AGRICULTURAL SOURCES AND SINKS OF CARBON

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Abstract. Most existing agricultural lands have been in production for sufficiently long periods that C inputs and outputs are nearly balanced and they are neither a major source nor sink of atmospheric C. As population increases, food requirements and the need for more crop land increase accordingly. An annual conversion of previously uncultivated lands up to 1.5 x 10^7 hectares may be expected. It is this new agricultural land which suffers the greatest losses of C during and subsequent to its conversion. The primary focus for analysis of future C fluxes in agroecosystems needs to be on current changes in land use and management as well as on direct effects of CO_2 and climate change. A valid assessment of C pools and fluxes in agroecosystems requires a global soils data base and comprehensive information on land use and management practices. A comprehensive effort to assemble and analyze this information is urgently needed.

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1. Introduction

Of all the major biomes of the terrestrial biosphere, agroecosystems represent the land areas of the globe most subject to continuous anthropogenic disturbance. Land use changes involving major transformations from forests, grasslands and savannas have converted large areas from relatively stable, undisturbed ecosystems to agroecosystems under extensive and intensive management. The introduction of agriculture involving land clearing or breaking of sod, cultivation, replacement of perennial vegetation by annual crops, and nutrient subsidies in the form of fertilizers has had major impacts on C pools and fluxes in large regions of the globe. In the initial phases of these transformations there have been major losses of CO_2 to the atmosphere as soil C pools adjusted to increased soil disturbance and reduced C inputs. In many areas under intense pressure for production, this has led to serious soil degradation by erosion and nutrient losses. These trends continue in many areas of the world. On the other hand, in countries able to provide subsidies of energy and technology, agricultural productivity has shown continuing increases, land degradation has slowed or reversed, and soil C pools have stabilized or slightly increased. For analysis of future C fluxes in agroecosystems the primary focus needs to be on current changes in land use and management as well as future adjustments in management when agricultural communities respond to climatic change.

2. Assessment of Sources and Sinks

2.1. INVENTORY OF AGRICULTURAL SOILS

In order to assess the involvement of agriculture as a source or sink in the overall C budget, data on the amounts of land actually and potentially used for crop production are required. According to FAO statistics and their evaluation by Bouwman et al. (1990a), the total area of crop land at the present time amounts to about $1.5 \cdot 10^9$ ha. Roughly half of this area is located in the temperate climatic zones and the other half is in the tropical and subtropical areas of the world (Table 1, Sauerbeck, 1992).

As population increases, especially in the developing countries, food requirements and the need for more crop land increase accordingly. Estimates for the period until 2025 assume an additional requirement of only about +5% in the temperate zone, but more than 60% in the tropical/subtropical zone. This would add up to an overall increase of 36% from $1.5 \cdot 10^9$ ha at present to more than $2 \cdot 10^9$ ha within less than 40 yr (Sauerbeck 1992).

Considering the amount and quality of the soils which are still available for potential agricultural uses, it is questionable whether these projected land requirements can in fact be met. For the time being, however, an annual conversion of somewhere between 1 and 1.5×10^7 ha of formerly virgin land must be assumed. It is this new agricultural land which suffers the greatest losses of C during and subsequent to its conversion.

Table 1: Projections of human population, arable land requirement, and N-fertilizer consumption for 1990-2025, for temperate or tropical and subtropical climates (Bouwman 1990b, Sauerbeck 1992).

Region	Population 1990	 2025	Arable land 1990	 2025	N-Fert. Use 1990	 2025
	x 10^6		10^6 ha		kton N yr^{-1}	
Temperate Areas	1,156	1,335	689	720	40,427	45,289
% of total	22	16	47	36	51	38
% change till 2025		+15		+ 6		+12
Tropical and subtropical	4,084	7,042	787	1,286	39,137	73,081
% of total	78	84	53	64	49	62
% change till 2025		+72		+63		+87
Total	5,240	8,407	1,476	2,006	79,564	118,370
% change till 2025		+63		+36		+49

