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Mrabet R.

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Soil quality and carbon sequestration: Impacts of no-tillage systems

R. Mrabet
Institut National de la Recherche Agronomique (INRA)
Regional Agricultural Research Center of Meknes, P.O. Box 578, Meknes 50000, Morocco
rachidmrabet@yahoo.co.uk

SUMMARY – The agriculture sector world-wide accounts for about one fifth of the annual anthropogenic increase in greenhouse forcing, producing about 50 to 75% of anthropogenic methane and nitrous oxide emissions and about 5% of anthropogenic CO_2 emissions. Plowing or soil inversion is a principal cause of CO_2 emission from croplands. There is scientific evidence that soil tillage has been a significant component of the increase in atmospheric CO_2 which has occurred in the last few decades. No-tillage (NT) adoption is an essential step to sustainable agricultural development worldwide. In fact, no-tillage is practiced on 90 million ha world-wide, predominantly in North and South America but its uptake is also increasing in Africa, Australia and other semi-arid areas of the world. NT is primarily used as a means to protect soils from erosion and compaction, to conserve moisture and reduce production costs. This article collates pertinent information on carbon sequestration and soil quality under no-tillage systems. The use of NT significantly improved soil aggregation and carbon and nitrogen sequestration in the surface of the soils. In both tropical and temperate soils, a general increase in C levels was observed under no-tillage compared with conventional tillage. No-tillage can improve soil structure and stability thereby facilitating better drainage and water holding capacity that reduces the extremes of water logging and drought. Particulate organic matter was a more sensitive indicator of soil quality changes under different tillage and stubble management than total organic carbon. These improvements to soil structure also reduce the risk of runoff and pollution of surface waters with sediment, pesticides and nutrients. Under no-tillage, a richer soil biota develops that can improve nutrient recycling and this may also help combat crop pests and diseases.

Keywords: No-tillage systems, carbon sequestration, soil quality, sustainable agriculture.

RESUME *– "Qualité du sol et séquestration du carbone: Impacts des systèmes de semis direct". L'agriculture contribue au cinquième de l'augmentation anthropogénique des émissions des gaz à effet de serre (50-75% de méthane et oxyde nitrique et 5% de CO_2). Le labour et la manipulation des sols par des outils de travail du sol sont les principales causes des émissions de CO2 des terres mises en culture. Il a été montré scientifiquement que le travail du sol contribue à l'augmentation du niveau du CO2 atmosphérique. Le semis direct est une étape essentielle pour un développement agricole durable dans le monde. En effet, ce système est pratiqué sur une superficie de 90 millions d'hectare à l'échelle mondiale. Il est plus pratiqué en Amérique du nord et latine avec une augmentation d'adoption en Australie, Afrique et autres zones semi-arides. Les raisons majeures de cette augmentation des superficies en semis direct sont la protection des sols contre l'érosion et la compaction, la conservation de l'eau et la réduction des coûts de production. Cet article résume l'état des acquis de recherche en matière de séquestration du carbone et de la qualité du sol sous semis direct. L'effet majeur de changement vers le semis direct est la localisation du carbone (stratification) en surface de la matière organique. Aussi bien sous climat tempéré que tropical et subtropical, une augmentation générale des stocks de C du sol est observée avec les pratiques de non labour. Les indicateurs de la santé du sol sont positivement affectés par les systèmes de semis direct. En fournissant des éléments nutritifs et en stabilisant la structure, la matière organique accumulée par ces systèmes contribue au maintien de la productivité agricole et à la qualité de l'environnement (réduction du ruissellement et la contamination des eaux). La réhabilitation de la biologie du sol par l'application continue du semis direct permet d'améliorer les différents cycles nutritifs et de lutter contre certains ravageurs et maladies.*

Mots-clés : *Semis direct, séquestration du carbone, qualité du sol, agriculture durable.*

Conventional agriculture: A privileged path to carbon emissions and losses from soils

