WHAT DO FARMERS MEAN WHEN THEY SAY THEY PRACTICE CONSERVATION AGRICULTURE? A COMPREHENSIVE CASE STUDY FROM SOUTHERN SPAIN

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Abstract

Conservation agriculture (CA), which is promoted worldwide to conserve soil, water and energy and to reduce production costs, has had limited success in Europe. The objectives of this study were to assess annual crop systems currently managed under CA in southern Spain, identify obstacles to CA adoption, and recommend strategies to overcome those obstacles. We employed the following methods: i) examination of original government data used to monitor CA; ii) survey of CA farmers to characterize their practices and perceptions; iii) agronomic, economic and energetic comparison of minimum tillage (MT) and conventional tillage (CT); and iv) a stakeholder focus group to identify strategies for improving CA. Farmers selectively implemented some components of CA while disregarding others as a strategy to adapt to local conditions. Although most researchers define CA as a system that combines minimum soil disturbance, maintenance of crop residues, and crop rotation, in practice most farmers and organizations equated CA with direct seeding of cereals without considering residues or crop rotation. Official national statistics did not include all of these CA components either. Examination of government data revealed that only 13% of monitored plots were not tilled consecutively. The most common CA system (50% of farms) was direct seeded wheat rotated with tilled sunflower. This system (classified as MT) and CT were not significantly different with regard to wheat yield, soil quality, net return or energy use in either crop, which was likely due to similar residues management, recurrent soil disturbance in MT, and disuse of moldboards in CT. In wheat, fertilizers represented the largest energy input (68% TEI) in both systems followed by diesel consumption (12% and 19% in MT and CT, respectively). To overcome the most important identified problems in CA, we highlight the need for collaborative research with farmers and other stakeholders to develop appropriate drill technology for spring crops, identify non-cereal crops that are better adapted to CA than sunflower, improve residues management, increase energy efficiency through better fertilizer management, and promote CA among farmer groups excluded by socioeconomic barriers. Finally, international standards to guide data collection and statistical analyses on all components of CA will enable researchers and institutions to compare information and find solutions to common problems.

1. Introduction

Promoted worldwide to conserve soil and water resources, conservation agriculture (CA) integrates three main elements to improve soil quality and crop productivity in the long term: minimal soil disturbance, permanent ground cover, and crop rotation (FAO, 2013). Cultivated on over 120 Mha globally, CA accounts for 57% and 69% of the arable cropland in South America and Australia-New Zealand, respectively. In contrast, only 0.5% of arable land is managed under CA in Europe. Spain, Italy, France, Finland and Germany possess the most area under CA in Europe, with Spain leading the continent with nearly 800,000 ha of mostly perennial crops and cereal monocultures (FAO, 2015; MAGRAMA, 2013). However, the methodology used by the Spanish Ministry of Agriculture, Food and Environment (MAGRAMA) to calculate the area of annual crops under CA management only considers direct seeding of cereals, sunflower, and cereal fodder crops while failing to provide information on residues management, rotations or direct seeding of other crops like legumes (MAGRAMA, 2014a). Improving our understanding of how and why farmers implement all three of these components is necessary to maximize the environmental and economic benefits of CA in Europe.

The diversity of soils, climatic conditions, and socioeconomic contexts as well as potential environmental risks may partly explain the restricted expansion of CA in Mediterranean countries like Spain (Kassam et al., 2012). Factors directly affecting farmers' decision to adopt CA include: 1) problems with crop establishment and management of crop residues; 2) increased weed abundance; 3) cost of and limited access to herbicides; 4) lack of capital investment for inputs and machinery; and 5) inadequate extension and government policies supporting CA (Knowler and Bradshaw, 2007; Soane et al., 2012). Moreover, uncertainties about environmental hazards have given some analysts pause about CA, particularly given the intensive use of herbicides and genetically modified (GM) crops to control weeds (Gattinger et al., 2011).

