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Cropping systems, carbon sequestration and erosion in Brazil, a review¹

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Abstract – Soils represent a large carbon pool, approximately 1500 Gt, which is equivalent to almost three times the quantity stored in terrestrial biomass and twice the amount stored in the atmosphere. Any modification of land use or land management can induce variations in soil carbon stocks, even in agricultural systems that are perceived to be in a steady state. Tillage practices often induce soil aerobic conditions that are favourable to microbial activity and may lead to a degradation of soil structure. As a result, mineralisation of soil organic matter increases in the long term. The adoption of no-tillage systems and the maintenance of a permanent vegetation cover using Direct seeding Mulch-based Cropping system or DMC, may increase carbon levels in the topsoil. In Brazil, no-tillage practices (mainly DMC), were introduced approximately 30 years ago in the south in the Paraná state, primarily as a means of reducing erosion. Subsequently, research has begun to study the management of the crop waste products and their effects on soil fertility, either in terms of phosphorus management, as a means of controlling soil acidity, or determining how manures can be applied in a more localised manner. The spread of no-till in Brazil has involved a large amount of extension work. The area under no-tillage is still increasing in the centre and north of the country and currently occupies ca. 20 million hectares, covering a diversity of environmental conditions, cropping systems and management practices. Most studies of Brazilian soils give rates of carbon storage in the top 40 cm of the soil of 0.4 to 1.7 t C ha⁻¹ per year, with the highest rates in the Cerrado region. However, caution must be taken when analysing DMC systems in terms of carbon sequestration. Comparisons should include changes in trace gas fluxes and should not be limited to a consideration of carbon storage in the soil alone if the full implications for global warming are to be assessed.

no-tillage / mulch / stocks / fluxes / greenhouse gas / Brazil

1. INTRODUCTION

Concerns about global warming and increasing atmospheric greenhouse gas concentrations (CO₂, CH₄ and N₂O) have led to questions on the role of soils as a source or sink of carbon (Houghton, 2003). Excluding carbonated rocks, soils constitute the largest surface carbon pool, approximately 1500 Gt, equivalent to almost three times the quantity stored in the terrestrial biomass and twice the amount stored in the atmosphere. Therefore, any modification of land use or land management can induce changes in soil carbon stocks, even in agricultural systems in which carbon is perceived to be in a steady state (Lal et al., 1997; Six et al., 2002).

No-tillage is presumed to be the oldest system of soil management. In some parts of the tropics, no-tillage is still practised as part of slash-and-burn agriculture. After clearing an area of forest, by controlled burning, seed is placed directly into the soil. However, as mankind developed more systematic agricultural systems, cultivation of the soil became an accepted prac-

tice as a means of preparing a more suitable environment for plant growth. Paintings in ancient Egyptian tombs portray farmers tilling their fields using a swing-plough and oxen, prior to planting. Indeed, tillage as symbolised by the mouldboard plough became almost synonymous with agriculture (Dick and Durkalski, 1997). No-tillage can be defined as a crop production system where soil is left undisturbed from harvest to planting except for fertiliser application.

In the southern part of Brazil, no-tillage was developed in response to soil erosion problems and declining levels of land productivity under “conventionally” tilled systems. The underlying land management principles that led to the development of no-tillage systems were: prevention surface sealing caused by rainfall impact, achievement and maintenance of an open soil structure and reduction of the volume and velocity of surface runoff. Consequently, the no-tillage strategy was based on two essential farm practices: (i) not tilling and (ii) keeping soil covered at all times. The particular no-tillage system

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considered in this paper is referred to as ‘a direct seeding mulch-based cropping system’ (referred to here as DMC).

Farming methods that use mechanical tillage, such as the mouldboard plough, secondary tillage tools for seedbed preparation or disking for weed control, can cause soil carbon loss by several mechanisms: (1) by disrupting soil aggregates, which protect soil organic matter from decomposition (Karlen and Cambardella, 1996; Six et al., 1999); (2) by stimulating short-term microbial activity through enhanced aeration, resulting in increased net release of CO₂ and other gases to the atmosphere (Bayer et al., 2000a, b; Kladvik, 2001), and (3) by mixing fresh residues into the soil where conditions for decomposition are often more favourable than on the surface (Karlen and Cambardella, 1996; Plataforma Plantio Direto, 2003). Furthermore, conventional tillage can leave soils more prone to erosion, resulting in further loss of soil carbon (Lal, 2002). DMC practices, however, reduce soil disturbance and often result in a significant accumulation of soil carbon (Sá et al., 2001; Schuman et al., 2002) and consequently a reduction of gas emissions, especially CO₂ (Lal, 1998; Paustian et al., 2000). Furthermore, in Brazilian conditions, the possibility of an earlier seeding date with direct seeding often enables a second crop cycle with a commercial or cover crop. Consequently, more biomass is returned to the system each year. Despite this, there is considerable evidence that the main effect in terms of carbon storage, of no-tillage systems, is seen in the topsoil with little overall effect at deeper layers (Six et al., 2002).

