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Climate change and carbon sequestration in the Mediterranean basin: Contributions of no-tillage systems

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Abstract. Agricultural systems are subject to a wide range of risks and uncertainties in most parts of the Mediterranean basin. This region is experiencing climate change that in no way can be considered normal, and the challenge that this brings to agriculture is twofold. The first challenge relates to the need to reduce greenhouse gas emissions that generate the changes to climate. The second challenge relates to the impacts of climate change on production, and the capacity of agriculture to adapt where it is most vulnerable. Strategies for sustainable management include conserving soil organic matter, minimizing erosion, enhancing soil fertility and balancing production with environmental needs, especially drought. It is agreed upon that no-tillage agricultural ecosystems have the potential to sequester carbon dioxide from the atmosphere and partially mitigate global climatic change. Climate change will become an additional driver for developing no-tillage practice across the Mediterranean basin, as land managers respond to the impacts of climate change on their production base, and governments undertake a range of activities to address the impacts of climate change in agriculture and land management.

Keywords. No-tillage – Carbon sequestration – Drought mitigation – Climate change.

Changements climatiques et séquestration du carbone dans le bassin méditerranéen : Apports et contributions des systèmes de semis direct

Résumé. *Les systèmes agricoles sont soumis à un vaste éventail de risques et aléas dans la plus grande partie du bassin méditerranéen. Cette région subit actuellement un changement climatique qui ne peut aucunement être considéré normal, posant ainsi un double défi à l'agriculture. Le premier défi concerne la nécessité de réduire les émissions de gaz à effet de serre qui entraînent le changement du climat. Le second se rapporte aux impacts du changement climatique sur la production, et la capacité de l'agriculture de s'adapter là où elle le plus vulnérable. Les stratégies pour une gestion durable comprennent la conservation de la matière organique des sols, la minimisation de l'érosion, l'amélioration de la fertilité du sol et l'équilibrage entre production et besoins environnementaux, surtout face à la sécheresse. Il est convenu de reconnaître que les écosystèmes agricoles en non-labour ont le potentiel de piéger le dioxyde de carbone présent dans l'atmosphère et d'atténuer partiellement le changement climatique global. Le changement climatique deviendra ainsi un moteur additionnel pour développer la pratique du non-labour à travers le bassin méditerranéen, car les gestionnaires des terres modifient leur mode de production et les gouvernements entreprennent des actions sur l'agriculture et la gestion des terres pour contrer les impacts du changement climatique.*

Mots-clés. *Non-labour – Séquestration du carbone – Atténuation de la sécheresse – Changement climatique.*

I – Introduction: The central role of soil management

Applications of atmosphere-ocean general circulation models in the Mediterranean region suggest that climate change could result in significant warmer conditions and lower precipitations (Gibelin and Déqué 2003). The mitigation of CO_2 emission into the atmosphere is important and any information on how to implement adjustments to agricultural practices and improve soil organic matter (SOM) stock would be helpful. At the Marrakech meeting of the COP-7, sequestering atmospheric C in agricultural soils was advocated as a possibility to partially offset fossil-fuel emissions. Such an endeavor requires a paradigm shift in our thinking of soil and its management. In fact, the recent attention to global warming have motivated the scientific community to search for efficient soil management and cropping systems to convert CO_2 from the air into soil organic carbon (SOC) (Lal, 2007). A considerable part of the depleted SOC pool can be restored through conversion of marginal lands into restorative land uses, adoption of conservation tillage with cover crops and crop residue mulch, nutrient cycling including the use of compost and manure, and other systems of sustainable management of soil and water resources (Lal, 2004). Tillage and land management practices clearly influence a whole host of interactions between soil quality and crop performances and these interactions are more complex under changing climate and society of the Mediterranean region. It enhances or retards soil quality improvement, soil erosion, and emissions of greenhouse gases from agriculture, and may help maintain or improve the productive base under the conditions of climate change.

Changes in soil moisture, structure, organic matter content, and soil biology brought about by tillage practice, soil management or climate may affect all these processes. Schlesinger (1986) has estimated that aggressive tillage may be primarily responsible for a 30-50% decrease in soil carbon worldwide since soils were brought into cultivation over 100 years ago. In this paper, we are trying to get answers to the hypothesis that no-tillage system can be a key management variable for Mediterranean agriculture in order to maintain its capacity to produce and compete in a changing climate. Alternatively, we would value if conservation farming businesses may benefit from the changing climate. In fact no-tillage research has started in early 1970s in Italy and France and in early 1980s in Spain and Morocco. No-tillage (NT) systems has become increasingly popular in the world (Fig. 1) and in the Mediterranean countries particularly Spain (Sánchez-Girón *et al*., 2007), France (Trocherie and Rabaud, 2004), Tunisia (AFD, 2006), Portugal (Carvalho and Basch, 1994) and Morocco (Mrabet, 2008b) over the last decade (Table 1).

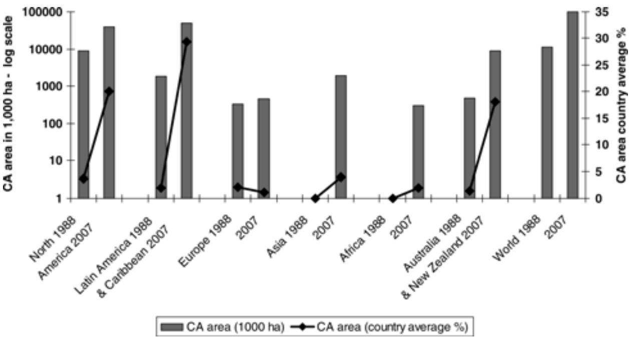

Fig. 1. Development of no-tillage agriculture (CA) over the last 20 years by world region in total area (ha) and as average percentage across the adopting countries of the respective region (FAO, 2008).

Clearly over the past decade, there have been substantial reductions in the aggressivity and intensity of conventional tillage (in terms of depth and number of passes), with corresponding increases in no-tillage between harvest and the sowing of the next crop. It appears there will be substantial shifts in land management practice, to more conservative tillage practices and with large tracts of land being farmed with no or minimum till in these countries and in the Mediterranean basin at large. It is worth noticing that no-tillage system has become the standard management in a Mediterranean country, Australia. Worldwide, the annual increase in NT acreage is about 5.3 million ha (Kassam *et al*., 2009). No-tillage plays a key role in cropping system sustainability due to its impact on soil properties, crop yields, economic returns, labor, and energy requirements. In this paper, we also explore the relationships between no-tillage systems and in-field and off-site climate change impacts.