The 1997 Kyoto Protocol to the UN Framework Convention on Climate Change established an international policy context for the reduction of carbon emissions and increases in carbon sinks in order to address climate change (Smith, 1999). Agricultural systems contribute to carbon emissions through several mechanisms: (i) the direct use of fossil fuels in farm operations; (ii) the indirect use of embodied energy in inputs that are energy-intensive to manufacture (particularly fertilizers); and (iii) the cultivation of soils resulting in the loss of soil organic matter. Conventional agriculture is one of the main drivers of climate change. Plowing or soil inversion is a principal cause of CO_2 emission from croplands. There is scientific evidence that soil tillage has been a significant component of the increase in atmospheric CO_2 which has occurred in the last few decades (Lal, 1997). Historically, intensive tillage of agricultural soils has led to substantial losses of soil C that range from 30% to 50% (Davidson and Ackerman, 1993). These CO_2 losses are related to soil manipulation and fracturing which facilitate the movement of CO_2 out of the soil and oxygen into it. Conventional agriculture operations (moldboard plow) bury nearly all the residue and leave the soil in a rough, loose, and open condition resulting in maximum CO_2 losses and a consistent reduction of the CO_2 sink effect of the soil (Cole, 1996). In other words, plowing, wind and water erosion and any other process that disrupts the soil will increase the mineralization of soil organic matter (SOM). All this contributes to global warming.

The need for agricultural involvement in greenhouse gas mitigation has been widely recognized since the 1990s. In other side, the movement for sustainable agriculture is growing in momentum throughout the world (Brundtland, 1988). At Marrakech meeting of the COP-7, sequestering atmospheric C in agricultural soils is being advocated as a possibility to partially offset fossil-fuel emissions (Smith, 2004). Such an endeavor requires a paradigm shift in our thinking of soil and its management.

Agricultural ecosystems represent 11% of the earth's land surface and include some of the most productive and carbon-rich soils. As a result, they play a significant role in the storage and release of C within the terrestrial carbon cycle (Lal and Bruce, 1999). The Intergovernmental Panel on Climate Change has given broad definitions of the management practices that could be used to sequester and/or retain soil carbon. There are three main categories: agricultural intensification; conservation tillage; and erosion control (Table 1). The restoration of soil organic carbon (SOC) pool in arable lands represents a potential sink for atmospheric CO_2. Restorative management of SOC includes using organic manures, adopting legume-based crop rotations, and converting conventional tillage to conservation tillage systems. Where proper soil and residue management techniques are implemented, agriculture can be one of many potential solutions to the problem of greenhouse gas emissions. Additionally, agriculture conservation practices such as the use of different cropping and plant residue management, as well as organic management farming, can enhance soil carbon storage. In other way, carbon sequestration is highly related to soil and management systems. This paper summarizes the effects of no-tillage systems on soil quality indicators and carbon sequestration.

Table 1. Carbon sequestration potential of strategies for arable land (Pg C/year) (Lal and Bruce, 1999)

Practice	Potential
Soil erosion control	0.08-0.12
Soil restoration	0.02-0.03
Conservation tillage and residue management	0.15-0.18
Improved farming/cropping systems (intensification)	0.18-0.24
Total	0.43-0.57

Pg = Petagram = 10^{15} g = 1 billion tons.

Worldwide implementation of no-tillage systems

In an NT system, crops are planted in previously unprepared soil by opening a narrow slot, trench, or band of sufficient width and depth to achieve proper seed coverage and fertilizer placement. No other soil preparation is performed and the soil remains covered by plant residues from previous crops and/or cover crops, and most plant residues remain undisturbed on the soil surface after seeding.

No-tillage agriculture is already practiced successfully on around 90 million hectares worldwide but particularly in North and South America and the rice-wheat system of South Asia. Despite the fact that the United States has the biggest area under no- tillage, it is interesting to note that in this country no-tillage accounts for only 21% of all cropland hectares. In Brazil, no-tillage accounts for about 50%, in Argentina for 55%, and in Paraguay for 60% of all cropland hectares. Paraguay is now the leading country in the world in terms of percentage of no-tillage adoption. NT accounts for about 3.6% in the rest of the world, including Europe, Africa and Asia. Despite good and long lasting research in this part of the world, no-tillage has had only small rates of adoption. NT in Europe is at the moment very little developed (estimated at <1%-2% of its agricultural land), far behind the countries previously mentioned. Currently, France and Spain are the two countries in Europe where these techniques are practiced the most (Derpsch, 2005).