2.2. QUANTIFICATION OF C POOLS AND FLUXES

Different approaches have been used to assess the amounts of soil organic C (SOC) which are presently stored in agricultural soils (Eswaran, 1993). Schlesinger (1984) assumed 7.9 kg m^{-2} and arrived at a global total of 111 Gt for 1.4 billion ha of cultivated land. Buringh (1984) assumed 9.5 kg m^{-2} for 1.5 billion ha of cropland for a total of 142 Gt and 11.6 kg m^{-2} for 3.04 billion ha of grassland for a total of 353 Gt. Buringh also gave estimates for the C content of the various soil orders, which, for cropland, ranged from 2.0 kg m^{-2} for Aridisols to 13 kg m^{-2} for Mollisols and 10 kg m^{-2} for Oxisols. The high value for Oxisols is probably realistic, although a low SOC content for these soils had been assumed in the past. As most of the increase in cultivated land in the next 35 yr will be in the tropics and subtropics (Table 1) a realistic assessment of the SOC pool in these soils is important.

These pool size estimates are rather rough, the variation with soil orders and C contents at different soil depths are large, and it will be difficult to arrive at more reliable figures soon. However, soil mapping has become an international priority and improved soil C estimates will become available if supported by adequate analytical work.

To understand the turnover of and the CO_2 fluxes from these overall soil C pools, one needs to realize that soil organic matter consists of several sub-pools of exceedingly different accumulation rates and residence times. Soil organic components are often characterized on the basis of their density, size, and chemical composition. These components consist of a continuum from labile compounds that mineralize rapidly to more recalcitrant residues that accumulate as they are deposited during advanced stages of decomposition. The turnover rate of the labile and stable pools of soil organic C vary from a few months to several thousand years. The most resistant components of SOC are highly polymerized humic substances. The resistance of humic substances to microbial degradation results from both physical configuration and chemical structure. These substances become complexed with clays and mineral colloids so they are greatly influenced by soil texture and structure.

The organic C most rapidly lost within just a few years after land conversion is - apart from the native standing plant biomass - the more recent and labile, but quantitatively rather small soil humus fraction. This is then followed by a more gradual but long-lasting loss of stabilized SOC due to continuous disturbance by soil tillage. This is true for plowed grassland and forest soils in temperate zones as well as for cleared tropical forests.

3. Managing Soils for C Storage

3.1. MANAGEMENT OPTIONS

It is well documented that soil organic C levels decline when land is converted from grassland or forest ecosystems to cropland. This decline is most rapid in the first few years following conversion and then continues at slower rates until a new steady state is reached. After 50 to 100 yr SOC levels are often 50 to 60% lower than the initial levels.

Most existing agricultural lands have been in production for sufficiently long periods that they are approximately in steady state, and thus are neither a major source nor major sink of atmospheric C. However, conversion of previously uncultivated lands (Watson et al., 1990; Leggett et al., 1992) into agricultural production, driven by increasing population and land degradation, results in large C fluxes to the atmosphere of approximately one fourth of the emissions from fossil fuels (Brown et al., 1993).

Soil management practices have significant effects on both the rate and extent of SOC decline and on restoration of SOC levels. Improved management of crop residues, reduced tillage and inputs of more biomass with higher crop production offer the greatest potential for reducing the decline and for storing some additional C in soils. At the same time, reduced tillage will generally require lower inputs of fossil fuel.

3.2. LIMITATIONS FOR C STORAGE

The extent to which soil management can influence gains or losses of soil C is highly variable and difficult to predict. Stewart (1993) points out that the maintenance of SOC becomes more difficult as temperatures increase and the amounts of precipitation decrease. The reasons are many, but are dominated by the fact that organic matter decomposition rates are accelerated with rising temperatures, and the production of biomass to replenish the SOC reserves becomes less as water becomes more limiting.

Sauerbeck (1993) postulates that under optimum soil management it might be feasible to increase the C level of existing arable soils in the temperate zones (690 x 10^6 ha) by up to 1 kg m^{-2}. This soil C increase would represent about a 10% increase of SOC in these soils. Sauerbeck estimates that it would take 50 to 100 yr to reach this new level of SOC and that little additional SOC could be stored unless a new set of management practices was initiated. Such a change in SOC would sequester in the order of 6.2 Gt of C over the 50 to 100 yr period.