The objective of this paper is to provide a synthesis of the effects of DMC on carbon sequestration and erosion in Brazil.

2. THE EXPANSION OF NO-TILLAGE IN BRAZIL

The history of DMC started in the south of Brazil. The first scientific no-tillage experiment was conducted in 1969 by the Federal University of Rio Grande do Sul in the southern part of the country on an area of 1 ha; however, the trial was interrupted by the accidental destruction of the no-tillage seeding machine after the first seeding (Borges Filho, 2001). Several other studies were set up at the beginning of the 1970s in Parana state near Londrina and Ponta Grossa (Borges Filho, 2001; Sá et al., 2001; Six et al., 2002). The effectiveness of no-tillage systems at controlling soil erosion and reducing costs encouraged farmers in Parana State to take up the practice. This uptake corresponded with the release of modern herbicides, such as glyphosates, in the 1970s, which made no-tillage systems easier to manage. During the crop year 1974/75, DMC systems were adopted by approximately 235 farms, (representing ca. 16500 ha of cultivated land) in Parana State. Until the end of the 1970s the spread of DMC was slow and limited to Parana and Rio Grande do Sul, mainly due to a lack of technical assistance and a lack of studies demonstrating the advantages of DMC. At the beginning of the 1980s, producers began to organise themselves into associations to promote DMC, the most well known being the “Clube da Minhoca” (literally meaning “The Earthworm Club”) and the “Clubes Amigos da Terra” (The Friends of the Soil Clubs) (Borges Filho, 2001).

In the Cerrado regions (the central area of Brazil covered mainly by Savannah), DMC was imported from the south at the beginning of the 1980s. However, the systems had to be adapted

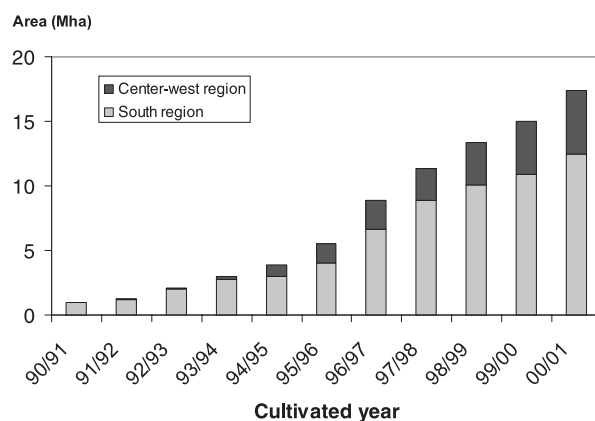


Figure 1. Cultivated area under direct seeding mulch-based cropping (DMC) systems in Brazil. Adapted from Febrapdp (2004).

somewhat in order to be applicable to this area. Winters in the Cerrado region are dryer and hotter than in the south and summers are hot and humid, inducing a rapid rate of crop residue decomposition. One of the first trials involving DMC was carried out in 1981 in Rio Verde in Goiás State, by Eurides Penha. Penha seeded 200 ha of soybean on soybean residues from the previous crop. The year after, another farmer tried DMC systems with soybean and maize in Santa Helena de Goiás, a neighbouring city (Borges Filho, 2001). In the beginning, the expansion of DMC was slow and only really began to accelerate at the end of the 1980s. During the cropping year 1991/92 the area under DMC in the Cerrado region was approximately 180 000 ha, representing 13.3% of the total land under DMC in Brazil. From the early 1990s onwards, the rate of expansion of DMC in the Cerrado region became faster than in the rest of Brazil (Fig. 1).

