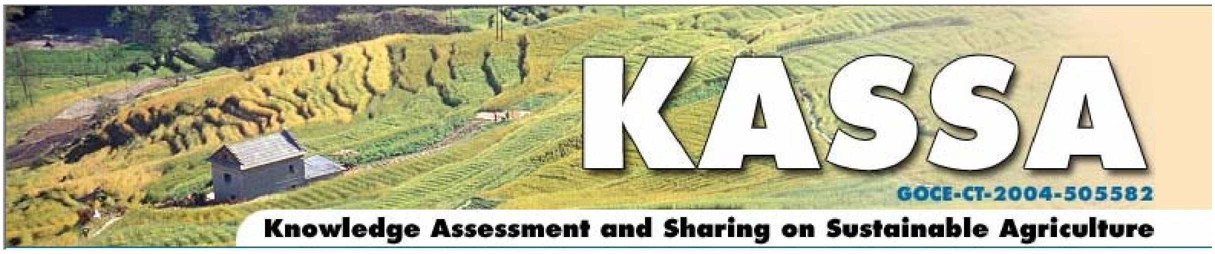

Deliverable 1.2 - Appendix A1

Conservation agriculture research in Spain

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TABLE OF CONTENTS

1. Introduction

1.1. General background

Spain has a size of about 50 million ha with a large percentage of this surface (approximately 80%) devoted to extensive agricultural systems mostly under dryland conditions. Approximately 20 million ha are grown with extensive field crops, with barley, wheat and sunflower crops accounting for more than 6.5 million ha mostly under rainfed cropping systems. Other important dryland crops are olive (2.4 million ha), vineyard (1.2 million ha) and almond (0.66 million ha). Intensive crops are always grown under irrigated conditions. Orchard trees as citrus (orange and lemon) are grown in 0.28 million ha while apples, pears, peaches and other fruit crops occupy 0.18 million ha. Horticultural crops account for 0.62 million ha and more extensive crops such as corn, alfalfa, sugar beet and cotton account with 0.85 million ha.

Climate in Spain is very diverse. Thus, in North and Northwestern Spain, climate has a marked Atlantic character, with moderate and regular annual precipitation (800-1200 mm on average). Mediterranean-type of climate characterises a wide strip of land extending from Northeast to Southeast Spain along the Mediterranean coast. In this area, where annual precipitation varies from 350 to 700 mm, the rainfall pattern is characterised by erratic and highly variable precipitations. In Central Spain, climate is typically continental, with variable Atlantic or Mediterranean influences and an annual precipitation between 400 and 700 mm. On average, rainfall mainly occurs in autumn and spring months, winter is dry and cold and summer is dry and warm or hot. Average annual air temperature is about 13-14ºC, with frequent extreme temperatures below zero during winter months and over 40ºC in summer months.

Likewise, soil types are also very varied. About 17% of the surface correspond to soils poorly developed (*Entisols*), generally in mountain areas. Fertile alluvial soils (1.6%) can be found on river terraces. With a medium fertility level, about 60% of Spanish soils are poorly differentiated but moderately deep (*Inceptisols*). *Aridisols*, including soils with calcium carbonate, gypsum and salt accumulations, represent about 9% of the surface. Similarly, 9% of soils are *Alfisols* (9%), fertile soils of which one third correspond to typical Mediterranean red soils. Organic carbon rich soils (*Mollisols*) only occupy 0.2% of the territory. About 1.6% of soils have a high content in clay (*Vertisols*) and are located mainly in Andalusia and Extremadura. Finally, well-developed acid soils (*Ultisols* and *Spodosols*) occupy only 0.4% of the territory mostly in North Spain (de la Rosa, 2001). This soil diversity reflects differences not only in climate but also in geological origin, vegetation, land use and historical development. In general, soils are basic and calcareous in Central and Eastern Spain and acid in North and Northwestern Spain. Although soil texture is also very diverse, in general, loamy-textured soils dominate in many regions. Soil organic matter (SOM) content is, generally, low. This is due, among other factors, to more than 2000 years of continuous cultivation and to a low development of natural vegetation due to adverse climatic conditions in dry, semi-arid areas. The most important soil factors directly influencing crop productivity in rainfed areas are soil depth and soil water holding capacity.

As a consequence of both climate and soil diversity, very different agroecosystems can be found in Spain. Thus, grassland agricultural systems can be found in many and different geographical areas of Spain. The potential of these systems varies from those located in humid coastal or mountain areas in North Spain to those found in dry Castile tablelands or in the "*dehesas*" in South-western Spain. Probably, the most important agroecosystem in Spain is that represented by the main Mediterranean crops such as winter cereals (barley and wheat), olive, vineyard, and almond trees. This system spreads over rainfed areas in North and Central Spain regions (Castile-Leon, Castile-La Mancha, Aragon, Catalonia) and South Spain (Andalusia). A third main agroecosystem develops on irrigated areas of main river watersheds. Rice system extends over small areas in Southwestern Spain (e.g., the Guadalquivir River *marismas*) and Northeastern Spain (e.g., the Ebro River delta). Finally, a fourth important agroecosystem is that found in the Mediterranean coastal areas (e.g., Valencia) where agricultural land is intensively cropped and irrigated. In these areas, citrus and horticultural crops are of high economic value. Due to this large diversity of natural and agricultural environments Spain is one of the richest countries in Europe in terms of animal and plant biodiversity.

The modernisation of the Spanish agriculture began in the early 1960's, linked to the industrialisation process of Spain at that time and guided by the Green Revolution principles (Cubero and Moreno, 1993). However, while modern intensive production methods were adopted in some regions, in other regions more extensive production systems remained, concurrent to the establishment of new irrigation areas. In general, modernisation did not change much the traditional structure of small size farms and population remained excessively in rural areas tied to the land and traditional production systems (Garrido, 2000). Currently, this structural change is one of the main problems that the Spanish agriculture faces. Finally, the political division of Spain in 17 Autonomous Communities or Regions which are able to develop specific regulations, especially in environmental and agriculture relationships, can also influence the distribution and development of agricultural production systems.

As a result, intensive agricultural production in Spain does not reach the levels of other European Union countries (Garrido, 2000). Consequently, environmental problems derived from soil and water pollution and contamination are only present in specific intensive production areas. Nevertheless, an uneven distribution of population among agricultural, urban and industrial areas and an increasing abandonment of agricultural lands might be factors of environmental problems (e.g., risk of forest fires). A second important environmental issue, with a serious social and economic impact in Spain, is that driven by a limited water availability for agriculture and other uses. The fact that water resources are not well distributed in all regions, planning for a better water use management has been very controversial during the last years. However, there is no doubt that the worst environmental issue facing the Spanish agricultural systems is soil erosion. The average soil loss by water erosion 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 loses can reach 60-80 t ha^{-1}.

In summary, Spain has a large diversity of farming production systems as a consequence of its soil, climate and natural diversity. This large natural and structural heterogeneity is the main feature of the agriculture-environment relationships in Spain. On the basis of the knowledge available, **C*onservation agriculture*** (CA) appears to be the most important sustainable alternative system to traditional agricultur to cope with negative agri-environmental problems like the loss of fertile soil in areas prone to soil erosion processes.

