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Changes in soil organic matter content in time as impacted by different farming systems and practices

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Summary

We briefly review previous estimates of carbon sequestration in Europe before providing the current best estimates of GHG mitigation through carbon sequestration in Europe. Restoration of organic soils (peatlands drained for agriculture) offers by far the greatest per-area GHG mitigation potential, though the areas affected are relatively small on a Europe-wide basis (though significant in Northern countries) and the cost is relatively high (due to the opportunity cost when the land is rewetted so that it can no longer grow crops). Cropland and grazing land management offer the greatest potential for most of the European area (since croplands and grazing lands are widespread) with the most prominent options including for croplands: including improved agronomy, improved nutrient management, improved tillage/residue management, improved water management, improved rice management, agroforestry and potential for land cover (use) change (e.g. setaside) and for grazing lands: pasture improvement, optimised grazing intensity, increased productivity (including fertilization), improved nutrient management, better fire management, and species introduction (e.g. deep rooted species). We conclude that protecting existing stocks of carbon in high-carbon soils (peatlands) is a priority, and for soils already under agriculture, the most effective options are rewetting of cultivated organic soils, with other options such as cropland and grazing land management, and the restoration of degraded lands also having significant potential due to the large areas involved.

1. Introduction

Agriculture contributes around 10-12% of direct emissions to global anthropogenic greenhouse gas emissions, with the figure rising to up to 30% if indirect emissions (e.g. land clearing for agriculture) are taken into account (Smith 2012). Despite accounting for a significant proportion of global GHG emissions, agricultural practices can make a significant contribution at low cost to increasing soil carbon sinks, reducing GHG emissions, and contributing biomass feedstocks for energy use (Smith *et al.* 2008). In agriculture, GHG mitigation is possible through emission reduction (e.g. more efficient use of N fertilizers), through enhancing sinks (e.g. cropland and grassland management to enhance soil carbon stocks; estimated historical loss of carbon from soils is ~ 50 Pg C; Houghton 1999), and displacement of emissions (e.g. bioenergy for fossil fuel substitution; Smith *et al.* 2007a). There are many tens of potential individual mitigation options, but these are often grouped. For the IPCC Fourth Assessment Report (Smith *et al.* 2007a), the practices were grouped as follows:

1) Cropland management: including improved agronomy, improved nutrient management, improved tillage/residue management, improved water management, improved rice management, agroforestry and potential for land cover (use) change (e.g. setaside).

2) Grazing land management and pasture improvement: including optimised grazing intensity, increased productivity (including fertilization), improved nutrient management, better fire management, and species introduction (e.g. deep rooted species).

3) Improved management of agricultural organic/peaty soils

4) Restoration of degraded lands

5) Livestock management: improved feeding practices, specific agents and dietary additives, longer-term management changes and animal breeding

6) Manure management

7) Bio-energy production

Practices 1 to 4 rely on carbon sequestration is soils, so we will focus on those practices in this brief report.

There is no universally applicable list of mitigation practices. The proposed practices need to be evaluated for individual agricultural systems according to the specific climatic, edaphic, social settings, and historical land use and management. For non-livestock mitigation options, mitigation potentials per unit land area for different climate regions (cool-dry, cool-moist, warm-dry, warm-moist) can be defined (Smith *et al.* 2008) – see section 3.

2. GHG mitigation in Europe and the role of soil carbon sequestration

Early estimates of the GHG mitigation potential in agriculture in Europe focussed largely on soil C sequestration and focussed on croplands. The first estimates (Smith *et al.* 1997, 1998) did not consider a baseline and examined technical potential only, with estimated soil C sequestration potentials of around 30-140 Mt CO_2-eq. yr^{-1}. Later developments included baseline estimates (Smith *et al.* 2000) and examined combined scenarios using different options on different pieces of land, with combined estimates of upto 200 Mt CO_2-eq. yr^{-1}, enough to meet Europe's emission reduction targets under the Kyoto Protocol. A later study gave some consideration to N_2O and CH_4 (Smith *et al.* 2001), but the extent to which these could be included was limted by lack of available data, and estimates were still of technical, rather than economic potential. Other estimates during the same period derived even higher estimates (70-600 Mt CO_2-eq. yr^{-1}) for technical potential of soil C sequestration in agriculture (Vleeshouwers & Verhagen 2002).

