government and farmer-led research, development and extension, farmer and industry innovation, as well the economic viability of conservation agricultural practices. Similar mechanisms, as well as voluntary incentives and cross-compliance provisions (e.g. the Conservation Compliance provisions in the Farm Bill legislation) have helped to promote widespread adoption of conservation agriculture practices in the United States. Conservation tillage has recently been reported as being used on 65-70% of the cropland area for soybean, corn and wheat production (Claassen et al., 2018[7]). Within the European Union, conservation tillage was used on 22% of arable land and cover crops on 9% of arable lands in 2016 (Panagos et al., 2020[83]).

Among Member States of the European Union, Green Direct Payments accounted for 30% of direct payments of the Common Agricultural Policy (CAP) 2014-20. These payments can in principle provide climate mitigation and/or adaptation benefits by protecting soil carbon pools under permanent grassland, and encouraging landscape resilience through crop diversification and establishment of ecological focus areas. The Rural Development Programme (RDP), under Pillar II of the CAP, also has an important environmental component. At least 30% of the budget of each Member States' RDP must be devoted to voluntary measures that are beneficial for the environment, and 20% must have cross-cutting impacts that address climate change Priority 5 of the RDP in particular, addresses "resource efficiency and shift to low carbon and climate resilient economy” in the AFOLU and food sectors. Sub-priority 5E (i.e. carbon conservation and sequestration) is particularly relevant for net SCS.

One example of the large-scale provision of credit for GHG mitigation in agriculture is from Brazil’s Low-Carbon Agriculture Program. This provides low-interest loans to farmers for the implementation of sustainable agricultural practices and is part of its broader ABC Plan, which also includes support component for training technicians and farmers, financing for R&D, and monitoring of activities and results. Eligible practices for funding under the Program include no-till agriculture, the restoration of degraded pasture, the planting of commercial forests, and the integrated production of crops, livestock and forest. Between 2010-11 and 2018-19, 61 650 ABC contracts worth a total of BRL 15.64 billion were signed.

3.2. Technical challenges and barriers specific to net SCS policy design

In addition to the technical barriers for landholders’ adoption of net SCS practices discussed in Section 2.5, the design and implementation of net SCS policies also face a number of challenges and costs. These challenges are discussed here from the perspective of both the landholder and policy maker. Some of these challenges such as non-permanence are unique to net SCS, while others such as additionality and MRV are not unique to SCS, but they are more acute issues for policies promoting the adoption of SCS relative to other mitigation practices.

3.2.1. Transaction costs and MRV

Transaction costs occur across all stages of the policy cycle (from policy planning to enforcement), and include normal financial transaction expenses (legal and broker fees, etc.), and costs associated with contracting carbon offsets such as MRV and contract compliance ((McCarl, 2002[84]; Van Kooten, Shaikh and Suchanek, 2002[85]; Mooney et al., 2004[86]; Mooney et al., 2004[87]). The inherent spatial and temporal variability of soil carbon gains 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 from the risk of farmers abandoning net SCS practices, can raise additional monitoring and enforcement costs and may also lead to litigation costs (Cacho, Lipper and Moss, 2013[88]).

The need for accurate and cost effective soil carbon measurement tools that can be applied in different conditions and contexts, remains a barrier to the widespread implementation of SCS policies. In a recent global survey targeting farmers, policy makers and other stakeholders, a quarter of responses identified the need for systematic farm level monitoring to support the implementation of SCS policies and initiatives (CIRCASA, 2020[89]). A clear consensus also emerged on the need to develop new cost-effective tools and methods for monitoring soil carbon changes, rather than on improving access to already available knowledge and methods (CIRCASA, 2020[89]).

Transaction costs raise the total cost of implementing of net SCS programmes for both government agencies administering policies and for landholders engaging and complying with policies. Table 3 presents a typology of transaction costs and associated activities for carbon sequestration contracts and offsets (Cacho, Lipper and Moss, 2013[88]).

