Title: **The economics of soil C sequestration and agricultural emissions abatement**

Keywords: Carbon sequestration, land use, valuation, markets, agricultural policy

1. Introduction

Soil resources underpin all ecosystem service categories and as a critical natural capital they are vital for regulating biophysical processes and ultimately human wellbeing. But human pressures, including population growth, climate change, urbanisation and food demand, are depleting soil stocks and undermining the flows of the valuable services they provide. These services include the climate mitigation and adaptation functions, the importance of which is now becoming more fully appreciated by policy-makers.

There are many reasons to maintain soil, but this paper focuses on the regulating service provided by carbon (C) sequestration, which can provide a compelling economic reason for soil conservation and management. We focus on the supply and demand for this service, which locates soil in the broader global policy agenda on climate change mitigation. Much of this discussion is applicable to land use in both developed and developing countries. The paper is structured as follows. Section two provides an introduction to the biophysical properties of soil to sequester carbon and the way this can be influenced by specific management practices. Section three considers a number of relevant economic concepts in relation to both market and policy developments for valuing soil carbon sequestration. Sections four and five provide a brief discussion and a conclusion.

2. The basis of soil carbon sequestration

Soil carbon sequestration is all about soil organic matter (SOM); how to maintain and increase it, how to assess and promote its value, and how to measure and monitor it. The organic matter in soil (consisting of 55-60% C by mass) spans an enormous range of compounds and properties that collectively influence and govern major soil functions that affect plant growth, element cycling and ecosystem carbon balance. In terms of plant nutrition, organic matter supplies much of the nitrogen (N), phosphorous (P) and sulphur (S) utilized by plants in native ecosystems and significant amounts in many highly managed agricultural systems. More broadly, much of the cycling of N, P, S and other plant nutrients, between organic and inorganic forms and gaseous, aqueous and precipitated phases are driven by biogeochemical and biophysical processes involving the soil organic matter. Finally, SOM-C is one of the largest terrestrial C pools, and thus C flux as CO_2 between soil-plant systems and the atmosphere has a direct impact on the earth's C budget and CO_2 concentrations in the atmosphere.

The carbon contained in SOM is the result of a dynamic balance of plant-derived C added to soil as organic residues and C losses from SOM, primarily as CO_2 respired by the soil biota. Gains or losses of soil organic C stocks reflect either a net uptake of CO_2 (via the plant) or a net release of CO_2 from/to the atmosphere. Thus soil carbon sequestration can be achieved by increasing plant C inputs to soils, storing a larger proportion of the plant-derived C in the longer-term C pools in the soil, or by slowing decomposition (Paustian et al., 1997).

A variety of management practices, particularly in cropland and grassland soils, can influence these process-level controls on soil C sequestration, and values for individual practices or combinations of practices have been extensively reviewed (e.g. Denef et al. 2011, Eagle et al. 2012, Franzluebbers 2010, Ogle et al. 2005, Paustian 2014, Smith et al. 2008). A further review of soil C sequestration rates and potentials by different management practices, soil types, climate regions, etc. is beyond the scope of this paper. Nonetheless, a short overview of the broad classes of management interventions that can be used (also see Paustian 2014) will serve as a background for the discussion of the economics of C sequestration.

Increasing plant C inputs to SOM by increasing net primary production (NPP) and/or the proportion of NPP entering the soil (i.e., as root material or post-harvest residues) can take a variety of forms. Among the most effective ways is to shift from annual to perennial plants (e.g., increased proportion of ley crops in rotation, arable land set-asides), since perennials – particularly grasses – tend to allocate a much higher proportion of C to root systems, which may also yield a higher proportion of the added C as SOM (Rasse et al. 2005). However, substituting perennials for annual crops has potential 'leakage' effects, if annual crop production is displaced to previously uncultivated soils (see below). Increasing the duration of vegetation cover by planting during bare-fallowed periods (i.e., cover crops, reducing summer fallow frequency in semi-arid systems) can increase plant-derived C inputs without displacing food crops, although agronomic and economic feasibility need to be considered. Finally, increasing productivity of the existing crop vegetation can be achieved by reducing nutrient and/or water limitation, by increasing fertilizer and irrigation inputs. In many cases, increased NPP may be largely towards harvested products and not greater residues, while increasing the level of management inputs may increase production of non-CO_2 greenhouse gases (GHGs) (i.e., N_2O, CH_4), negating all or some of increased soil C stocks.