At present, approximately 63 million ha are under no-tillage systems throughout the world, with the USA having the largest area (~ 21.1 million ha) (Derpsch, 2001). The 20 million ha covered by DMC in Brazil (Febrapdp, 2004) make the country the second largest adopter of the practice in the world. The expansion of DMC in Brazil has taken place not only as a result of the conversion from conventional tillage in the southern region (72%), but also following the clearing of natural savannah in the central-western area (28%). More recently, due to the high profit margins involved, ranchers in the Amazon region have started to convert old pastures into soybean/millet DMC systems. During the cropping year 2000/01 DMC systems dominated in the southern region (Parana – 5 Mha, Rio Grande do Sul – 3.6 Mha and Santa Catarina – 1 Mha) and the Cerrado region (4.9 Mha), and was also significant in Mato Grosso do Sul (1.7 Mha) and São Paulo State (1 Mha).

3. CARBON SEQUESTRATION

For the purpose of this review the term ‘carbon sequestration’ is used according to the definition given by Bernoux et al. (2005). “Soil carbon sequestration”, for a specific agro-ecosystem in comparison with a reference one, should be considered as the result (for a given period of time and portion of space)

of the net balance of all greenhouse gases, expressed in C-CO₂ equivalent or CO₂ equivalent, computing all emission sources at the soil-plant-atmosphere interface, and also all the indirect fluxes (gasoline, enteric emissions, etc.). When comparing a DMC system with a conventional tillage system this means that not only is carbon storage taken into account, but the resulting greenhouse gas fluxes such as N₂O and CH₄ at the field and farm level are also taken into account.

3.1. No-tillage, conventional tillage and carbon storage

Lindstrom et al. (1998) reported that globally, conservation or reduced tillage can store 0.1–1.3 t C ha⁻¹ yr⁻¹ and could feasibly be adopted on up to 60 percent of arable lands. These estimates depend on continued use of conservation tillage. Use of intensive tillage or mouldboard ploughing can negate or offset any gains made in carbon sequestration.

Changes in soil carbon stocks under no-tillage have been estimated in earlier studies for temperate and tropical regions. Cambardella and Elliott (1992) showed an increase of 6.7 t C ha⁻¹ in the top 20 cm in a wheat-fall rotation system after 20 years of no-tillage, compared with 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 the highest accumulation rates generally occurring in temperate conditions. Lal et al. (1998) calculated a carbon accumulation rate 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 with the conventional tillage of maize, which represents an accumulation rate of 0.17 t C ha⁻¹ yr⁻¹. More recently, a review by Six et al. (2002) reported that in both tropical and temperate soils, a general increase in carbon levels (325 ± 113 kg C ha⁻¹ yr⁻¹) was observed under no-tillage systems compared with conventional tillage.

In the tropics, specifically in Brazil, estimates of the rate of carbon accumulation have generally been restricted to the two main regions under DMC (the south and central west). In the southern region, Sá (2001) and Sá et al. (2001) estimated a greater accumulation rate (0.8 t C ha⁻¹ yr⁻¹ in the 0–20 cm layer and 0.9 t C ha⁻¹ yr⁻¹ in the 0–40 cm layer) after 22 years under DMC compared with the same period under conventional tillage. The authors mentioned that 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 DMC system compared with 0.10 t ha⁻¹ yr⁻¹ for the conventional system in the first 30 cm layer of an Acrisol, in the southern part of 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 due to no-tillage, in the Cerrado region located in the central west. Estimates by Amado et al. (1998, 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 central-western part of Brazil (Castro Filho et al., 1998, 2002; Lima et al., 1994; Peixoto et al., 1999; Resck et al., 2000; Riezebos and Loerts, 1998) reported soil carbon

accumulation rates due to no-tillage varying from 0 to 1.2 t C ha⁻¹ yr⁻¹ for the 0–10 cm layer.

More detailed accumulation rates are reported in Table I. Rates are organised by region and are derived from published and unpublished material. In the Cerrado region carbon accumulation rates vary from 0.4 to 1.7 t C ha⁻¹ for the 0–40 cm layer, which is similar to the range found in the southern region (–0.5 to 0.9 t C ha⁻¹). Mean rates of carbon storage were similar among “Cerrado” (0.65 t C ha⁻¹), “South” (0.68 t C ha⁻¹), and “Other” (0.60 t C ha⁻¹) regions, when the soil surface layer was considered (0–20 cm). More variability was found in the southern region (–0.07 to 1.6 t C ha⁻¹) for the 0–20 cm layer than in the other regions. However, it is important to mention that these mean values aggregate different soil and crop types and the variability is high. For instance, the mean value of 0.68 t C ha⁻¹ for the southern region was obtained by averaging 15 observations (Tab. I) and the associated standard deviation is 0.54 t C ha⁻¹.