No-tillage systems: A prime strategy for carbon sequestration

Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere (FAO, 2000). The idea is to: (i) prevent carbon emissions produced by human activities from reaching the atmosphere by capturing and diverting them to secure storage; or (ii) remove carbon from the atmosphere by various means and store it. Carbon sequestration in soils is based on the assumption that fluxes or movements of carbon from the air to the soil can be increased while the release of soil carbon back to the atmosphere is decreased. Instead of being a carbon source, soils could be transformed into carbon sinks, absorbing carbon instead of emitting it. This approach relies on the main natural processes that control the carbon cycle: photosynthesis, through which carbon from the air is converted into organic material, and respiration, through which carbon is returned to the atmosphere.

The conservation of sufficient SOM levels is crucial for the biological, chemical and physical soil functioning in both temperate and tropical ecosystems. Appropriate levels of SOM ensure soil fertility and minimize agricultural impact on the environment through sequestration of carbon (C), reducing erosion and preserving soil biodiversity (Six *et al.*, 2002a). Soil carbon sequestration can be accomplished by management systems that add high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, and enhance soil fauna activity. Continuous no-till crop production is a prime example (Table 2). The impact of No-tillage practices on carbon sequestration has been of great interest in recent years. The literature is replete with studies that show an increase in SOC stock with conversion to NT, at least in the surface soil (Dick *et al.*, 1991; Mrabet *et al.*, 2001a). NT impacts SOC stock in two ways: (i) by reducing disturbance which favors the formation of soil aggregates and protects SOC encapsulated inside these stable aggregates from rapid oxidation (Six *et al.*, 2000); and (ii) by modifying the local edaphic environment: bulk density, pore size distribution, temperature, water and air regime that might also restrict SOC biodegradation (Kay and VandenBygaart, 2002). Paustian *et al.* (1998) and Lal *et al.* (1998) summarized the rate of accumulation of soil organic carbon (SOC) stock under NT at 300-800 kg SOC/ha/year.

Based on US average crop inputs, no-till emitted less CO_2 from agricultural operations than did conventional tillage, with 137 and 168 kg C/ha per year, respectively (Paustian *et al.*, 1997). The relative importance of CO_2 emission by tillage practices is reported in Table 3. Results from semiarid Alberta (Canada) by Larney *et al.* (1997) suggested that although relative increases in soil organic matter were small, increases due to adoption of NT were greater and occurred much faster in continuously cropped than in fallow-based rotations. Hence intensification of cropping practices, by elimination of fallow and moving toward continuous cropping is the first step toward increased C sequestration. Reducing tillage intensity, by the adoption of NT, enhances the cropping intensity effect.

The stratification of soil properties is an important effect of No-tillage systems (Mrabet, 2002b) that could potentially be used as an indicator of soil quality (Franzluebbers, 2002). Stratification of organic C is common with no-tillage. Zibilske *et al.* (2002) in semi-arid Texas, demonstrated that the organic carbon concentration was 50 percent greater in the top 4 cm of soil of a no-tillage experiment compared with plowing, but the difference dropped to just 15 percent in the 4 - 8-cm depth zone. This is typical of organic carbon gains observed with conservation tillage in hot climates. Bayer *et al.* (2001), working on a sandy clay loam Acrisol, also found that the increase in total organic C was restricted to the soil surface layers under no-tillage but that the actual quantity depended on the cropping system.

Similar to the merits of No-tillage reported in North America, Brazil and Argentina (Lal, 2000; Sa *et al.*, 2001), several studies have reported the high potential of carbon sequestration in European soils (Smith et al., 2000a,b). Smith *et al.* (1998) estimated that adoption of conservation tillage has the potential to sequester about 23 Tg C/year in the European Union or about 43 Tg C/year in the wider Europe including the former Soviet Union. In addition to enhancing SOC pool, up to 3.2 Tg C/year may also be saved in agricultural fossil fuel emissions. Smith *et al.* (1998) concluded that 100% conversion to no-tillage agriculture could mitigate all fossil fuel C emission from agriculture in Europe.

