Conservation Agriculture Under Mediterranean Conditions in Spain

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Abstract Intensive agriculture with deep tillage and soil inversion causes rapid soil deterioration with loss of soil organic matter content. This practice leads to a decrease of soil biological activity, a damage of the physical properties and a reduction of crop yields. Conservation agriculture aims to achieve sustainable and profitable agriculture through the application of three basic principles: minimal soil disturbance by conservation tillage, permanent soil cover and crop rotations. Any practice of conservation agriculture must maintain on the soil enough surface residues throughout the year. Conservation tillage is thus any tillage and planting system that maintains at least 30% of the soil surface covered by residues after planting to reduce soil erosion by water. Here we review the main advances about the adoption of conservation agriculture under Mediterranean conditions in Spain. There are major cost savings, e.g. fuel and fertilizers costs, compared with conventional agriculture. Conservation tillage has been proven to be highly efficient for water storage, to increase moderately the organic matter in the soil top layer, and to improve soil physical properties and aggregation. However, no tillage may induce greater soil compaction in some cases. Here, an occasional tillage is advised. Furthermore, conservation tillage can reduce soil CO_2 emissions, mobility and persistence of herbicides. In general, conservation tillage enhances biodiversity compared to conventional tillage. Crop yields under conservation tillage are similar or even greater than yields of traditional tillage. All these benefits

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show that conservation agriculture in Spain is a more sustainable alternative than conventional agriculture. Nonetheless, we have found from the literature analysis some constraints for its adoption, mainly due to inadequate extension and technology transfer systems and lack of access to specific inputs.

Keywords Conservation tillage • Soil quality • Water storage • Environmental impact • Socio-economic impact • Soil carbon sequestration • CO_2

1 Introduction

Intensive agriculture causes rapid soil deterioration, with loss of soil organic matter content, leading to a decrease of soil biological activity, a damage of the physical properties and a reduction of crop productivity. Losses of organic matter derive from the soil inversion by tillage that characterizes other kind of agriculture, such as organic farming and integrated agriculture. Conservation agriculture aims to achieve sustainable and profitable agriculture through the application of three basic principles: minimal soil disturbance (conservation tillage), permanent soil cover and crop rotations. In general, conservation agriculture includes any practice which reduces changes or eliminates soil tillage and avoids residues burning to maintain enough surface residues throughout the year. Soil is protected from rainfall erosion and water runoff; soil aggregates are stabilised, organic matter and the fertility level naturally increase, and less surface soil compaction occurs. Furthermore, the contamination of surface water and the emissions of CO_2 to the atmosphere are reduced, and biodiversity increases (ECAF 1999). The efficiency of conservation agriculture to reduce soil erosion and to improve the organic content and water storage is universally recognized. This is particularly important in arid and semi-arid zones, in which soil organic matter content is very low and the climatic conditions leads to continuous losses. In these conditions, water is the limiting factor for crop development under rainfed agriculture and the management of crop residues is of prime importance to obtain sustainable crop productions (Du Preez et al. 2001).

Basically, this is the general picture in Spain, where about 80% of its surface is devoted to extensive agriculture, mostly under dryland conditions. In general, soils are basic and calcareous in Central and Eastern Spain and acid in North and North-Western Spain, most of them with a low soil organic matter content, due, among other factors, to more than 2,000 years of continuous cultivation and to a low development of natural vegetation under adverse climatic conditions in dry and semi-arid areas, very frequent in Spain.

Besides limited water availability for agriculture and other uses, the worst environmental issue facing the Spanish agriculture is soil erosion. The average soil loss by water impact in Spain has been estimated in about 34 t ha^{-1} $year^{-1}$, with low rates in North-Western areas and high rates in Eastern and Southern Spain, especially in Andalusia, where annual soil losses can reach 60–80 t ha^{-1}. On the basis of the knowledge available, conservation agriculture appears to be the most important sustainable alternative system to conventional agriculture based on intensive tillage to cope with negative agro-environmental problems like the loss of fertile soil in areas prone to erosion processes (Photos 1 and 2).

