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Potential for carbon sequestration in European agriculture

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Introduction

The Kyoto Protocol allows carbon emissions to be offset by demonstrable removal of carbon from the atmosphere. Thus, land use, land use change and forestry (LULUCF) activities that may reduce atmospheric CO_2 levels are included in the Kyoto targets.
Article 3 of the Kyoto Protocol has defined that anthropogenic activities in the land use, land use change and forestry sector could affect the emissions of greenhouse gases from sources and removals by sinks. Article 3.3 describes activities such as afforestation, reforestation and deforestation that are accounted for as GHG sources or sinks. Article 3.4 additionally mentions that the Parties may decide to account for additional human-induced activities aiming for carbon sequestration in agricultural soils by improved management. The Bonn Agreement, formulated at COP6bis in July 2001, clarifies the implementation of Article 3.4 as follows: In the context of agriculture, eligible activities comprise 'cropland management', 'grazing land management' and 'revegetation' provided that these activities have occurred since 1990, and are human-induced. The Marrakech Accord, agreed at COP7 in November 2001, sets legally binding guidelines for reporting and accounting for agricultural carbon sinks. Thus, carbon sequestration in agricultural soils is a potentially suitable mechanism to ensure compliance with the EU's obligation to cut its GHG emissions.
However, the amount of sequested carbon is only accountable under the Kyoto Protocol when the cropland management is elected which is only the case for Portugal so far, whereas most member states have not yet estimated the emissions and removals from agricultural soils (ECCP, 2006). An estimated effect will not be part of the Kyoto accounting.

In general, carbon sequestration in ecosystems occurs when carbon (C) entering the system through gross primary production (photosynthesis) is greater than the C leaving the system through plant and heterotrophic respiration, lateral transfers, leaching and harvest. However, there is evidence that under current agricultural practices, many European soils are losing organic carbon and thus constitute sources of atmospheric CO_2 rather than sinks (Bellamy et al., 2005). Historically, many soils used for agriculture have lost 20-40 % or more of their carbon through practices that led to low rates of C addition to soil and increased oxidation of soil organic matter. This may be the case for arable cropping systems, which have tended towards greater specialisation and monoculture, and for farmed organic soils, such as peatlands. It is estimated that European croplands lose 78 Mt C per year. Practices that reverse this trend are adding more organic matter or humus, which contains about 50 % carbon by mass, to soils and/or are slowing its oxidation. Measures to enhance carbon sequestration in agricultural soils through building up soil organic matter stocks are potential tools for mitigating global warming as well as enhancing soil protection. Thus, there is a high potential for carbon sequestration as well as for a reduction of GHG emissions from soils (Robertson et al., 2000).

The biological potential for carbon sequestration in agricultural soils through optimised land management could extend to 90-120 Mt CO_2 equivalent a^{-1} (EU-15) with a range of options available including reduced and zero tillage, set-aside, perennial crops and deep rooting crops, more efficient use of organic amendments (animal manure, sewage sludge, cereal straw, compost), improved rotations, irrigation, bioenergy crops, extensification, organic farming, conversion of arable land to grassland or woodland, and reversion of surplus farmlands to natural ecosystems. These practices enhance soil C sequestration and will also improve the quality and fertility of soils as well as helping to reduce erosion and soil compaction.

According to the 'working group on sinks related to agricultural soils' of the European Climate Change Programme ECCP I (ECCP, 2001) various measures within agricultural production have the potential to reduce greenhouse gas emissions by capturing and storing carbon, as well as by enhancing natural sequestration processes in soils (Table 1). According to the estimates provided by the experts of ECCP (ECCP, 2006), there is the potential to sequester up to 60-70 Mt CO_2 a^{-1} in the agricultural soils of the EU-15 during the first commitment period, which is equivalent to 1.5-1.7 % of the EU's anthropogenic CO_2 emissions. This amount of 60-70 Mt CO_2 a^{-1} would make up 19-21 % of the total reduction of 337 Mt CO_2 a^{-1} to which the EU is committed during the first commitment period. However, ECCP reported in 2006 (ECCP II) that the estimated carbon sink potentials in agriculture and forestry of ECCP (2001) appear to be too optimistic in view of the state of implementation of policies and measures. Realistically, it is estimated that agricultural soils in the EU-15 can sequester up to 16-19 Mt C a^{-1} during the first Kyoto commitment period, which is less than 20 % of the theoretical potential and equivalent to 2 % of European anthropogenic emissions (Freibauer et al., 2004).

