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Carbon cycling and sequestration opportunities in South America: the case of Brazil

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Abstract. A carbon emission inventory of the Brazilian agricultural sector was used to compare greenhouse gas emissions with estimated carbon offsets promoted by two main changes in agricultural management: the replacement of conventional tillage by no-tillage and the cessation of annual burning in sugar cane production. Using the IPCC revised 1996 guidelines for national greenhouse gas inventories, we estimate that 12.65 Mt C are emitted annually from agricultural land in Brazil. Ongoing conversion of conventionally tilled land to no-tillage currently accumulates 9 Mt C yr^{-1}. Industrial by-products like alcohol and bagasse from sugar cane processing substitute fossil fuel for transportation and power generation offsetting 10 and 8 Mt C yr^{-1}, respectively. An additional opportunity for 0.53 Mt C yr^{-1} sequestration is presented by avoiding burning before harvesting of sugar cane. These data show that there could be almost full compensation between sources and sinks/offsets in the agricultural carbon cycle. There is a great opportunity to achieve this mitigation benefit because the adoption of new technologies is increasing rapidly.

Keywords: Carbon sequestration, soil carbon, no-till, sugar cane, biofuel, burning, South America, Brazil

INTRODUCTION

Brazil is the fifth largest country in the world (8 550 000 km^2) and is the most representative area of the South American subcontinent, owing to its large variations in climate, vegetation, soils and agriculture use. Therefore, Brazil is a suitable case study to demonstrate carbon cycling and sequestration opportunities in South America.

Like other South American countries, Brazil is a non-Annex I party according to the United Nations Framework Convention on Climate Change (UNFCCC) signed at Rio de Janeiro in 1992 (United Nations 1992). These countries are not obligated to reduce gas emissions, but can do so voluntarily. Another possibility is to use the Clean Development Mechanism (CDM) projects under the Kyoto Protocol. CDM allows governments or private entities in Annex I countries to implement emission reduction projects in non-Annex I countries in order to meet their emission reduction for the commitment period of 2008–2012 and, thereby, enable developing countries to benefit financially through projects of emission reduction (United Nations 1998). According to Marland *et al.* (2002) Brazil has the 18th highest fossil fuel CO_2 emission rate in the world. However, when greenhouse gas emissions from deforestation are included, Brazil becomes one of the top ten CO_2 emitters.

In this article we do not discuss aspects of emissions related to deforestation and carbon sequestration by plantations. Instead, we analyse the opportunities of reducing gas emissions and/or sequestering carbon in the agricultural sector. There are two main strategies to mitigate climate change: either modifying land use and/or modifying the management practices within the same land use; our emphasis is on the second of these two options. The two main land management changes currently underway in Brazil are (i) the use of no-tillage systems instead of conventional tillage, and (ii) the avoidance of burning as an integral part of the conventional system for harvesting sugar cane.

The main objective of this article is to compare the balance between CO_2 emissions from agricultural land and soil carbon sequestration in Brazil, and to quantify the effect on this balance of the introduction of these two changes in management.

CO_2 EMISSION FROM AGRICULTURAL LAND IN BRAZIL

The procedures adopted to estimate CO_2 emission from agricultural land in Brazil are fully described in Bernoux *et al.* (2001, 2002). Briefly, soil organic carbon stocks to a depth of 30 cm were estimated for Brazil on the basis of a map of different soil–vegetation associations combined with results