Changing from conventional tillage to no-till is therefore estimated to both enhance C sequestration and decrease CO_2 emissions (West and Marland, 2002). The benefits of NT systems on carbon sequestration may be soil/site specific, and the improvement in soil organic matter may be inconsistent in fine textured and poorly drained soils (Wander *et al.*, 1998).

Table 2. Carbon sequestration under conservation agriculture in selected regions

Measure	Region	Potential soil carbon sequestration rate (t C/ha/year)	Reference
No-tillage	Canada	0.07-0.14	Smith *et al.*, 2000a,b
		0.16	Janzen *et al.*, 1998
	Europe	0.3-0.4	Freibauer *et al.*, 2004
Conservation tillage	Australia, Canada, USA	0.2-0.4	Watson *et al.*, 2000
	Drylands	0.1-0.2	Lal, 1999
	Europe	< 0.4	Freibauer *et al.*, 2004
	Tropical areas	0.2-0.5	Lal, 1999
Conservation agriculture	Drylands	0.15-0.3	Lal, 1999
	Tropical areas	0.3-0.8	Lal, 1999
Elimination of Fallow	Canada	0.17-0.76	Watson *et al.,* 2000
Mulch farming and cover crop	Drylands	0.05-0.1	Lal, 1999
	Tropical areas	0.1-0.3	Lal, 1999
	Europe	0.2-0.7	Freibauer *et al.,* 2004

Table 3. CO_2 emissions over 19 days following different tillage methods (Reicosky and Lindstrom, 1993)

Tillage method	Cumulative CO_2 emissions (t/ha)
Moldboard plow	9.13
Disk plow	3.88
Chisel	3.65
No-tillage	1.84

No-tillage systems: Simultaneous improvements of soil aggregation and C sequestration

Appropriate physical, chemical and biological management of soils is one of the key factors to maintain or improve their agricultural productivity and/or combat soil and environmental degradation. The soil quality concept evolved throughout the 1990s in response to increased global emphasis on sustainable land use and with a holistic focus emphasizing that sustainable soil management requires more than soil erosion control (Karlen *et al*., 2003). The overall benefits of soil carbon sequestration need to be viewed as an opportunity to improve soil quality as well as the environment. In general there is a favorable interplay between carbon sequestration and various recommended land management practices related to soil fertility and quality. No-tillage systems offer great agro-ecological potentials: it typically conserves the soil, improves the soil ecology, stabilizes and enhances crop yield and provides various environmental services.

Soil aggregation is one of the principal processes responsible for carbon sequestration in soils (Lal *et al*., 1997) and in turn, structural degradation provokes soil organic matter loss (Six *et al*., 1999). In other terms, aggregation and carbon sequestration processes are strongly associated (Golchin *et al.,* 1994; Angers and Chenu, 1998). Changes in tillage intensity and crop rotations can also affect C sequestration by changing the soil physical and biological conditions and by changing the amounts and types of organic inputs to the soil. Soil structure and soil aggregation play an important role in an array of processes such as soil erodibility, organic matter protection and soil fertility (Six *et al*., 2002a).

The favorable effect of No-tillage systems on soil aggregation has been reported for different soil types and climates (Schjønning and Rasmussen, 1989; Mrabet *et al*., 2001b; Oyedele *et al*., 1999). With regard to physical properties, SOM and living organisms associated with SOM play the main role in soil aggregation at different scales of soil organization (Robert and Chenu, 1991) both at micro and macro level.

Soil management systems that leave more plant residues on the soil surface generally allow improvements in soil aggregation and aggregate stability (Ibno-Namr and Mrabet, 2004). Kouakoua *et al*. (1999) found a strong correlation between aggregate stability in water and the carbon content of bulk clayey Ferralsols from Africa. A medium to high correlation was found between the mean geometric diameter, the mean weight diameter, the amount of aggregates >2 mm, and total organic carbon content of Latosols from Brazil (Madari *et al*., 2005). Both the quantity and the quality of soil C inputs influence C storage and the potential for C sequestration by affecting soil structure and aggregate formation (De Gryze *et al*., 2005). They found that aggregate formation increases linearly with increasing amounts of low-quality residue added. These findings are in agreement with Ibno-Namr and Mrabet (2004).