Exogenous additions of organic matter, particularly those containing less decomposable, more recalcitrant organic matter fractions (e.g., livestock manure, compost, biochar) can increase soil C stocks both from the C addition itself and from a stimulation of plant C inputs that may result from the soil amendment. Inclusion of the amended C itself as part of the C sequestration may or may not represent a removal of atmospheric CO_2, depending on the effect of the C removal from its original place of origin. Hence a broader comparative life cycle approach would be needed to quantify the GHG mitigation impacts.

There are two principal ways by which soil management practices can reduce rates of decomposition and thereby increase the stock of C stored in soils. One is by reducing the level of physical disturbance of the soil by reducing tillage intensity – through adoption of reduced or no-till methods in annual crops as well as with the reduction or elimination of tillage through conversion of annual to perennial crops. It is well recognized that the mixing and changes in soil structure associated with tillage tends to stimulate microbial activity and SOM decomposition, and that reduced tillage can promote the formation of more stable soil aggregates that can partially protect some organic matter from microbial attack, leading to longer mean residence times for SOM (Six et al. 2000). However, reduction in tillage may be associated with issues, including increases in the accumulated weed seeds in the soil (Cardina et al., 2002). Another direct effect on decomposition rates is associated with management of flooded or partially-flooded soils. Flooding tends to greatly reduce organic matter decay rates due to reduced aeration. Soils formed under these conditions (peat and muck soils as well as 'aquic' soils) and which have subsequently been drained for agricultural uses can have sustained rates of CO_2 loss, on the order of >10 Mg C ha^{-1} yr^{-1} over many years. Hence, reverting such soils to wetland conditions or even reducing water table depths while maintaining agricultural use can substantially reduce emissions.

Common to all three of the overarching processes for C sequestration – increased plant-derived C inputs, adding recalcitrant C pools to soils, slowing decomposition – and the management practices involved, are that: i) rates of C accumulation are modest[1], in most cases less than 0.5-1 Mg C ha^{-1} yr^{-1}, ii) duration of C accumulation is limited, generally occurring over no more than a few decades and with decreasing rates over time[2], iii) the actual impact in terms of GHG

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[1] Some higher rates of SOC accumulation (on the order of 1-3 Mg C ha^{-1} yr^{-1}) have been reported for perennial grass conversions on annual cropland or degraded pastures (Conant et al. 2001) and avoided losses of C through rewetting of peat soils can be on the order of 10 Mg C ha^{-1} yr^{-1} or more (Smith et al. 2008)

[2] Different carbon sources have different soil residence times, for example higher residence times have been suggested for biochar although some of the claims remain contested.

mitigation often must also consider effects on other gases (i.e., full GHG accounting) and potential indirect and offsite impacts (e.g., leakage).

While there are many advantages soil C sequestration, and “win-win” and “no regrets” options can be identified (Smith, 2012), there are a number of issues associated with soil C sequestration which need to be addressed to make it effective as a climate mitigation option (Smith, 2005, 2008). These issues are i) limited duration of the carbon sink (the carbon is only removed from the atmosphere until the soil reaches a new equilibrium soil carbon level (Smith 2005), ii) non-permanence (carbon sinks can be reversed at any stage by poor soil management (Smith, 2008), and iii) leakage/displacement (e.g. increasing soil C stocks in one area may lead to soil C losses in another; IPCC, 2000). Smith (2012) reviewed these is some detail.