Table 1. Conservation Agriculture adoption by Mediterranean countries in percentage of total arable and permanent cropland area for 2008-2009 (Kassam *et al*., 2009)

Country	Area under no-tillage (1000 ha)	Percentage of crop area
Spain	650†	3.7
France	200††	10.2
Italy	80	0.8
Portugal	25	1.5
Tunisia	6	0.1
Morocco	4	< 0.1

†1.25 million hectares of reduced tillage (Sánchez-Girón *et al*., 2007).
††6-44% of cropped land is under reduced tillage depending on crop type (Oort, 2006).

II – Agriculture, soils and climate's parameters of the Mediterranean basin

The Mediterranean basin is at the crossroads of the most important environmental, economic, and political concern of the twenty-first century. The Mediterranean climate, which occupies 10% of the land mass of the planet, is characterized by rains concentrated in winter, this is during the period of short days, and an intense and long period of summer drought. The Mediterranean region lies in a transition zone between the arid climate of North Africa and the temperate and rainy climate of central Europe and it is affected by interactions between mid-latitude and tropical processes. This climate is one of the most aggressive in respect of erosion, as a result principally of violence of autumn storms, which come after several months of absolute drought. The variability of Mediterranean climate renders the production (quality and quantity) irregular. The Mediterranean basin (the size of Australia), which lies at the point of contact of three continents, is characterized by a wide range of bio-climates and a variety of soils and crops with different characteristics and behaviors. It harbors a huge variety of agro-ecosystems. The dry season duration clearly illustrates that, while the south and the East are characterized by a long dry season, averaging 7 months without any precipitation, in the north part, the dry season is relatively limited and does not succeed 2-3 months. Different soil tillage methods are practiced in the region, but still traditional plowing and soil cultivation predominate. Moldboard and deep plowing operations have for centuries been a feature of the high cropping system's productivity. Arable lands and particularly cereal lands are decreasing in acreage in Mediterranean Europe due to high production costs, while they are increasing in the other side of the sea. This later increase is due to cultivation of marginal lands to satisfy growing population.

III – The climate change dilemma

Nations around the world are in the process of negotiating a new climate regime to address the issues of climate change and forge new international agreements entailing deep cuts in greenhouse emissions and a complex of associated measures on mitigation, adaptation, financing, and technology. The Mediterranean climate is currently the focus of intense research on climate related issues (Somot *et al*., 2007). The intent is to produce a new climate regime that will launch the world toward a low-carbon future, thus avoiding the potentially devastating effects of climate change. As it appears in IPCC's 2007 report, the Mediterranean is a climate change vulnerability "hotspot". By the end of the century, the average annual temperature on the Mediterranean will probably rise by between 2.2 and 5.1°C, well above the global average. Rainfall totals are likely to decline between 4 and 27. The warming is expected to be larger than the global average, with also a large percent reduction of precipitation, and an increase in inter-annual variability (Lionello *et al*., 2008). Climate change projections point at the development of more arid conditions in most parts of the world, except in the northern countries. In analyzing data from 1961 to 2006, del Río *et al*. (2010) found a decrease of 11% in annual rainfall in Spain and the decrease is more pronounced in the Mediterranean part. For Southern Portugal, Mourato *et al*. (2010) concluded that the annual precipitation regime is becoming drier in the winter and spring seasons. Climatologists calculate projections from atmospheric models which transform assumptions of greenhouse gas emissions (in particular, carbon dioxide) into climate projections. Arable land area, crop yield potential and the length of crop growing season are expected to decrease. In some African countries, yields from rain-fed agriculture could decrease by 50% by 2020 (IPCC, 2007). Climate change may add to existing problems of desertification, water scarcity and food production, while also introducing new threats to human health, ecosystems and national economies of countries. The most serious impacts are likely to be felt in North African and eastern Mediterranean countries. As a consequence, adaptation to climate change and emissions reduction may represent a welcome opportunity to guide the economic development of the region in a more sustainable direction.

IV – Soil respiration: reducing build up of atmospheric CO_2 using no-tillage systems

Since the industrial revolution, global emissions of carbon (C) are estimated at 270 ± 30 billion ton due to fossil fuel combustion and 136±55 Pg due to land use change and soil cultivation (Lal, 2004). The important role of emissions from soils in the carbon cycle has only been clearly recognized for nearly a decade. Gas exchange between soils and the atmosphere may be an important contributing factor to global change due to increasing release of greenhouse gases. Estimates from Raich and Potter (1995) show that soil respiration on a global scale is 77 Pg C year^{-1}, which is approximately 10 times the contribution of industrial CO_2 emissions (Schlesinger and Andrews, 2000). Due to the large order of magnitude, small changes in soil CO_2 flux across large areas can produce a great effect on CO_2 atmospheric concentrations. Soil disturbance by tillage caused an immediate sharp increase in soil CO_2 flux. This is a relatively short process lasting less than 3 h from tillage (López-Garrido *et al*., 2009). The amount of CO_2 emitted immediately after tillage was proportional to the degree of soil disturbance produced (Alvaro-Fuentes *et al*., 2007; Fig. 2). Reicosky *et al*. (1997) concluded that the increase in CO_2 flux immediately after tillage (short-term) was the result of a physical release of CO_2 entrapped in soil pores from previous microbial activity rather than changes in microbial activity at the time of tillage.

Figure 3 from the study by Akbolat *et al*. (2009) in southern Turkey, the NT and heavy disc harrow plots produced the lowest soil respiration (CO_2 efflux) of 0.3 and 0.7 g m^{-2} h^{-1}, respectively, relative to moldboard, chisel plow and rotary tiller plots for a period of 46 days. It is also clear from the figure that the rainfall event had less influence on soil CO_2 efflux in the NT plot than in the conventional tillage plots. No-tillage operations with residue can decrease the burst of soil CO_2 flux found in intensive tillage, and the CO_2 flux under no-tillage remained low during the first days to months after tillage application. In other terms, no-till farming reduces the unnecessarily rapid oxidation of soil organic matter to CO_2 which is induced by tillage. In fact, conventional farming practices "burn" SOC just as we burn fossil fuels today. However, in the case of SOC this historical decline can be reversed, which is not the case for fossil fuel reserves.