Table 3. Typology of transaction costs and associated activities for carbon sequestration contracts and offsets

Cost	Buyer	Seller
Search and negotiation	• Find sites and contact potential participants • Establish baseline for region • Estimate project offsets • Design individual farm plans • Draft contracts • Provide training	• Attend information sessions • Undertake training • Design farm plan
Approval	• Validate the project proposal • Submit proposal to relevant authority	• Obtain documentation required for participation
Project management	• Establish and run local office • Establish permanent sampling plots • Maintain database and administer payments to landholders • Arrange sale of carbon offsets	• Purchase equipment for measuring trees and sampling soil • Attend project meetings
Monitoring	• Monitor activities against contracts • Maintain carbon inventory • Verify and certify carbon offsets	• Measure carbon stocks • Deliver annual report to project office
Enforcement and insurance	• Maintain buffer of C • Purchase liability insurance • Settle disputes	• Protect plot from poachers and fire • Purchase insurance • Cover legal cost of disputes

Source: Cacho, Lipper and Moss (2013[88]).

While transaction costs include some variable costs, such as farm labour input, a significant proportion of transaction costs are fixed and invariant to farm size (OECD, 2019[67]). This includes “information costs” from time spent searching for information about policies and practices. There are associated economies of scale from spreading the fixed costs over a larger farm area. However, other market and biophysical factors can affect the extent to which transaction costs act as a barrier to adoption, which can affect the breakeven carbon price that landholders require to profitably supply carbon credits. Antle et al. (2007[90]) show that transaction costs can create a relatively high breakeven price when sequestration rates are low (equal to about USD 30/tC), compared to a much lower threshold price when sequestration rates are higher (USD 20/tC). Thus, transaction costs are likely to be particularly important when C prices are low and in regions where C sequestration rates are low.

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 as little as EUR 0.2-0.7/tCO_2eq^{-1} for Clean Development Mechanism (CDM) projects in Latin America. Mooney et al. (2004[86]) also estimated low MRV costs for net SCS, accounting for only 3% of credit value. However, more substantial transaction costs, accounting for up to 65-85% of total credits have been reported in an offset scheme in Western Canada (Fulton, Cule and Weersink, 2005[91]).

There is additional evidence of transaction costs from other land use sectors. For example, (Pearson et al., 2013[92]) assess transaction costs for forest C sequestration projects in tropical country based on case studies and then use an economic land use model to investigate how transaction costs affect the efficiency and cost of forest C projects globally. On a per tonne basis, transaction costs ranged from USD 7.71/t CO_2 (South America) to just USD 0.09/t CO_2 (East Africa). On a per unit area basis, the range of costs was from USD 89/ha (South-East Asia) to USD 1 426/ha (South America). Regarding different transaction cost categories, insurance to address permanence was the largest cost category, representing 41% to 89% of total transaction costs. The other two categories that exceeded 5% of total transaction costs were monitoring (3–42%) and regulatory approval costs (8–50%). The global model showed that the inclusion of transactio n costs reduced the amount of C sequestered by about 30%. Scenarios showed that increasing C prices toward the end of century would lower the size of this reduction to 21%.

The transaction costs associated with carbon contracts and offsets reduce land holders' willingness to participate in the carbon market directly as individuals. However, participation rates could be increased through the use of aggregators that pool individual farmer contracts into a larger project to exploit economies of scale and manage risk (Cacho, Lipper and Moss, 2013[88]). To explore this potential, (Cacho, Lipper and Moss, 2013[88]) develop a model that considers a contract between a group of landholders (the sellers) that produce offsets through changes in their land management practices, and an aggregator (the buyer) who buys carbon offsets to sell them in the international market. They show that the most influential transaction costs on project feasibility were annual fixed costs to the buyer that includes project management costs, such as salaries and running a local office, and monitoring costs associated with the certification and verification of carbon offsets. The second most influential transaction costs were variable enforcement costs and the third most influential cost was the carbon credit buffer cost.

3.2.2. Permanence

Non permanence is a risk for net SCS measures and policies as carbon is accumulated slowly but can be lost rapidly. Carbon sequestration occurs when carbon is transferred to pools that have a relatively long lifetime (such as woody biomass or soil organic matter). However, sequestered carbon can be re-released into the atmosphere at any time if practices are not maintained or as a result of indirect or natural effects (Smith, 2005[93]). For policies to be effective, soil carbon stocks must be maintained over the long run.