1.2. The development of conservation agriculture in Spain

As stated before, Spain has a history of more than 2000 years of land cultivation, being mouldboard ploughing the traditional tillage system. According to Fernández-Quintanilla (1997), it was in the 1970's when the concepts of tillage reduction and the use of CA 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. Scientists and technical advisers from agricultural extension services, farmer co-operatives and national and multinational companies played a crucial role during the first years of development and dissemination of CA techniques in Spain.

During the last decade, more than twenty research groups have continued assessing and gaining new local knowledge on CA for different agricultural systems in Spain. However, the main agents for the development and adoption by farmers of CA technologies have been the eleven new farmer CA associations and other CA consortia created across Spain (Tamames, 2002). From 1985 to present a large number of scientific and technical events (seminars, congresses and all sort of field demonstration activities) have been organised for knowledge dissemination. Important events were the First and Second Meetings on Winter Cereals, which were held, respectively, in Madrid in 1983 and in Pamplona in 1985, the First Symposium on Minimum Tillage, held in Madrid in 1986, and several other national and international meetings and workshops organised by the *Spanish Association for Conservation Agriculture* (AEAC-SV), such as those held in Cordoba (1996), Burgos (1997), Zaragoza (1998), Badajoz (1999), Madrid (2001), Zaragoza (2002) and Albacete (2004). In November 2005, the International Congress on Conservation Agriculture on "The challenge of Agriculture, Environment and the New Common Agricultural Policy" will be held in Cordoba (Spain). It is worth to mention a recent publication specifically devoted to dissemination of CA techniques (Gil-Ribes et al., 2004). On the other hand, the ***Spanish Conservation Tillage Research Network*** (SCTRN) was launched in 1996 to identify the state-of-the-art of conservation tillage research in Spain (Hernanz et al., 1998).

The main factors that first influenced the development of CA were the need for labour simplification, farmer time requirements for other activities, as livestock or orchard intensive production, and savings of fuel and costs for machinery required for tillage and other kind of inputs. Despite of the advantageous environmental aspects of CA practices (soil water conservation, soil protection, and increase of SOC and soil biological activity) described in scientific and technical reports and publications, it was at a later second stage when these facts were recognised by farmers.

As an example that could be valid in many of the Spanish autonomous regions, the development of CA in Castile-Leon, currently with more than 0.6 Million ha under CA, has been influenced by the following factors:

- Technical improvements and availability of all kind of machinery and equipment necessary to practice no-tillage, particularly specific machinery for direct seeding, as well as wide-spectrum herbicides with minimum environmental impact.

- A continuous reduction in agricultural output prices in the world market.

- A better environmental conscience in society and new policies promoting and subsidising agricultural techniques more respectful with the environment.

- The creation of regional conservation tillage associations, which have helped to disseminate CA techniques among farmers.

- The organisation of “field demonstration days” about direct seeding in different provinces and areas in which the practice of this tillage system has increased.

- The local support by public (e.g., Provincial Delegations) and private (e.g., savings banks) organisations and entities through funding for grants and field days organisation to farmers interested in CA techniques.

- The allocation of new subsidies from European, national or local funds to farmers adopting CA practices.

- The interest of international organisations, such as FAO, World Bank and other institutions, in launching CA programmes.

The advent and development of the Common Agricultural Policy (CAP) in the European Union have promoted in the past decade the implementation of different policies oriented to protect soil and water as main natural resources. In this context, CA may play an important role, since apart from being respectful with the environment CA is aimed to increase crop yield and, consequently, farmers’ life quality. In Spain, CAP regulations and directives have been applied in different aspects and with different intensity. Regarding CA, whereas in some Autonomous regions the adoption of CA practices for soil and water conservation has been encouraged and even subsidised (e.g., in Castile-Leon), in other regions CA has not been taken into account at all. Currently, the Spanish Ministries of Agriculture and Environment have shown a great interest in CA as a potential strategy for carbon sequestration in agricultural soils.

2. Conservation agriculture research in Spain

2.1. Conditions of obtaining of results

2.1.1. Research groups

One of the objectives of the *Spanish Conservation Tillage Research Network* was to identify those research and experimentation groups and teams working on CA across Spain (Hernanz et al., 1998). In the 1996-1998 period, 22 groups belonging to different research organizations (e.g., Instituto Nacional de Investigación Agraria, Consejo Superior de Investigaciones Científicas) and universities were identified, with the following distribution by Autonomous Regions: Andalusia (4), Extremadura (1), Castile-La Mancha (3), Madrid (2), Valencia (1), Castile-Leon (1), Navarra (1), Aragon (4), Catalonia (2), Galicia (1), Asturias (1) and Basque Country (1). Currently, most of these groups remain active in CA research.

2.1.2. Research approach used

From the mid 1970's, in perennial crops, and the late 1970's in annual crops, a large number of CA field studies have been carried out across Spain. Most of these studies have been either short- or long-term specific-site tillage experiments within experimental farms of agricultural research institutes or collaborative farms, as in the case of the tillage experimental networks of Navarre (Arnal, 1997) and Aragon (Pérez Berges, 1998). Only a very limited number of experiments could be qualified as on-farm trials.

The research approach used in the different trials has been both basic and applied in most of the studies. Only in a very few cases, the field experimentation has been implemented as a farmer's initiative. Hernanz et al. (1998) inventoried a total of 137 field CA experiments conducted across Spain from 1981. A significant number of these experiments ended after a few years of trial (4 years on average). It is estimated that about 20-25 experiments are still active as long-term experiments.

2.1.3. Biophysical conditions

CA studies compiled all over Spain have been undertaken under variable climatic and soil conditions. Thus, in Andalusia, the average annual precipitation at the experimental sites ranged from 450 and 650 mm, with clay soils (*Vertisols*) as the dominant soil type. In Extremadura and Madrid, experimentation was conducted on loam or clay loam textured soils and a rainfall of 450-500 mm. In the experimental sites located in Castile-La Mancha, Castile-Leon, Aragon and Catalonia, soils were mostly loamy and annual precipitation varied from 350 to 600 mm. In Navarre, annual rainfall varied from 350 to 900 mm and from 800 to 1300 mm in trials documented in Galicia, Asturias and the Basque Country. Apart from extreme aridity in some of the sites located in Aragon, Navarre, Catalonia and Castile-La Mancha, no other soil constraints appear to have been taken into account.

2.1.4. Cropping systems and tillage technologies

Most of the experiments have been conducted under dryland conditions. The main cropping systems have been *winter cereal (wheat or barley) monoculture*, *winter cereal-fallow rotation*, *legume-winter cereal rotation* and *sunflower-legume-winter cereal rotation*. Winter cereal continuous cropping and winter cereal-fallow rotation are the main cropping systems studied in experiments conducted in Navarre, Aragon, Catalonia and Castile-La Mancha, whereas the legume-winter cereal and sunflower-legume-winter cereal are more representative of experimentation carried out in Castile-Leon and Andalusia. A very limited number of experiments have been conducted under irrigated or humid conditions (annual precipitation higher than 700 mm), for instance, in maize for grain (Andalusia) or maize for forage (Galicia). With regard to perennial crops, only a few experiments have been conducted in olive (Andalusia) and vineyard and almond crops (Aragon and Castile-La Mancha) (Zaragoza and Delgado, 1996; Zaragoza, 1997; Zaragoza et al., 2002).