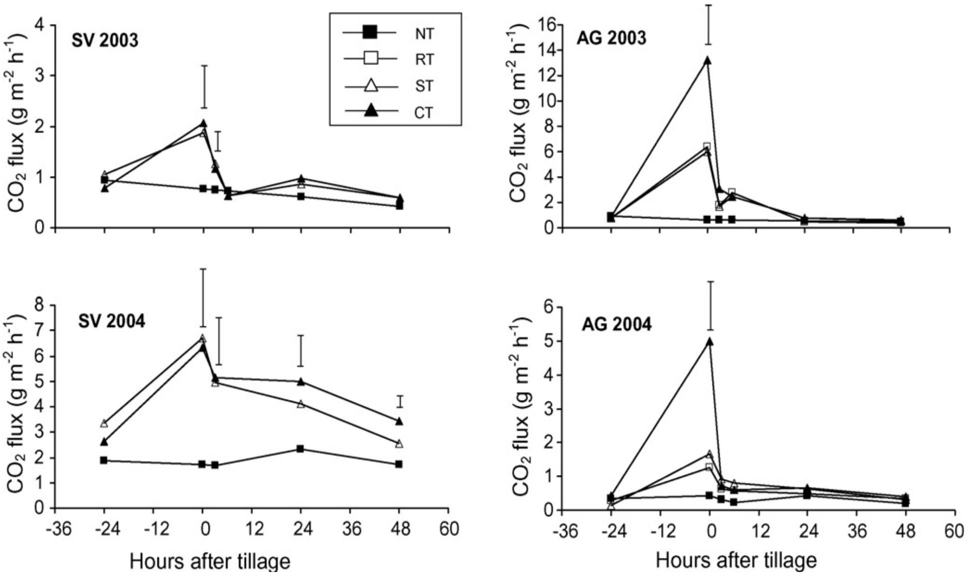

Fig. 2. **Short-term soil CO_2 flux following tillage operations (CT, conventional tillage; ST, subsoil tillage; RT, reduced tillage; NT, no-tillage) in November 2003 and November 2004 in Agramunt in a barley–wheat rotation (AG 2003 and AG 2004, respectively) and in July 2003 and August 2004 in Selvanera in a wheat–barley–wheat–rapeseed rotation (SV 2003 and SV 2004, respectively). Bars represent LSD ($P < 0.05$) for comparison among tillage treatments, where significant differences were found (from Alvaro-Fuentes *et al*., 2007)**.

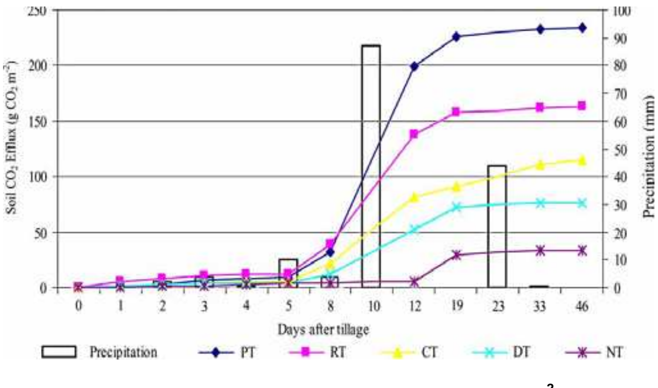

Fig. 3. **Temporal changes in soil CO_2 efflux (g CO_2 m^{-2}) and daily rainfall (mm) during the study period of 46 days in the months of October to November, 2006. PT, RT, CT, DT, and NT refer to moldboard plow, rotary tiller, chisel plow, heavy disk harrow, and no-tillage systems, respectively (from Akbolat *et al*., 2009).**

Differences in CO_2 emissions between tillage systems may not be the sole result of short- or medium term effects of tillage but instead the combined effect of short- and long-term effects. In Central Spain, mean soil CO_2 efflux during a two-year period was measured as 768.2 g C m^{-2} $year^{-1}$ under conventional tillage and 643.3 g C m^{-2} $year^{-1}$ under reduced tillage for rainfed winter barley (Sánchez *et al*., 2002). The sharp increase in CO_2 emission immediately following tillage was attributed to increased soil aeration from disturbance. However, in Northern France and based upon an experiment that lasted for 33 years, Oort *et al*. (2007a) found that over a period of 331 days of measurements CT and NT emitted 3160 ±269 and 4064 ±138 kg CO_2-C ha^{-1}, respectively (Fig. 4). The differences in CO_2 emissions in the two tillage systems resulted from the soil climatic conditions and the amounts and location of crop residues and SOM. A large proportion of the CO_2 emissions in NT over the entire measurement period was probably due to the decomposition of old weathered residues.

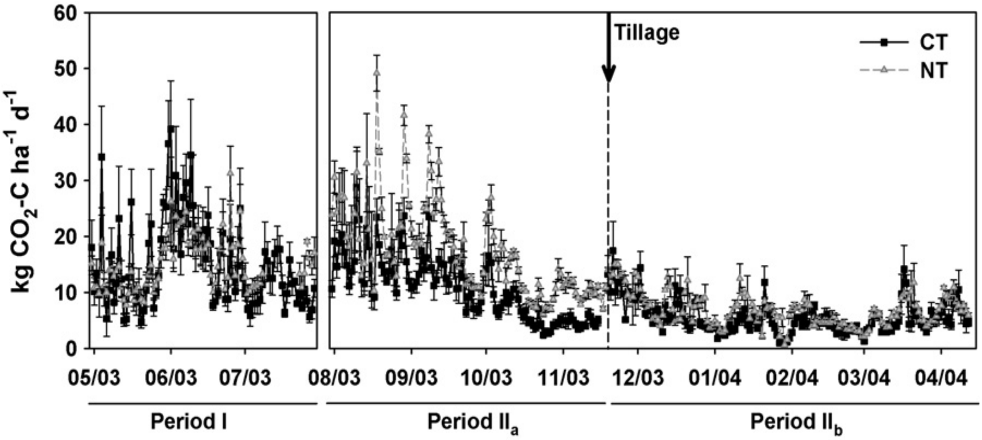

Fig. 4. Daily CO_2 emissions in the conventionally tilled (CT) and non-tilled (NT) plots. Error bars indicate standard deviations (from Oorts *et al*., 2007a).

V – Carbon sequestration: Stabilizing fixation of atmospheric carbon dioxide in soils

Carbon sequestration refers to the storage of carbon in a stable solid form. Carbon dynamic in the soil is attracting considerable research effort given its implication in terms of global climate change. In dryland farming, maintaining or reaching an adequate level of SOM is crucial to sustaining soil fertility, increasing soil moisture storage and mitigating drought. Under high temperatures and low precipitation, organic matter is oxidized quickly and development of sustainable farming systems becomes difficult. In Mediterranean region, dryland soils have not been deliberately managed to sequester carbon and tillage has reduced soil carbon. Based on an analysis of IPCC using the method of Ogle *et al*. (2005), agricultural lands in the Mediterranean basin can potentially sequester carbon and mitigate greenhouse gas emissions through adoption of reduced and no-till management, use of high C input rotations that include hay, legumes, pasture, cover crops, irrigation or organic amendments, setting aside lands from cropland production, and through cropping intensification. In fact, most Annex I parties are attempting to estimate the potential for increased agricultural soil carbon sequestration to partly offset their growing fossil fuel greenhouse gas emissions. Tillage operations (with their form, depth, frequency, and timing) and the management of crop residues are important in carbon sequestration and conservation, particularly in dry areas. Smith *et al*. (1998) concluded that 100% conversion to no till agriculture could mitigate all fossil fuel C emission from agriculture in Europe.