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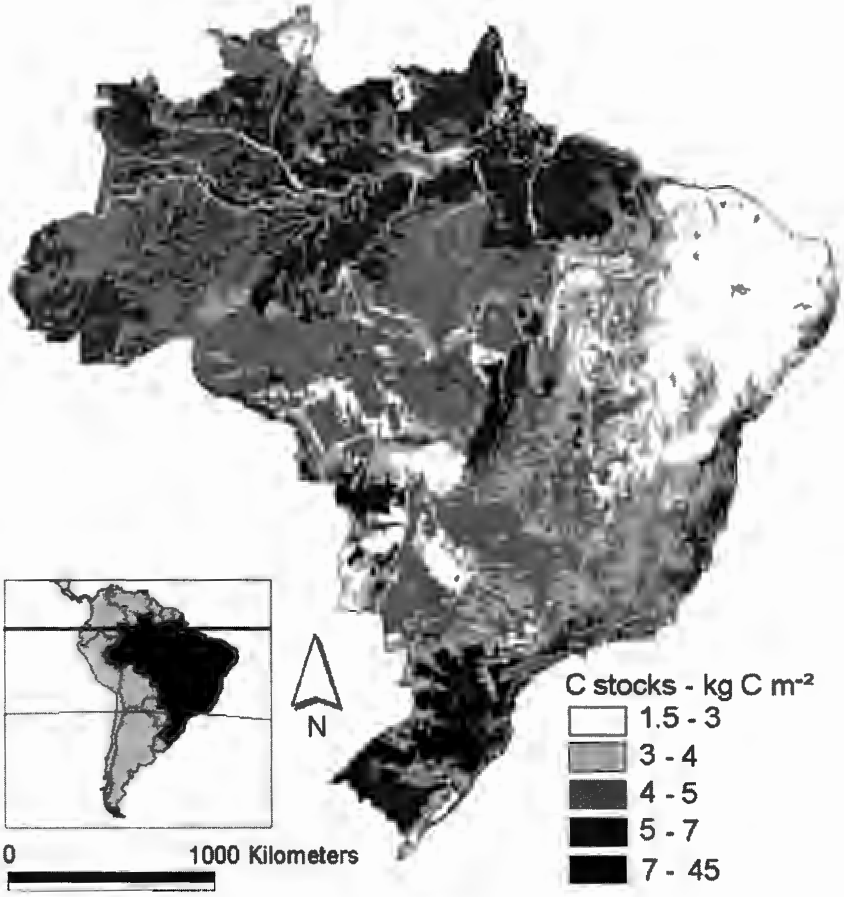

Figure 1. Map of soil carbon stocks (0–30 cm) in the soils of Brazil. (From Bernoux *et al.* 2002.)

from a soil database. The soil–vegetation map was derived by combination of soil (EMBRAPA 1981) and vegetation (IBGE 1988) maps at the 1 : 5 000 000 scale. The original soil and vegetation classifications were simplified to six soil classes (from 2698 map units divided into 69 soil types) and 15 vegetation categories (from 2021 map units divided into 94 vegetation types) on the basis of criteria recommended by IPCC/UNEP/OECD/IEA (1997). The soil–vegetation map comprised 75 categories in 21 111 map units. Mean representative carbon stocks of the map categories were calculated using a soil profile database (Bernoux *et al.* 2002) containing information on carbon concentration, bulk density, soil type and native vegetation. Approximately 2694 soil profiles were used to obtain the range of 1.5–41.8 kg C m^{-2} for the mean representative carbon stocks (Figure 1). In total, Bernoux *et al.* (2002) estimated that about 36.4 ± 3.4 Pg C was stored in the 0–30 cm layer in Brazil.

Using the map of the Brazilian soil carbon stocks for the 0–30 cm layer, Bernoux *et al.* (2001) calculated the first approximation of CO_2 fluxes from soils in Brazil for the 20-year periods 1970–1990 and 1975–1995. The methodology employed was an adaptation of the approach proposed by the IPCC in 'Revised 1996 guidelines for national greenhouse gas inventories' IPCC/UNEP/OECD/IEA (1997), which is based on the variation in soil carbon stocks as a function of change in land use. They showed that the annual fluxes for Brazil indicate a net emission of CO_2 to the atmosphere, which decreased from 93.3 Tg CO_2 for the period 1970–1990 to 46.4 Tg CO_2 (or 12.65 Tg C) for the period 1975–1995. This important change is associated with the rapid changes of land use in Brazil (Bernoux *et al.* 2001).