The volatility of soil carbon stocks stems primarily from the ease with which landowners can revert back to conventional farming practices (Murray, Sohngen and Ross, 2007[94]). Some net SCS practices, such as no-till and set-aside measures, are relatively easily reversed (OECD, 2019[67]). The associated maintenance costs may also reduce the incentives for net SCS practices over time. For most net SCS practices, the rate at which soils store additional carbon will begin to decline after some decades, before reaching a new steady state, which varies depending on soil type and conditions, but is typically reached after 20 to 30 years (Watson et al., 2000[95]). No further mitigation benefits will accrue once this point is reached. Nevertheless, SOC stocks must still be maintained. Where maintenance is costly, the risk of reversal is likely to be high (Bossio et al., 2020[58]).

Climatic events, such as droughts, which are expected to increase in frequency with climate change, can also have important impacts on soil carbon stocks. Based on a meta-analysis of 1 495 observations from 60 studies, (Canarini, Pødenphant Kiær and Dijkstra, 2017[96]) show that carbon rich soils are more likely to lose carbon after intense droughts, than carbon poor soils.

3.2.3. Additionality

Additionality is essentially a question of policy attribution – i.e. it places a burden of proof on demonstrating that a mitigation measure would not have taken place without the policy, taking into account the incentives provided by other existing policies and intended actions of landholders. To be additional, policies need to stimulate 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 (Glenk and Colombo, 2011[97]).

Another important consideration for additionality is that payments to landholders should only be made for the net sequestration that occurs as a consequence of changes in their management practices and not for the sequestration that occurs due to climatic factors beyond their control. Similarly, landholders should only be liable to pay for the net CO_2 emissions that they are responsible for, and not for those that occur due to factors that are beyond their control, such as droughts, floods and fires. However, in practice, it will be challenging to construct reference baselines that account for these considerations.

The potential for non-additionality can vary with the types of net SCS practices employed and according to policy choice and design. A fundamental concern for the latter is the specification and accuracy of the baseline used. This is a particularly serious concern for market-based instruments, such as baseline-and-credit emission trading schemes, and policies that provide payments to landholders (e.g. abatement subsidies and offset schemes that are part of a broader ETS or carbon tax policy). If policies fund projects that are non-additional, then the impact on emissions reductions could be overstated and policies could end up overpaying for net SCS.

The risk of non-additionality also depends on the balance of private costs and benefits of specific net SCS measures. For example, where it can be clearly demonstrated that the adoption of a net SCS measure imposes a net cost on a landholder, additionality is less likely to be a concern.

3.3. Policy design options for addressing challenges specific to net SCS

The barriers to uptake discussed in the previous section collectively lower the market potential for mitigation through net SCS. In the absence of effective policy intervention, net SCS is unlikely to have an impact on offsetting global GHG emissions. Therefore, policies that are tailored to overcome barriers to uptake will be needed to encourage widespread adoption of economically efficient net SCS practices.

Challenges relating to additionality and permanence have led to scepticism about the policy potential of net SCS in agricultural soils. The need for effective tools for MRV can also act as a barrier to effective policy implementation. Addressing these issues is challenging and will generally increase policy-related transaction costs. These costs could be reduced by simplifying the policy. However, this will come at the expense of reduced efficiency and increased levels of uncertainty. Thus, policy makers face a challenge in designing policies that adequately address these concerns, but at the same time provide adequate incentives for the adoption of net SCS practices.

Policy design options that can address some of these challenges are discussed in this section. This is particularly important for market-based instruments – to satisfy the beneficiaries making payments to landholders or to justify penalties for emissions, an acceptable degree of durability and accuracy for reported sequestration and emission outcomes is needed. However, this can be both challenging and costly, given the uncertainty associated with building, maintaining and measuring soil carbon stocks. Policy makers typically face a trade-off between maximising the effectiveness of policies and minimising the associated transaction costs.

3.3.1. Transaction costs and MRV

The activities responsible for transaction costs are necessary for the effective operation of net SCS programmes and for the most part cannot be avoided. While transaction costs can be significant, they should decrease over time as farmers and policy makers find new ways to minimise the time and resources needed to comply with and administer new policies (OECD, 2019[67]).