Much of the blame for the C loss has been assigned to the practice of plowing the soil, and tilled soils are viewed by many as a depleted C reservoir that can be refilled. Based on C sequestration data from 67 long-term experiments, West and Post (2002) determined, on average, an increased sequestration rate of 0.57±0.14 t C ha^{-1} $year^{-1}$ in response to a shift from conventional to no-till practice, and similarly Follett (2001) found the sequestration of SOC to range from 0.10 to 0.60 t C $ha^{-1}year^{-1}$ from a literature compilation. A survey of sequestration-related research has shown that in no-tilled soils, the soil organic C (SOC) is concentrated near the surface, while in tilled soils it is distributed deeper in the profile; so that apparent SOC gains from no-till based on near-surface samples disappear when deeper samples are included (Baker *et al*., 2007). However, Mrabet *et al*. (2001) found that stratification of SOC in the top soil under NT was not accompanied by reduced SOC in deeper horizon as compared to a conventional tillage system. Consequently, the net change in SOC depends not only on the C loss as CO_2 emissions but also on the C input by residue retention. Mrabet (2006) found a positive linear response of SOC to residue application rate after 5 years. These research findings were also reported by Jordan *et al*. (2010) in Spain (Fig. 6). This carbon sequestration can continue for 20 to 35 years before reaching a new plateau of saturation (Kimetu *et al*., 2009). For most soils, the potential of C sequestration upon conversion of plow tillage to no-tillage farming with the use of crop residue mulch and other recommended practices is 0.6 - 1.2 Pg C $year^{-1}$. Particularly, soils with low inherent levels of organic matter, frequent under semi-arid conditions, could be the most functionally improved with NT. In fact, the concentrations of organic matter in top soils in Mediterranean regions routinely increase under no-tillage, due to a favorable shift in the balance of accumulation and decomposition (Table 2). In semi-arid Morocco, soil carbon was 13.6% higher on zero-tilled land but only 3.3% on conventionally tilled land (Mrabet *et al*., 2001) and soil organic carbon and nitrogen concentrations were significantly higher over a period of 4-13 years (Mrabet, 2008a). This sequestration ability of this soil may go further due to its initial low soil organic matter and its high clay content. In Morocco, the best results of no-tillage system seem to be obtained on the heaviest clay soils. In Syria, SOM was increased by conservation tillage, particularly by no-till direct drilling from 0.8 to 0.95% in a three-course wheat-lentil-summer crop rotation and from 1.3 to 2.8% in a two-course wheat-lentil cropping systems (Ryan *et al*., 2006).

In three distinct long-term experiments located in northeast Spain, the NT system increased the SOC content only at the soil surface (0-10 cm depth) due to the accumulation of crop residues. The increased level of SOC in the soil surface could be explained by lower CO_2 emissions as shown in Fig. 3 from the same experiments. López-Fando *et al*. (2007), in central Spain, reported 13% more SOC in no-tillage compared to conventional tillage in the 0-30 cm depth. Also, Ordóñez-Fernández *et al*. (2007) in southern Spain measured 20% more SOC stock under NT than under CT in the top 26 cm soil depth. However, when deeper soil layers were considered, the amount of SOC accumulated was greater under CT than under NT due to the placement of crop residues all along the soil profile (Álvaro-Fuentes *et al*., 2008). In other words, after >15 yr of tillage testing, the beneficial effect of NT on SOC sequestration has been observed only in the first 10 cm of soil. In North Tunisia, no-tillage system helped to increased soil organic matter by 3% in three years compared to conventional tillage system (AFD, 2006).

The amount and quality of crop residues added through cropping systems with no-tillage (NT) soils is the key component to increase carbon (C) sequestration in agricultural land and mitigate carbon dioxide (CO_2) to the atmosphere. Results by Ibno-Namr and Mrabet (2004) in Morocco and Basch *et al*. (2008) in Portugal give evidence of the potential contribution of the combined effect of no till and crop residue return to the build-up of SOM even under conditions of relatively low biomass production of Mediterranean rainfed agriculture. However, there are limits to the capacity of any soil to continue to sequester carbon over time, even in a favored environment, and there is still very little information on the influence of no-till on rates of carbon turnover. In one example, organic matter continued to increase for a couple of decades (in a tropical soil) after management changed to no-tillage (Six *et al*., 2002a). This is the case of France after 33 years of NT (Oorts *et al*., 2009). In other cases, studies are needed to insure that currently effective carbon sequestration practices result in stable carbon forms for the long term (at least 20-50 years). As for the Mediterranean soils which have low soil organic matter, Six *et al*. (2002b) and Stewart *et al*. (2007) hypothesized that soils with high organic matter status have a lower C stabilization efficiency compared with low OM containing soils. However, Alvaro-Fuentes and Paustian (2010) simulated continuous trends in SOM build-up under NT, mainly under continuous barley system (Fig. 5). According to López-Bellido *et al*. (2010), in order to maintain SOC level, the amount of above ground biomass residues returned to soil must exceed 2.23 and 1.93 Mg C/ha/year for NT and CT, respectively. In fact, according to the same authors, in a period of 20 years, NT soil content in SOC doubled CT content. With NT, reduced use of tractors and other powered farm equipment results in lower gas emissions. Up to 70% in fuel savings have been reported. NT systems can also help reduce the emissions for other relevant greenhouse gases, such as methane and nitrous oxides (FAO, 2008).

Table 2. Tillage systems effect on soil organic matter (g kg^{-1}) in different Mediterranean countries

Country	Soil order	Horizon (cm)	Years	NT	CT	References
France	Alfisol	0-5	4	21.5	17.3	Monnier *et al*. (1976)
	Alfisol	0-5	33	22.6	11.0	Oorts (2006) & Oorts *et al*. (2007b)
Syria	Inceptisol	0-10	10	17.5	11.0	Ryan (1998)
Tunisia	Isohumic	0-20	4	27.5	24.1	Ben Moussa-Machraoui *et al*. (2010)
	Fersialitic	0-20	4	22.4	15.5	
Morocco	Calcixeroll	0-5	5	17.3	16.6	Mrabet (2008a)
	Calcixeroll	0-2.5	11	28.9	23.5	Mrabet *et al*. (2001)
Italy	Cambisol	0-40	3	7.5	7.5	Borin *et al*. (1997)
	Entisol	0-10	-	20.1	14.3	Basso *et al*. (2002)
Portugal	Cambisol	0-20	3	14.8	12.9	Basch *et al*. (2008)
	Vertisol	0-10	-	25.3	19.1	Carvalho & Basch (1995)
Spain	Xerocrept	0-5	18	22.5	15.0	Álvaro-Fuentes *et al*. (2008)
	Xerofluvent	0-5	15	18.8	8.8	Álvaro-Fuentes *et al*. (2008)
	Calciorthid	0-5	16	13.7	8.7	Álvaro-Fuentes *et al*. (2008)
	Calcisol	0-5	7	12.5	10.1	Fernandez-Ugalde *et al*. (2009)
	Haploxeralf	0-5	14	11.0	7.0	Hernanz *et al*. (2002)
	Haploxeralf	0-10	8	11.6	8.8	Medeiros *et al*. (1996)
	Xerofluvent	0-5	3	17.2	15.7	López-Garrido *et al*. (2009)