Photo 1 Conventional tillage using mouldboard ploughing in semi-arid conditions

Photo 2 Direct drilling in semi-arid conditions

Any practice of conservation agriculture must maintain on the soil enough surface residues throughout the year, an importance aspect when considering tillage. As pointed out by Gajri et al. (2002), initially, the concept of minimum tillage was aimed at reducing the number of tillage trips across the field. Later, the emphasis was put on leaving the soil surface covered with residues, rather than merely reducing the number of operations, and the term *conservation tillage* was introduced (Hill 1996). Sometimes, no distinction between conservation tillage, minimum tillage or reduced tillage is made (Bradford and Peterson 2000). Types of conservation tillage include no-tillage, ridge tillage, mulch tillage and zone tillage (see Hill 1996 for definitions). Designs for tillage experimentation have been reviewed by López and Arrúe (1995).

The most commonly definition used for conservation tillage is any tillage and planting system that maintains at least 30% of the soil surface covered by residues after planting to reduce soil erosion by water. Where soil erosion by wind is a primary concern, the system must maintain a 1.1 Mg ha^{-1} flat small grain residue equivalent on the surface during the critical wind erosion period. Basically, is a year-round conservation system that usually involves a reduction in the number of passes over the field and/or in the intensity of tillage, avoiding ploughing (soil inversion) (Gajri et al. 2002), that would incorporate residues into the soil mass.

Permanent soil cover (cover crops) imply sowing of appropriates species, or growing spontaneous vegetation, in between rows of trees, or in the period of time in between successive annual crops, as a measure to prevent soil erosion and to control weeds. Cover crops are generally managed with herbicides with a minimal environmental impact (ECAF 1999). Steep gradients of the terrain with a lack of soil cover (frequent in olive groves) under Mediterranean climate, which typically has long periods of drought followed by torrential storms, conduces to a serious loss of soil and fertility irrespective of the tillage system applied. Alternative cover olive-grove systems have recently been introduced for these situations (Castro et al. 2008). The importance of crop rotations can be seen in Karlen et al. (1994), however not always is possible to use a wide range of crops in such as dryland conditions and a choose of winter cereals could be used (Alvaro et al. 2009).

2 Conservation Agriculture in Spain: Main Research Topics

According to Fernández-Quintanilla (1997), it was in the 1970s when the concepts of tillage reduction and the use of conservation agriculture practices for annual and perennial crops were first introduced in Spain mainly through knowledge gathered in the USA. The release on the market of new herbicides, as paraquat and gliphosate, for a full control of volunteers and weeds before sowing was definitely a key factor.

Since mid 1970s, in perennial crops, and the late 1970s in annual crops, a large number of conservation agriculture field studies have been carried out across Spain, implemented as a farmer's initiative in some cases. Most of these studies were based on the comparison of conventional primary tillage (i.e., mouldboard ploughing with soil inversion) with two forms of conservation agriculture, (i) minimum or reduced tillage, in which the conventional primary tillage is replaced by a vertical or surface tillage with different ploughs (e.g., chisel or cultivator) and (ii) no-tillage or direct drilling. The main research topics considered by different Spanish research groups could be classified according four main knowledge areas: (1) socio-economic aspects: energy use and consumption, (2) soil quality and water saving, (3) environmental issues, and (4) crops and crops protection.

2.1 Socio-economic Aspects: Energy Use and Consumption

At the beginning, the main driving forces for conservation agriculture development in Spain were based on labour simplification and savings of fuel and costs for machinery required for tillage and other kind of inputs. Later, the advantageous agronomic and environmental aspects of conservation agriculture practices (soil water conservation, soil protection, and increase of soil organic carbon and soil biological activity) were recognised by farmers. Important cost savings have been reported for minimum tillage and zero tillage in Spain, compared with conventional tillage. Reduction in fuel consumption can range between 30% (minimum tillage) and 60% (no-tillage); time saving for tillage operations, derived from reduction of the number of labours, can reach up to 45% (no-tillage) (Hernanz et al. 1995; Sombrero et al. 2001b; Sánchez-Girón et al. 2004) (Table 1).