Different transaction cost categories are related as a buyer may invest more resources *ex ante* to design better baselines, farm plans and contracts that could result in less resources used for monitoring, enforcement and insurance in the project implementation stage. Moreover, increased expenditure *ex ante* by the buyer could also result in lower transaction costs for the landholders. For example if the buyer produces detailed representative farm plans that reduce the cost to landholders of preparing their farm plan and gaining approval, or increased expenditure *ex ante* by the buyer on monitoring and certification may reduce the costs that need to be covered by the landholders (Cacho, Lipper and Moss, 2013[88]).

Monitoring and verification of carbon removals, which can comprise up to 42% of the total transaction costs of carbon credits, is an essential first step in the design of market-based instruments for net SCS. More generally, MRV is required to assess the effectiveness of policies and progress made toward mitigation targets. MRV systems generate essential knowledge that can feedback into improved policy design and performance. However, implementation challenges relating to MRV lower the mitigation potential of net SCS measures and must be addressed to improve policy performance. Specifically, there is a need for accurate and cost effective soil carbon measurement tools that can be applied in different conditions and contexts, to support SCS policy implementation and enable the harmonisation of measurement approaches among countries (CIRCASA, 2020[89]).

To operate efficiently and cost-effectively, MBIs need to be based as closely as possible on actual emissions and emission reductions. However, as direct measurement is typically labour intensive, time consuming, and expensive, particularly over large areas, indirect methods of measuring carbon stocks and emissions are often favoured (Law et al., 2015[98]). Simple emission proxies can be used to reduce transaction costs, but the efficiency of these policies tends to be low, particularly if payments are conditional on the implementation of a specific practice as farmers are not free to choose the most efficient net SCS practice in a given location (Antle et al., 2003[99]). For example, per hectare grants typically do not account for the variation in abatement costs spatially, temporally and across farm types, making them a less cost-effective option (MacLeod et al., 2015[100]).

Some policy design solutions have been developed to try and reconcile the cost and accuracy trade-offs associated with MRV implementation. For instance, the use of process-based models, supplemented with measurements, can lower the MRV costs for net SCS and provide estimates that are much closer to direct measurement than those that rely on emissions proxies (OECD, 2019[67]).

However, these methods require strong technical capacity and institutional support, which may not be available in all countries. Smith et al. (2020[101]) examine the approach used by members of the Global Research Alliance of Agricultural Greenhouse Gases (GRA) for estimating changes in mineral soil carbon stock for the cropland reporting category. The authors find that only a handful of developed countries employ a Tier 2 (uses country-specific data) or Tier 3 approach (uses advanced methods and detailed country-specific data), with the majority of countries either relying on Tier 1 methods (simple emissions proxies) or simply excluding changes in soil organic carbon in croplands, to calculate agriculture and LULUCF emissions in their national inventories. With increased obligations for reporting on GHG under the Paris agreement, it is important that all countries increase the accuracy with which they estimate GHG emissions.

Knowledge sharing can also facilitate the development of MRV systems at the national and local level. Countries using higher tier approaches for national inventory reporting can also share their inventory methods to aid the development of inventories in less developed countries (Smith et al., 2020[101]). However, the most common MRV methods used at national level are not necessarily well suited to farm-level measurement nor have sufficient accuracy to support the use of MBIs at that level.

Grosjean et al. (2016[69]) note the contribution that existing policies and frameworks can make to MRV development. Frameworks developed for other environmental policies can be adapted for use for net SCS policies. This can help reduce transaction costs by reducing the costs of developing new MRV protocols. Given that a large share of MRV-related costs are fixed costs that are invariant to farm size, it may also be possible to reduce some of the transaction costs on a per-farm or per-emission basis by aggregating farms into larger units for MRV purposes (OECD, 2019[67]).

Smith (2012[102]) notes that the high costs associated with MRV development can render net SCS economically uncompetitive. However, some existing policies provide evidence to the contrary, with MRV tools being used to create fungible abatement credits under abatement payment and offset schemes in Australia, Canada and the United States. Although these tools are not perfect, they provide evidence that the transaction costs associated with the MRV are not prohibitive. They can also provide valuable insights to support the development of MRV frameworks for market-based instruments in other schemes.

3.3.2. Permanence

Although addressing reversal risk is recognised as an important consideration in the design of effective policies for net SCS, policies valuing temporary over permanent carbon sequestration are sometimes favoured. However, this can create inefficiencies if policies value emission reductions, which are permanent, and temporary sequestration equally (Gramig, 2012[103]). For sequestration and permanent emission reductions to be valued at the same carbon price, there should be no time limit on permanence requirements (Thamo and Pannell, 2016[104]).