VI – Soil fertility and nitrogen management

Soil fertility decline due to tillage has been reported Mediterranean wide. Hence, improving soil productivity in drought-prone environments is a daunting challenge because of the many traits involved and their interactions with the environment. Given the inherent low fertility of many dry-area soils, judicious use of stubble, crop residue, farmyard manure and inorganic fertilizer is particularly important. In fact, there is in general a favorable interplay between carbon sequestration and various recommended fertilization practices related to soil fertility under no-tillage systems. Lahlou *et al*. (2005) found better poral distribution of a clay soil under NT than CT. This formed porosity is responsible for to improved growing season moisture regime and soil storage of water and nutrients. Hence, crops under NT require less fertilizer and pesticides to feed and protect the crop, thus leading to a lowering of potential contamination of soil, water, food and feed. According to Angas *et al*. (2006), reducing tillage and optimizing nitrogen fertilization are important strategies for soil and water conservation and sustainability of Mediterranean agricultural systems. No-till farming provides significant soil health benefits that lead to improved soil condition and plant growth. No-tillage has proven to be an effective strategy to improve soil quality and fertility in Mediterranean semi-arid areas of Morocco (Mrabet *et al*., 2001); in Spain (Fernández-Ugalde *et al*., 2009) and Tunisia (Ben Moussa Machraoui *et al*., 2010). Most researchers agree that the N fertilizer requirements are greater when no-till is used, but the differences disappear after 10 years of continuous practice. Cantero-Martínez *et al*. (2003), in semiarid Spain, concluded that no additional fertilizer is needed when minimum tillage or no tillage systems are used. In their research work, López-Bellido *et al*. (2010) found that nitrogen fertilizer rate has no effect on SOC sequestration. No-tillage systems are suitable for improving yield and for optimal environmental and economical use of N in Mediterranean conditions. However, we believe that further research is needed to better assess the impact of this increased soil fertility with the adoption of NT practices. The magnitude of and mechanisms for long-term differences in soil fertility under no-tillage and conventional tillage are still relatively poorly known.

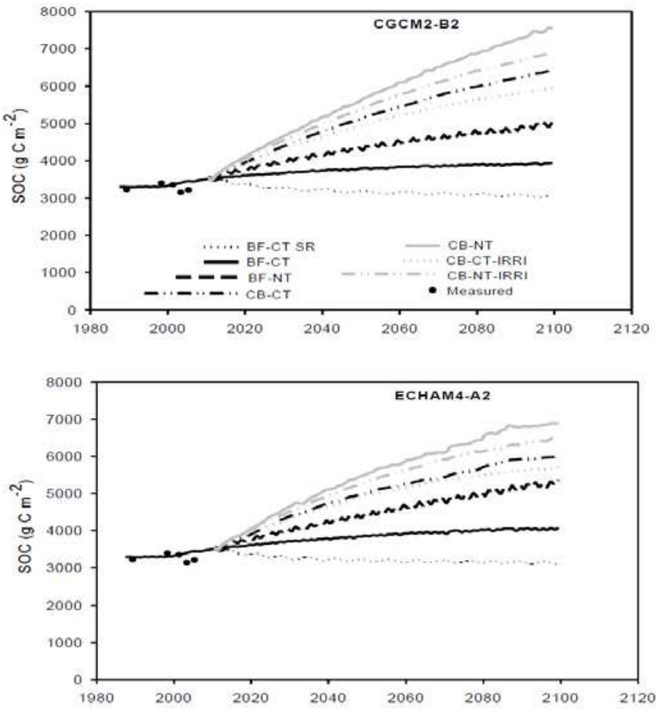

Fig. 5. Temporal SOC dynamics from 2010 to 2100 for the different management scenarios (BF = Barley fallow, CB = continuous barley) (From Alvaro-Fuentes and Paustian, 2010).

VII – Mitigation of accelerated erosion for soil conservation

Soil erosion is the most widespread form of soil degradation in the Mediterranean basin (García-Ruiz, 2010). This region is particularly prone to erosion because it is subject to long dry periods followed by heavy bursts of erosive rain, falling on steep slopes with fragile soils. The long history of landscape transformation, including deforestation, forest fires, frequent land-use changes and cultivation in extreme topographic and climatic conditions is also a prime reason for high erosion rates. Water erosion can result in the loss of 20 to 40 t/ha of soil in a single storm, with more than 100 t/ha in extreme events greatly exceed the average rate of soil formation (< 1 t/ha/yr), increasing the risk of desertification in the region. In other terms, any soil loss of more than 1 t/ha/yr can be considered as irreversible within a time span of 50-100 years. In Spain, the largest area with high erosion risk is southern and eastern (covering 44 per cent of the country's territory), with local erosion hotspots on the southern coast. Portugal, one-third of the country is at a high risk of erosion. In France, Italy and Greece, the areas with a high erosion risk cover from 1 to 20 per cent of the land surface respectively. In other terms, most affected are zones in Maghreb region, Andalusia, Corsica, Central Italy and Greece.

Erosion rate is very sensitive to both climate and land use, as well as to detailed conservation practice at farm level. Hence, under climate change, Mediterranean agriculture needs to be alert to the possibility of increased erosion risk. No-till vegetation cover is crucial to the maintenance of a number of factors that may lessen the impacts of erosion, including reducing the direct temperature effects of sunlight on soil, preserving channels for water infiltration, reduced slaking in heavier soils, and preserving structural integrity of the topsoil to resist wind and water erosion events. The literature overwhelmingly supports success of no-tillage practices in achieving reduction of soil erosion and runoff. The erosion risk decreases as the soil surface is continuously covered mainly during the rainy season. No-tillage management reduces the potential for soil erosion by mitigating the effects of wind and water on soil movement. In fact, the efficiency of no-tillage for reducing soil erosion and improving water storage is universally recognized.