Madari *et al.* (2005) reported that Ferrasol under NT had a more similar distribution of aggregate size classes and total organic carbon to the forest soil than conventional tillage (disc plowing followed by two light disc harrowings, CT). The most pronounced difference between tillage systems was observed in the surface soil layer (0–5 cm). In this layer, NT had higher aggregate stability, had higher values of aggregate size distribution (MWD_{NT}: 7.9 mm, MWD_{CT}: 4.3 mm), and had on average 28% greater total organic carbon in all aggregate size classes than CT. Soil under NT had greater total organic carbon in macro-aggregates (NT: 22 g/kg; CT: 13 g/kg). In semiarid Morocco, No-tillage affected organic matter content of aggregates in all classes of a calcixeroll soil (Fig. 1).

By increasing macro-aggregation, NT increased organic carbon accumulation in soil. In their review, Six *et al*. (2002b) reported that increased soil C levels under NT compared with CT are a result of a 1.5 times slower C turnover, partially induced by an increased macro-aggregation and a decreased macro-aggregate turnover, leading to a stabilization of C within micro-aggregates.

According to Blanco-Canqui and Lal (2004), questions still remain on how SOC interacts physically and chemically with aggregates, and research is needed to understand the mechanisms responsible for the dynamics of aggregate formation and stability in relation to C sequestration. The quality and quantity of plant residues define the amount of organic matter and thus the SOC pool in aggregates. The nature of plant debris (C: N ratio, lignin content, and phenolic compound content) affects the rate of SOC sequestration. Mechanisms of interaction of aggregate dynamics with SOC are complex and embrace a range of spatial and temporal processes within macro- (>250μm) and micro-aggregates (< 250 μm). A relevant mechanism for SOC sequestration within aggregates is the confinement of plant debris in the core of the micro-aggregates. The C-rich young plant residues form and stabilize macro-aggregates, whereas the old organic C is occluded in the micro-aggregates. Interactions of clay minerals with C rich humic compounds in correlation with clay mineralogy determine the protection and storage of SOC.

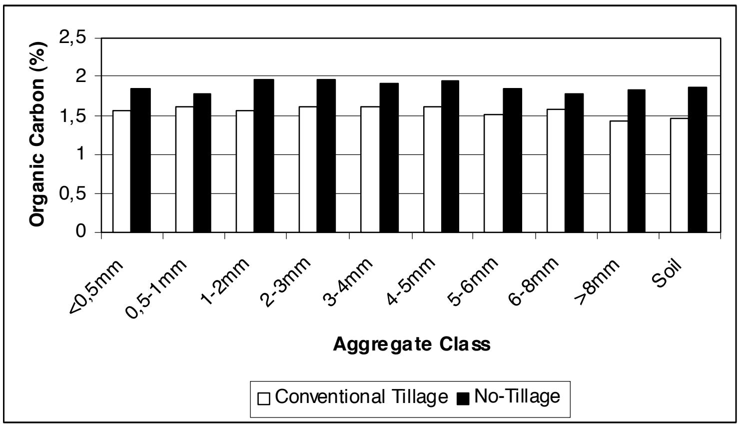

Fig. 1. Effect of tillage system on organic carbon of soil and its aggregates (Tab, 2003).

No-tillage systems: Soils are becoming more active

Biological activities in the soil are vital to soil productivity through the activities of earthworms, termites and the many other living creatures in the soil. These influence water infiltration rates by their burrowing in the soil and their mucilage promotes soil aggregation. Conservation agriculture systems permit the development of a more stratified soil structure that supports a greater abundance and diversity of soil organisms such as micro-organisms, nematodes, earthworms and micro-arthropods.