Soil carbon pools are smaller now than they were before human intervention. Historically, soils have lost between 40 and 90 Pg C globally through cultivation and disturbance (Houghton 1999; Houghton et al. 1999; Schimel 1995; Lal 1999). There have been various estimates of the global technical potential for soil carbon sequestration, which have been made in different ways. For soil carbon sinks, the best options are to increase C stocks in soils that have been depleted in carbon, i.e. agricultural soils and degraded soils. Estimates of the potential for additional soil carbon sequestration vary widely, with early estimates based on an assumed potential to restore historic losses. These estimates were of the same order as for forest trees, which could sequester between about 1 Pg C y^{-1} (the lower figure of IPCC 1996) and 2 Pg C y^{-1} (Trexler 1988 [cited in Metting et al. 1999] ~ 3.7-7.3 Pg CO_2 yr^{-1}), which at the time, was between 1/3 and 2/3 of the annual increase in atmospheric carbon levels. Other studies during the 2000s suggested similar potentials, with the most recent estimates falling within this range. The most recent estimates are 1-1.3 Pg C yr^{-1} ~ 3.7-4.8 Pg CO_2 yr^{-1}; Smith et al., 2008; Lal, 2004). Economic mitigation potentials are considerably lower than these technical potentials (Smith et al., 2008), and this is the subject of the following sections.

3. Economics of soil C sequestration

Why is soil carbon management an economic issue? The short answer is that it may be a relatively low cost way of reducing emissions and governments might therefore want to prioritise it before other expensive ways of addressing climate change. More generally the sequestration function is scarce, has non-renewable characteristics and we have to make choices about how to manage (or invest in) it to gain most benefit for society. The weighing up of input costs and output benefits is generally what defines an economic issue. Making choices typically requires us to develop commensurate metrics to help guide decision-making.

Alternatively we can consider soil, or land as a factor of production, which with other man-made capital and labour is an input to the production of food. The way this key function is managed also determines the generation of other ancillary or coincidental outputs related to the composition and functioning of soil ecosystems, including the regulation of water flows, and of specific interest here, the regulation of carbon (GHG) emissions from soil. A key distinction to note is that while the food production is largely a private process (i.e. privately owned inputs generating output that can generate ‘capturable’ revenue for the provider), generation of other ecosystem services (or disservices) has more of a public good nature. This means that the private actions are generating outcomes or so-called externalities that are less tangible or capturable for the provider. These outputs are enjoyed by others who do not pay for the benefits they provide, and generally cannot be feasibly excluded from their enjoyment. This distinction on capturable and non-capturable benefits is an important factor in why markets for soil goods and services “fail”, and why they may not spontaneously emerge. It also plays an important role when it comes to public policy and the development of incentives to manage soils for their carbon sequestration benefit, sometimes termed internalising the externality.

The value of soil carbon, or more technically the ability of soil to sequester carbon, is currently the most conspicuous global public good benefit arising from soil management. Maintaining stocks of soil carbon adds to the global greenhouse gas mitigation effort and contributes to the avoided costs of the damages associated with the stock of greenhouse gases already accumulated in the atmosphere. This climate benefit can be valued in two different ways. First, we can try to estimate what the actual damages costs of another unit of carbon emissions might be – the so-called shadow cost of carbon. Alternatively, we can look at markets where this carbon mitigation is already traded to determine the prevailing willingness to pay for carbon that is sequestered by different means including through soils. Both routes present challenges that mean that we are only able to determine a notional value for soil carbon. Nevertheless the values are indicative and offer significant incentive signals.