Some studies performed in Brazil reported that organic carbon (OC) contents under DMC and conventional systems can be very similar (Corazza et al., 1999; Freixo et al., 2002; Roscoe and Buurman, 2003; Sisti et al., 2004). Sisti et al. (2004) reported that the soil under native vegetation (measured in areas neighbouring the experimental site) had a high carbon and nitrogen content (37 g C and 3.1 g N per kg soil) in the first 5 cm depth. Carbon and nitrogen contents declined to approximately half these values in the 10–15 cm layer. The carbon concentration in the top 5 cm of soil was considerably higher in all three rotations managed with DMC compared with the conventional system, although not as high as under the native forest. Machado and Silva (2001) showed decreases in SOC of 23.4% and 47.8%, respectively, at 0–5 cm depth for DMC and conventional tillage systems, when compared with an adjacent non-cultivated area. The study was carried out on an Oxisol in the south of Brazil, following 11 years of soybean-wheat cultivation. However, the authors also found SOC in the 0–40 cm layer to be the same as the forest soil for both DMC and conventional tillage.

Another important point when comparing soil carbon stocks in DMC and conventional systems is to avoid comparing superficial layers such as 0–5 cm and 0–10 cm. In conventional systems involving tillage, homogenisation occurs in the first 20 cm and thus a superficial layer cannot be compared directly without bias.

3.2. Fluxes of other greenhouse gases

Increasingly, attention is being focused on the relationship between atmospheric carbon dioxide concentrations and carbon concentrations in soil. Carbon dioxide makes the largest contribution to climate change simply because of its abundance in the atmosphere compared with other greenhouse gases. Changes in farming practices, such as altering tillage intensity and crop rotations, may alter carbon sequestration in the soil and thereby help to alleviate carbon dioxide accumulation in the atmosphere. However, fluxes of other greenhouse gases such as N₂O and CH₄ at the field and farm level may be altered by DMC. Six et al. (1999) reported that CH₄ uptake increased (0.42 ± 0.10 kg C-CH₄ ha⁻¹ yr⁻¹) and N₂O emissions increased (2.91 ± 0.78 kg N-N₂O ha⁻¹ yr⁻¹), in temperate soils, under

Table I. Carbon storage rates. Accumulation following conversion of a conventional tillage system to DMC in direct seeding mulch-based cropping (DMC) systems in Brazil.

Place	State ^a	Succession or dominant plant ^b	Reported soil classification	Clay (%)	Layer (cm)	Duration (yr)	Rate (t C/ha)	Source	
<i>Cerrados region</i>									
Planatina	DF	S/W	Latossol (Oxisol)	40–50	0–20	15	0.5	Corazza et al., 1999	
					0–40	15	0.8		
Sinop	MT	R – S/So – R/So – S/M – S/E	Latossol (Oxisol)	50–65	0–40	5	1.7	Perrin, 2003	
Goiânia	GO	Rice/Soya	Dark red Latossol		0–10	5	0.7	ud	
Rio Verde	GO	M or S/Fallow S/M or So or Mi	Red Latossol	45–65	0–20	12	0.8	Scopel et al., 2003	
Not specified	?	M or S	Dark Red Latossol (Oxisol)	>30	0–40	16	0.4	Resck et al., 2000	
<i>Southern region</i>									
Londrina	PR	W/S	Oxisol		0–10	22	0.31	Machado and Silva, 2001	
					0–20	22	0.25		
					0–40	22	–0.17		
Londrina	PR	S/W – S/L – M/O	Red Latossol		0–20	7	0.5–0.9	Zotarelli et al., 2003	
Londrina	PR	S/W/S or M/W/M or S/W/M	Oxisol Typic Haplorthox		0–10	14	0.4 ^d	Castro Filho et al., 1998	
					0–20		0.2 ^d		
Londrina	PR	S/W/S or M/W/M or S/W/M	Oxisol Typic Haplorthox		0–40	21	0 ^c	Corazza Filho et al., 2002	
Ponta Grossa	PR	(S or M)/(O or W)	Oxisol Typic hapludox	40–45	0–40	22	0.9	Sá et al., 2001	
Tibagi	PR	(S or M)/(O or W)	Oxisol Typic hapludox	40–45	0–40	10	–0.5	Sá et al., 2001	
Tibagi	PR	M/W – S/O – S/O	Red Latossol Oxisol	40–45	0–10	22	1.0 ^d	Venzke Filho et al., 2002	
Tibagi	PR	M/W – S/O – S/O	Red Latossol Oxisol	42	0–20	10	1.6	Siqueira Neto, 2003	
Toledo	PR	S/O S/O	Haplic Ferrasol Haplic Ferrasol		0–10	3	–0.68 ^d	Riezebos and Loerts, 1998	
					0–10	10	0.37 ^d		
Passo Fundo	RS	W/S	Oxisol		0–10	11	0.59	Machado and Silva, 2001	
					0–20	11	–0.07		
					0–40	11	0.29		
Passo Fundo	RS	W/S	Red Latossol Typic hapludox	63	0–30	13	0 ^c	Sisti et al., 2004	
					0–30	13	0.4		
					0–30	13	0.7		
Passo Fundo	RS	W/S	Red Latossol Typic hapludox	63	0–10	11	0.3	Freixo et al., 2002	
					0–20	11	0 ^c		
					0–30	11	0 ^c		
					0–10	11	0.4		Freixo et al., 2002
					0–20	11	0.2		
0–30	11	0 ^c							