A common feature to many of the CA experiments inventoried in Spain is the tillage systems that have been compared. In general, the traditional primary tillage (i.e., mouldboard ploughing with soil inversion) is compared with two forms of CA, a 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 no-tillage or direct drilling,

2.2. Significance and impact of the results obtained

2.2.1. Main research lines and topics identified

Research topics studied until 1998 differed widely among research groups. In order to identify the significance of the knowledge acquired by the groups at different Spanish regions, the subject matters of the research activities carried out by the groups were classified according eight main knowledge areas: 1) *energy use* and *consumption*; 2) *socio-economic aspects; 3) soil physics*; 4) soil *chemistry and fertility*; 5) *soil biology*; 6) *crop response*; 7) *crop protection*; and 8) *environmental issues*.

Crop response to conservation tillage was the major research theme. Thus, 100, 72 and 68% of the groups studied crop yield, crop development and crop growth, respectively. On a lesser extent, other crop related aspects were also investigated, for example, water use efficiency (40%), yield quality (48%) and nutrient use efficiency (28%). Soil hydraulic properties and soil water content dynamics were studied by 56% of the teams, while the dynamics of soil nutrients was studied by 60% of the groups. Other aspects, such as soil structure, SOM and soil mechanical properties were the subject matter in 40 to 48% of the studies. Soil thermal properties were the subject less studied (24%).

On the other hand, 44 and 48% of the groups conducted studies dealing with machinery and energy consumption, respectively. Only 16% of the groups were specifically concerned about the development and testing of new tillage tools and equipment. With regard to plant protection studies, the evolution of weed populations was studied by 72% of the groups, but only 20 and 24% of the groups investigated the incidence of pest and diseases, respectively.

However, there were a few studies dealing with soil biological aspects and, surprisingly, with environmental issues. Only 16% of the studies were aimed to investigate soil erosion processes as affected by tillage. Other subjects like soil and surface water pollution by both fertilisers and pesticides were much less studied (less than 10%).

Overall, most of the inventoried research studies were focused on those subjects directly related to the concern and interests showed by farmers. However, and according to the above percentages, it should be assumed that there is a lack of knowledge on those subjects considered by less than 50% of the research groups (Hernanz et al., 1998). In the last years, new agronomic and environmental topics such as SOM dynamics, and C stratification and sequestration have merged in regions were long-term tillage experiments have been maintained.

2.2.2. Main scientific and practical results obtained

In this section we will concentrate on major findings achieved by the different Spanish CA research groups in the 1996-2005 period. Knowledge from the different studies compiled by the Spanish partners is summarised according to their agronomic, environmental and socio-economic impacts.

2.2.2.1. Agronomic impacts

In the autonomous regions of ***Andalusia*** and ***Extremadura***, only Moreno et al. (1997) have investigated in an integrated way the long-term effects of tillage systems on soil physical properties (bulk density, penetration resistance, infiltration, hydraulic conductivity, soil water content), crop development, crop yield and water use by the crop in a typical wheat-sunflower rotation under rainfed conditions. This research has shown the benefits of conservation tillage for soil and crops, particularly in years with a precipitation much lower than normal, and is a reference for the agriculture and the environment in semi-arid regions. Other studies related to the effects of CA techniques on soil physical properties, soil water storage and depletion and crop growth and development in Southern Spain have been carried out by Moreno et al. (1998, 2000a, 2000b, 2001).

The effects of subsoil compaction on soil properties and crop growth and yield, and the use of models to simulate the subsoil compaction process have been investigated only in few works (Coelho et al., 2000; Moreno et al., 2003; Perea et al., 2003). From the results of these works the authors gave recommendations to establish the most appropriate tillage system.

A significant number of studies have dealt with the effects of different tillage systems on crop yield for different crop rotations and N fertiliser rates under rainfed conditions, with particular attention to no-tillage (López-Bellido et al., 1996, 1997, 1998, 2000; López-Bellido and López-Bellido, 2001; López-Bellido et al., 2001, 2002, 2003a, 2003b; González et al., 2003; Bravo et al., 2003; Ordoñez et al., 2003; López-Bellido et al., 2004a, 2004b). In most of these studies, the authors concluded that crop yields were greater under no-tillage than under conventional tillage, especially in years with rainfall lower than normal. Similarly, in some of these works, it was also shown an increase of SOC and an improvement of the nutrient status in the soil under no-tillage compared to conventional tillage. Practically nothing about nutritional status of the crops has been investigated. Only in Murillo et al. (1998, 2000) the nutritional status of the crop was studied under conservation tillage and traditional tillage. These authors also showed the differences in crop development, at the earlier stages, between both tillage systems.

However, the increase in SOC observed under no-tillage in most of the studies carried out in Andalusia and also in Extremadura (López-Piñeiro et al., 2004) is not probably the best parameter to indicate an improvement in soil quality. Under Mediterranean conditions a better indicator of soil quality improvement might be the stratification of SOC (concentration in the surface divided by that deeper in the soil profile). In general, whatever the soil and climatic conditions are, high stratification ratios would indicate a good soil quality. In relation to this subject, it is worth to mention the detailed studies by Murillo et al. (2004) and Moreno et al. (2005) on SOC stratification ratio under conservation and traditional tillage. In these works it has also been shown the influence of long-term tillage effects on the loss of total and active $CaCO_3$, which were more significant under traditional tillage than under conservation tillage.

Ordoñez et al. (2001) and Agrela et al. (2003) investigated methods to estimate the percentage of soil surface covered by the residues of precedent crops and its evolution under different tillage systems. Soil microbiology under different tillage systems is a topic poorly studied in Andalusia. Only the recent works by Muñoz et al. (2004) and Madejón et al. (2005) dealt with some microbial activity aspects.

As in other regions in Spain, one of the major soil constraints in ***Madrid*** *and* ***Castile-La Mancha*** regions is the low SOM content. The continuous application of agricultural and crop residues produced significant changes in the levels of fertility and in the concentration, composition, and mineralization of the SOM after 16 years of trial (Dorado et al., 2003a, 2003b). On the other hand, the long-term effects (1983–1996) of tillage systems on water stability of pre-wetted and air dried aggregates, SOC stratification and crop production were studied in a loam soil by Hernanz et al. (2002). Tillage treatments included conventional tillage, minimum tillage and zero tillage under winter wheat and vetch rotation and under continuous monoculture of winter wheat or winter barley. Aggregate stability of slaked aggregates was greater under zero tillage than under conventional and minimum tillage in both crop rotations (11% vs 3%, respectively). Significant differences in stocked SOC were observed at depths of 0–10 and 0–20 cm, where zero tillage had the highest SOC content in both rotations. Crop production with wheat–vetch and continuous cereal showed no differences among tillage systems. Yields were strongly limited by the environmental conditions, particularly the amount of rainfall received in the crop growth season and its distribution. Similar yield and improved soil properties under zero tillage suggests that it is a more sustainable system for the semi-arid Mediterranean region of Spain.