Table 1: ECCP I projected emission reductions by carbon sequestration measures (ECCP, 2001).

Measure	**Sequestration potential per unit area [t CO_2-eq. ha^{-1} a^{-1}]**	**Emission reduction potential during first commitment period (EU15) [Mt CO_2-eq. a^{-1}]**
Promotion of organic input	1-3	20
Permanent revegetation of set-aside (increased soil carbon; part of afforestation)	2-7	15
Biofuel production on set-aside (increased soil carbon)	2-7	15
Promotion of organic farming	>0-2	14
Promotion of permanently shallow water table on peatland	5-15	15
Zero and/or conservation tillage	>0-3	<9

Promotion of organic input

The promotion of organic input on arable land due to a better use of animal manure, crop residues, cover crops, compost and sewage sludge by applying the available material on cropland instead of on grassland or elsewhere as it is common practice, represents a recommended measure for carbon sequestration. The ECCP working group indicates a carbon sequestration potential of this measure of 1-3 t CO_2 ha^{-1} a^{-1} with a potential in the EU-15 of 20 Mt CO_2-eq. a^{-1} during the first commitment period (Table 1).

This measure is easy to implement and additionally has a positive long-term impact on farm income due to better soil fertility. On-farm composting can also provide an additional source of income (capital and operational costs incurred by setting up a composting facility at farm level may be offset by: 1) a fee for taking organic waste; 2) income from selling compost; 3) savings in fertiliser, water consumption, disease suppression).

However, for the implementation of this measure it must be considered that it is contradicting the ECCP measure 'improved implementation of the Nitrates Directive' with the aim to limit the application of manure and sewage sludge (estimated reduction potential of 10 Mt CO_2-eq. a^{-1}). Thus, it is important to weigh the benefits against potential undesirable side-effects, such as increased risk of nitrate leaching and GHG emissions from the soil (Smith et al., 2000). The residue management also has the potential to increase GHG emissions and costs due to transport (dependent on the distance), purchase of organic material and compost production. The widespread production of compostable waste limits the distance between production and application sites of compost in most cases as well as transportation costs.

By contrast, chemical fertiliser can be partly replaced, leading to reduced emissions from fertiliser production. The higher residue return may also improve soil conditions (soil fertility and structure) and therefore increases productivity and sustainability and reduces soil erosion.

Permanent revegetation of set-aside (land use change)

Land use change is defined as a permanent revegetation of arable (set-aside) land or extensification of arable production by introduction of perennial components (e.g. by afforestation). One common case is the land use change (abandonment) of marginal cropland reseeded to permanent grassland or surplus cropland seeded to permanent grassland. The conversion of arable land to grassland includes the possibility to expand field margins, on which grass can be grown, and possibly shrubs or trees. According to the ECCP 'working group on sinks related to agricultural soils' this measure has an estimated emission reduction potential of 2-7 t CO_2 ha^{-1} a^{-1} with a total potential in the EU-15 of 15 Mt CO_2-eq. a^{-1} during the first commitment period (Table 1).

However, it must be considered that the change to more grassland may be connected with more animals causing more manure which can again increase GHG emissions. In any case, when considering any land management change the likely effect on other non-CO_2 greenhouse gases needs to be considered.

The implementation of this measure and the impact on the farm income is regionally specific and only positive if linked to compensation payments for nature protection.

Biofuel production

Biofuel production on arable land (set-aside) with, for instance, short rotation coppice and perennial crops has, according to the ECCP working group, a high indicated carbon sequestration potential of 15 Mt CO_2-eq. (Table 1; ECCP, 2001). However, the benefit from substitution of fossil fuels by bioenergy is much greater than the effect from carbon sequestration (ECCP I identified a technical potential of bioenergy from agriculture, forests and waste of 200-600 Mt CO_2-eq.).