In Mediterranean countries such as Tunisia, Morocco, Italy, Spain and Portugal, soil and water conservation has been found to be enhanced by the presence of crop residue mulch on the surface under no-till by increasing infiltration and reducing evaporation from the surface. It is also well known that the stratification of soil organic matter under no-tillage is required for controlling soil erosion and sediment loss. In fact, accumulation of soil organic matter generally reduces water runoff volume and sediment transport from agricultural fields. The mulch layer contribute to increase the roughness and the interception of raindrops, what delay runoff generation. Negligible runoff flow or sediment yield were determined under just 5 Mg ha^{-1} year^{-1} mulching rate (Fig. 6). However, soil loss is enhanced in tilled soils by the high susceptibility of soil particles and aggregates to become detached and transported by erosive agents.

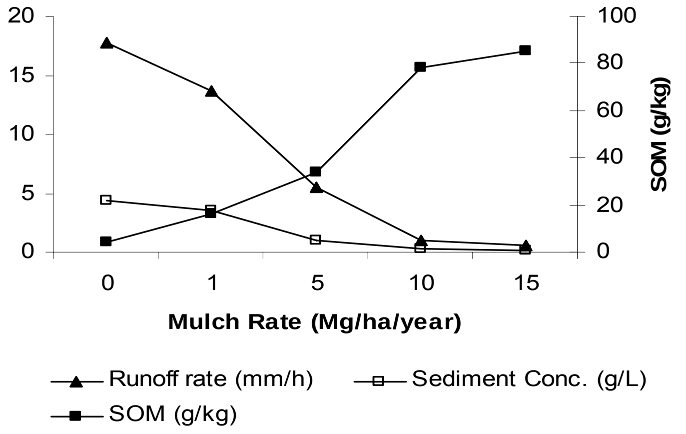

Fig. 6. Variation of mean SOM, runoff rates and sediment concentration under different no-till mulching rates (From Jordán *et al*., 2010).

VIII – Drought mitigation: No-tillage moderating impact in harsh environments

In the USA, the national level of no-till farmland increased 38% from 1998 to 2006, while the drought impacted states of Nebraska, South Dakota, and Kansas saw an increase of 67% over this same period. In fact, Ding *et al*. (2009) found that extremely dry conditions increase the adoption of conservation tillage practices, including no-tillage systems in the USA. Hence, because no-till conserves soil moisture and enhances water availability, its adoption is one strategy Mediterranean agricultural producers can use to reduce their risk associated with drought. The Mediterranean has had to deal with, and adapt to, serious climate stresses throughout history. Ironically, an increase in heavy precipitation events is expected with a decline in the evenness of rainfall distribution adding to the risk of both flooding and drought for the main crops in these areas. The projected changes in climate for Mediterranean basin are likely to have substantial impacts on the agricultural sector, both directly (e.g. water and temperature), and indirectly (e.g. soil effects, hydrology, pests, weeds and markets). Crop yields in the arid and semi-arid regions of Northern Africa, Southern Europe and the Middle East are expected to decrease by as much as 10-30% by the 2080 (Fig. 7). Hence, the central issue in agriculture is how to effectively use unpredictable growing season precipitation.

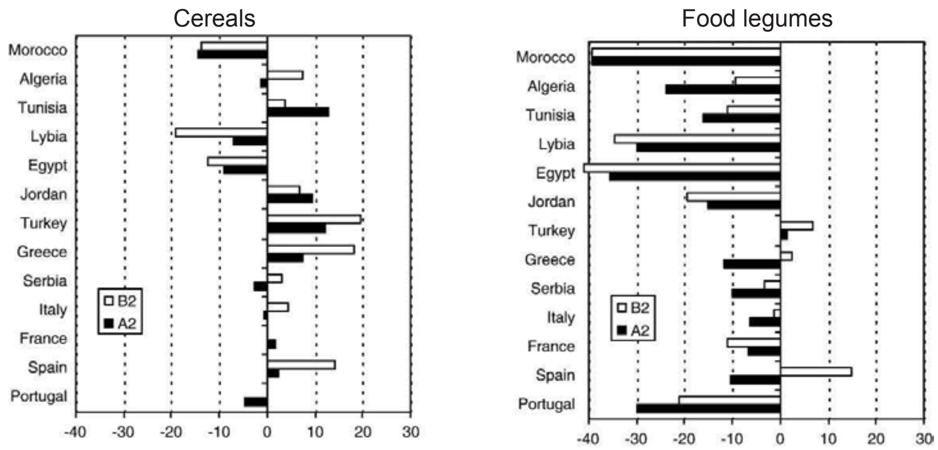

Fig. 7. Impact of climate change on crop productivity for cereals and food legumes. The changes in the figure are expressed as percentage differences between future (both A2 and B2 scenarios) and present yields (From Giannakopoulos *et al*., 2009).

In the Mediterranean basin, the experimental results suggest that no-till, when applied on suitable land with favorable weather and proper management could produce yields at least as high as conventional tillage. Pioneering studies in Morocco over the last 20 years or so have indicated that NT can function in areas with as little as 270-358 mm rainfall (Mrabet, 2008b). Fernández-Ugalde *et al*. (2009) recommended to farmers to consider adopting NT practices to compensate for the scarce and irregular precipitation pattern throughout the growing season in Spain. A wide range in crop yield response to tillage systems is reported in Table 3. Short-term (<4 years) and medium-term (4-8 years) yield effects of tillage systems have been found to be variable (positive, neutral or negative yield responses) as shown in Table 3. Short-term benefits are important, because they determine to a large extent the attractiveness of NT to farmers, and some of the negative effects presented in Table 3 discourage their adoption of NT and perception by decision makers. The variability in short-term crop responses to NT is principally the result of the interacting effects of crop nutrient requirements, seed drill performances, weed control, soil characteristics and climate. Under conditions where moisture is limiting crop yields this may give rise to yield improvements in the short term. However, in wet or humid conditions, the opposite may occur due to weed infestation if herbicides are not appropriately applied.