Table I. Continued.

Place	State ^a	Succession or dominant plant ^b	Reported soil classification	Clay (%)	Layer (cm)	Duration (yr)	Rate (t C/ha)	Source
Santa Maria	RS	M and Mu/M	Ultisol	15	0–20	4	1.3	Amado et al., 2001
Eldorado do Sul	RS	M/G	Podzólico vermelho escuro		0–17.5	5	1.4 ^d	Testa et al., 1992
		M/La			0–17.5	5	0.6 ^d	
		O/M			0–17.5	5	0.2 ^d	
Eldorado do Sul	RS	O+V/M+C	Clay loam Acrisol Typic Paleudult	22	0–17.5	9	0.84	Bayer et al., 2002
Eldorado do Sul	RS	O/M	Clay loam Acrisol Typic Paleudult	22	0–30	9	0.51	Bayer et al., 2000b
		O+V/M+C			0–30	9	0.71	
Eldorado do Sul	RS	O+V/M+C	Clay loam Acrisol TypicPaleudult	22	0–17.5	12	1.26	Bayer et al., 2000a
Lages	SC	M or S / W or O	Cambissol		0–20	8	1.0	Bayer and Bertol, 1999
Other regions								
Campinas	SP	S or C / M	Rhodic Ferralsol Typic Haplorthox	60	0–20	3	0.8 ^{de}	De Maria et al., 1999
					0–20	8	0.4 ^{de}	
Sete Lagoas	MG	M/B	Dark red Latossol Typic Haplustox		0–15	10	0 ^c	Roscoe and Buurman, 2003
					0–45		0 ^c	

^a PR = Parana, RS = Rio Grande do Sul, DF = Distrito Federal, SC = Santa Catarina, SP = São Paulo, MT = Mato Grosso, GO = Goiás, MG = Minas Gerais; ^b Dominant succession: W = Wheat (*Triticum aestivum*), S = Soybean (*Glycine max*), So = Sorghum (*Sorghum vulgare*), R = Rice (*Oriza sativa*), E = *Eleusine coracana*, O = Oat (*Avena sativa*), V = Vetch (*Vicia sativa*), M = Maize (*Zea mays*), B = Beans (*Phaseolus vulgaris*), Mu = Mucuna (*Stizolobium cinereum*), C = cowpea (*Vigna unguiculata*), L = Lupine bean (*Lupinus angustifolios*), La = Lablabe (*Dolichos lablab*), G = Guandu (*Cajanus cajan*); ^c 0 means that the difference was not significant; ^d Calculated using an arbitrary soil bulk density of 1.2 g cm⁻³; ^e value reported for OM, C = OM/1.724, ud = unpublished data from Metay.