Similar increases are not likely in all soils. Aridisols cover large regions of the world and are characterized by hot dry climates. These soils are inherently low in SOC. Kimble (1990) analyzed 98 pedons as part of a global assessment and found an average SOC of 4.2 kg C m^{-2}. It is unlikely that the SOC in most of these soils could be increased by more than a small fraction. Also, many of the Aridisols are located in developing countries where populations are great and continue to increase at a rapid rate (Table 1). Therefore, even the small amounts of crop residues that are produced in these water deficient regions are often utilized as fodder for animals or fuel for cooking. Under such conditions, these soils do not have a significant potential as a sink for C, but neither will they be a major source because of their low content of SOC.

The likely potential for soil management to sequester C ranges from 0 to about 1 kg m^{-2} for important soil groups. Assuming an average of 0.5 kg m^{-2} as an achievable goal for agricultural cropland, about 7 Gt of C sequestration could be achieved. However, this increase would take at least 50 yr and could be achieved only once.

4. Tradeoffs for Management of Biomass Production and Soil Organic C

Managing croplands to increase SOC has implications for the emission of several greenhouse gases (GHG) and for environmental quality in general. Some of these effects occur off-site.

4.1. CARBON COSTS OF FERTILIZER MANUFACTURE

The potential for increasing SOC in agricultural systems is strongly influenced by the levels of C inputs. These, in turn, largely depend on the supply and improved utilization of inorganic and organic N sources. On average, the energy required to produce 1.0 ton of nitrogen in fertilizer releases approximately 1.5 tC to the atmosphere. This constitutes the largest share of the fossil C use of agriculture. The production of 80 Mt of fertilizer N in the world (Table 1) results in the release of about 120 MtC to the atmosphere each year. Thus, the C sink associated with increased SOC is partially offset by the fossil C used for production of the additional N. As pointed out by Flach et al. (1993), the need for continuous N inputs to maintain an increased equilibrium SOC value can, eventually, totally offset the C credits for the increased SOC.

Some options for increasing SOC do not require additional N input. For example, Lee et al. (1993) project that the adoption of no-till and winter cover crops can increase SOC in the U.S. cornbelt, while keeping N inputs constant. In this case, because tillage has been reduced, there might actually be a reduction in energy required for agricultural management. If similar increases could be obtained for large regions, as suggested by Sauerbeck, potentially, most of the fossil C cost of fertilizer production could be offset by increasing SOC.

A permanent C benefit can be achieved by increasing the efficiency of N utilization. For example, if increased N efficiency were to result in a reduction of 10% in the use of N fertilizer, world-wide fossil C emissions would be decreased by about 12 Mt yr^{-1}.

4.2. INFLUENCE ON EMISSION OF OTHER GREENHOUSE GASES

Of the fertilizer N applied to agricultural soils, about 1.1% may be emitted from the soil into the atmosphere during a cropping season as N_2O-N (CAST, 1992). A considerable fraction of the fertilizer N is removed from the field to which it was applied through NH_3 volatilization, erosion and nitrate leaching. An unknown fraction of this N is eventually converted to N_2O and emitted to the atmosphere (Duxbury et al., 1993). Over the course of about 50 yr more than 80% of the N applied to a field is returned to the atmosphere (about 60% in 1 to 10 yr) through denitrification (McElroy et al., 1977) after it has been processed through the food chain. Generally, greater than 95% of this N returns to the atmosphere as N_2 but some unknown amount is released as N_2O (Duxbury et al., 1993). Thus, to the extent that increases in SOC depend on increased N inputs, the GHG benefits of sequestering atmospheric C will be partially offset by increased N_2O emissions. Since N_2O has about 270 times the global warming potential of CO_2 and a relatively long (100 to 200 yr) atmospheric residence time (Isaksen et al., 1992) the magnitude of this offset is not well quantified.

Changes in land use practices and related N inputs modify the magnitude of soil CH_4 oxidation (Mosier et al., 1991). The net effect of land cover changes and increased N deposition to temperate ecosystems have resulted in about 30% reduction in the CH_4 sink relative to the soil sink assuming no disturbance to any of the temperate ecosystems (Ojima et al., 1993).