Table 3. Cereal and row crop yield (Mg ha^{-1}) under no-tillage and conventional tillage in the Mediterranean region

Country	Species	Rotation	NT	CT	Years	References
	Winter cereals					
Morocco	Bread wheat	Continuous wheat	2.47	2.36	4	Mrabet (2000)
	Bread wheat	Wheat-fallow	3.70	2.60	10	Mrabet (2008a)
		Continuous wheat	1.90	1.40	10	
	Bread wheat	Wheat-fallow	3.10	2.40	19	
		Continuous wheat	1.60	1.60	19	
Tunisia	Durum wheat	Continuous wheat	3.90	3.30	2	Vadon et al. (2006)
	Durum wheat	Wheat-lentil-watermelon	2.18	1.94	5	M'hedhbi *et al.* (2004)
Syria	Durum wheat	Wheat-lentil	3.33	3.85	5	Thomas *et al.* (2007)
	Barley	Barley-vetch	1.55	1.39	7	Jones (2000)
		Continuous barley	1.09	1.01	7	Jones (2000)
Turkey	Bread wheat	Wheat-corn	2.40	3.35	-	Yalcin (1998)
		Wheat-Fallow	2.50	2.50	5	Avci (2005)
Spain	Wheat	Cereals-sunflower-legumes	3.80	4.07	6	Ordóñez-Fernández *et al.* (2007)
	Bread wheat	Wheat-vetch	4.72	4.29	8	Medeiros *et al.* (1996)
	Bread wheat	Wheat-vetch	3.16	3.03	16	Sánchez-Girón *et al.* (2004)
	Barley	Continuous barley	3.02	3.04	16	
Italy	Wheat	Wheat-soybean	3.97	4.36	16	Mazzoncini *et al*. (2008)
	Durum wheat	Continuous wheat	2.37	2.16	3	De Vita *et al.* (2007)
	Row crops					
Syria	Lentil		1.10	1.10	12	Pala *et al*. (2000)
	Chickpea		0.80	0.77	12	
	Lentil		1.12	1.14	5	Thomas *et al*. (2007)
	Vetch		0.67	0.77	7	Jones (2000)
Spain	Vetch		5.90	5.9	16	Sánchez-Girón *et al*. (2004)
	Pea		4.38	4.38	8	Sánchez-Girón *et al.* (2007)
	Faba bean		1.74	2.00	11	López-Bellido *et al*. (2003)
	Sunflower		1.03	1.09	8	Ordóñez-Fernández *et al*. (2007)
Italy	Soybean		2.60	3.08	16	Mazzoncini *et al*. (2008)
	Corn		5.07	8.07	4	De Vita et al. (2007)
Turkey	Corn		6.40	6.70	2	Bayhan *et al*. (2006)
Morocco	Corn		1.61	1.50	4	Mrabet (1997)
	Sunflower		2.71	3.02	2	Aboudrare *et al*. (2006)

On an Orthic Luvisol, Carof (2006) reported no soil tillage effect on wheat yield over a period of three year in Northern France. This author, however, reported that living cover depressed grain yield under no-tillage system. In Southern Italy, while NT ameliorated soil quality attributes and reduced soil erosion hazard, mean durum wheat grain yield for a period of six years were similar among tillage systems. However, in dry years, NT was yielding 12 to 34% higher than CT (Di Fonzo *et al*., 2001). Experiments showed that seedbed preparation using either moldboard or chisel plowing with or without deep tillage did not consistently influence the vegetative and yield of row crops when compared to the no-tillage systems (Table 3). In Spain, cop yields averaged across 16 years of field experimentation showed no statistical differences between tillage systems (Sánchez-Girón *et al*., 2004; Table 3). In the Mediterranean zone of Spain, López-Bellido *et al*. (1996) reported increased wheat yield under NT than CT, while López-Bellido *et al*. (2002) showed that sunflower can be seeded on untilled soils. The tillage system did not exert a consistent influence on sunflower yield for 9 years; thus, continuous no-tillage may represent an economically and environmentally viable alternative to conventional tillage for sunflower production under rainfed Mediterranean conditions. This is also reported by Ordóñez-Fernández *et al*. (2007) and Aboudrare *et al*. (2006) for Morocco (Table 3). It is clear from the various long-term experiments on tillage systems, shown on table 3, that moldboard or disk plowing is not a sustainable system of soil management. The major recommendation is that there is a need to eliminate deep plowing and inversion operations for seedbed preparation. In most cases, no-tillage system permitted higher yields in the long-term. However, for the thorough emergence of this system, farmers should appropriate adequate drills and perform strategic weed control.

As pointed out by Ben Moussa-Machraoui *et al*. (2010), the superior effect of NT in comparison to CT can be due to lower water evaporation from soil combined with enhanced soil water availability. These high water evaporation reductions associated with better water entry in the soils are important in droughty years or in dry areas (Mrabet, 1997). However, biomass production in these contexts is limited and most of straw and stubble is exported from fields for animal feeding. In here, for mitigating drought using no-tillage systems, it is worth planning crop residue use according to climatic conditions and permitting high straw exports in wet years and maximum retention in dry years of surface mulch. From results by Mazzoncini *et al*. (2008), in Central Italy, wheat grain yields in NT, averaged over the 16 seasons, were significantly lower (8.9%) than in CT. The loss of wheat productivity with NT soil management was generally low and tended to diminish when plentiful rainfall did not occur within a few days after planting, a good weed control was assured, and less than normal rainfall occurred during the grain filling period. When these conditions happen in combination, it is likely that NT grain yield will be equal or greater than CT. This combination occurs frequently in Italy, particularly in the central, southern, and insular areas. However, in North-east Italy, Borin *et al*. (1997) favored more the shift to no-tillage and reduced tillage systems because of reduction in carbon dioxide emission and energy consumption rather than to grain yields. In southern Italy, De Vita *et al*. (2007) reported superior yield and WUE with NT when precipitation was <300 mm during the wheat cycle (November-May). Under these conditions, the NT treatment expressed its superior nature for wheat yield ensuring also a good level of grain quality.

From Fig. 8 (Morocco), no-tillage system is permitting higher wheat yields in all environments, from water stressed to favorable climatic conditions. However, It is also clear from Fig. 9 (Italy) that higher yields of wheat are associated with no-tillage, mainly in dry years. Hence, no-tillage systems should help farmers achieve more sustainable and profitable yields over years, thereby decreasing risks. From studies by Lahlou *et al*. (2005) in Morocco and Fernández-Ugalde *et al*. (2009) in Spain, the increased plant-available water content under NT, due to the improvement of soil structural properties (i.e. aggregate stability, pore-size distribution), is responsible for stabilized and higher crop yields under NT in drought-prone areas. In Moroccan farmer's field, wheat yield increased with no-tillage system compared to conventional tillage (Fig. 10). No-tillage systems were applied for 4 to 9 years without any depression of wheat production. Wheat production under no-tillage in a drought year like 1999 expresses the stabilizing effects of favorable conditions of soil properties and microclimate when applying no-tillage and residue cover. However, crop failure in case of farmer's field under conventional tillage mean that conditions for degradation were prevalent. At the farmer's site characterized by sloping lands, in average over the period, NT gave a yield of 2.5 Mg/ha while yield under CT did not exceed 1.49 Mg/ha (Fig. 10a). At the second farmer's site which is of medium soil depth, NT reached a yield of 2.23 Mg/ha. The conventional tillage system allowed in average 0.93 Mg/ha over the four years (Fig. 10b). Hence, the average gain in yield under NT *vs* CT is 1.01 and 1.30 Mg/ha for the sites.