3.1 The shadow price or social cost of carbon

Early in the debate about cutting global greenhouse gas emissions and the role for governments in mitigation, it was recognized that there was a need for a single metric or pseudo price to reflect the damage cost of emitting carbon. This signal, in effect an imputed extra externality cost, would then help steer development away from carbon-intensive growth options. The social cost of carbon (SCC) was the metric to do this job. The SCC represents the value or full cost of an incremental unit of carbon (or greenhouse gas equivalent) emitted now, calculating the full cost of the damage it imposes over the whole of its time in the atmosphere. It measures the externality that needs to be incorporated into our current decisions on policy and investment options. The SCC matters because it signals what society should, in theory, be willing to pay now to avoid the future damage caused by incremental carbon emissions. Because the amount of damage caused by each incremental unit of carbon in the atmosphere depends on the concentration of atmospheric carbon today and in the future, the SCC varies according to the emissions and concentration trajectory the world is on. Needless to say the actual calculation of an SCC is fraught with difficulties and there has been much debate about the relevant emissions scenarios, damages categories that are included in the calculation, and how we should treat future costs and benefits (including highly controversial values for human life, or ‘value of statistical life’). Much of this debate was neatly summarized in Stern (2007), which gave further impetus to the need for a carbon price metric by demonstrating the potential global damages costs outcomes by not acting on emissions mitigation. Suffice to say that several governments have adopted certain values that are now routinely considered in public investment appraisal (cost-benefit analysis) decisions. For example, the UK government currently advises a short term price of carbon of £60 per tonne CO_2e in 2020 (DECC, 2009), with this damage cost rising further into the future. Table 1 shows similar values employed by the US Environmental Protection Agency. In the table the estimates are shown according to the alternative discount rate assumptions used to collapse predicted future costs to their present value equivalents.

3.2 Formal carbon markets

A carbon price has also emerged from the interaction of supply and demand in the formal carbon market which is developing in many parts of the world in response to direct government regulation of industrial emissions. At the same time as introducing a shadow price of carbon for use in their own appraisals, many governments also acted to regulate the significant level of emissions generated by private sector sources. High emissions sectors such as energy, manufacturing and transport can be regulated in a number of ways including voluntary measures or more direct regulation on the levels of emissions. But economic theory has for a long time advocated the role of market-based approaches as an efficient alternative to direct regulation for controlling emissions. In the context of carbon, this has led to a considerable debate over the relative merits of a carbon tax versus an emissions trading scheme. The relative merits of these alternatives have been widely debated (see Parry and Pizer 2007), with a strong argument made for the certainty delivered by an overall cap on emissions and the allocation of permits to emit a share of the cap. This process is the essence of a carbon market where polluters hold permits and can sell any they do not use as a result of avoiding emissions. In this way market-based instruments (MBIs) harness the incentive of participants to seek their own ways of reducing emissions in order to profit at the expense of other polluters who find it more costly to mitigate and may therefore need to acquire more permits. The price of carbon or for permits is then determined by the interaction of supply and demand. Regional markets have evolved in different parts of the world. The Carbon Brief (2014) documents 46 carbon markets in operation with notable examples in Europe, North America, and Australia and more recently a pilot scheme in China. Like other asset markets, carbon markets have been depressed during the recent global recession, leading some commentators to lament the impact of their introduction. This down-turn is likely to be temporary, but ultimately the increasing number of markets represents a trajectory for the evolution towards a global carbon price, which is the most efficient global solution to what Stern (2007) termed the "greatest market failure the world has seen".

Table 1: Social cost of carbon (2011 US$ / tCO_2) for specific discount rates. Source: EPA (2014).