Adoption of no-till and cover crops will, in many cases, cause an increase in soil water content. If this results in increased occurrence or duration of anaerobic soil conditions, there is the potential for increased production and release of CH_4 and N_2O from soils. Methane has a global warming potential of about 11 relative to CO_2 (Isaksen et al., 1992), so increased production of CH_4 and N_2O through changes in management could partially offset the GHG benefits of increasing SOC.

4.3 WATER QUALITY

Excessive application of fertilizers and organic wastes to croplands results in increased N and P concentrations in surface waters and in groundwater. These cause eutrophication of surface waters, with concomitant degradation of both aquatic life and water quality. Increased N (especially NO_3) concentrations in groundwater can make well-water unfit for human consumption. Thus, it is critical that fertilizer and manure applications for SOC sequestration be made in ways that do not result in excessive N loading.

Adoption of reduced tillage systems will, in many cases, lead to a substantial decrease in soil erosion. The protection of the soil is, in itself, a positive environmental contribution. Decreased erosion also reduces the delivery of sediments to surface waters. However, it is possible that reduced tillage might, under certain conditions, contribute to water pollution. Under reduced tillage systems, use of herbicides for weed control might be increased. Another consideration is that by increasing infiltration of water into and through the soil, agrochemicals might be more easily transported to aquifers.

4.4. BIOMASS PRODUCTION FOR C OFFSETS

The production of perennial crops (trees and grasses) as dedicated biomass energy feedstocks provides an opportunity for agricultural systems to reduce the demand for fossil fuels (Wright and Hughes, 1993). It also provides an alternative source of income to landowners in areas of excess food production. While economic availability of land is difficult to determine, there are in the U.S. and the E.C. currently about 40 to 60 M ha of land in set-aside or cropland removal programs. Larger amounts of excess cropland are predicted for the future.

Oilseeds and grain crops which can be converted to liquid transportation fuels are likely to occupy some portion of this available land, but there would be little overall reduction of C emissions due to the large energy inputs required for production and conversion to liquid fuels. Short rotation woody crops (such as hybrid poplars) grown on croplands with good moisture retention capacity and/or croplands with moderate wetness limitations are anticipated to yield 10 to 15 Mg biomass ha^{-1} yr^{-1} now (1990-2000), but have the potential of yielding 20 to 25 Mg biomass ha^{-1} yr^{-1} (Wright and Hughes, 1993). Perennial grasses (such as switchgrass) which can reduce erosion losses on croplands with moderate erosion susceptibility appear to have similar yield potentials. Both are suitable for conversion to electricity or liquid fuels through a wide variety of conversion processes. Fossil fuel inputs to short rotation woody crops, including diesel fuel for tractors and harvesters, pesticides and herbicides and N-fertilizers (at average rates of 50 kg ha^{-1} yr^{-1}) for trees, will have an approximate C cost of 0.3 Mg C ha^{-1} yr^{-1} at current yields and 0.4 Mg C ha^{-1} yr^{-1} at high yields. Perennial grasses will be slightly higher due to higher fertilizer additions and annual harvest. The fossil fuel offset benefits will depend largely on assumed yields and on the conversion process used (Sampson et al., 1993).

5. Competition for Limited Soil Resources

5.1. HISTORY OF LAND USE CHANGES

The need for food and fibers has grown with the growth of the world's population since the beginning of time. Until the late 19th century, almost all increase in food and fiber production was achieved through increases in the land area used for farming at the expense of forest and grass land. In recent times, food production has been increased to a large degree through gains in the production per unit land area, at least in the developed countries.

The conversion of forest land to farmland involved a large initial release of CO_2 from the destruction of vegetation, often through fire, and a smaller annual release of C from the soil organic matter over the next 100 to 150 yr until soil organic matter reached a new steady state, usually about one half of the original SOC content. In grassland soils the initial loss of C from the vegetation was much smaller, but the loss of soil organic matter was of similar magnitude as in forest soils.