MAJOR CHANGES IN MANAGEMENT PRACTICES

Conventional versus no-tillage systems

Conversion of native vegetation to cultivated cropland under conventional tillage has resulted in a significant decline in soil organic matter content (Paustian *et al.* 2000; Lal 2002). Farming methods that use mechanical tillage, such as the mouldboard plough for seedbed preparation or discing for weed control, can promote soil carbon loss by several mechanisms:

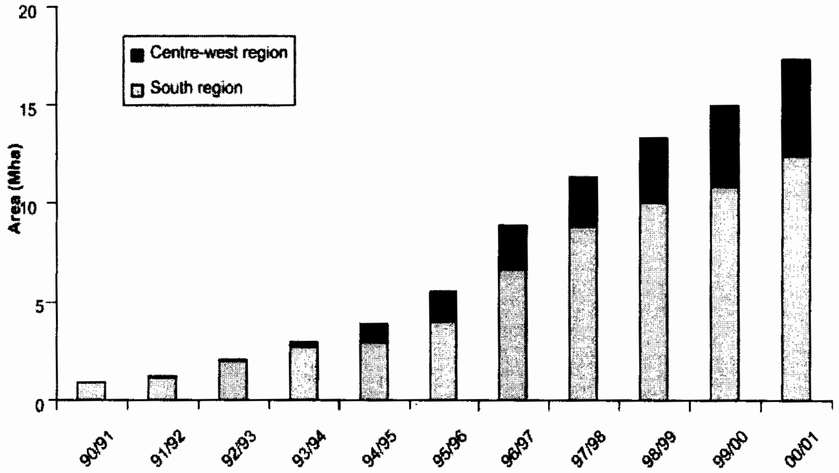

Figure 2. Cultivated area under no-tillage in Brazil for years 1990 to 2001. (Adapted from Febrapdp 2002.)

- disruption of soil aggregates, which protect soil organic matter from decomposition (Karlen & Cambardella 1996; Six *et al.* 1999);
- stimulation of short-term microbial activity through enhanced aeration, resulting in increased levels of CO_2 and other gases released to the atmosphere (Bayer *et al.* 2000a, b; Kladivko 2001);
- mixing of fresh residues into the soil where conditions for decomposition are often more favourable than on the surface (Karlen & Cambardella 1996; Plataforma Plantio Direto 2003).

Furthermore, tillage can leave soils more prone to erosion, resulting in further loss of soil carbon (Lal 2002). No-tillage practices, however, cause less soil disturbance than conventional tillage, often resulting in significant accumulation of soil carbon (Sá *et al.* 2001; Schuman *et al.* 2002) and consequent reduction of gas emissions, especially CO_2, to the atmosphere (Lal 1998; Paustian *et al.* 2000). There is considerable evidence that the main effect is in the topsoil layers with little overall effect on carbon storage in deeper layers (Six *et al.* 2002).

Globally, approximately 63 million hectares of land are presently under no-tillage systems, with the USA having the largest area at about 21.1 million hectares (Derpsch 2001). In Brazil, no-tillage systems started in the south region (Paraná State) in 1972 as an alternative to the misuse of land, which had caused erosion (Denardin & Kochhann 1993). This alternative quickly expanded to different states and the planted area under no-tillage has since then increased exponentially (Figure 2). In the early 1990s the area covered by no-tillage was 1 million ha, which had increased 10 times by 1997. Now, the 17–18 million ha covered by no-tillage practice (Febrapdp 2002) make Brazil the second largest adopter in the world. This expansion is taking place not only as result of the conversion from conventional tillage in the southern region (72%), but also after clearing natural savannah in the centre-west area (28%). More recently, due to the high profits that result, ranchers in the Amazon region are converting old pastures to soybean/millet under no-tillage.

Burning versus non-burning harvesting sugar cane system

The sugar cane crop offers one of the most cost-effective renewable energy sources that are readily available in developing countries (Macedo 1998). It is a highly efficient converter of solar energy and has the highest energy-to-volume ratio of all energy crops (Johnson 2000). Sugar cane is a perennial crop that is harvested on an annual cycle. There may be up to six cycles before re-planting, and generally only a short fallow between ploughing out the old cane and re-planting. On the majority of farms in Brazil sugar cane is grown as a monoculture (Macedo 1997). It is a highly flexible resource, offering alternatives for production of food, feed, fibre and energy. Such flexibility is valuable in the developing world where fluctuations in commodity prices and weather conditions can cause severe economic hardships.

For biomass energy production, sugar cane is an excellent feedstock in terms of efficiency and flexibility, providing gaseous, liquid and solid fuels (Ripoli *et al.* 2000). It offers the potential for climate change mitigation through substitution of fossil fuels without the need for excessive subsidies or expensive infrastructure development.