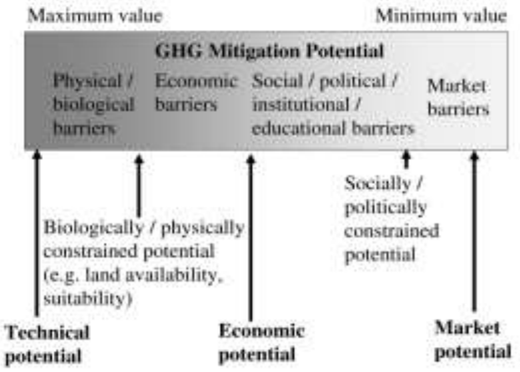

Figure 1. Relationship between technical, economic and market GHG mitigation potential (Smith, 2012). Different categories of barriers to implementation (Smith *et al.* 2007b), which each reduce the realised potential, are shown. Technical potential is the full biophysical potential of a mitigation measure if all barriers could be overcome. Economic potential is the potential that could be realised at a given carbon price. Market potential is the potential actually seen under current market conditions. Policy can be used to move the market potential closer to the economic potential. Figure adapted from figures used by Smith *et al.* (2005) and adapted by Smith & Olesen (2010).

By the middle of the decade (2000s), no new measures had been introduced in Europe to encourage C sequestration and it was clear that soil C sequestration would play a minimal role in meeting the then upcoming targets of the Kyoto Protocol first commitment period (2007-2012). Smith *et al.* (2005) examined the level of soil C sequestration in four European countries, and for EU15, and showed that it was almost negligible. This led to the distinction between *potential* sequestration and *likely* sequestration with a conceptual framework to compare these potentials proposed (Smith *et al.* 2005). In light of more recently adopted terminology, we can recast these potentials in terms of technical, economic and market potential, as shown in figure 1.

Since the mid-2000s, new assessments of agricultural mitigation potential have been made, using bottom-up mitigation factors similar to those used by Smith *et al.* (2008) and also using systems models based on IPCC methodologies, such as MITERRA. In the PICCMAT project, a range of cropland mitigation activities were examined for their impact on soil C and on N_2O emissions in EU27 (PICCMAT 2008). For individual measures on croplands and grazing lands, the potential was estimated to be much lower (20 Mt CO_2-eq. yr^{-1}) than the earlier estimates of technical potential made in the late 1990s. The lower potentials are partly due to a smaller geographical area considered (EU27 compared to geographical Europe as far East as the Urals), but also due to more limited application of the measures (e.g. 5-15% increases in practices compared to full implementation when assessing technical potential). The soil carbon sequestration practices considered in these studies were: use of catch crops, zero and reduced tillage, residue management through incorporation of residues or through composting, optimized fertilizer type and timing (for N_2O only), crop rotation, adding legumes, agroforestry and use of grass as soil cover in orchards and vineyards (PICCMAT 2008). Figure 2 summarises the mitigation potential for a range of practices for EU27 (PICCMAT 2008).

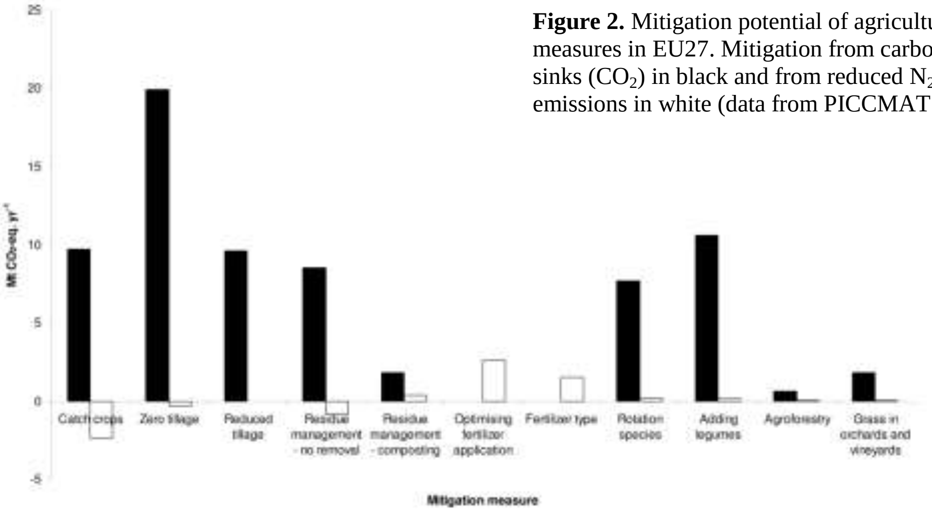

Figure 2. Mitigation potential of agricultural measures in EU27. Mitigation from carbon soil C sinks (CO_2) in black and from reduced N_2O emissions in white (data from PICCMAT 2008).