Year	5% Average	3% Average	2.5% Average
2015	$12	$39	$61
2020	$13	$46	$68
2025	$15	$50	$74
2030	$17	$55	$80
2035	$20	$60	$85
2040	$22	$65	$92
2045	$26	$70	$98
2050	$28	$76	$104

The existence of carbon markets creates a distinction between traded and non-traded sectors. The former are the key polluters that have been obliged to participate through the allocation of permits by government, for example the industries in the European Union Emissions Trading Scheme. These tend to be the more conspicuous sources that are easily monitored. But for technical reasons some sectors such as agriculture and land use change - and hence soil - are not included in these markets. Here the measurement and therefore control of emissions is biophysically complex and typically arising from the operations of thousands of small operators. In short, both the supply and demand conditions for reliable permits are more difficult to ascertain, leading to uncertainty about how market supply and demand would set the associated carbon price. Market development will therefore depend on improvements in the monitoring, reporting and verification of emissions and the development of monitoring at scale across many farms. These issues are additional to the permanence issue that was previously mentioned. In practical terms these so-called transactions costs of including millions of small sources in any MBI could possibly outweigh the benefits (De Pinto et al 2010). This ultimately means that some sources of emissions mitigation, including from soils, are largely excluded from the powerful incentive to trade into formal emissions trading. In this case the only alterative policy or market options are voluntary compliance or informal carbon markets.

3.3 Voluntary compliance and informal markets

Beyond formal trading arrangements there is also a growing voluntary credit and offset carbon market that has developed largely around forestry and renewable energy and some cases soil. These transactions are in theory an option for anyone who can offer valid emissions reductions to anyone who wants to buy them; theoretically this demand might come from industries in the traded sector (i.e. inside a formal trading scheme) who find it more costly to comply with their obligations and who are willing and allowed to pay for validated offsets in the informal sector. A recent example of a voluntary scheme that aims to reduce the amount of greenhouse gas entering the atmosphere from activities on the land is the Carbon Farming Initiative in Australia (Australian Government 2014). This objective therefore creates a blurred boundary between formal and informal trading sectors; the rules varying globally according to formal scheme stipulations. In practice and irrespective of scheme rules the demand can come from anyone wishing to substantiate green credentials by purchasing validated carbon credits to offset their own emissions.

The recent level of soil carbon credit transactions in informal schemes has been mixed. This has much to do with the difficulties of certification and MRV, which in turn influences the demand and willingness to pay for this form of credit relative to more verifiable and permanent credit sources (e.g. in forestry). Thus where soil credits have been created and traded, they have tended to transact at low values reflecting their uncertainty.

What constitutes a valid reduction for a verified and validated credit is a sticking point to market growth. There is much uncertainty about how to verify the variety of agricultural emissions reductions as the basis of valid credits. This is reflected in a variety of protocols and farm-based calculators, none of which can claim to be an industry protocol or standard. Even if a standard tool could be agreed, further concerns relate to the permanence of reductions and whether they are additional to what would have happened anyway. Other commentators suggest that emissions reductions will simply lead to displacement abroad if they are associated with lower domestic output as a result (Carlton et al., 2013). Ultimately, this means that voluntary contracts in agriculture are more complex and viewed as less reliable than say woodland credits, which are technically more verifiable. This in turn means that such credits are likely to be valued much less than more definite emissions reductions, from say forestry. Indeed forestry offsets constitute the majority of early voluntary trades worldwide.

Nevertheless, with better science and monitoring it would be hasty to assume that these problems cannot be overcome. International experience particularly with soil carbon credits has shown that a market for credits can be based on more pragmatic measurements applied on a regional scale. In a number of Canadian provinces and US states, as well as several developing countries, uncertainty has simply been side-stepped with regional voluntary credit markets emerging based on default soil carbon values. More ambitious initiatives in China seek to unlock soil carbon payments for grassland management: in a FAO and ICRAF partnership with Chinese science institutions, a joint measuring methodology that involves modelling has won approval by Verified Carbon Standard (VCS).

Moreover, validation issues are still conspiring to depress the price of soil carbon credits. Serious questions are also being posed about the validity of stand-alone institutions that are brokering these trades. For example, the Chicago Climate Exchange, which was the main independent market for mid-west soil carbon credits has apparently been mothballed in the wake of a depressed US credit market. This in turn reflects the failure of the Obama administration to instigate an economy-wide cap and trade scheme in the US. If there is no country-wide cap and trade scheme then there is simply less pressure for high polluting industries to seek out all available credits. This inevitably dampens demand for the more hard-to-get-at reductions offered by agriculture.