However, the acceptance of conservation agriculture technologies in Spain is still low, especially in those areas where these technologies were not initially well introduced. As pointed out by Cantero-Martínez and Gabiña (2004) and Angás et al. (2004), this low degree of adoption is a consequence of inadequate extension and technology transfer systems and lack of access to specific inputs, machinery and

Table 1 Net margin (Euros/ha) of a economical study conducted in the Ebro Valley in 2006, comparing different tillage system in three different areas (arid, semiarid and subhumid) for three different farm sizes

Zone/farm ha	Intensive	Vertical	Minimum	No tillage	[a]No tillage
Arid/300	257.11	268.54	316.94	305.62	302.15
Arid/150	256.08	266.47	310.64	297.06	295.56
Arid/75	242.98	246.75	289.59	268.96	280.66
Semiarid/300	203.51	241.09	246.69	265.16	261.69
Semiarid/150	202.40	239.00	240.30	256.60	255.10
Semiarid/75	189.38	219.30	219.34	228.50	240.20
Semihumid/300	365.04	376.47	403.27	401.97	398.50
Semihumid/150	364.01	374.40	396.97	393.41	391.91
Semihumid/75	350.91	354.68	375.92	365.31	377.01

[a] No tillage is used but planting machine is rented for sowing operations (Cantero-Martínez et al. 2009)

Table 2 Main driving forces and constraints for conservation agriculture in Spain

Driving forces
Better economy (labour simplification; less time requirements for tillage operations; less fuel consumption; less machinery required for tillage; less power machinery)
Flexible sowing time. Double crop possibilities in some areas
Better water economy and soil protection. Better soil quality
Greater nutrient-use efficiency. Less use of fertilizers. Faster crop establishment and development. Same yield or slight yield increases (10–15%)
Potential constraints
Economic reasons. Farmer's reluctance and fear to acquire new and expensive specific machinery or to higher herbicide costs
Occasional soil deterioration (compaction, poor aeration, waterlogging)
Crop residue management difficulties. Occasional allelopathic problems
Occasional higher incidence of weeds, pests and diseases (the reverse situation can be a driving force)
Irregular incidence of rodents and slugs
Poor crop development under particular conditions (lower soil temperatures under irrigated spring crops)
Insufficient information and technical support
Social relationships among farmers (criticisms discouraging hesitant farmers)

equipment. Table 2 shows the main driving forces and constraints for conservation agriculture in Spain, information derived from different farmer surveys carried out along this country.

In summary, important cost savings (fuel, fertilizers) have been reported for conservation agriculture in Spain compared with conventional tillage. However, its adoption is still low mainly due to inadequate extension and technology transfer systems and lack of access to specific inputs, machinery and equipment. Crop residue management difficulties and occasional higher incidence of weeds, pests and diseases, besides social relationships among farmers (criticisms) may also difficult the establishment of conservation agriculture in local scenarios.

2.2 Soil Quality and Water Storage

The efficiency of the conservation tillage to improve the water storage in soil is universally recognized. This is very important in arid and semi-arid zones, where management of crop residues is of prime importance to obtain sustainable crop productions (Du Preez et al. 2001; Lampurlanés and Cantero-Martínez 2006; Moreno et al. 1997; Pelegrín et al. 1990). Organic matter is highly related to the soil capacity for water storage; most soils under Mediterranean semi-arid conditions are rather low in organic matter. Increases in soil organic carbon under conservation tillage (reduced tillage, minimum tillage, no-tillage) have been reported by different authors in Spain (Álvaro-Fuentes et al. 2008a; Bescansa et al. 2006; Bravo et al. 2003; De Santiago et al. 2008; Hernánz et al. 2002; López-Bellido et al. 1997; L· pez-Fando and Pardo 2001; Ordóñez Fernández et al. 2003, 2007; Murillo et al. 1998).

However, semi-arid Mediterranean conditions may suppose a limiting factor for the accumulation of organic carbon in the top soil layers. Thus, the simple determination of the total content of organic carbon can not be the best indicator of the improvement caused by conservation tillage. Under semi-arid conditions could be more interesting the knowledge of the stratification ratio of soil organic carbon, defined as the content at the surface layer (e.g., 0–5 cm) divided by the content at deeper layers (Franzluebbers 2002; Murillo et al. 2004; Moreno et al. 2006; López-Fando et al. 2007). As reported by Franzluebbers (2002), stratification ratio greater than 2 are not frequent in degraded soils. As pointed out by Franzluebbers (2004), soils with low inherent levels of organic matter could be the most functionally improved with conservation tillage, despite modest or no change in total standing stock of soil organic carbon within the rooting zone. Stratification of soil organic matter pools with depth under conservation tillage systems has consequences on soil functions beyond that of potentially sequestering more carbon in soil. The "more is better" argument referred to soil organic carbon is weaker when applied to agricultural productivity, where the benefits of greater soil organic matter contents on intensively managed arable soils are sometimes obscure (Sojka and Upchurch 1999). In the absence of a clear critical point and demonstrable ecological consequence, the setting of soil quality targets within a continuum requires human value judgments (Sparling et al. 2003).