Biological activity is generally greater and both microbial and soil fauna populations are higher under zero-tillage regimes relative to conventional tillage (Doran, 1987; Franzluebbers and Arshad, 1996; Montero *et al.*, 2004). No-tillage favors development of fungi, which are very active in soil aggregation. The amount of bacteria can increase by several orders of magnitude, from 10^3 to 10^{12}, as soon as the source of SOM is abundant. Many of the gains of No-tillage are due to enhanced soil health such as a greater abundance of soil micro-organisms, and enhanced drainage through the pores created by undisturbed earthworm communities (Machado and Silva, 2001; Machado *et al.*, 2003). Consequently, loss of organic matter during cultivation, and especially loss of the soil microbial component, can adversely affect both the physical, biological, and nutrient status of soils. In NT, residues accumulate at the surface where the litter decomposition rate is slowed due to drier conditions and reduced contact between soil microorganisms and litter (Salinas-Garcia *et al.*, 1997). Finally, the proportion of the microbial biomass composed of total fungi (Frey *et al.*, 1999) and mycorrhizal fungi (O'Halloran *et al.*, 1986) is generally higher in NT compared to CT and it has been observed that fungi (especially mycorrhizal) contribute to macro-aggregate formation and stabilization. No-till systems benefit soil fauna and microbial activity, reflected in higher numbers of earthworms and most insect groups (Boyer *et al.*, 2001). These practices create a more undisturbed rhizosphere environment, which is highly favorable to symbionts such as *rhizobium* and or *mycorrhizal* fungi, and hence improve plant nutrition (particularly nitrogen and phosphorus) and lower fertilizer needs (Mrabet *et al.*, 2001b).

Particulate organic matter (POM) or light fraction (LF) is generally considered one of the primary indicators of soil quality, both for agriculture and for environmental functions (Leifeld and Kogel-Knabner, 2005). Soil organic matter fractions with turnover times of years to decades, such as POM or LF, often respond more rapidly to NT-induced changes in the SOC pool than more stabilized, mineral-associated fractions with longer turnover times (Cambardella and Elliott, 1992; Gregorich and Janzen, 1996; Six *et al.*, 1998; Bessam and Mrabet, 2003).

LF and POM are thought to represent undecomposed plant residues and partly decomposed plant material at an early stage of decomposition, thus characterizing a transitional stage in the humification process (fungal hyphae, seeds, spores, faunal skeletons and humic material coating sand grains) (Dalal and Bridge, 1996). In fact, POM has several attributes that make it suitable as an indicator for relating soil or agronomic management practices to consequences for soil quality. These attributes include a rapid half-life and positive correlations with the biologically-active SOM fractions, N mineralization and soil aggregation (Wander and Drinkwater, 2000). Alvarez *et al.* (1995) reported an increase in labile forms of organic matter under no-tillage in the Argentine rolling pampa, indicating a decrease in the mineralization of the organic fraction. This study also noted that although organic C increased by 42 - 50 percent under no-tillage compared with plowing and chisel tillage, there was also a marked stratification in the distribution of C under the no-tillage regime that was not evident in the ploughed system.

Linking results from size and density separation of soils to aggregate dynamics has strengthened the potential of LF and POM as useful indicators for changes in soil C (Haynes, 1999; Six *et al.*, 2002a, 2004). Denef *et al.* (2004) reported that for three mineralogically different soils, total SOC levels as well as concentrations of POM and mineral-C associated with micro-aggregates within macroaggregates were greater with NT compared with CT. They also identified and isolated a POM fraction that explains almost the difference in total SOC between NT and CT. This fraction corresponds to the POM located within the microaggregates. This finding supports that enhanced microaggregate formation and stabilization of C due to reduced macroaggregate turnover can be a mechanism promoting C sequestration in NT compared with CT systems in temperate soils dominated by 2:1 clay mineralogy. These findings were supported by Kong *et al.* (2005).