3.4 Agri-environmental policies and incentives.

When a market-based solution does not emerge, a second best approach is for government to intervene on the demand side to transact on behalf of wider society. As noted above, government creation of a pseudo price in the shape of SCC already skews development away from carbon-intensive growth. But government can also intervene to buy public goods directly from farmers. Using agri-environmental payments many OECD governments have implemented payments for landscapes, water quality and other environmental services. While the market relies on the polluter pays principle, the government can also incentivize the supply of carbon sequestration by the ‘provider get’ principle. It can do this by promoting a variety of soil conservation measures such as no/low tillage, prevention of compaction, avoidance of peat conversion and the use of cover/catch crops and reduce bare fallow. These measures can and are included within forms of mandatory and voluntary schemes in operation in different OECD countries. The schemes are often based on payment for costs incurred and foregone revenues, with monitoring largely by observing input compliance rather outputs, which are less visible and more problematic to verify. This latter distinction creates further economic incentive challenges addressed below.

Other economic criteria are necessarily considered in the choice of measures for inclusion within agri-environmental schemes (OECD 2010). The first efficiency consideration is that measures should be cost-effective (CE). The second is, like all such public good schemes, the design must be mindful of behavioural barriers. Specifically, the fact that there is asymmetric information between the regulator (government) and the agent (farmers), who are being paid to comply with an outcome that is largely unobservable. This form of principle-agent problem can create incentive compatibility issues that require a deeper understanding of farmer behaviors and motivations.

3.5 Cost-effectiveness

In designing policies which might include soil management measures government want to ascertain the relative efficiency or cost-effectiveness of measures to include. In the case of carbon sequestration measures, a key metric is the relative cost of reducing a tonne of CO_2e by soil measures relative to other agricultural measures (e.g. alternative animal feeding) or measures in any other sector of the economy. As a rule, in seeking to meet an overall reduction target government wants to choose all measures from the cheapest to the most expensive, with a threshold set by the shadow cost of carbon, which defines the benefit relative to cost.

To make this comparison it is necessary to understand relative abatement costs offered by different measures and to compare these along a cost schedule called a marginal abatement cost curve (MACC). MACCs collect data on implementation costs (normally on farm) and the resulting emissions reductions achieved over a time horizon by measure implementation. Several analyses for the agricultural sectors in different countries have highlighted the potential for relatively low cost, and in some case negative cost soil measures, the latter being the case if a measure both reduces emissions and actually saves rather than costs money to the land manager or farmer. For example a national analysis for France (see Figure 1) included analysis of the CE of developing no-till cropping systems within applicable areas in the territory to store carbon in soils; specific analysis conducted for i) switching to continuous direct seeding; ii) switching to occasional tillage, 1 year in 5, iii) switching to continuous superficial tillage. These measures were selected with an a priori screening of all possible soil measure for their applicability within French agriculture and known technical effectiveness. The analysis indicated that the measures has a cost effectiveness (€/tCO_2e) of 12 (6 to 233), 8 (4 to 135) and -3 (-2 to 11) respectively, the numbers in parenthesis indicating levels of analytical uncertainty over both cost and biophysical effectiveness. While the latter is important to bear in mind, the analysis does suggest that the continuous superficial tillage option falls into the politically and economically attractive win-win category. Moreover, all options would seem reasonable relative to the carbon prices outlined in table 1. And would therefore be likely candidates for promotion through agri-environmental schemes.