In ***Central Spain***, long fallowing is practised for water storage and conservation in the soil profile (Tenorio et al., 2001, 2002). These authors showed in a tillage comparison experiment (no tillage and minimum tillage versus conventional tillage) under different rotations (cereal-fallow, leguminous-cereal, and cereal monoculture) that the soil water stored at sowing was 10 % higher under the barley-fallow rotation than under barley monoculture or a vetch-barley rotation. The authors concluded that in areas with high evaporation this benefit would only be possible under no-tillage fallow management system. Water use efficiency values were significantly higher under conventional tillage and no-tillage than under minimum tillage (Tenorio et al., 2002).

In the autonomous region of *Castile-Leon*, several authors have studied the influence of CA practices on soil properties (Sombrero et al., 1996, 1998; De Benito et al., 1998, 1999; Alvarez et al., 2004). SOM presented significant and important differences between the three tillage systems in the upper 30 cm of soil. After 10 years of trial, SOM content significantly increased in the first 15 cm of soil of the conservation plots compared to conventional plots. Regarding crop rotations, SOM in the first 15 cm was higher under rotations including legumes than under cereal monoculture or cereal-fallow mainly iof soil in the two locations. Nitrogen conten presented the same trend. Soil phosphorus and potassium content increased under conservation tillage systems but no differences were found among crop rotations. Soil water content was higher under conservation tillage than under conventional tillage, especially in dry years. Soil compaction was significantly different among tillage systems for the first 30 cm, corresponding to conventional tillage the lowest values. Below 30 cm there was no differences between tillage treatments. After harvest, no differences in soil compaction were observed among tillage treatments in the 0-30 cm layer, but below this depth conservation tillage presented the lowest values (plough pan effect).

The response of crop rotations to CA techniques has also been studied in semi-arid areas of Castile-Leon (Sombrero et al., 1997, 1998a, 1998b; 1999a; Escribano et al., 1998). As a conclusion of these studies, the use of minimum and no tillage was recommended as a viable management practice for cereal production in those areas. Fallow-cereal and legume-cereal rotations have a strong positive influence on cereal production. These rotations are also important in weed control for minimum and no tillage. The cereal/cereal rotation under these CA systems needs a specific herbicide for barren brome control. Legume and fallow included in cereal rotation increased cereal yield and reduced brome severity. The results of studies on crop rotations showed that yields were significantly lower in the cereal/cereal rotation than in the cereal/fallow and cereal/legume rotations.

Weed population evolution under different CA management systems has also been evaluated in Castile-Leon (Abascal, 1998; Altable, 2003; González-Barragán et al., 2004; Nieto, 2000; Sombrero et al., 2001, 2004). In general, weed density and biomass were significantly higher in minimum tillage than conventional tillage, though the total weed number was significantly lower under no-tillage than than minimum tillage system. Weed inversion was observed after 10 years of trial. Crop rotations had also a big influence on weed density and biomass, which were significantly higher in cereal/cereal than in cereal/fallow and cereal/legume.

In ***Northern Spain***, the most difficult weed to control in cereal cropping systems under conservation tillage is barren brome (Bromus sterilis L.). At tillering and heading stages, the density of this winter annual grass was significantly higher under conservation tillage systems than under conventional tillage. With regard to crop rotations, brome density was significantly higher under cereal monoculture than under cereal-fallow or cereal-legume rotations.
Navarrete et al. (2002) have studied the evolution of weeds under different tillage systems during 20 years and found that tillage reduction is not detrimental for weed control in any crop. Likewise, Catalan et al. (2004) have shown that there is a different response in weed

population to the application of different tillage systems and that, regardless of the tillage systems, the cereal monoculture is the factor that influences the most weed proliferation.

In ***Catalonia***, long-term studies by Angás et al. (1999), Angás and Cantero (2000), Gabrielle et al. (2002) and Cantero-Martínez et al. (2003) in a northeastern area of the Ebro Valley were aimed to establish the optimal nitrogen (N) fertilisation for different tillage systems. To this end, the response of a barley crop for the interaction of tillage x N fertilization for growth, yield, yield components and water productivity was evaluated. Two models (CERES and CROPsyst) were tested as support decision tools for agronomic recommendations. The use of conservation tillage improved the yield and water-use efficiency (WUE) of barley and proved to be a valuable system, especially under dry conditions, providing a greater water storage in the recharge period from October to January. Moderated N fertilisation increased biomass and yield of barley in all years and conditions, but very little additional response was obtained from higher rates of N in these semi-arid conditions. N fertilisation for these sites could be reduced in 50% of the applied rates by the farmers or even more in dry years. N fertilisation increased WUE, but when available water was not limiting, an excess of N increased water consumption without improving WUE.Nitrogen fertilization could be reduced more when tillage is used. No additional fertilisation is needed when minimum tillage or no tillage is used. Only in wet years, higher yields were obtained in no-tillage when some N fertilizer is applied. 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, 2001a, 2001b, 2003), Lampurlanés and Cantero (2004) and Cantero et al. (2004) have evaluated the use of conservation tillage practices in the long term. These authors assessed the agronomic responses of barley and wheat in terms of growth, yield and its components, water use and WUE, soil mineral N and some soil physical properties under winter cereal monoculture and cereal-fallow rotation, with special observations on the growth and development of the crop root system. The results showed that in soils with high water-holding capacity, surface conditions were of major importance in soil water storage and determined the differences among tillage systems. No-tillage resulted potentially better for semi-arid regions 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, no-tillage proved to be better because of the lower soil water-holding capacity. In these soils, yield depends on favourable rainfall distribution throughout the growing season, including the grain filling period.

Crop residues of the preceding crop should be left spread over the soil to reduce evaporation losses during the March to October fallow sub-period and then to increase the water storage efficiency. If residue mulch at the end of the spring is insufficient, soil mulch should be created with a shallow pass with the cultivator. Under the actual CAP conditions, the traditional fallow-crop rotation is not economically interesting in that area. In the case of compulsory use of this rotation because of the subsidies, chemical fallow keeping residues should be much more oriented to soil and water conservation. The practice of long fallowing every four or five years should be considered to improve other cultural aspects such as optimisation of N fertilisation or weed control in order to reduce production costs.

Also in *Catalonia*, Álvaro et al. (2003) evaluated the performance of a vetch crop in rotation with winter cereals under no-tillage system in dryland conditions. They measured crop growth and development, yield, and water and soil nitrogen and found that vetch crop performed well under these conditions five of six years. Better yield was obtained when vetch was harvested for forage in May compared to that harvested for grain in June. Vetch can be included in crop rotation with winter cereals under no-tillage also with a better weed control.