Although under semi-arid climate there could not be a great enrichment of soil organic carbon at surface in conservation tillage, slight increases could have created particular conditions for the physico-chemical and biological soil dynamics. It has been reported that despite the stratification ratio of the total soil organic carbon may only slightly increase under conservation tillage, other variables related to the biological dynamics of the soil, such as microbial biomass carbon and some enzyme activities (and their stratification ratios) may increase to a greater extent (Madejón et al. 2007; Murillo et al. 2006). Nutrients, and general soil fertility, are also positively affected by the soil organic matter increase derived from the conservation tillage establishment (Bravo et al. 2006, 2007; de Santiago et al. 2008; Ordóñez Fernández et al. 2003; L· pez-Fando and Almendros 1995; Moreno et al. 2006, Martín-Rueda et al. 2007; Saavedra et al. 2007).

Short- and long-term experiments under conservation and conventional tillage have shown that organic matter also influences soil physical properties and aggregation (Álvaro-Fuentes et al. 2007c, 2008b; Lampurlanés and Cantero-Martínez 2003; López et al. 1996; Moreno et al. 1997, 2000, 2001; Moret and Arrúe 2007a, b). In general, aggregate stability was greater under conservation tillage, especially under no-tillage than under conventional tillage and minimum till-age or reduced tillage.At long-term, higher soil bulk density and compaction under no-tillage than under conventional tillage (and reduced tillage) have been reported (Álvaro-Fuentes et al. 2008a; Moret and Arrúe 2007a, b). The hydraulic conductivity was significantly lower under no-tillage than under the tilled treatments due to a lower number of water transmitting pores per unit area. The effects of subsoil compaction on soil propertiesand the use of models to simulate the subsoil compaction process have been investigated by Coelho et al. (2000); Moreno et al. (2003); Perea et al. (2003). Soil density tended to be greater under reduced tillage in dry years, although there were no differences in years with high rainfall (Moreno et al. 2001). However, in many cases those situations do not create a depression on the crop productivity.

In relation to water storage, conservation tillage is frequently highly efficient to reduce soil water losses, especially in years with rainfall lower than the average (Moreno et al. 2000). The use of cover crops in olive orchards at Andalusia have been carried out by Pelegrín et al. (2001) who specifically investigated cover crop systems for soil and water conservation and designed a seed driller for cover crop sowing under no-tillage management conditions.

Results obtained by López et al. (1996) suggested that reduced tillage could replace the conventional tillage without adverse effects on soil water content and storage. However, no-tillage was not a viable alternative for extremely arid zones of NE Spain. On the contrary, Lampurlanés et al. (2001, 2002, 2003), Lampurlanés and Cantero-Martínez (2004) and Cantero-Martínez et al. (2004) showed that no-tillage resulted potentially better for semi-arid regions of NE Spain because it maintains greater water content in the soil and promotes root growth in the surface soil layers and, in some cases, deep in the soil profile also, especially in years of low rainfall. In shallow soils because of the low soil water-holding capacity, no-tillage proved to be better under low amount and frequent events of rainfall in spring that matching with the filling grain period of the crop. Moret et al. (2006, 2007a) quantified the efficiency of long fallow and tillage for soil water storage in NE Spain showing that conservation tillage systems could replace conventional tillage for soil management during fallow without adverse effects on soil water conservation. Tillage effects on water storage during fallow in NE Spain have also been exhausted discussed by Lampurlanés et al. (2002).

Water storage is related, among other factors, to residues management and evolution. López et al. (2003, 2004, 2005b) have studied the evolution of barley residues during four long fallow periods under conservation tillage, reduced tillage and no-tillage, and under both continuous cropping and cereal-fallow rotation. The lack of residue-disturbing operations in no-tillage makes this practice the best strategy for fallow management. Under no-tillage, the soil surface still conserved between 10% and 15% of residue cover after long-fallowing and percentages of standing residues ranging from 20% to 40% of the total mass after the first 11–12 months.