Houghton (1977) estimated the annual C emission from land use changes at about 0.6 Gt in 1860 and at about 2.5 Gt in the 1980's. Carbon emission from the burning of fossil fuels exceeded emission from land use changes for the first time in the early 1960's. Wilson et al. (1978) documented significant decreases in values of $\delta^{13}C$ of cellulose in bristlecone pine in California with influx of soil organic matter-derived CO_2 into the atmosphere between 1850 and 1890 due to extensive land clearing and pioneer agriculture. This was before major inputs from fossil fuels.

The change of forest and grassland to agricultural land has been mostly irreversible with the exception of parts in the eastern United States where large areas that were converted to farmland in the 19th century were found unsuitable for sustained farming and reverted to forest.

5.2. ALTERNATIVE LAND USES: FOOD, FIBER AND ENERGY

At the present time some 80% of the potentially arable land of the world is being farmed. Much of the remaining land that might be converted to farmland is in developing countries and of poor quality. Conversion to farmland may require greater investments in capital energy and skill than are available, and may be associated with a major release of C from vegetation and soils.

Currently, the annual increase in world-wide agricultural production is about keeping pace with the increasing worldwide demand (CAST, 1992). There have been no major catastrophic reductions in world-wide production in recent years, but the world's food reserves are small (about 20% of the annual consumption), the world's population is growing rapidly and is expected to double by the year 2030, and large parts of the world's population are still living on an inadequate diet. Crosson (1992) has estimated that the demand for U.S. grains and soybeans will grow by about 1.4% annually in the next 20 yr, and that yields will increase at about the same rate. Hence, even in the United States, the areas of productive cropland available for release for fuel wood production are likely to be small. Yields may be increased more, and land may be released, if there are financial incentives.

Large areas of the world have soils that present major difficulties for agricultural production, but we have no breakdown as to the land areas that are subject to specific problems. The major problems are excess salinity, excess wetness, excess acidity caused by S in the soil, shallow and/or highly erodible soils, steep topography, and excess stoniness. Some of these problem soils may be advantageously used for fuel wood production if tolerant fast growing wood species are available. Real energy offset requires that the fuel wood be harvested economically and that there is a local market with an energy demand that would otherwise be satisfied with fossil fuels.

6. Uncertainties and Research Needs

6.1. COLLATION AND ORGANIZATION OF DATABASES

This analysis is based on information that has been accumulated by a small number of investigators. Although we are confident that this is the best information available and that these investigators did excellent work within their constraints of time and money, we have noted significant inconsistencies among the various sources. For better analyses of the impact of global warming, much better data bases are needed.

An international soils data base is being developed by ISRIC, the International Soil Resource Information Center in Wageningen (Netherlands) in cooperation with IGBP (International Geosphere-Biosphere Programme), FAO (Food and Agriculture Organization of the United Nations) and USDA (United States Department of Agriculture) (Scholes and Skole, in prep.). A realistic assessment of the SOC pools and dynamics requires comprehensive information on land use and management practices in addition to the soil data. A comprehensive effort to assemble this information is urgently needed.

7. Summary

7.1. SCIENTIFIC CONSIDERATIONS

* Existing agricultural lands are neither a major source nor major sink for atmospheric C.

* Agroecosystems in temperate regions may be converted to a net C sink up to a total of 7 Gt C during 50-100 years by use of appropriate soil management practices including enhanced use of crop residues, reduced tillage, and increased crop production with greater additions of organic C.

* Production of perennial grasses or trees as energy sources can offset significant C fluxes, but will be constrained by competition for limited land resources.

* Conversion of new lands into agricultural production, driven by increasing populations and land degradation, results in large C fluxes to the atmosphere (see Tropical forests) of approximately one-fourth of emissions from fossil fuels.

7.2. POLICY CONSIDERATIONS

* Policies should encourage technical assistance in developing countries to maintain and improve production on existing farm lands and to decrease land conversion.

* Policies should enable and encourage farmers to improve C sequestration in agroecosystems. These should support practices that improve crop residue management, reduced tillage and increased biomass production.

* Policies should encourage the development of energy crops, preferably on marginal lands to avoid competition with food crop production.

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