As a first step, an accounting system that records both carbon gains or carbon losses from storage pools is needed to record net changes in carbon stocks at the farm-level or whichever unit of aggregation the policy incentive is applied (Murray, Sohngen and Ross, 2007[94]). Comprehensive accounting, *ex ante* discounting and temporary crediting are the main accounting methods used to address impermanence (Table 4).

Under comprehensive accounting, credits are provided as carbon is stored in soils and are debited as carbon is returned to the atmosphere. Credits are received when generated, thereby boosting the attractiveness of upfront investment. Under this method, carbon stock measurements are taken at regular time intervals and the net credit or debit quantities are imputed as the change in stock between the different periods, meaning that MRV must be carried out indefinitely (Murray, Sohngen and Ross, 2007[94]). This approach was incorporated into the Kyoto Protocol. When land enters the Kyoto process, it has to continue to be accounted for, and any carbon sink reversal will lead to a loss of carbon credits during the commitment period in which it occurs (Smith, 2005[93]).

Under the *ex ante* discounting approach, the amount and timing of the expected release of sequestered carbon in the future is estimated and determines the amount of credits issued at the beginning of the project. Determining the value of carbon requires an *ex ante* assumption about the permanence of carbon storage. This approach is advantageous in that it does not require MRV of emissions (Murray, Sohngen and Ross, 2007[94]). Alberta's offset scheme for conservation cropping employs this approach. Under the scheme, the amount of credits issued for an activity is scaled down by the probability that sequestration might be reversed (7.5–12.5%) in the next 20 years (Government of Alberta, 2012[105]).

Under temporary crediting, a finite life is placed on the credit. The credit is treated as if it must be redeemed in the future, allowing for reversal risk to be checked. McCarl (2006[106]) discusses three approaches to temporary crediting: temporary Certified Emission Reductions, carbon "rental", and carbon 'leasing'. The temporary Certified Emission Reductions (tCER) approach suggests that reductions be granted with an expiration date, after which the tCER needs to be regenerated by continuing the project, by establishing a new sequestration project, or by delivering permanent reductions. Under the carbon "rental" system, credits are assigned instantaneously to the renter while debits are incurred when carbon is released or at the end of the rental lease. If there is no reversal of sequestration, the lease can be renewed or taken up by another renter. Under the 'leasing' approach, investors can lease certified emission reductions from the country hosting the project. While these approaches are favourable in that they allow for up-front payment, the transaction costs associated with MRV and contract renewal can be significant.

The Clean Development Mechanism (CDM) addresses the issue of permanence in projects by issuing temporary credits, which must be replaced upon expiration. However, according to Olschewski and Benítez (2005[107]), this replacement requirement increases the cost of using temporary credits to the buyer, compared with a full-price permanent credit, and in doing so reduce the monetary value of the credit and the net revenue flow to the project.

Permanence obligations under Australia’s Emissions Reduction Fund (ERF) involve a combination of these accounting methods. Carbon sequestration projects in the ERF are required to choose a permanence period of either 25 or 100 years. If a natural disturbance causes a decline in the amount of carbon stored during the project period, regrowth must be managed to allow the carbon stock to return to previously reported values. Alternatively, carbon credits equivalent to the loss of carbon caused by the disturbance can be returned to the Clean Energy Regulator. Discounting is also used. A 20% reduction in the number of carbon credits issued is applied to 25-year projects in order to cover the costs of replacing carbon stores after the project ends (Clean Energy Regulator, 2019[108]).

Buffer pools can also be created to manage the risk of impermanence. Each project contributes a percentage of its offsets (based on the risk of reversal) to a pool, which can then be used to replace unforeseen losses of carbon stocks. In addition to the aforementioned permanence obligations, the ERF contains a risk of reversal buffer. The buffer applies to all sequestration projects and reduces the carbon abatement issued during a reporting period by 5%. The risk of reversal buffer is intended to protect the Emissions Reduction Fund against temporary losses of carbon and residual risks that cannot be managed by the other permanence arrangements. This discount prevents over-crediting and protects the government from having to find additional abatement to meet its targets (Clean Energy Regulator, 2018[109]).