The objective of the works by Santiveri et al. (2002) and Berenguer et al. (2004) was to establish optimal N fertilization in a corn-wheat rotation under irrigated conditions and different tillage practices. The agronomic responses of corn and wheat in terms of growth, yield, yield components and soil mineral N were evaluated. The best soil management option was the minimum tillage. Under traditional, very intensive tillage, some physical soil problems as low infiltration and surface crusting were observed. Under no-tillage soil compaction and crop residues accumulation were the main problems.

The effect of conservation tillage systems on earthworm activity as a biological indicator has been studied in *Catalonia* (Ojeda et al.,1997; Cantero 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.

Recently, Santiveri et al. (2003, 2004) have evaluated in *Catalonia* the influence of crop residues under different tillage systems on soil water conservation, soil temperature and crop emergence. No-tillage kept the soil cover up to 80% six months after harvest, which favoured soil water storage conservation during the rainy period (September-January). The greater amount of crop residues in autumn under no-tillage also favoured seed emergence after sowing. However, if the amount of residues is higher than 2.5 t ha^{-1} at sowing time, crop residues must be partially removed at harvest to avoid later problems with planters at sowing.

In semi-arid ***Aragon*** (NE Spain), López et al. (2003, 2004, 2005) have also studied the evolution of barley residues during four long fallow periods under conventional 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. With no-tillage, the soil surface still conserved a residue cover of 10–15% after long-fallowing and percentages of standing residues ranging from 20 to 40% of the total mass after the first 11–12 months. In both conservation and reduced tillage, primary tillage operations had the major influence on residue incorporation, with percentages of cover reduction of 90–100% after mouldboard ploughing and 50–70% after chiselling. Measured and predicted data indicate that, under no-tillage, 80–90% of the initial residue mass is lost at the end of fallow and that 60–75% of this loss occurs during the first 9–10 months (López et al., 2005).

The capability of long fallowing for soil water conservation has been questioned in some dryland regions. This topic has been investigated in Central Aragon through different studies (López et al., 1996a; Moret et al., 2000, 2005b). Water storage efficiency of long fallowing in the cereal-fallow rotation with respect to the continuous cropping system has been evaluated and compared under both conventional and conservation tillage techniques. Results by López et al. (1996a) from the first 2 years of trial in a long-term tillage study suggested that reduced tillage, under both cropping systems, could replace the conventional tillage without adverse effects on soil water content and storage. However, no-tillage was not a viable alternative in the most arid zones of Aragon. After 8-10 years of trial, the studies by Moret et al. (2000, 2005b) were aimed to quantify soil water losses, soil water storage and precipitation storage efficiency of long fallow. The total soil water loss at the end of fallow was similar for the three fallow management systems. Overall, long fallow precipitation storage efficiency was small (11% on average). Neither soil water storage nor precipitation storage efficiency were significantly affected by the tillage system. This would imply that conservation tillage systems could replace conventional tillage for soil management during fallow without adverse effects on soil water conservation. As part of this investigation, the capability of the Simple-Soil-Plant-Atmosphere Transfer (SiSPAT) model to simulate the soil water balance and its components over long fallowing was demonstrated. The model estimated that about 81% of fallow seasonal precipitation is lost by evaporation in long-fallow periods with both a dry autumn in the first year of fallow and a rainfall above normal in spring. The comparison between measured and simulated soil water loss showed that tillage practices decreased soil water conservation in the short term.

The influence of tillage on soil physical properties and aggregation has been evaluated in *Aragon* at both short-term, during or at the end of the growing season of a barley crop (López et al., 1996a, 1996b, 1997b), and long-term, over the fallow period in the cereal-fallow rotation (Moret and Arrúe, 2005). Results from these studies showed that after 2 years of trial in a long-term tillage experiment, soil macroporosity (biopores) was higher under no-tillage and reduced tillage than under conventional tillage as a consequence of a higher worm density. No significant differences in soil aggregation properties and hydraulic properties (e.g., saturated hydraulic conductivity and sorptivity) were found between tillage treatments. In contrast to the conventional and reduced tillage systems, high values of soil strength were observed after sowing in most of the plough layer (0-40 cm) under no-tillage. After 8-10 years of trial in a long-term tillage experiment, topsoil was more compacted under no-tillage than under conventional and reduced tillage plots. 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. No significant differences in hydraulic properties were found between conventional and reduced tillage.

Studies on the influence of tillage on growth, yield and water use efficiency (WUE) of winter barley have also been carried out in *semi-arid Aragon* (López and Arrúe, 1997a; Pérez-Marco, 1998; Moret et al., 2005d). Short-term results from these studies indicate that reduced tillage (chiselling) can be recommended as a viable alternative to conventional tillage (mouldboard ploughing) without detrimental effect on crop yield. On the contrary, no-tillage reduced barley growth, yield and WUE when compared with reduced and conventional tillage. In the long-term, no clear differences in crop yield were observed among tillage treatments, which indicates that conventional tillage can be substituted by conservation tillage for fallow management in semi-arid dryland cereal production areas in central Aragon. An analysis of yield data from all the tillage comparison trails conducted so far in Aragon by the Center for Agricultural Techniques (Government of Aragon) indicates that, on average, winter cereal yield under no-tillage is about 9% lower than under traditional tillage (Pérez-Berges, 2004).

During the last two decades, the Instituto Técnico de Gestión Agrícola (ITGA) of ***Navarre*** has carried out a series of demonstration and experimentation trials on CA techniques for rainfed cereal cropping systems under different agro-climatic zones of this autonomous region (Anal, 1997; Perez de Curia, 2003, 2004a). Currently, about half of agricultural land in

Navarre is cultivated under conservation tillage techniques. The surface under minimum tillage and no-tillage has increased in the humid areas of Northern Navarre and in the drier areas of Central and Southern Navarre, respectively. The effects of conservation tillage versus conventional tillage on soil physical and chemical properties, weed evolution, crop growth and yield of cereal crops, crop residue, and production costs, including CA machinery performance, have been investigated (Bescansa et al., 1998, 2004, 2005; Pérez de Ciriza et al., 2000; Enrique et al., 2001, 2004; Imaz et al., 2003, 2004). With the exception of soil P, which was greater under no-tillage, no differences in soil pH, electrical conductivity and other macronutrients have been found among tillage systems (Bescansa, 1998). Also, an increase in SOC at the surface horizon has been observed under conservation tillage (Imaz et al., 2004). In semiarid Navarre, soil water content and storage is higher under conservation tillage than under conventional tillage (Bescansa et al., 2005). In these areas, crop yields were significantly greater under no-tillage than under conventional tillage. In contrast, crop yields were lower in subhumid areas (Pérez de Ciriza, 2004a, 2004b, 2004c).

2.2.2.2. Environmental impacts

In ***Andalusia***, several recent 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; López-Granados et al., 2005). 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. Other studies on the use of cover crops in olive orchards have been carried out by Pelegrín et al. (2001, 2003) 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.

In ***Central Spain***, soil losses by water erosion are also a major environmental issue. De Alba et al. (2001) studied the effect of different tillage systems (no-tillage vs conventional tillage) and found that no-tillage system clearly reduces the amount of soil lost by water erosion.