The Brazilian ethanol programme remains the world's largest CO_2 mitigation programme (Johnson 2000). At present in Brazil, sugar cane is cultivated on about 5 million ha (Figure 3a), with an average annual production of approximately 300 million tonnes (FNP 2002). In 1999/00 about 19 million tonnes of sugar and 12 million cubic metres of alcohol (Figure 3b) were produced (CENBIO 2002).

Two procedures are adopted for sugar cane harvesting. Traditionally, sugar cane was burnt in the field to remove leaves and insects a few days before harvesting, in order to facilitate manual cutting (Thorburn *et al.* 2001). However, since May 2000 this common practice has been progressively

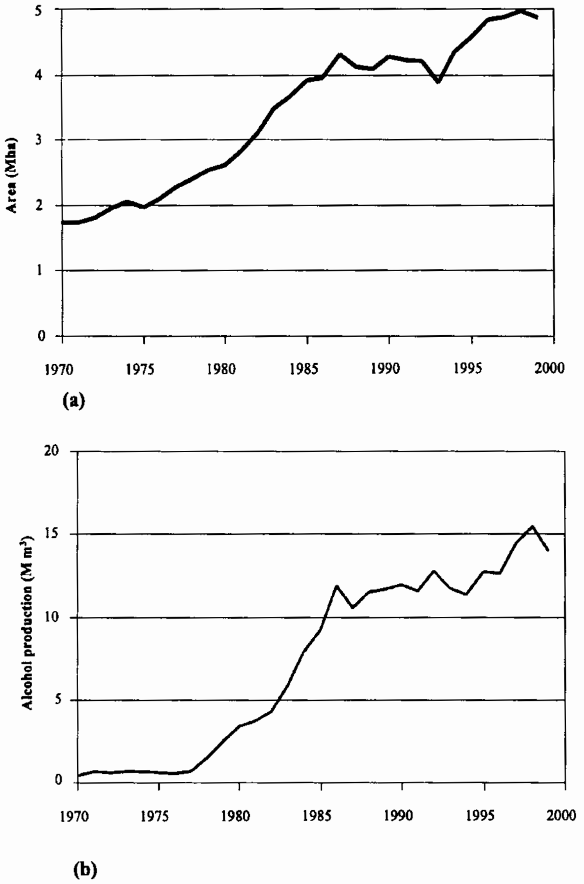

Figure 3. Area under sugar cane in Brazil (a) and production of hydrated + anhydrous alcohol in Brazil (b). (Adapted from FNP 2002 and CENBIO 2002.)

prohibited by law in some areas of Brazil. In addition to CO_2 emission, other pollutant gases are emitted during the burning period, causing respiratory problems and ash fall over urban areas (Andreae & Merlet 2001). Even though the law will not be fully implemented before 2030, the adoption of mechanical harvesting has increased exponentially in Brazil during the last decade. In 1997 about 20% of the Brazilian sugar cane area was harvested by machine (Silva 1997) and it is estimated that about 80% of the planted area in the most productive sugar cane region in Brazil will use mechanical harvesting in the next 20 years (CENBIO 2002).

The current mechanical approach is only suitable for slopes of less than 12% (Luca 2002), and when the burning ban is fully implemented steeply sloping land will likely go out of sugar cane production unless new harvesting methods are developed. By the return of crop residues to the soil surface, the mechanical approach has indirectly favoured soil organic matter accumulation (Thorburn *et al.* 2001; Luca 2002) and gas emission reduction as compared to the burning system (Andreae & Merlet 2001).

CARBON SEQUESTRATION RELATED TO CHANGES IN MANAGEMENT PRACTICES

Conventional versus no-tillage systems

Changes in soil carbon stocks under no-tillage have been estimated in earlier studies for temperate and tropical regions. Cambardella & Elliott (1992) showed an increase of 6.7 t C ha^{-1} in the top 20 cm in an autumn-sown wheat system after 20 years of no-tillage in comparison to conventional tillage. Reicosky *et al.* (1995) reviewed various publications and found that organic matter increased under conservation management systems with rates ranging from 0 to 1.15 t C $ha^{-1} yr^{-1}$, with highest accumulation rates generally occurring in temperate conditions. Lal *et al.* (1998) calculated carbon sequestration rates of 0.1 to 0.5 t C ha^{-1} yr^{-1} in temperate regions. For the tropical west of Nigeria, Lal (1997) observed a 1.33 t C ha^{-1} increment during 8 years under no-tillage as compared to the conventional tillage of maize, which represents an accumulation rate of 0.17 t C $ha^{-1} yr^{-1}$.