In summary, increases in soil organic carbon under conservation tillage (reduced tillage, minimum tillage, no-tillage) have been reported by different authors in Spain, although under semi-arid Mediterranean conditions there could not be a great enrichment of soil organic carbon at surface. However, slight increases of organic matter have created particular conditions for the physico-chemical and biological soil dynamics increasing soil quality. In general, better soil physical properties and aggregation under conservation agriculture have been reported. However, greater compaction under no-tillage can result at long-term in particular scenarios, which could make advisable an occasional tillage labour.

Conservation tillage has been proved to be highly efficient to water storage, especially in years with rainfall lower than the average, and can replace conventional tillage for soil management during fallow, due to the lack of residue-disturbing operations.

2.3 Environmental Factors. Soil Erosion and Biodiversity

Several studies have been focused on the development of simulation models and expert systems to predict the effects of tillage systems on water erosion under different climatic conditions and to design site-specific agricultural machinery (Simota et al. 2005; de la Rosa et al. 2005; Dexter et al. 2005; Horn et al. 2005; Díaz-Pereira et al. 2002; Gómez et al. 2002). These models provide a tool for recommendations for site-specific land use and management strategies. In order to obtain new knowledge for a better management of the olive crop, Gómez et al. (1999, 2004, 2005) have studied the effects of different tillage systems on soil physical properties, infiltration, water erosion and yield of olive orchards.

In areas where strong and dry winds are frequent (such as *Aragon*, NE Spain), fallow lands are susceptible to wind erosion due to insufficient crop residues on the surface (López et al. 2001). Results obtained by López (1998), López and Arrúe (1997, 2005) and López et al. (1998, 2000, 2003, 2005) indicated that reduced tillage, and especially no-tillage, could be considered as a viable alternative to conventional tillage for wind erosion control during the fallow period in these areas. Consequently, no significant dust emission and saltation transport was observed in conservation tillage plots (Sterk et al. 1999; Gomes et al. 2003). Reduced tillage provides higher soil protection than conventional tillage through a lower wind-erodible fraction (aggregates <0.84 mm in diameter) of soil surface (on average, 10% less) and a significantly higher percentage of soil cover with crop residues and clods (30% higher).

Adoption of conservation tillage can reduce soil CO_2 emissions to the atmosphere thus minimising soil organic carbon losses and mitigating the greenhouse effect (Arrúe 1997). Álvaro-Fuentes et al. (2004, 2007a, b, 2008a) have evaluated the influence of conventional tillage and conservation tillage (reduced tillage and no-tillage) on short- and long-term CO_2 fluxes at NE Spain. Soil CO_2 emissions just after tillage were 40% higher under conventional tillage than under no-tillage as the CO_2 accumulated on soil pores was released to the atmosphere after the tillage event (Reicosky et al. 1997). At the same time, tillage has an effect during the whole growing season increasing microbial decomposition resulting in a 20% higher soil CO_2 emissions under no-tillage than under no-tillage during the whole growing season. Reduction of CO_2 fluxes under reduced tillage respect conventional tillage have also been reported by Sánchez et al. (2002, 2003) in the Spanish plateau. The influence of N fertilization on N_2O and CO_2 emissions under rainfed Mediterranean conditions have recently been studied by Menéndez et al. (2008) and Morell et al. (2007).

The transport and persistence of herbicides in soils under conservation tillage (reduced tillage) has also been studied in Spain (Cox et al. 1996, 1999; Cuevas et al. 2001). Results from these studies showed that the mobility and persistence of herbicides (e.g., trifluralin and metmitron) were lower under conservation tillage than under conventional tillage.

In general, conservation tillage enhances biodiversity. The effect of tillage on nematode populations was early studied by López-Fando and Bello (1995). The effect of conservation tillage systems on earthworm activity as a biological indicator has been studied in NE Spain (Cantero-Martínez et al. 2004). The most important finding never described in the Iberian Peninsula was the higher earthworm population and activity measured under no-tillage compared to conventional tillage. Soil moisture conditions, as influenced by the climatic conditions of the year, was a determinant factor for the number of the earthworms during and between years. Tillage system influences greatly the earthworm population in the long term experiments and much higher populations were found during several years under no-tillage. Despite the number of earthworm adults and eggs were influenced by the water regime of the year, in drier years the level of adults was always higher under conservation tillage systems in the first 30 cm of the soil profile.