In ***Central Aragon*** (NE Spain), where strong and dry winds are frequent all year round, fallow lands are susceptible to wind erosion due to insufficient crop residues on the surface and loose, finely divided soils by multiple tillage operations (López et al., 2001a). Over the last decade, several field studies on wind erosion have been carried out in *Central* Aragon (López and Arrúe, 2005). In 1995, a joint CSIC-CNRS research programme studied the effects of tillage on soil surface conditions and dust emission (López et al., 1997,1998; López, 1998). As a continuation of this research, the European WELSONS project (Wind Erosion and Loss of Soil Nutrients in Semi-arid Spain), which was carried out from 1996-1999 in another site in Central Aragon, evaluated the role of land preparation practices on the degradation of agricultural soils by wind erosion (Gomes et al., 2003). More recently, the risk of wind erosion on fallow lands has been assessed at a regional scale (López et al., 2001a, 2001b).

First results from the study conducted by López et al. (1997, 1998a, 1998b) indicated that reduced tillage, with chiselling as primary tillage, could be considered as a viable alternative to conventional tillage for wind erosion control during the fallow period in semi-arid Aragon. The percentage of soil cover with crop residues and clods was 15% after chiselling and only 4% after mouldboard ploughing. The frontal area of this nonerodible material and soil roughness was reduced four times after mouldboard ploughing. These results were later confirmed in studies carried out in other different experimental fields (López et al., 1999, 2000a, 2000b, 2002). Overall, soil erodibility is significantly higher in conventionally tilled plots than in reduced tillage plots. Consequently, no significant dust emission and saltation transport was observed in reduced 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). Random roughness was also higher after reduced tillage than after conventional tillage (15% vs. 4%). Results from other studies regarding the effect of type of tillage on soil erodibility indicated that chiselling might substantially reduce the wind-erodible fraction at the soil surface as compared to disk harrow and mouldboard ploughing. On average, while this fraction was only 10% after chiselling, after either mouldboard ploughing or disk harrowing this percentage was significantly higher (36%) (López et al., 2001a). These authors also showed that soil losses by wind erosion can be reduced to tolerable levels if reduced tillage, with chiselling as the primary tillage, is adequately adopted in the dryland cereal production areas of semi-arid Aragon. However, as above mentioned the lack of residue-disturbing operations under no-tillage makes this practice the best strategy for wind erosion control during the long-fallow period (López et al., 2003, 2005).

Adoption of CA systems can reduce soil CO_2 emissions to the atmosphere thus minimising soil organic carbon (SOC) losses and mitigating the greenhouse effect (Arrúe, 1997a, 1997b). In ***Central Spain***, López-Fando and Pardo (2001) have shown after 12 years of trial for three crop rotations (barley-vetch, barley-sunflower and barley monoculture) that no-tillage resulted in values of SOC storage greater than when conventional tillage is applied. They concluded that no-tillage could be an effective technology for removing C from the atmosphere and sequestering it into the soil in the study area. In that context, Álvaro-Fuentes et al. (2004a, 2004b) have evaluated the influence of conventional and conservation tillage systems (e.g., reduced tillage and no-tillage) on short-term CO_2 fluxes from the surface soil under various cereal cropping systems in three semi-arid rainfed farming areas of the ***Ebro River Valley***. In the three sites, CO_2 fluxes observed 24 h before tillage were low and similar under all the different tillage systems. However, immediately after tillage, a significant increase in CO_2 emissions was measured in the tilled treatments, particularly under conventional tillage. Results from these studies suggest that CA practices are a feasible option to reduce SOC losses associated to conventional tillage in semi-arid areas of the Ebro River Valley.

The transport and persistence of herbicides in soils under CA systems has also been studied in Spain (Cox et al., 1996, 1999; Calderón et al., 2000; Cuevas et al., 2001; Cuevas, 2004). Results from these studies showed that the mobility and persistence of herbicides (e.g., trifluralin and metmitron) were lower under conservation tillage than under traditional tillage.

2.2.2.3. Socio-economic impacts

In semi-arid zones of ***Castile-Leon***, studies by Sombrero (1995), Sombrero et al. (1999b, 2001) and Escribano et al. (1997) have shown that no-tillage and minimum tillage reduced production costs thus influencing farm profitability. Compared to conventional tillage, fuel consumption reduction represented up to 66% under no-tillage and 32% under minimum tillage. Similarly, it is also important to highlight that time saving for all tillage operations was about 45 and 22% under no-tillage and minimum tillage, respectively. In North Spain, after six years of trial at three different locations, the average economic benefit of no-tillage compared to conventional tillage was 40 Euros/ha. For minimum tillage, this benefit was about 90 Euros/ha in Navarre, similar in Burgos and 60 Euros/ha lower in Madrid.

In the autonomous region of *Madrid***,** Hernanz et al. (1995) showed the important energy and production cost savings that may be achieved through minimum tillage and zero tillage, compared with conventional tillage. These energy savings ranged from 7 to 11% for cereal crops, whereas for vetch crops the reduction was 10% for minimum tillage and 15% for zero tillage. Production costs for minimum tillage were 13–24% less than for conventional tillage. For zero tillage these reductions ranged from 6 to 17%. This means that using no-tillage farmers can handle four times more land area than using traditional tillage (Sánchez-Girón et al., 2004).

The MEDRATE (Mediterranean Rainfed Agriculture Technologies Evaluation) Project (www.iamz.ciheam.org/RAP-RAG/research.htm#Research) was aimed to evaluate agricultural practices in nine countries of the Mediterranean Basin, including Spain, in order to improve crop productivity and environment conservation in arid and semi-arid production systems. Angás et al. (2004), Cantero-Martínez (2002, 2003), Cantero-Martínez and Gabiña (2004a, 2004b) and Cantero-Martínez et al. (2004) reported results from this project in which up to 17 technologies were evaluated. Among those technologies, conservation tillage showed to be an important technology to be developed in dryland systems of the Mediterranean region. Field research on these technologies was conducted in all countries, with variable results among partners. Most of the research topics were related with water conservation and soil erosion issues. Studies on matters like crop rotation, fertilization, sowing dates or variety performance under different tillage systems were scarce. In general, the degree of adoption of CA techniques by farmers was low as a consequence of inadequate extension and technology transfer systems and lack of access to specific inputs, machinery and equipment.

A practical guidebook on CA practices in annual crops was developed by López-Granados et al. (1998). This guide has helped to promote conservation tillage in Spain giving overall recommendations for all agricultural practices. Recently, Sisquella et al. (2004a, 2004b) have developed specific guidelines and techniques for environmental management of main irrigated crops in the ***Ebro River Valley***, with special emphasis in the development of conservation tillage systems. In ***Central Aragon***, wind erosion prevention relies, indirectly, on benefits from some compensatory agri-environmental measures issued by the regional government on the basis of the EU Regulation 2078/92 (López et al., 2003; Riksen et al., 2003). Farmers adopting these measures are however obliged to comply with three Good

Agricultural Practices issued at the national level for soil protection: prohibition of straw burning, prohibition of traditional tilling in the slope direction and obligation to keep grazing within certain stocking rates based on local annual average precipitation. López and Arrúe (2005) discussed specific soil conservation measures and recommendations to prevent wind erosion in semi-arid Central Aragon.