In the tropics, specifically in Brazil, the rate of carbon accumulation has been estimated in the two main regions (south and centre-west) under no-tillage systems. In the southern region, Sá (2001) and Sá *et al.* (2001) estimated greater sequestration rates of 0.8 t C $ha^{-1} yr^{-1}$ in the 0–20 cm layer and 1.0 t C $ha^{-1} yr^{-1}$ at 0–40 cm soil depth after 22 years under no-tillage compared with soils under conventional practice over the same period. The authors mentioned that the accumulated carbon was generally greater in the coarse (>20 μm) than in the fine (<20 μm) particle-size fraction, indicating that most of this additional carbon is weakly stable. Bayer *et al.* (2000a, b) found a carbon accumulation rate of 1.6 t $ha^{-1} yr^{-1}$ for a 9-year no-tillage system compared with 0.10 t $ha^{-1} yr^{-1}$ for the conventional system in the first 30 cm layer of an Acrisol in southern Brazil. Corazza *et al.* (1999) reported an additional accumulation of approximately 0.75 t C $ha^{-1} yr^{-1}$ in the 0–40 cm soil layer attributed to no-tillage in the savannah region located in the centre-west. Estimates by Amado *et al.* (1998) and Amado *et al.* (1999) indicated an accumulation rate of 2.2 t $ha^{-1} yr^{-1}$ of soil organic carbon in the first 10 cm layer. Other studies considering no-till systems carried out in the centre-west part of Brazil (Lima *et al.* 1994; Castro-Filho *et al.* 1998; Riezebos & Loerts 1998; Vasconcellos 1998; Peixoto *et al.* 1999; Spagnollo *et al.* 1999; Resck *et al.* 2000) reported soil carbon sequestration rates due to no-tillage varying from 0 up to 1.2 t C $ha^{-1} yr^{-1}$ for the 0–10 cm layer.

As mentioned before, no-tillage systems in Brazil can vary significantly between regions. Therefore, in our calculations of additional soil carbon accumulation due to no-tillage we have used a weighted average value of 0.5 t C $ha^{-1} yr^{-1}$ in the first 10 cm depth. This weighted average value was calculated using soil carbon sequestration rates for the southern region (72% of the no-till area) and also for the centre-west region (28% of the no-till area).

The total area in Brazil under no-tillage in 2000/01 was about 18 million ha, and the weighted average soil carbon accumulation rate due to no-tillage adoption is 0.5 t C $ha^{-1} yr^{-1}$ in the first 10 cm depth, giving an estimated change in total soil carbon of about 9 Mt yr^{-1}. In addition, we should include a carbon-offset due to a significant reduction in fuel consumption (60–70%) by machinery in no-tillage systems compared with conventional tillage (Plataforma Plantio Direto 2003).

It is important to mention that there is a lot of controversy regarding whether no-tillage really does sequester much soil carbon, especially when the whole soil profile is considered (Smith *et al.* 1998). Most studies that have looked at the whole profile have shown insignificant soil carbon gains. The quantity of residues returned, variations in the practices implemented and perhaps the type of climate are factors likely to influence the outcome. According to Smith *et al.* (1998) only certain fixed amounts of soil carbon can be gained, up to a new equilibrium limit, which is reversible if management reverts to conventional tillage.