Table 4. Options available to address impermanence in carbon sequestration policies

	Comprehensive accounting	*Ex ante* discounting	Temporary crediting/leasing
Description	Balances debits and credits as they occur over time.	Accounts for possible future losses by reducing the amount of credits issued at the beginning of the project based on expectation of reversal.	Balances debits and credits for finite periods with provision for future reversal.
Feasibility of implementation	Boosts attractiveness of investment as credits are received when generated, though this may hamper balancing of accounts at the end of a finite-life project.	Relatively easy to impose discounts on credits if amount and timing of reversal can be estimated.	Enables up-front payment; balancing the accounts at the end of the project is also possible.
Transaction costs	MRV carried out indefinitely.	No MRV necessary as credits are reduced according to a formula, rather than the observed change in carbon.	Involves MRV and contract renewal costs.

Source: Murray, Sohngen and Ross (2007[94]).

3.3.3. Additionality

A credible baseline, against which credits can be determined, is fundamental for the generation of offset credits. The choice of baseline influences the costs of providing credits and the amount of credits supplied. It also has equity implications in cases where baseline levels of adopted net SCS practices (e.g. no-till and reduced tillage) among landholders is uneven. Thus, the baseline choices trade-offs between equity and efficiency. Furthermore, a poorly defined baseline may lead to the overprovision of credits relative to the amount of environmental benefits delivered. Therefore, the concept of additionality is closely tied to the choice of baseline and it is a key criterion for ensuring that practices deliver environmental benefits and thus for safeguarding the integrity of MBIs.[3]

World Bank (2016[110]) notes that additionality is a generic concept and different approaches have been used to operationalise it. Under e*missions additionality* (or *environmental additionality* in general), a sequestration practice is considered additional if it results in lower level of emissions than would be the case under business as usual. Hence, under this additionality concept, a sequestration practice or action is considered additional as long as it lowers emissions from a baseline scenario without consideration of whether practice adoption would have been profitable, even without an incentive payment or credit revenue. Under *financial additionality*, a sequestration practice is considered additional if practice adoption results in profit forgone (either through higher costs or lower revenue) than would be the case under business as usual (World Bank Group, 2016[110]). Hence, under this concept a practice adoption is additional if revenue from carbon credits make otherwise non-profitable adoption profitable. Finally, under *technological additionality,* a sequestration practice (e.g. no-till adoption) is considered additional if it results in the accelerated deployment of a technology than under the baseline.

Different methods, such as checklists of criteria, barrier analysis, common practice, best practice and performance benchmark have been used to determine different additionality concepts (World Bank Group, 2016[110]). Employment of eligibility criteria alone simplifies the determination of additionality, but may increase the possibility of non-additional projects considered additional in cases where the scope of eligible practices is broad. Barrier analysis aims to identify the financial, technological, institutional, and regulatory barriers that hinder practice adoption, and only considers the adoption of a practice if some of these barriers exist then (World Bank Group, 2016[110]). Common practice, best practice and performance benchmark methods try to identify additionality with the uptake of a certain sequestration practice and employ a threshold penetration rate, above which the practice is considered non-additional.

Eligibility criteria are often used to determine whether carbon sequestration projects are additional. For example, the American Carbon Registry Standard employs a three-prong test for additionality. Projects are required to demonstrate that they exceed currently enforced laws and regulations, exceed common practice in the relevant industry sector and geographic region and face at least one of three implementation barriers (financial, technological or institutional) (American Carbon Registry, 2010[111]). Thamo and Pannell (2016[104]) note the limitations of the common practice approach, claiming that it does not provide significant benefits in terms of reduced transaction costs, can result in non-additional practices qualifying for benefits and can rule out what are likely to be the least cost, genuinely additional abatement measures, namely increases in adoption where there is already (without the carbon price) moderate adoption.

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[3] Regarding the proposed approaches for baseline determination, the Label Bas Carbone scheme offers two options: (i) specific reference scenario and (ii) generic scenario (sector-regional). In both options a basic C intensity is estimated. The first option is favoured, and includes two sub options: comprehensive evaluation with a tool, or sample based testing (random testing). Neither of the methods subject the applicant to discounts in the mitigation estimate, while in the generic method a 10% discount is imposed on applicant. There may also be further discounts to account for risks of non-permanence (e.g. 10-20%).