3. Adoption of conservation agriculture practices. Critical factors and future requirements

3.1. Surveys of adoption and acceptance

In order to evaluate the degree of adoption of CA technologies (i.e., conservation tillage) and the impact of agricultural research and technology transfer services on the development of CA practices, a series of farmer surveys have been conducted across Spain from 1990 to present. The first one was carried out in Andalusia (Valera, 1990). In Catalonia, CA technologies were evaluated in 1993 on the basis of more than 100 surveyed farmers and technical advisers (Cantero, 1995; Cantero et al., 1995, 1996). In Aragon, a first survey on conservation tillage perception was made in 1995 on the basis of 25 farmers from Central Aragon (Ben Abdallah, 1995). Later on in 1998, a larger survey was made on the basis of 206 participants from all around Aragon (Pérez Berges, 1998). Also, information on adoption and acceptance constraints is given by Hernanz et al. (1998). More recently, other CA related farmer surveys have been conducted. For instance, the survey made by Sisquella et al. (2004a, 2004b) within the framework of the project TRAMA (LIFE programme) on crop production technologies and environmental management in the Ebro River Valley or a recent national survey aimed to outline the technical and scientific programme of the coming 3rd Mediterranean Meeting on Direct Drilling to be held at Zaragoza in 2006 (http://www.iamz.ciheam.org/SD2006).

Despite these surveys have been made in different regions and years, their results can be comparable for many of the surveyed topics. In general, it can be concluded that the acceptance of CA technologies in Spain is still low. In areas where these technologies were not initially well introduced, the level of adoption is very low. However, when the technologies were introduced and adopted by some farmers in a given area, this normally resulted in a quick spreading throughout the area.

Adoption of CA in Spain has taken place in two steps. Firstly, a widespread adoption of minimum tillage techniques occurred as a transition from intensive, repeated tillage towards a reduction in the number of tillage operations. In a second step, minimum tillage keeping more than 30% of the soil surface covered with crop residues and no-tillage have been adopted on a lesser extent. The adoption of reduced tillage techniques started on annual crops and under rainfed conditions. In Navarre and some areas of Catalonia, this took place about 25 years ago. Afterwards, CA techniques were introduced in many areas of Castile-Leon (Burgos, Valladolid, Segovia, Leon, Soria) between 10 and 15 years ago, in Aragon, Castile La-Mancha (Albacete) less than 10 years ago and more recently in a few areas of Galicia, Andalusia and Extremadura. In the last decade, the adoption and development of CA practices in perennial crops (e.g., olive) has been very significant in Andalusia. Currently, the adoption of CA in Spain is slowly increasing in many areas and particularly in irrigated annual and perennial crops. In traditional CA areas, farmers are concerned about several agronomic and technical aspects of the related technologies, such as fertiliser use and recommendations, crop residue management and control of specific weeds, pests and diseases.

According to the results of the above mentioned farmer surveys, the main reasons or advantages envisaged by farmers for the adoption of CA systems are, by order of importance, the following:

1. A much better economy at a farm level (labour simplification; less time requirements for tillage operations; less fuel consumption; less machinery required for tillage; less power machinery).

2. Flexible sowing time.

3. A much better water economy through a higher accumulation and infiltration of water in the soil profile and lower water losses by evaporation and runoff. This is especially well appreciated by dryland farmers in areas where the water available for crop growth becomes a limiting factor in dry years.

4. 4. Soil protection. Reduction or full control of soil erosion. Soil organic matter increase. Less or complete removal of soil crusting. Better soil structural stability.

5. Double crop possibilities in some areas.

6. Same yield or slight yield increases (10-15%). Greater yield stability. Faster crop establishment and development (e.g., better emergence observed in crops sown in autumn due to warmer soil conditions in October and November).

7. Greater nutrient-use efficiency. Less use of fertilizers.

3.2. Constraints to adoption

Farmers and technical advisers have mentioned different disadvantages to the use of CA technologies. Some of the reasons and constraints to CA development in Spain are the following:

- Economic reasons. Farmer’s reluctance and fear to acquire new and expensive specific machinery or to higher herbicide costs.

- Soil compaction, poor aeration, waterlogging and reduction of infiltration are among the main soil-related shortcomings. Inefficient sowing in extreme sandy and clayed soils has also been point ed out.

- Crop residue management is a very important concern among farmers. How do straw and stubble have to be managed or how much crop residues have to be removed and when are frequent questions posed not only by the beginners but also by the more experienced farmers. Allelopathic problems are also mentioned and not well described and analysed.

- A higher incidence of weeds, pests and diseases is another constraint, but this cannot be generalised since in many areas a much lower incidence of weeds and insects and a better control of some diseases have been reported.

- Crop yield is not questioned by farmers who have shifted to CA. They are more concerned about the time required for the new system to reach a complete stabilisation (soil and technology) .

- Reported irregular incidence of rodents and slugs in CA fields is another negative aspect associated to biological activity and biodiversity.

- Disadvantages associated with the use of fertilisers or fertiliser use efficiency have been reported but, surpisingly, with a low frequency.

- A poor crop development is described in irrigated spring crops due to lower soil temperatures in the February-April period.

- The practice of direct seeding or no-tillage is more complicated than the traditional ones and requires more information and technical advice.

- In some areas, farmers complain about insufficient information and technical support on CA technologies from public extension services. The interest of the Administration and policy makers in CA is very variable and do not often respond to long-term requirements for CA systems to be developed and adopted.

- Finally, aging and social relationships among farmers have been sometimes a constraint to the development of new crop technology and, certainly, to the adoption of CA. Farmers who are against these techniques criticise them and discourage hesitant farmers. Rural population aging directly have also a direct effect on farmer rejection of new CA techniques.

3.3. Technology transfer

Because the first step of CA development in Spain was in the hands of technical advisers and technical staff of co-operatives and commercial companies, knowledge transfer took place mainly from results obtained abroad, for instance in the USA and Australia.

The second step in the process of technology transfer in Spain has been associated to the results obtained in Spain from long-term experiments initiated by research centres, universities and other public institutes for the assessment and development of CA systems. During this phase, the co-operation between these public institutions and the extension services of the Departments of Agriculture in the different autonomous regions was scarce but intense. More collaboration was received, however, from the technical personnel of private cooperatives and companies interested in the development of CA.

During the last decade, technology transfer has been mainly conducted, as mentioned above, by new and well-motivated farmer associations for CA, always in collaboration with the producers of knowledge, such as research institutes, and private co-operatives and companies.

3.4. Research priorities for different regions

Hernanz et al. (1998) identified a series of research gaps and priorities in the different regions of Spain. Seven years after this study most of these priorities are still valid. The following priority research topics respond to the lack of knowledge in specific matters at a regional level and also to the particular characteristics of soil, climate and cropping systems

***Southern Spain* (Andalusia and Extremadura)**

- Long-term evaluation of conservation tillage effects on weed population dynamics and response to herbicides.
- Improvement of herbicide application in direct drilling.
- Development of equipment for crop residue management.
- Aptitude of different crops for CA technologies.
- Soil suitability for CA systems.
- Integrated studies on the effects of tillage systems on soil properties, crop development, nutritional status of the plants and crop yield.