For semi-arid Morocco, the major threats to soil productivity and agricultural sustainability are over-grazing and straw exportation. However, in no-tillage agriculture, it is recommended to maintain a crop residue cover to protect the soil surface from the erosive forces of wind and water. Surface residues not only shelter the soil by a non-erodible cover, but also increase infiltration and reduce evaporation and soil temperature (Mrabet, 1997). The level of residue needed under no-tillage to equal the effect of intensive tillage on soil water storage is in the range of 2-4 Mg/ha (60-80% cover) (Mrabet, 1997). At the same time, Mrabet (2002a) reported that wheat grain yield was not affected by residue cover when at level higher than 70%. This means that farmer can partially export straw from field without affecting his production. However, in terms of soil quality improvement, Mrabet *et al.* (2003) expressed that organic carbon, particulate organic matter and nitrogen contents are proportional to residue level under no-tillage system. Retaining an increased residue cover by no-tillage enhanced in long and medium terms soil organic matter and improve soil structure (Fig. 2).

POM and aggregation are both related to crop nutrient acquisition, nitrogen leaching and organic matter dynamic. In other terms, in well aggregated soils, POM is thought to be predictive of N mineralization potential (Boone, 1994; Yakovchenko *et al.,* 1998).

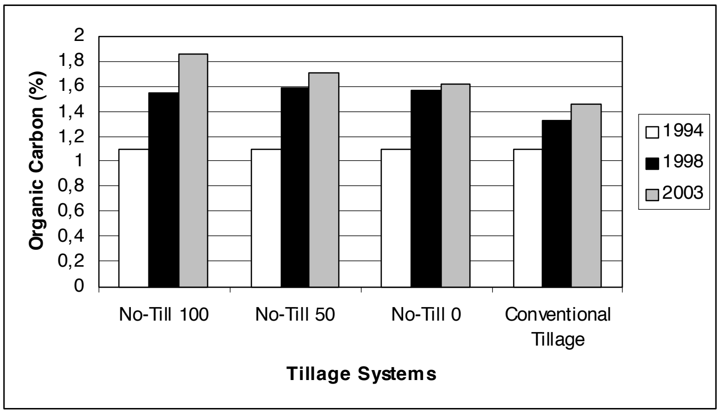

Fig. 2. Time-Tillage and residue cover effects on organic carbon of a surface horizon (0-5 cm) of a Calcixeroll soil in semiarid Morocco (experiment started in 1994, Average annual rainfall: 358 mm, No-Till 100, No-Till 50 and No-Till 0 correspond to no-tillage plots with full cover, 50% partial cover and bare) (modified from Mrabet *et al*., 2001a; Ibno-Namr and Mrabet, 2004).

No-tillage systems: More water in C sequestering soils

Changes in land use and land management also have an important effect on the partition of precipitation between runoff and storage or infiltration, with an increase of the latter in NT with soil cover. Soil cover will prevent erosion. Tillage operations in a CT system compact the soil below the tilled zone, disrupt surface-vented pores, increase the break down of residues and increase surface sealing (Roth *et al.*, 1988). These authors reported that soil with 100% residue cover facilitated complete infiltration of a 60-mm rainfall, whereas only 20% of rain infiltrated when the soil was bare and subject to surface sealing. Conventionally tilled soils under continuous cultivation tend to become less porous with time in the plow layer. Conversely, some soils under no-tillage management tend to become more porous with time (Voorhees and Lindstrom, 1984). Other studies indicated that, even though bulk density was greater and total porosity lower for no-till soils than for tilled soils, the ponded infiltration for the NT soils was equal to or greater than the tilled soils (Sauer *et al.*, 1990). This was attributed to a more stable soil structure in the NT soils and to an increased number of continuous earthworm channels that connected to the soil surface. Greater infiltration rates measured in NT than in CT probably resulted from the flow of water through macropores (Meek *et al.* 1990) and reduced surface sealing due to a complete residue cover (Zuzel *et al.*, 1990). Benjamin (1993) and Chan and Mead (1989) reported that soil under a no-till system had 30-180% greater saturated hydraulic conductivity than the soil tilled with a moldboard and chisel plow.