The link to climate change mitigation is based on its carbon neutrality and potential for additional carbon sequestration. The sustainable use of biomass for energy production, that is the use of biomass at a rate at which it can be reproduced on the same land, is per se carbon neutral. Carbon neutrality implies that the carbon, which is released to the atmosphere through the combustion process, is sequestered equally in the re-growing biomass. Most biomass production schemes will, however, sequester additional carbon in a so-called buffer stock, which allows for continuous biomass production and its storage. The growth of all plants is based on the absorption of carbon dioxide from the atmosphere. Carbon content in dry biomass is about 50 % (weight). The CO_2 is released back into the atmosphere during the decay or combustion of biomass.

Promotion of organic production

At present, eight EU member states (AT, BE, DE, EE, GR, LT, MA, SI) report measures to promote organic production with an emission reduction potential of 14 Mt CO_2 (Table 1; ECCP, 2001). Only two member states quantified estimates of very low CO_2 sequestration effects (Slovenia: 0.009 Mt CO_2-eq. a^{-1}; Greece: 0.067 Mt CO_2-eq. a^{-1}). However, Smith et al. (2005) reported that the magnitude of carbon sequestration in organic farming is highly uncertain. An estimated effect on C sequestration will not be part of Kyoto accounting. Soil effects will only be accountable under the Kyoto Protocol when cropland management is elected.

Promotion of permanently shallow water table of farmed peatland

Cultivation of organic soils is the opposite of C and N sequestration, having large CO_2 and N_2O emissions, the more drained and cultivated (root crops) the more emissions. In terms of CO_2-eq., emissions from drained peatlands are typically 2-10 times higher than from mineral agricultural soils. Behrendt et al. (1994), for instance, give a mineralisation rate in the range of 2.9-6.7 t C ha^{-1} a^{-1} in drained peatlands in Germany. According to ECCP I (ECCP, 2001) the cultivation of peatlands leads to a release of 8-20 t C ha^{-1} a^{-1} under land use systems with deep drainage and intensive mechanical soil disturbance, especially after deep ploughing. In total, anthropogenic emissions from agricultural peatlands in the EU-25 are estimated at >40 Mt CO_2-eq. (ECCP, 2006) and are estimated to hold ca. 42 Gt carbon in the form of peat (Byrne et al., 2004). Five to ten percent of the arable land has organic soils in northern Europe. In Sweden organic soils have been estimated to emit ca. 10 % of the total anthropogenic emissions from all sectors (Kasimir Klemedtsson et al., 1997). #

Thus, re-establishing peatland dynamics by the increase of the water level to decrease the mineralisation could lead to additional carbon sink. Groundwater level just below the ground gives lower emissions of CO_2 and N_2O, while CH_4 emission is kept small (an overall benefit remains). According to ECCP1 the promotion of permanently shallow water table of farmed peatland is estimated to have an emission reduction potential of 15 Mt CO_2-eq. a^{-1} (Table 1). This measure is not documented in Member States reports, but most Member States use default emission factors to calculate emissions from organic soils. However, the interaction with other greenhouse gases (CH_4, N_2O) must be considered.

Peatland restoration could therefore be a regionally interesting GHG mitigation option next to positive effects on biodiversity, water retention, and environmental protection (FAO, 2001). However, a reduced cultivation of organic soils, due to the creation of a more shallow water table and the rewetting of grassland on peat soils imply a drastic change of current agricultural practices, and loss of income, which would have to be compensated by the Community. Peatland conservation programmes have been already developed in some member states (e.g. in the Netherlands and Germany). Due to the high significance of peatlands for the environment, the federal state of Mecklenburg-Western Pomerania in Germany compensates peatland restoration with 1,500 € ha^{-1} and plans to restore 60% of the cultivated peatlands by 2020 (UMMV, 2003).