***Central and Central-eastern Spain* (Castile-La Mancha, Madrid and Valencia).**

- Long-term response of crop rotations to different CA systems.
- Long-term effects of conservation tillage on weed population dynamics and response to herbicides.
- Crop residue decomposition and management, including the development of specific equipment.
- Aptitude of different crops for CA technologies.
- Soil suitability for CA systems.

- Soil fauna and microbiology under CA systems.
- Influence of CA systems on the growth of crop root systems.
- Influence of tillage systems on soil fertility and fertilization technolgies.
- Development of inter-row cover crops in perennial crops, especially for olives, vineyards and citrus.

***North and North-western Spain* (Castile-Leon, Galicia, Asturias, Cantabria and Basque Country)**

- Response of crop rotations to different tillage systems.
- Soil suitability for CA systems.
- Crop residue decomposition and management, including the development of specific equipment.
- Economic and social impact of CA.
- Impact of CA on soil erosion processes (e.g., water, wind and tillage erosion).
- Effects of livestock management on soil physical properties under CA systems.
- Long-term effects of conservation tillage on weed population dynamics and response to herbicides.
- Development of CA technology for humid agrosystems, especially for forage crops and renovation of permanent pastures.
- Development and recommendation of equipment in permanent pastures and forage crops.

***North-eastern Spain* (Navarre, La Rioja, Aragon and Catalonia)**

- Response of crop rotations to different tillage systems
- Soil suitability for CA systems
- Crop residue decomposition processes and management. Development of equipment for crop residue management in order to establish recommendations for crop residue management especially under extreme dryland conditions with low residue production.
- Impact of CA on soil water erosion under annual crops
- Effects of livestock management on soil physical properties under CA.systems

- Long-term effects of conservation tillage on weed population dynamics and response to herbicides

- Development of inter-rows cover crops for perennial crops, specially olive, almond and vineyards

- Local studies on the interaction between CA systems and application of organic fertilisers (manures and slurry).

At a national level, special efforts should be made to increase the studies on SOC stratification, loss of $CaCO_3$, and microbial activity under CA systems.

4. Conclusions and proposals

4.1. Future research needs

Future research topics on CA systems should be aimed to innovate in these techniques to facilitate their use among the farmers on one hand and, on the other to solve new problems arising during the innovation process.

As it has been shown in the previous section, different research requirements have been detected for different Spanish regions. At a national level, however, it is possible to summarise research needs as follows:

1. Integrated studies on crop residue management and CA with emphasis on soil physical, chemical and biological processes evaluation. An important lack of knowledge has been detected on allelopathic effects driven by CA practices. The final objective of these studies should be the establishment of a set of recommendations as a function of the amount of crop residues, soil and climate characteristics and farming systems, including livestock husbandry.

2. Integrated studies on the influence of CA technology on the dynamics of weed population and weed control strategies (sowing rate and time of sowing, crop rotations, herbicide applications, etc.). Studying and understanding weed population inversion under CA systems should be an important issue.

3. Integrated studies on the influence of CA technology on specific incidences of pest and diseases and control strategies. This is another important issue for CA to be included as a component within comprehensive Integrated Crop Management (ICM) strategies.

4. Studies on the sutitability of annual and perennial crops for CA techniques under both rainfed and irrigated conditions, as well as on the adoption of crop rotations adapted to those technologies.

5. Further studies will be required to quantify at local scale the impacts of CA on soil biology and biodiversity of farming systems.

6. In specific areas there is still an important lack of knowledge on the reduction of soil erosion by means of CA technologies. This is an issue of paramount importance taking into account that Spain is a Mediterranean country very prone to soil erosion and desertification processes.

7. Also, there is an urgent need for holistic integrated studies to establish the best CA management practices tailored to specific soil types, climate conditions and crops and cropping system and to define maps establishing CA guidelines for specific geographical areas and regions.

8. Finally, policy makers and agri-environmental measures (EU regulations and specific rules issued by the governments of autonomous regions) should promote and improve the available knowledge about CA techniques to make their development and implementation easier.

4.2. General conclusions

In Spain, interest and research on CA begun approximately 35 years ago, when the first field trials were established by research institutions due to farmers' demands. However, the largest expansion of CA technologies has taken place in the last 20 years.

The wide experience and research knowledge available in Spain on CA has been gathered through both short and long-term field experiments carried out all over the Spanish geography. Though currently there is an important network of long-term field experiments, this network is still insufficient to cover all research needs.Taking into consideration that most of the CA trials have lasted 3-4 years on average, the establisment of new, well designed long-term experiments in integrated research sites is a crucial issue for the improvement of scientific knowledge about CA in Spain.

So far the intensity of CA research has been very irregular in Spain. There is a clear lack of information in humid areas in the North Central and Northwest regions devoted to forage crop and in Central and Eastern areas (e.g., Levante) where the agricultural activity is mainly focused in horticultural and orchard crops.

Globally, there is an important knowledge gap on the biological aspects affected by CA systems (soil biology, biodiversity and development of weeds, incidence of pests and diseases and their control) in practically all the autonomous regions and agroecosystems.

On the other hand, it would be necessary to promote multidisciplinary studies for a proper evaluation of CA practices. Generally, most. short and long-term studies are focused only in one or two topics. For instance, many studies have been conducted to assess specific soil physical effects, whereas there is very limited information from integrated site-specific studies on the suitability of CA as a function of soil, climate and cropping system characteristics.

The highest impact of CA technologies has taken place in rainfed areas dedicated to annual winter crops, such as as winter cereal, forage and grain legumes and canola. The interest in CA is much lower, and consequently with less impact and knowledge, in irrigated field crops, such as alfalfa, corn, sunflower and other summer crops. In the last five to ten years it has been observed an increasing interest on using CA technologies in perennial crops, such as olive, almond and vineyards.

The degree of adoption of CA techniques in Spain has been also highly variable. Hence, there are areas in which CA is used in 80-90% of the territory and other areas where the adoption level and interest in CA techniques is almost inexistent. It may be said that the acceptance of CA techniques in Spain is still low. However, when the technologies are well introduced and adopted by some farmers in a certain area, this results in a rapid dissemination throughout the area.

In principle, there is a large variety of machinery available for practicing CA in most cropping systems and producers are promptly informed about its use by agricultural machinery companies staff.

Nowdays, the main problems detected when CA techniques are applied in rainfed areas are associated to weed control and crop residue management. Other secondary problems come from an incomplete control of deseases in humid areas and also from application of organic fertilisers (manure and slurry). In humid and irrigated areas problems derive from soil compaction in a first instance, but also from other aspects, particularly the lack of specific experiments and research in these areas.

Finally, though public agricultural extension services depending on the regional governments do not frequently advise local farmers, this is not a big issue in terms of technology transfer. In fact, there is a permanent CA technical information flow from researchers, farmer co-operatives technical advisors and private companies to Farmer's Associations, who distribute it to the producers.

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