Australia's Emissions Reduction Fund also includes eligibility criteria with some similarities to the American Carbon Registry, for instance, by ensuring that projects must not be required under existing regulations, i.e. the Fund includes criteria for projects to demonstrate that they exceed currently enforced laws. Further, projects must be new and must not have been implemented before registration and must not be likely to occur as a result of funding from other government programmes (Clean Energy Regulator, 2018[112]).

Additionality can also be measured against a dynamic baseline, which captures expected future carbon changes under "business as usual" conditions. Analytical approaches for calculating a baseline are based on deduction, extrapolation or simulation (McCarl, 2006[106]). Accurate baselines can be expensive to construct. However, costs can be reduced by using secondary guidelines (e.g. assumptions used in related projects) or a hybrid approach (employing a combination of secondary guidelines and localised work on key elements) (McCarl, 2006[106]).

3.3.4. Environmental co-benefits and additionality

As discussed, to maximise economic welfare, all of the synergies and trade-offs among different environmental goods and services from net SCS practices need to be considered when designing and implementing policies.

The consideration of environmental co-benefits presents additional challenges for their measurement, pricing and for their integration into a coherent and efficient market-based policy. It has been debated in this context whether a single agri-environmental practice should be allowed to earn credits from multiple environmental markets. There are different options for doing this, with different implications for cost, efficiency and additionality.

One option is to allow "stacking" of credits, whereby a farmer receives multiple credit revenues for a practice that delivers multiple environmental benefits. This applies, for example, to situations where a farmer receives a government incentive payment for a practice adoption and credit revenue for environmental co-benefits in environmental markets.

The stacking of environmental credits has both advantages and disadvantages. On the one hand, it increases farmers' incentives for changing to more sustainable practices, since multiple revenue sources are more likely to cover farmers' opportunity costs of adopting these practices (Lankoski et al., 2015[66]). More importantly, stacking may provide incentives for a more optimal combination of environmental outputs and encourage more desirable multi-benefit environmental practices that may not be profitable with a single revenue stream.

On the other hand, where co-benefits are produced jointly and revenue for delivering the primary environmental benefit covers the adoption costs of the practice, it is questionable whether environmental co-benefits can be considered additional (Lankoski et al., 2015[66]). In this case, co-benefit credits from secondary markets would represent a windfall gain for farmers and a decrease in the environmental effectiveness of the combined markets (Marshall and Selman, 2011[113]).

In direct contrast to credit stacking is allowing the sale of credits only to one (primary) market. While this eliminates non-additionality between environmental co-benefits it can prevent the adoption of low-cost multi-benefit practices if revenue from the one allowed market does not cover their adoption costs.

An alternative to both the unrestricted stacking of environmental credits and restricting access to a single environmental market is to use a financial additionality criterion to decide which practices are eligible for sale of credits to multiple markets. To satisfy this criterion farmers need to demonstrate that adoption of the practice is not viable without a combined revenue stream from multiple markets (Marshall and Selman, 2011[113]). Thus, if the adoption of an environmental practice is already profitable with credit sales to the primary market, secondary markets fail the financial additionality test (Marshall and Selman, 2011[113]). For example, if a farmer establishes a green set-aside and a carbon payment fully compensates the farmer's foregone profit, this practice adoption would fail the financial additionality test in water quality markets, and thus water quality co-benefits of the green set-aside would be considered non-additional.

A final additional policy option for addressing inter-market additionality is to create a single aggregator institution that buys bundled environmental services from farmers and then unbundles them and sells credits within the individual markets.

Each policy option can influence the supply of eligible environmental credits and their equilibrium market prices. For example, stacking increases the number of farmers' revenue streams, but through increased supply reduces credit prices and therefore revenue from each individual market (Cooley and Olander, 2011[114]). These price reductions will in turn increase reliance on multiple markets to cover adoption costs of net SCS practices. These credit price changes can also further complicate the concept of financial additionality and the associated choice of baseline. Environmental practices that were originally financially non-additional in the secondary markets may become additional if reduced credit revenue from the primary market no longer covers adoption costs (Cooley and Olander, 2011[114]).

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