In summary, conservation tillage could be considered as a viable alternative to conventional tillage for wind and water erosion control during the fallow period. Furthermore, adoption of conservation tillage can reduce soil CO_2 emissions to the atmosphere thus minimising soil organic carbon losses (that can enhance soil erosion) and mitigating the greenhouse effect. Soil CO_2 emissions just after tillage were 40% higher under conventional tillage than under no-tillage. Conventional tillage also had an effect during the whole growing season increasing microbial decomposition, resulting in a 20% higher soil CO_2 emissions than in conservation tillage. Mobility and persistence of herbicides were lower under conservation tillage than under conventional tillage. In general, conservation tillage enhances biodiversity, and for example, a higher earthworm population and activity were measured under no-tillage compared to conventional tillage.

2.4 *Crops and Crops Protection*

Conservation tillage is also especially important to achieve sustainable yields in semi-arid climate regions: However, the implementation of no tillage systems has occasionally caused yield losses, especially in humid and subhumid regions due to cooler and wetter soil conditions, inadequate physical properties, thermal and aeration regimes, root growth increased grassy weeds and residue problems during seeding (Kirkegaard et al. 1995; Gajri et al. 2002).

Nevertheless, with correct management, the global experience with conservation tillage does not result in smaller harvests than conventional tillage (Warkentin 2001; Gajri et al. 2002). In water-limiting environments, no till and other moisture conservation practices can increase crop yields (Gajri et al. 2002). This is corroborated by global results related to crop response in Spain, one of the major research subjects of the Spanish groups.

Conservation Agriculture has been developed in Spain since late seventies and has been focused mainly in field crops under dryland conditions as winter cereals. Less attention has been paid to field crops under irrigation. Only some studies have been conducted in orchards as olive, vineyards or almond under dryland condition or deficit irrigation. No studies have been done in horticultural crops.

In field crops, many studies at the dry conditions of SW Spain have shown that crop yields under conservation tillage (reduced tillage, no-tillage) were similar to or even greater than those in conventional tillage. A significant number of studies have dealt with the effects of these tillage systems on crop yield under different crop rotations and N fertiliser rates in rainfed conditions, with particular attention to no-tillage (Bravo et al. 2003; González et al. 2003; López-Bellido and López-Bellido 2001; López-Bellido et al. 1996, 1997, 1998, 2000, 2001, 2002, 2003a, b, 2004a, b; Moreno et al. 1997; Murillo et al. 1998). Murillo et al. (1998, 2000) reported data about the nutritional status of the crop, and showed the differences in crop development, at the earlier stages, frequently slightly better under conventional tillage although the difference disappeared at more advanced stage of growth.

In semi-arid central Spain, Hernanz et al. (2002) and Sombrero et al. (1998, 2001a, 2004) compared different conservation tillage systems (minimum tillage, reduced tillage, no-tillage) to conventional tillage and showed that in general there not were differences in the crop yields. As a conclusion, the use of conservation tillage, especially no-tillage, was recommended as a viable management practice for cereal production in those areas. Total number of weeds was significantly lower in no-tillage than in other conservation tillage systems, although greater than in conventional tillage (Sombrero et al. 2001a, 2004). In NE Spain barren brome (Bromus sterilis L.) is the most difficult weed to control in cereal cropping systems under conservation tillage although, in general, tillage reduction is not detrimental for weed control in any crop (Catalán et al. 2003). Crop yield was also higher under conservation tillage in North Spain, except for subhumid areas. In Northern areas of Spain delay of planting under no-tillage has proven to be an effective method for brome control and effective reduction of some pest as Hessian fly (Mayetiola destructor) and diseases as Helmintosporium and Oidium.