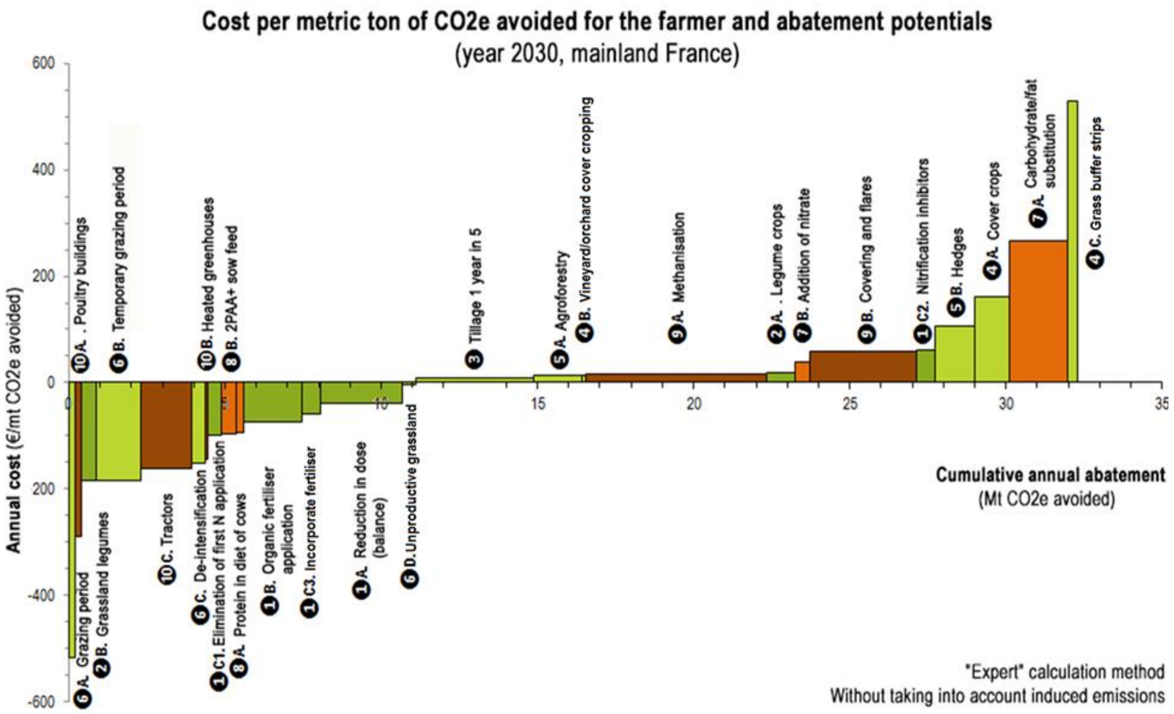

Figure 1: Example MACC curve, showing cost per metric ton of CO_2e avoided for the farmer and abatement potential for France. Source: Pellerin et al (2013)

3.6 Incentive and behavioural barriers

MACCs do not show all costs and some hidden costs can influence farmer behaviours. The formulation of agri-environmental measures, cost-effective or otherwise, involves a transaction between government and farmers willing to opt into relevant schemes that target soil carbon measures. This transaction is characterised by asymmetry of information that must be overcome if the buyer is to achieve effective and additional (soil carbon sequestration) at least cost on behalf of society. Problems occur in that the costs of complying are potentially different between the supplying agents, and are unobservable to the buyer. This means that a uniform compensation rate would be inefficient. The scale of the monitoring task is also formidable for the regulating agent. There is also a tendency for moral hazard and adverse selection. In the first case, farmers who are anticipating payments can exaggerate the gravity of their soil condition and what they had planned to do with their land. In the latter case, a payment scheme incentivises the wrong farmers to participate in schemes – i.e. those who do not offer the best sequestration potentials. These problems further increase the transactions costs of any scheme and economists have spent considerable effort considering how schemes can be designed to reduce the incentives to cheat. Part of the compliance cost (and quality) challenge can be addresses by monitoring input compliance instead of the largely unobservable levels of sequestration. This can also include the mandatory use of accounting tools and audits as a precondition to scheme participation.