no-tillage when compared with conventional tillage. These increased N₂O emissions lead to a negative global warming potential of the DMC system when expressed on a C-CO₂ equivalent basis. Global warming potentials are measurements of the relative radiative effect of a given substance (in this case CO₂) compared with another substance and integrated over a determined time period. For example, one kg of CH₄ is as effective, in terms of radiative forcing, as 23 kg of CO₂. On a carbon or nitrogen mass basis, 1 kg of C-CH₄ is equivalent to 8.36 kg of C-CO₂ and 1kg of N-N₂O to 126.86 kg C-CO₂. The authors studied other changes induced by no-tillage and concluded that “from an agronomic standpoint no-tillage is beneficial, but from a global change standpoint more research is needed to investigate the interactive effects of tillage, fertilizer application methodology and crop rotation as they affect carbon accumulation, CH₄-uptake and N₂O-fluxes, especially in tropical soils, where data on this matter is still lacking”. This is particularly true for the N₂O fluxes when legume crops are used as cover crops or green fertiliser, as some studies tend to show that N₂O emissions may be enhanced as a result (Flessa et al., 2002; Giller et al., 2002)

Few results have been published regarding N₂O emissions in tropical regions. Pinto et al. (2002) showed low NO and N₂O emissions, low nitrification rates and the majority of inorganic N to be in the form of NH₄⁺, all indicative of a conservative N cycle in the Cerrado. Passianoto et al. (2003) suggested that no-tillage regimes will result in lower CO₂ emissions than degraded pastures, but higher N₂O and NO emissions in Amazonia and that the addition of N fertiliser stimulates N₂O and NO emissions. A recent study (Metay, 2004) compared the production and emission of N₂O from two treatments: conventional tillage and DMC (no-tillage and direct sowing in the cover crop after weed-killer application). The main crop was rice (*Oriza sativa*) and the cover crop a fodder grass (*Bracharia*) with a legume (*Crotalaria*). The experiment was established at “Embrapa Arroz e Feijão” field experiment station, in Santo Antonio de Goiás (Goiás State, Brazil) in 2002–2003. Data on climate, soil temperature, soil mineral nitrogen, soil moisture and soil carbon sequestration rates were monitored for more than one year as potential determinants of the greenhouse gas emissions. Twelve chambers in each of the treatments were used to measure greenhouse gas fluxes. Fluxes were measured

twice a week. Chambers were sealed for 2 hours to allow gases to accumulate. The chamber atmosphere was sampled 5 times during this period in 13-mL vacuum container tubes that were previously purged of other gases. N_2O fluxes were calculated by linear interpolation.

N_2O concentrations in the soil atmosphere were determined using permanent gas samplers inserted into the soil at various depths (10, 20 and 30 cm). The results demonstrated that N_2O emissions were very low ($< 1 \text{ g ha}^{-1} \text{ day}^{-1}$) for both systems. Peaks of N_2O were observed after fertilisation. N_2O is produced mainly by denitrification, which may be explained by low NO_3^- levels in soils and a $< 60\%$ water-filled pore space (WFPS) within the soil for the majority of the time. Low WFPS under these crops can be caused by evaporation at high temperatures (more than or equal to 25°C). However, measurements of gas concentrations in soil showed that the production of N_2O is reasonably prolific (concentrations of 1 to 30 times the atmospheric concentration). This suggests that N_2O is produced but cannot diffuse to the soil surface, either because denitrification is complete and N_2 is produced or because the N_2O is nitrified before diffusing. Microporosity in the upper layer needs to be studied further to understand better the diffusion and compaction conditions in these soils (Yamulki and Jarvis, 2002). Samples were taken immediately after fertilisation (November, December and January). After fertilisation, a higher variability in fluxes may occur, which agrees with the general principle that fertilisation increases the emissions of N_2O due to a higher availability of organic N (Weitz et al., 2001). Further measurements of potential denitrification are necessary to understand better the capacity of this particular soil to produce and emit N_2O .

Six et al. (2004) recognised that few studies have reported CH_4 flux differences between DMC and no-tillage systems and that all those that have, have found a significant enhancement of CH_4 uptake with the adoption of DMC (on average $0.6 \text{ kg ha}^{-1} \text{ yr}^{-1}$). Preliminary results obtained in the Cerrado region near Rio Verde confirm this observation. CH_4 fluxes were analysed in November 2003 and January 2004 in 3 DMC systems aged 9, 11 and 13 years, respectively, and a conventional tillage system. Preliminary results showed CH_4 absorption for all treatments, but higher absorption in the DMC systems. CH_4 sinks in the conventional tillage were 3.8 and $4.8 \text{ g C-CH}_4 \text{ ha}^{-1} \text{ d}^{-1}$ in November and January, respectively, whereas they varied between 8 and $16 \text{ g C-CH}_4 \text{ ha}^{-1} \text{ d}^{-1}$ in November and 7.3 and $14.3 \text{ g C-CH}_4 \text{ ha}^{-1} \text{ d}^{-1}$ in January in the DMC systems. In order to obtain a complete picture, data need to be collected throughout the entire cropping cycle. Only then can any general conclusions be drawn.