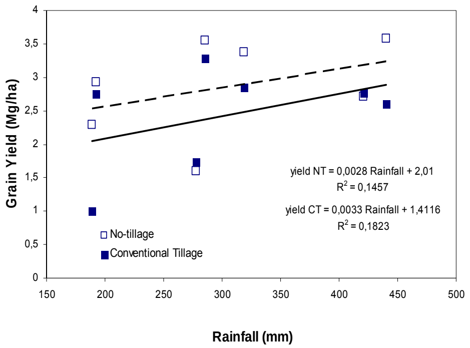

Fig. 8. Correlation between grain yield and rainfall during bread wheat cycle (November–May) in a semiarid area of Morocco (From Mrabet, 2008b).

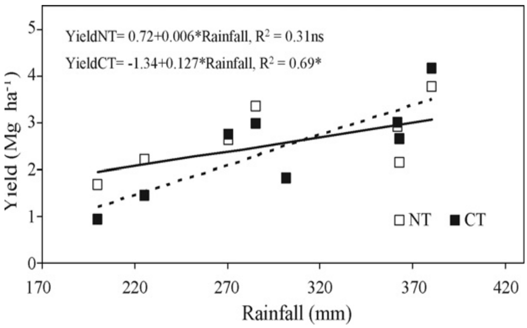

Fig. 9. Correlation between grain yield and rainfall during durum wheat cycle (November–May) at Foggia, Southern Italy (From De Vita *et al*., 2007).

Under no-tillage, the crop saved water, early in the season, leaving more water for the grain filling season. Because of this, the yield was slightly higher in the no-tillage treatment than in the traditional tillage for the dry years. Water use efficiency was always higher in the no-tillage treatment than in the traditional tillage. The conservation tillage applied seems to be highly effective in enhancing soil water recharge and water conservation, particularly in years with much lower than average precipitation.

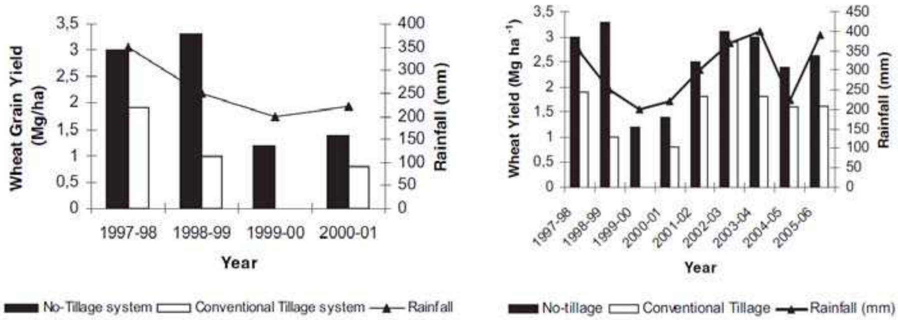

Fig. 10. Tillage system's effects on wheat grain yield in two semi-arid Moroccan farms with (a) sloping (left graph) land and (b) medium depth clay soil on flat (right graph) (Mrabet, 2008b).

No-tillage can assist in the adaptation to climate change by improving the resilience of agricultural cropping systems and hence making them less vulnerable to abnormal climatic situations. Better soil structure and higher water infiltration rates reduce the danger of flooding and erosion catastrophes after high intensity rainstorms. Increased soil organic matter levels improve the water holding capacity and enables crops to get through extended drought periods. Yield variations under no-tillage in extreme years, regardless of whether they are dry or wet, are less pronounced than under conventional tillage. Due to higher availability of moisture in NT soils, crops can continue towards maturity for longer than those under conventional tillage. In addition, the period in which available nutrients can be taken up by plants is extended, increasing the efficiency of use. The greater volume and longer duration of soil moisture's availability to plants (between the soil's field capacity and wilting point) has significant positive outcomes both for farming stability and profitability.

IX – Conclusions: No-tillage as a Mediterranean farming revolution

The Mediterranean basin is demonstrably in an era of complex problems requiring integrated scientific investigations. Knowledge of climate change is an obvious first step to maintain or improve production and land management in the future. Within this context, changing the intensity, timing, or form of tillage may be one of the management options more readily implemented to assist with adaptation to climate change. Considerable soil carbon research with relation to tillage systems has occurred in Mediterranean Europe in recent years in comparison with the other Mediterranean countries in the south or the east. From these studies, no-till management can increase soil organic C (SOC) levels. In other terms, agro-ecosystems can be adroitly managed to reduce carbon emissions and increase carbon sinks in vegetation and soil using no-tillage systems. One of Mediterranean agriculture's major opportunities to help mitigate the effects of climate-warming gases lies in management of soil to increase organic content, thereby removing carbon from the atmosphere (Thomas, 2008). The adoption of various tillage systems such as reduced tillage, or no-tillage practices has been demonstrated to reduce soil CO_2 efflux and conserve SOC pools in croplands. No-till, which has the possibility of increasing carbon sequestration in soil, has the potential to be included in trading credits for carbon, introducing the concept of farming carbon (Lal, 2007). However, the apparent carbon sequestration advantage for no-till inferred from previous studies likely reflects the tendency to sample carbon only near the soil surface. A sizable literature has studied the effects of no-tillage systems on soil erosion and hydrological processes worldwide but not in the Mediterranean basin. In the other hand, soil carbon sequestration and respiration data are still fragmentary and should be reinforced in the Mediterranean basin. Enforcement and improvement in monitoring and verification protocols for soil erosion and carbon sequestration in soil plant ecosystems in the Mediterranean region are needed for quantitative economic and policy analyses.

Decisions relating to the use or the shift of no-tillage will be made in the context of both the longer term strategic response to climate change, and the shorter term practical response to annual weather patterns. The challenge is to develop new techniques that increase crop biomass production, particularly for semiarid areas. Plant breeders and physiologists must be involved to insure that cultivars developed for economic and biological yields also improve soil. Specifically, the biological yield of above and below ground biomass should have properties, such as elevated lignin and suberin contents that promote accumulation of stable carbon forms in soil and in plant products. A more co-operative approach between Mediterranean researchers is needed in order to address more clearly these aspects. Although alternative tillage systems have been assessed in different agricultural regions of the Mediterranean for understanding crop responses to interactive effects of climate and soil management, long-term data are still scarce. There are, however, many barriers to implementing no-tillage management practices, the most significant of which in Mediterranean developing countries are driven by poverty. In other terms, if no-till soil management is to be used to help address the problem of global warming, priority needs to be given to implementing poverty and supportive policies of small-scale farmers. Efforts will also be required to mainstream climate change into development and poverty reduction strategies.

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