Burning versus non-burning harvesting of sugar cane

The net contribution of the Brazilian sugar cane industry to the evolution of atmospheric CO_2 is a combination of three activities, two industrial and one agricultural. The first activity is the substitution of gasoline as a fuel by alcohol. Since the early 1930s the Brazilian government has given incentives for alcohol production from sugar cane to be added to gasoline in the transportation sector (Sociedade Nacional de Agricultura 2000). Due to oil crises in 1973–74, Brazilian authorities created new incentives through the Brazilian alcohol program (Proalcool) to increase the production of alcohol to 10.7 billion litres per year (Coelho *et al.* 2000). During 1975–2000, 156 million m^3 of hydrated alcohol and 71 million m^3 of anhydrous alcohol were produced. Considering that 1 m^3 of gasoline is substituted for 1.04 m^3 anhydrous alcohol and 0.8 m^3 hydrated alcohol, and that gasoline contains on average 86.5% carbon (American Petroleum Institute 1988), we calculate that during 1975–2000, 172 Mt C were offset and consequently not emitted to the atmosphere, which gives an average annual offset of 6.8 Mt C. However, alcohol production and consumption are increasing every year in Brazil. If data just for the last 10 years were used, the offset would be about 10 Mt C yr^{-1}.

The second associated mitigation factor in the sugar cane system is related to the use of plant residues as a fuel. At the mill, the cane stalks are shredded and crushed to extract the cane juice while the fibrous outer residue, known as bagasse, is burnt to provide steam and electricity for the mill (Luca 2002). For instance, in 1998 approximately 45 Mt dry matter of sugar cane residues were produced in Brazil (Balanço Energético Brasileiro 1999). Assuming 2.35 t of residues substitute for 1 t of fossil fuel (Macedo 1997), we estimate that 8 Mt C were offset in 1998 due to use of sugar cane residues at the mill instead of fuel. This renewable energy resource, found mainly in developing countries, has obvious appeal for international efforts to reduce CO_2 emissions. Moreover, the organic wastewater stream from alcohol production, known as vinasse, can be used as fertilizer or can be converted to methane gas through anaerobic digestion. The transportation fleets used in sugar factories and ethanol distilleries in Brazil have in some cases been powered by methane gas (Johnson 2000). The production of alcohol has been viewed as a valuable means of saving foreign exchange in developing countries while at the same time providing local and global environmental benefits. In addition to climate mitigation and reduction of local pollutants, it can serve as an octane enhancer that might speed the phasing-out of leaded gasoline. The economic and environmental attractiveness of sugar cane as a renewable energy resource and the variety of options for increasing use of cane by-products and co-products could one day lead to sugar becoming the by-product rather than the main product.

The third activity associated with CO_2 mitigation in the sugar cane system is conversion to harvesting without prior burning. At present there are 5 Mha under sugar cane in Brazil (FNP 2002) of which approximately 20% (1.5 Mha) is harvested without burning (Silva 1997). In the absence of burning, sugar cane residues are returned to the soil surface with litter. This factor is significant because it contrasts with the alternative system in which cane is burnt before harvest removing dead and green leaves, whereby very little carbon is returned to the soil from the above-ground vegetation. For instance, Blair *et al.* (1998) found significant increases in the labile fraction in green refuse treatments compared to the refuse burning treatments in the surface soils of two 'green trash' management trials in Australia. In southern Brazil, Feller (2001) reported that an average of 0.32 t C ha^{-1} yr^{-1} was accumulated in 12 years in the first 20 cm depth of an Oxisol by omitting burning. Other estimates exist, but for shorter periods of non-burning. For instance, Luca (2002) reported increases ranging from 2 to 3.1 t C ha^{-1} and 4.8 to 7.8 t C ha^{-1}, respectively, for the top 5 cm and 40 cm depth during the first 4 years following non-burning. The corresponding annual increases ranged from 0.5 to 0.78 t C ha^{-1} yr^{-1} for the 0–5 cm layer and from 1.2 to 1.9 t C ha^{-1} yr^{-1} for the 0–40 cm layer. However, sugar cane is typically replanted every 6–7 years and tillage practices are commonly used. This procedure would probably have reduced the high rates presented by Luca (2002) had the study been for a longer period. In our estimate of carbon sequestration we have used the value found by Feller (2001) because it represents the longest period of harvest without burning in Brazil and incorporates cane replanting. Thus, considering the area under this management system and the mean annual carbon accumulation rate, a total of 0.48 Mt C yr^{-1} is sequestered in Brazil.