The sequestration rates were based on meta-analysis of long term experiments under different management practices (e.g. Smith et al., 1997, 1998, 2000), and whilst for some practices, the data were robust enough to develop statistically significant relationships, for others, the data were sparse. For this reason, it is desirable to use global meta-analyses, which cover the same bio-climatic zones as those found in Europe, to derive more robust estimates of soil carbon sequestration rates (Ogle et al., 2005; Smith et al., 2008a). We describe the most recent meta-analysis in the section 3, and present provide the current best estimates for carbon sequestration in agriculture.

3. Global meta-analyses of soil carbon sequestration rates under different management practices

Considering all gases, the global technical mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030 is estimated to be ~5500-6000 Mt CO_2-eq. yr^{-1}, almost 90% of which arises from soil carbon sequestration (Smith *et al.* 2007a; Smith *et al.* 2008). The range of the standard deviation, and the 95% confidence interval about the mean are 3000-8700, and 300-11400 $MtCO_2$-eq yr^{-1}, respectively, where the range is largely determined by uncertainty in per-area estimate of the mitigation measure (Smith *et al.* 2008). The regions with the highest potential are Southeast Asia (922 Mt CO_2-eq. yr^{-1}), South America (707 $MtCO_2$-eq. yr^{-1}), China (622 Mt CO_2-eq. yr^{-1}), India (480 Mt CO_2-eq. yr^{-1}) and Eastern Africa (434 Mt CO_2-eq. yr^{-1}). The practices with the highest technical potential are cropland management (1550 Mt CO_2-eq. yr^{-1}), grazing land management (1450 Mt CO_2-eq. yr^{-1}), restoration of cultivated organic soils (1250 Mt CO_2-eq. yr^{-1}), and restoration of degraded land (650 Mt CO_2-eq. yr^{-1}; Smith *et al.* 2007a; 2008). The economic mitigation potential is based on social cost and social discount rates, but excludes many externalities (McCarl & Schneider 2001; Moran et al. 2011). It is intended to estimate the achievable mitigation potential for a range of carbon prices, given the cost of implementing each mitigation measure (Smith *et al.* 2008). Carbon sequestration (removing atmospheric CO_2) largely drives the estimated global mitigation potential, rather than a reduction in non-CO_2 GHGs which largely drive current agricultural GHG emissions. However, significant potential is also available from reductions in methane and nitrous oxide emissions, and such emission reductions are permanent.

The estimates in table 1 are for per-area mitigation potential by gas (Smith et al., 2008). For soil carbon sequestration (or carbon emission reductions), estimates expressed as CO_2 mitigation potential and the low and high values for the 95% confidence interval were derived using mixed effect modelling on a large dataset of long term agricultural soil carbon experiments from a variety of countries, though temperate studies were more prevalent in the database (Ogle *et al.* 2005). Estimates were made using this method for all land-based mitigation options except estimates for soils under bio-energy crops and agro-forestry which are assumed to derive their mitigation potential mainly from cessation of soil disturbance; the figures for soils under bio-energy crops and agro-forestry are therefore assumed to be the same as for no-till within the same climatic region, and for organic soil estimates, which are derived using estimated emissions under drained conditions from IPCC guidelines (IPCC 1997, 2003). Further details are given in Smith et al. (2008).

As seen from table 1, restoration of organic soils (peatlands drained for agriculture) offers by far the greatest per-area GHG mitigation potential, though the areas affected are relatively small on a Europe-wide basis (though significant in Northern countries) and the cost is relatively high (due to the opportunity cost when the land is rewetted so that it can no longer grow crops). Cropland and grazing land management offer the greatest potential for most of the European area (since croplands and grazing lands are widespread) with the most prominent options including for croplands: including improved agronomy, improved nutrient management, improved tillage/residue management, improved water management, improved rice management, agroforestry and potential for land cover (use) change (e.g. setaside) and for grazing lands: pasture improvement, optimised grazing intensity, increased productivity (including fertilization), improved nutrient management, better fire management, and species introduction (e.g. deep rooted species).

4. Conclusion

In conclusion, there are many options to increase soil carbon content in agricultural soils, and a wide range of efficacies of carbon sequestration. The best estimates at present suggest that protecting existing stocks of carbon in high-carbon soils (peatlands) is a priority, and for soils already under agriculture, the most effective options are rewetting of cultivated organic soils, with other options such as cropland and grazing land management, and the restoration of degraded lands also having significant potential due to the large areas involved.