Reduced or no-tillage

In reduced or no-tillage (zero tillage) systems there is reduced or minimal disturbance by the planting equipment. Zero tillage systems represent an extreme form of cropland management in which any form of mechanical soil disturbance is continuously abandoned except for shallow opening of the soil for seeding, like continuous mulch-seed or direct drill. In reduced tillage systems soil disturbance is kept at a minimum compared to conventional ploughed systems. Reduced tillage systems involve reducing the number of passes with tillage equipment and managing the residues from the previous crop. These systems leave residue cover on the soil surface and depending on the crop most of the soil surface is covered throughout the year. Reduced tillage or no-tillage is the likely cause of C sequestration in the no-till system (Paul et al., 1997; Robertson et al., 2000).

The ECCP 'working group on sinks related to agricultural soils' indicate a sequestration potential of this measure up to 3 t CO_2 ha^{-1} a^{-1} with a potential in EU-15 (during the first commitment period) of <9 Mt CO_2 a^{-1} (Table 1). According to the EU project INSEA continuous reduced tillage over 20 years is found to add on average 0.2 t C ha^{-1} a^{-1} to soil organic carbon compared to conventional tillage, while minimum tillage provides 0.31 t C ha^{-1} a^{-1}. This could result in a technical potential of 74 and 113 Mt CO_2-eq. for EU-25 for reduced and minimum tillage, respectively. Also West & Post (2002) estimated a lower C sequestration potential of 0.57±0.14 t C ha^{-1} a^{-1} for no-tillage systems worldwide, and several studies on U.S. agriculture reported potentials ranging from 0.3 to 0.8 t C ha^{-1} a^{-1} for cropland soils and from 0.1 to 0.4 t C ha^{-1} a^{-1} for grassland soils (Lal et al., 1998; Bruce et al., 1999; Follett, 2001; Schumann et al., 2002). According to Smith et al. (2000) no-till farming is applicable to 87 % of arable area in Europe.

As sowing a crop without prior cultivation and with very little soil disturbance at seeding reduces additional operations such as ploughing, less fossil fuel is used which can reduce the energy input up to 50%. However, this measure may be connected with high initial machinery costs and probably with a more intensive machine usage and associated with increased pesticide usage due to less soil cultivation and its negative environmental side-effects. However, in some regions reduced or no-tillage represents additionally a suitable instrument for erosion control and soil conservation.

Reduced tillage includes a wide range of different practices, depending on various climate and soil conditions. The sequestration rate as well as the potential environmental and socio-economic impacts can thus (according to a few studies) only be estimated qualitatively, in comparison to zero tillage. Difficulties may occur in cultivation of heavy clay soils, without autumn ploughing and/or freezing of soil. Soil structure improves under most conditions, but increased bulk density may lead to reduced rootability and infiltration in some cases.

Moreover, N_2O emissions may increase, as soils may become more anaerobic and advance denitrification under no-till. Smith et al. (2000) suggest that when potential increases of N_2O production (1.46 kg N_2O-N ha^{-1} a^{-1}) are converted to carbon equivalents and included in the calculation, the total mitigation effect in terms of the GWP is reduced by about 50-60% compared to when only soil carbon sequestration is considered.

Reduced or no-tillage is not addressed by Member States in reporting on policies and measures as the inventory methods used by member states mostly do not differentiate the different cropland management practices. In addition, these soil effects are only accountable under the Kyoto Protocol when cropland management is elected.

Sink saturation, non-permanence and verifiability of carbon sequestration

In general, changes in carbon sequestration need to be considered over a longer time horizon since the effect is non-linear. Long-term experiments show that increases in soil carbon are often greatest soon after a land-use or land-management change is implemented. As the sink will saturate when a new equilibrium of soil organic matter is reached, carbon sequestration measures are only applicable for a limited time span of at maximum 20-100 years (Smith et al., 1997). Whilst soil carbon levels may not reach a new equilibrium until 100 years after land-use or land-management change, the carbon sequestration potential may already be minimal after 20 years. Therefore, soil carbon sequestration does not have limitless potential to offset CO_2 emissions.

Furthermore, ECCP concluded that carbon sequestration does not represent a real mitigation option because of the high risks associated with carbon sinks that may be non-permanent (Saggar et al., 2001). By reverting to old agricultural management or land-use practice, soil carbon is lost more rapidly than it accumulates. For practical purposes, therefore, in order to implement a meaningful carbon sequestration policy on agricultural land, management changes must be permanent. According to ECCP II stability in policy incentives would be necessary (if these measures are assed as beneficial) as, for instance, half of any carbon stored can be lost in the first year of tillage. Stockfish et al. (1999) reported that returning to conventional tillage after several years of no-tillage production might lead to a complete loss of the sequested carbon.