When sugar cane is burnt, other greenhouse gases like CH_4 and N_2O are emitted to the atmosphere. Results from Macedo (1998) show that 6.5 kg CH_4 ha^{-1} are released from the burning of sugar cane. Considering the total area of sugar cane undergoing non-burning harvesting (1.5 Mha) and that CH_4 has a global warming potential of 21, we have calculated that 0.2 Mt CO_2-equivalents (0.05 Mt C) are not emitted annually to the atmosphere as a result of adopting non-burning. The same calculation is required for N_2O emission; however, currently no adequate measurements of this gas are available for sugar cane.

In summary, when sugar cane is harvested mechanically without burning in Brazil, 0.48 Mt C yr^{-1} is sequestered in soil and methane emission equivalent to 0.05 Mt C yr^{-1} is avoided. This total of 0.53 Mt C yr^{-1} is the contribution of the agricultural sector. Moreover, the industrial sector contributes not only the $10\,\mathrm{Mt\,C\,yr^{-1}}$ offset due to substitution of fossil fuel by alcohol for transportation but also the $8\,\mathrm{Mt\,C\,yr^{-1}}$ by substituting fossil fuel for power generation at the mill. Combining the agricultural and the industrial sectors, sugar cane produced without burning gives a total of $18.5\,\mathrm{Mt\,C\,yr^{-1}}$ removed from the atmosphere.

SEQUESTRATION OPPORTUNITIES

The cultivated area under no-tillage in Brazil is increasing rapidly at an average of 2.4 million ha $\mathrm{yr^{-1}}$ over the last 5 years. Assuming the same growth pattern, projections show that in less than 10 years the cultivated area under no-tillage will have doubled. Consequently, current estimates for soil carbon accumulation ($9\,\mathrm{Mt\,C\,yr^{-1}}$) may double in the next 10 years.

The non-burning harvesting system adopted on 20% of the crop in Brazil contributes through soil sequestration and carbon offset at a rate of $18.5\,\mathrm{Mt\,C\,yr^{-1}}$. This rate is going to increase substantially as the non-burning system is expected to embrace 50% of the crop in the next decade (Macedo 1998).

CONCLUSIONS

Estimated annual fluxes for Brazilian agriculture indicate a net emission of $46.4\,\mathrm{Mt\,CO_2}$ (or $12.65\,\mathrm{Mt\,C}$) to the atmosphere for the period 1975–95. However, the main changes in agricultural management discussed in this article contribute together to CO_2 mitigation with a total of $9.53\,\mathrm{Mt\,C\,yr^{-1}}$. Of this total, $9\,\mathrm{Mt\,C\,yr^{-1}}$ relates to adoption of no-tillage and $0.53\,\mathrm{Mt\,C\,yr^{-1}}$ relates to introduction of sugar cane harvesting without burning. The implementation of these two practices is almost sufficient to compensate for the net soil emissions of $12.65\,\mathrm{Mt\,C\,yr^{-1}}$.

Apparently, no-tillage is more effective at sequestering carbon than harvesting cane without burning. However, we should emphasize that the area under no-tillage is about 10 times greater than the area under sugar cane. The carbon sequestration rate per unit area under no-tillage is slightly more than the rate for non-burning. If the CO_2-equivalent of N_2O emitted during burning of sugar cane were subtracted these rates would probably be similar. In addition to the CO_2 mitigation benefit due to no-tillage, sugar cane provides extra benefits derived from the substitution of fossil fuel by alcohol and bagasse.

In addition to the CO_2 mitigation related to the main management practices discussed here, the adoption of good management strategies has the potential to raise soil carbon levels and consequently improve soil structure. This would result in increased infiltration rates, better soil–water relations, reduced surface sealing and erosion which should lead to increased crop yields. The improvement and maintenance of soil carbon and soil structure are necessary for sustainable agricultural systems and conservation of the soil resource.

The estimate presented for Brazil reflects the general position throughout South America not only because Brazil covers a major part of the continent, but also because the other countries are adopting no-tillage and similar new management practices.

Adoption of new technologies such as no-tillage and mechanical harvesting are important strategies to mitigate climate change, but in the developing countries of South America social problems, for example unemployment of unskilled workers, should also be considered by decision makers. These social problems could be addressed using funds from developed countries raised by the Clean Development Mechanism (CDM) of the Kyoto Protocol. Under the Protocol these funds must be used to achieve sustainable development.

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