3.3. Carbon budgets at the farm level

Several studies in Brazil have shown that no-tillage systems are fuel-efficient compared with conventional systems. For example, Landers (2001) reported fuel consumption by a farmers' cooperative in Planaltina (Goías State) (covering 2270 ha) over a six-year period. During this period the land was converted from 100% conventional tillage, in the agricultural year 92/93, to 100% no-tillage in the agricultural year 1997/98. The total number of hours that tractors were used was 10630 in 1992/93 and 5135 in 1997/98, showing a decrease in fuel con-

sumption of $\sim 50\%$. Landers (2001) also noted that the number of machine operators was reduced to almost half, freeing up previous machine operators for employment in new farm enterprises. Studies on pesticide use in conventional tillage and DMC systems and resulting on-farm and off-farm emissions of greenhouse gases are lacking, highlighting an area that needs further investigation.

4. EROSION UNDER NO-TILLAGE AND CONVENTIONAL TILLAGE

Land degradation, caused by water-induced soil erosion, is a major threat to sustainable agricultural land use, causing serious and costly environmental deterioration. Pimentel et al. (1995) estimated the worldwide cost of soil erosion to be ca. US\$ 400 billion per year. According to Laflen and Roose (1998), water-induced soil erosion is a threat to the long-term sustainability of mankind in all regions of the globe. In the tropics, Lal (1995) estimated that the total transport or movement of carbon displaced by soil erosion is 1.59 Pg yr^{-1} . According to Lal, this estimate ranges from a low of 0.80 Pg yr^{-1} to a high of 2.40 Pg yr^{-1} . However, only a fraction of soil moved from its original place is transported out of the watershed. The delivery ratio for tropical watersheds may be as low as 10%. This implies that as much as $0.16 \text{ Pg C yr}^{-1}$ may be transported out of tropical watersheds with a range of 0.08 to $0.24 \text{ Pg C yr}^{-1}$.

In Brazil, almost every region has problems related to soil erosion. According to De Maria (2004), no-tillage reduces runoff and soil loss by approximately 70 and 90%, respectively. In order to reduce soil erosion rates, some Brazilian farmers have adopted appropriate farming systems, such as the use of cover crops, mixed crop rotations and conservation tillage. Conservation tillage systems have been developed as an alternative to conventional mouldboard ploughing, to reduce not only water but also wind erosion and to maintain and/or increase soil organic carbon contents (Six et al., 2002). These practices manage litter and crop residues with minimum and no-tillage. Keeping a mulch of crop residues protects the soil surface against raindrop impact, decreases evaporation, increases water storage, reduces production costs and slows down decomposition of soil organic carbon (Rosell and Galantini, 1997).

It has been reported (Bajracharya et al., 1998; Lal, 1995, 1997) that while deposition of eroded soil does not necessarily lead to the direct accumulation of carbon, it is likely to increase the overall sequestration of soil organic carbon by leading to an accumulation of organic material which has a greater potential to be converted into the stable form of soil organic carbon. Depositional and non-eroded areas increase potential accumulation of soil organic carbon, possibly by providing favourable conditions for aggregation. Carbon accumulation in soil seems to occur within aggregates. The above authors concluded that erosion is likely to lead to a gradual depletion of soil organic carbon by exposing the stable carbon pool in micro-aggregates in the soil surface and the subsoil, to processes of degradation by disrupting macro-aggregates and removing successive layers of soil.

5. CONCLUSION

Caution must be taken when analysing DMC systems in terms of carbon sequestration. Comparisons should not be limited solely to carbon storage in the soil but should include a consideration of associated trace gas fluxes. Associated fluxes of methane and nitrous oxide may change the final balance of C-CO₂ equivalents, based on the global warming potential of each gas. Most preliminary results tend to indicate that the adoption of DMC in Brazil is a promising strategy for mitigating carbon emissions to the atmosphere. Since the 1970s, DMC systems have been taken up by farmers in Brazil for a variety of reasons irrespective of carbon sequestration benefits. Therefore the use of DMC systems in Brazil is a good potential strategy for mitigating greenhouse gas emissions as the uptake of DMC is not dependent on carbon markets or political incentives.

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