The main problem of including agricultural soil carbon stock changes in the inventories of net GHG emissions is that of verifiability. The soil carbon pools are large and the changes are slow. However, even small changes in soil carbon pools may contribute significantly to national GHG emissions; such small relative changes in soil carbon pools are very difficult to determine from soil sampling (Olesen & Petersen, 2002). In addition, the carbon sequestration potential depends on many factors such as soil type or climate. Whilst clay soils accumulate carbon relatively quickly, sandy soils may accumulate practically no carbon even after 100 years of high carbon inputs (Christensen, 1996). Similarly, soils in colder climates, where decomposition is slower, may accumulate carbon more rapidly than soils in warmer climates.

Moreover, it has to be considered that C is not sequestered alone, but together with other nutrients such as N as humus is composed of both C and N. To be able to sequester C, there is a cost of N. The sequestered N is a future risk of N_2O emission, since the N content of the soil is one of the driving variables for N_2O emission (Smith et al., 2000).

Finally, only a small fraction of the biological potential for carbon sequestration in agricultural soils through optimised land management will be feasible until the first commitment period since carbon sequestration in agricultural soils requires a major change in crop rotations, land management and the dedication of the set-aside areas. The actual rate of carbon sequestration is highly uncertain (uncertainties in European scale estimates are large (>50 %), Freibauer et al., 2004) and still, there are no tools available to measure and monitor stock changes in soil carbon at a time scale as short as the first commitment period. Moreover, it is unclear how much of the potential carbon sink will be accountable to fulfil the commitments under the Kyoto Protocol as long as no political decisions on the scope and accounting system of Article 3.4 (land use/additional measures) have been taken. As carbon sequestration has to be calculated compared to baseline rates in 1990, the Intergovernmental Panel on Climate Change (IPCC) is going to prepare the methodology of estimating the 1990 emission levels (the base year 1990 can only be modelled retrospectively) and controlling / monitoring the reduction potential of different measures ("net-net" accounting).

Policy measures

The direct effects of existing CAP measures on carbon sequestration are difficult to quantify due to possible interactions with other socio-economic drivers (ECCP, 2001). Indirectly, however, some production-related policies and agri-environmental schemes have already helped to maintain carbon stocks in agricultural soils. In addition, new rural development plans were approved including the definition of Good Farming Practice, based on verifiable standards where soil protection received considerable attention. Specific effects include the increase in carbon stocks through afforestation subsidies, the encouragement of organic farming and the introduction of set-aside with its scope for bioenergy production with perennial crops (short rotation coppice etc.) and the support of energy crop production by

45 € ha^{-1} (for a maximal area of 1.5 Mio. ha). Also the second pillar of the CAP, by means of modulation, includes the promotion of sustainable and environmentally friendly production techniques or providing incentives for extensification.

However, according to Smith et al. (2000), additional policies would be required to encourage: 1) bioenergy crop production on surplus arable land where feasible (to allow surplus arable land to be put into long-term land use instead of short-term rotational set-aside), 2) woodland regeneration on surplus arable land where bioenergy crop production is not feasible, 3) a greater adoption of conservation tillage practices in areas where the land is suitable, and 4) the application of the majority of organic amendments to arable land, with inorganic fertilisation replacing current organic fertilisation of grassland and non-arable crops. The mechanisms to implement such policies include the use of tax benefits, subsidies, joint implementation projects, and improved extension and information dissemination. According to ECCP II (ECCP, 2006) cropland carbon sequestration under Article 3.4 of the Kyoto Protocol will not be an option in the future without incentives for carbon sequestration.

Due to the fact that calculating the carbon sequestration potential of the different measures is a very complex undertaking with high uncertainties and as various recent EU projects (e.g. CarboEurope - Greengrass, INSEA) are actually working on modelling of carbon sequestration, finally this measure has been neglected from modelling within the MEACAP project.

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