Carbon sequestration in agricultural soils counteracts desertification process through the role of increased soil organic matter in structural stability (resistance to both wind and water erosion) and water retention, and the essential role of soil surface cover by plant, plant debris or mulch in preventing erosion and increasing water conservation. Furthermore, soil aggregate stability has been recognized as a relevant factor in the control of water erosion of soils (Filho *et al.*, 1991) because erodibility of soils is directly related to aggregate stability. The continued existence of large pores in the soil that favor high infiltration rates and aeration depends on the stability of larger aggregates.

No-Tillage effects on soils are closely related to the management of crop residues in and on the surface of the soil. In semi-arid regions, moisture conservation is one of the key factors to consider. Unger and Jones (1998) reported that the amount of water stored and the fallow storage efficiency changed from 152 to 217 mm and from 15.2 to 35.2% when shifting from disking to no-tillage in Bushland (USA). These results were confirmed in Morocco by Bouzza (1990). During 5 years of conversion from continuous corn and conventional tillage to 2 or 6 year rotations under no-tillage, the soil density was not affected by the change in management. The soil density depended more on the time of the sampling than on management practices (Logsdon and Karlen, 2004). After 10 years of continuous comparative no-tillage and conventional tillage trails in Southwest Nigeria, Opara-Nadi and Lal (1986) observed that total porosity, moisture retention, saturated and unsaturated hydraulic conductivity, and the maximum water-storage capacity increased under no-tillage with mulch. The no-tillage system is perceived as having lower soil temperatures, wetter soil conditions, and greater surface penetration resistance compared with conventional and other conservation tillage systems (Unger and Jones, 1998; Karlen *et al.*, 1994; Mrabet, 1997).

According to the research conducted by Azooz and Archad (1996), total volume of soil pores with radii <14 µm (micropores) were significantly greater in NT than in conventional tillage (CT). Differences in volume of soil pores with radii >14 µm (macropores) between CT and NT were not significant. For the initial soil moisture conditions ranging from dry to field capacity, the infiltration rate values were greater by 0.24 to 3.01 cm h^{-1} in NT than in CT for the silt loam and by 3.30 to 4.13 cm h^{-1} for the sandy loam. Saturated hydraulic conductivity values were significantly greater in NT (range from 0.36 to 3.0 cm h–1) than in CT (range from 0.26 to 1.06 cm h–1). Unsaturated hydraulic conductivity increased more with increasing matric potential (less negative) in NT than in CT. Long-term NT practices kept soil pore structure and continuity undisturbed, which contributed to significantly greater hydraulic conductivity and infiltration rates in NT than in CT for both soils. However, Jarecki and Lal (2005) found no differences between tillage treatments in several soil properties including texture, available water capacity, and hydraulic conductivity; however, the NT decreased soil bulk density and pH in the 0 to 15 cm layer in a silt loam soil. In fact, poor drainage, easily compacted soils and wet climatic conditions are generally regarded as complicating factors for adopting no-tillage systems (Mannering *et al.*, 1988). With time, No-tillage can improve soil structure and stability thereby facilitating better drainage and water holding capacity that reduces the extremes of water logging and drought. These improvements to soil structure and carbon sequestration also reduce the risk of runoff and pollution of surface waters with sediment, pesticides and nutrients.

Evaporation of water from the soil is also reduced with maintenance of mulch cover. Mrabet (1997) showed that time to reach wilting point in a calcixeroll soil was proportional to residue cover under no-tillage. As reported by this author, no-tillage with residue cover of 60% permitted higher time to reach wilting point than any applied tillage system.

Conclusion

On croplands, tillage is the most important practice, which can have a major effect on the carbon pool, either negative with conventional plowing or positive, when No-tillage is applied. No-tillage practices claim to reverse historical carbon loss from soils, thereby reducing CO_2 in the atmosphere through storage in soil sinks - a process known as *sequestration*. Carbon sequestration and an increase in soil organic matter will have a direct positive impact on soil quality and fertility. There will also be major positive effects on the environment, and on the resilience and sustainability of agriculture. This information can be used by extension and private-sector consultants to promote the use of no-tillage production systems that result in increased soil carbon, improving soil quality and productivity in the long term and enhancing profitability of producers. It can also be used by policy-makers dealing with carbon sequestration issues.

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