Ultimately the issue of transactions costs depends on the behavioural attributes of participating famers and a deeper understanding of their intrinsic and extrinsic motives that govern the internal trade off between private profitability and the generation of a global public good (carbon sequestration). Like most of us, farmer behaviours are split by these motives, although recent psychological insights on targeting behavioural segments offer hope Moran et al (2013).

4. Discussion

Both markets and government policy have a role in increasing soil carbon sequestration, but as this paper suggests there are barriers in terms of market development and government policy. The evolution of carbon markets more generally increases the likelihood of all sequestration sources being integrated into a general global market framework. For this to happen there is a need for government of multilateral agreement regulation of the rules that define carbon credits as credible and verifiable commodities that are additional and permanent. In other words, markets cannot work without some degree of initial regulation.

As a general principle it is important to recognise that soil carbon sequestration may only be cost-effective in some circumstances and that the cost-effectiveness calculation can be extended to include co-benefits from conserving soil, including the maintenance of water quantity and quality, biodiversity and resilient livelihoods. This aspect in particular suggests that targeting sequestration in low-income countries can offer multiple local and global wins in terms of poverty alleviation and sequestration. Again, the institutional challenges for monitoring and paying for this service are formidable though not insurmountable. Recent developments under the auspices of the UNFCCC have developed protocols for the development of voluntary measures in many developing countries. Further the use of so-called Nationally Appropriate Mitigation Actions (NAMAs) offer a modality for non Annex 1 countries to offer mitigation actions for potential payment by countries and businesses regulated by more formal emissions limits.

Ultimately, however large the overall global technical potential for carbon sequestration in soil, current barriers suggest the true achievable contribution is somewhat constrained. First, not all sequestration is cost-effective and so we need to consider the magnitude of this economic potential as an initial caveat. On a global scale, MACC analysis similar to the type outlined in the previous section suggests that economic mitigation potentials for soil C sequestration are 0.4, 0.6 and 0.7 Pg C y^{-1} at carbon prices of 0-20, 0-50 and 0-100 USD t CO_2e^{-1}, respectively (Smith et al., 2008; Smith 2012). These potentials are somewhat smaller than the estimated global technical potential.

A further caveat then arises from market and policy (including incentive and behavioural) barriers outlined here. These reduce the economic potential to something we might term to be feasible. The disparity between the overall technical and feasible potentials is likely to be quite large but narrowing. In itself it suggests a clear policy and research agenda on the one hand to maximise feasible potential and on the other to minimise the costs of incentives and the monitoring and audit processes required to achieve it.

5. Conclusion

This paper highlights how an economic perspective on carbon sequestration might guide soil management decisions by private and public agents. The value of the carbon sequestration service can be revealed in terms of its input to food production and climate change mitigation. Focussing on the latter, this paper has outlined the role of carbon prices and the prospects for the evolution of global carbon markets that can provide a value or credit for sequestration through agricultural measures, including soil management. Currently, the global state of carbon markets is fragmented and the role of agriculture in these markets is still limited. This and several institutional and behavioural barriers have been identified as part of a basic challenge to find ways to circumvent a basic market failure that prevent the link between the supply of the service with the growing global demand for cost-effective sequestration. The supply of this good is largely determined by the role of millions of private agents taking individual decisions about how to manage their land and by extension the carbon in their soil. Markets are slow to evolve because transactions costs of dealing with many suppliers are high. Therefore the demand for the service has to be transacted by other means, including the use of voluntary carbon credits and the development of agri-environment schemes where government is the principal source of demand.

Soil carbon sequestration may not always be cost-effective. In some locations the biophysical effectiveness of measures may be low and the cost of their implementation high. In other locations the converse will be the case and soil measures may be cost saving as well as offering other environmental and social co-benefits. Overall an economic perspective provides part of the motive for soil carbon stewardship. Ultimately neither economics nor soil carbon in isolation are the right perspectives to take on the management of a critical capital asset, without which all life (including economic activity) would essentially be compromised.

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