Studies by Angás and Cantero-Martínez (2000), Gabrielle et al. (2002) and Cantero-Martínez et al. (2003, 2007) in NE Spain were aimed to establish the optimal nitrogen (N) fertilisation for different tillage systems. Two models (CERES and CROPsyst) were tested as support decision tools for agronomic recommendations. Conservation tillage improved the yield and water-use efficiency (WUE) of barley and proved to be a valuable system, especially under dry conditions, providing greater water storage in the recharge period October–January. Only in wet years, higher yields were obtained in no-tillage when some N fertilizer was applied (Angás et al. 2006). However, in dry years with scarce rainfall during autumn, N should not be applied in any tillage system. In the same area, Lampurlanés et al. (1997, 2001, 2002), Lampurlanés and Cantero (2003) and Cantero-Martínez et al. (2004) evaluated the use of conservation tillage in the long term. No-tillage resulted potentially better for semi-arid regions. In these soils, yield depends on favourable rainfall distribution throughout the growing season, including the grain filling period. Nonetheless, in particular areas (e.g. semi-arid Aragón, NE Spain) no-tillage reduced barley growth, yield and water-use efficiency when compared with reduced tillage and conventional tillage. On average, winter cereal yield under no-tillage was about 9% lower than in conventional tillage; in these conditions, reduced tillage (chiselling) is recommended as a suitable alternative to conventional tillage (mouldboard ploughing) without detrimental effect on crop yield (López and Arrúe 1997; Moret et al. 2007a, b).

Under irrigated agriculture soil compaction and crop residue accumulation were sometime constraints under no-tillage, being then minimum tillage the best soil management option under this system (Santiveri et al. 2002; Berenguer et al. 2004). However, a recent study by Muñoz et al. (2007) showed a consistent improvement of soil quality by direct seeding under irrigation. Conservation tillage is specific to site and soil conditions (Lal 1989), which makes necessary experimentation for each local scenario. For that reason, more studies are needed in Spain on this respect.

Conservation agriculture in Spain has been focused mainly in field crops under rainfed conditions as winter cereals; crop yields were similar to or even greater than those in conventional tillage. At the earlier stages, frequently slightly better plant growth has been reported under conventional tillage, although the difference disappeared at a more advanced stage of growth. Crop yield was also higher under conservation tillage in humid areas. When adequately managed tillage reduction is not detrimental for weed control in any crop. Different studies were aimed to establish the optimal nitrogen (N) fertilisation for different tillage systems. Only in wet years, higher yields were obtained in no-tillage when some N fertilizer was applied. However, in dry years with scarce rainfall during autumn, N should not be applied in any tillage system.

3 Conclusion

From this literature analysis we conclude that field experiments carried out all over the Spanish geography give wide experience and knowledge on Conservation Agriculture. The major findings show that there are important cost savings (fuel, fertilizers) compared with conventional agriculture. Conservation tillage has proved to be highly efficient to water storage, especially in years with rainfall lower than average. Under our Mediterranean conditions moderate increases of organic matter have been observed in the soil top layer. However, this moderate increase of organic matter creates particular conditions for the physico-chemical and biological soil dynamics increasing soil quality. In general, better soil physical properties and aggregation under Conservation Agriculture have been reported. However, greater compaction under no-tillage can result at long-term in particular scenarios, which could make advisable an occasional tillage labour. Furthermore, adoption of conservation tillage can reduce soil CO_2 emissions to the atmosphere thus minimising soil organic carbon losses. Mobility and persistence of herbicides were lower under conservation tillage than under conventional tillage. In general, conservation tillage enhances biodiversity compared to conventional tillage. Crop yields were similar to or even greater than those in traditional tillage, although at the earlier stages, frequently slightly better plant growth has been reported under conventional tillage, the difference disappearing at a more advanced stage of growth. All these advantages demonstrate that Conservation Agriculture in Spain can be a more sustainable alternative than the conventional agriculture. However, we have found from the literature analysis some constraints for its adoption, mainly due to inadequate extension and technology transfer systems and lack of access to specific inputs, machinery and equipment. Crop residue management difficulties and occasional higher incidence of weeds, pests and diseases, besides social relationships among farmers (criticisms) may also difficult the establishment of Conservation Agriculture in local scenarios.

Despite of all these findings we have detected from the literature analysis that would be desirable more integrated studies on the suitability of annual and perennial crops for Conservation Agriculture techniques under both rainfed and irrigated conditions, as well as on the adoption of crop rotations and cover crops adapted to those technologies.

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