Table 1. Per-area annual mitigation potentials for each climate region for non-livestock mitigation options (Smith et al., 2008a)

			CO_2 (t CO_2 ha^{-1} y^{-1})			CH_4 (t CO_2-eq. ha^{-1} y^{-1})			N_2O (t CO_2-eq. ha^{-1} y^{-1})			All GHG (t CO_2-eq. ha^{-1} y^{-1})		
Climate zone	**Activity**	**Practice**	**Mean estimate**	**Low**	**High**	**Mean estimate**	**Low**	**High**	**Mean estimate**	**Low**	**High**	**Mean estimate**	**Low**	**High**
Cool-dry	Croplands	agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.10	0.00	0.20	0.39	0.07	0.71
	Croplands	nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.07	0.01	0.32	0.33	-0.21	1.05
	Croplands	tillage and residue management	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90
	Croplands	agro-forestry	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
	Grasslands	grazing, fertilizaltion, fire	0.11	-0.55	0.77	0.02	0.01	0.02	0.00	0.00	0.00	0.13	-0.54	0.79
	Organic soils	restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	Degraded lands	restoration	3.45	-0.37	7.26	0.08	0.04	0.14	0.00	0.00	0.00	3.53	-0.33	7.40
	Manure / biosol	application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	-0.17	1.30	1.54	-3.36	7.57
	Bioenergy	soils only	0.15	-0.48	0.77	0.00	0.00	0.00	0.02	-0.04	0.09	0.17	-0.52	0.86
Cool-moist	Croplands	agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	Croplands	nutrient management	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
	Croplands	tillage and residue management	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	set-aside and LUC	3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
	Croplands	agro-forestry	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
	Grasslands	grazing, fertilizaltion, fire	0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.80	0.11	1.50
	Organic soils	restoration	36.67	3.67	69.67	-3.32	-0.05	-15.30	0.16	0.05	0.28	33.51	3.67	54.65
	Degraded lands	restoration	3.45	-0.37	7.26	1.00	0.69	1.25	0.00	0.00	0.00	4.45	0.32	8.51
	Manure / biosol	application	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
	Bioenergy	soils only	0.51	0.00	1.03	0.00	0.00	0.00	0.02	-0.04	0.09	0.53	-0.04	1.12
Warm-dry	Croplands	agronomy	0.29	0.07	0.51	0.00	0.00	0.00	0.10	0.00	0.20	0.39	0.07	0.71
	Croplands	nutrient management	0.26	-0.22	0.73	0.00	0.00	0.00	0.07	0.01	0.32	0.33	-0.21	1.05
	Croplands	tillage and residue management	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	set-aside and LUC	1.61	-0.07	3.30	0.02	0.00	0.00	2.30	0.00	4.60	3.93	-0.07	7.90
	Croplands	agro-forestry	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
	Grasslands	grazing, fertilizaltion, fire	0.11	-0.55	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.11	-0.55	0.77
	Organic soils	restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
	Degraded lands	restoration	3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
	Manure / biosol	application	1.54	-3.19	6.27	0.00	0.00	0.00	0.00	-0.17	1.30	1.54	-3.36	7.57
	Bioenergy	soils only	0.33	-0.73	1.39	0.00	0.00	0.00	0.02	-0.04	0.09	0.35	-0.77	1.48
Warm-moist	Croplands	agronomy	0.88	0.51	1.25	0.00	0.00	0.00	0.10	0.00	0.20	0.98	0.51	1.45
	Croplands	nutrient management	0.55	0.01	1.10	0.00	0.00	0.00	0.07	0.01	0.32	0.62	0.02	1.42
	Croplands	tillage and residue management	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
	Croplands	water management	1.14	-0.55	2.82	0.00	0.00	0.00	0.00	0.00	0.00	1.14	-0.55	2.82
	Croplands	set-aside and LUC	3.04	1.17	4.91	0.02	0.00	0.00	2.30	0.00	4.60	5.36	1.17	9.51
	Croplands	agro-forestry	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89
	Grasslands	grazing, fertilizaltion, fire	0.81	0.11	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.11	1.50
	Organic soils	restoration	73.33	7.33	139.33	-3.32	-0.05	-15.30	0.16	0.05	0.28	70.18	7.33	124.31
	Degraded lands	restoration	3.45	-0.37	7.26	0.00	0.00	0.00	0.00	0.00	0.00	3.45	-0.37	7.26
	Manure / biosol	application	2.79	-0.62	6.20	0.00	0.00	0.00	0.00	-0.17	1.30	2.79	-0.79	7.50
	Bioenergy	soils only	0.70	-0.40	1.80	0.00	0.00	0.00	0.02	-0.04	0.09	0.72	-0.44	1.89

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