Despite obstacles to adoption, CA represents a potentially viable alternative to conventional tillage for the conservation of water, energy and soil resources in European agriculture (Soane, 2012). Experimental studies in Spain show the capacity of CA to improve soil quality (Madejón et al., 2009; Melero et al., 2011) without yield penalty under both rainfed (Cantero-Martínez et al., 2007; Hernanz et al., 2014; Ordóñez-Fernández et al., 2007) and irrigated conditions (Boulal and Gómez-Macpherson, 2010; Cid et al., 2014; Panettieri et al., 2013). Compared with conventional agriculture, CA also has the potential to reduce production costs and improve energy efficiency by reducing diesel fuel and machinery inputs required for tillage (Hernanz et al., 2014; Moreno et al., 2011; Sánchez-Girón et al., 2007). Yet while experimental trials have demonstrated technical advantages, our knowledge about the costs and benefits of CA as practiced by farmers is limited. Most research has been carried out on-station under conditions with limited representativeness or reproducibility on scales relevant to commercial farms (Soane et al., 2012). Moreover, farmers' perceptions, motivations, and adaptations regarding CA have rarely been studied. Evaluation of not only agronomic and environmental problems but also the socioeconomic barriers to adoption is an important priority for research (Lahmar, 2010).

Understanding the complexity of CA systems, particularly interactions with local socioeconomic conditions, requires a multidisciplinary, participatory approach that enables researchers to collaborate with farmers to assess current practices and develop strategies for improvement (Bolliger et al., 2006). In the southern Spanish region of Andalusia, where only 7% of the c. 1.1 Mha dedicated to CA annual crops is direct seeded (MAGRAMA, 2013), the extent and duration of crop rotations, direct seeding, and other practices associated with CA are largely undocumented. Given the limited information available, the objectives of this study were to conduct an on-farm evaluation of annual crop systems under CA management in Andalusia, identify constraints to adoption, and recommend strategies for improving agronomic, socioeconomic and energetic aspects of current practices, focusing on research and technological development needs. Based on analysis of original data used by the Spanish government to generate national statistics on CA, we also discuss the need for international standards to guide the collection and reporting of information about CA.

2. Methods

2.1 Study area and approach

The study area covers the arable land dedicated to annual crops in western Andalusia, Spain. Wheat (*Triticum* spp.) and sunflower (*Helianthus annuus* L.) are the most common crops under rainfed conditions whereas cotton (*Gossypium hirsutum* L.), maize (*Zea* mays L.) and wheat are the most common crops under irrigation. Under both conditions, one crop is usually produced per year. The climate of the region is Mediterranean, characterized by mild, rainy winters and hot, dry summers. Soils in rainfed cropland are primarily deep clays and clay loams while those in irrigated land are silt loams. Details on soil, rainfall and temperature are provided in Section 2.4.1.

We assessed annual crop systems under CA using four methods. First, we examined original data used by the government to calculate national statistics on direct seeded crops to determine the number of consecutive years farmers practice direct seeding and to identify the most common CA rotations in Andalusia (MAGRAMA, 2013). Second, we conducted a general survey of farmers identified as CA practitioners in the study area to describe socioeconomic aspects of their farms, agronomic practices, and perceptions of the benefits and constraints of CA. Third, we compared the agronomic, economic and energetic attributes of the most common CA system in the study area, wheat-sunflower rotation under rainfed conditions, under both CA and conventional agriculture. Finally, we organized a focus group in which farmers, researchers, and other key stakeholders identified the most important problems with CA in annual crops and recommended strategies for improvement.

2.2 Examination of original government data on direct seeded crops in Andalusia

MAGRAMA has published the area of direct seeded grain cereals, sunflower and cereal fodder by region and year since 2008 (MAGRAMA, 2013). The methodology used to obtain these data is described elsewhere (MAGRAMA, 2014a; González-Sánchez et al., 2015). To identify the most common crop rotations and determine the number of years plots have been direct seeded in Andalusia, we obtained the original GIS database containing data from monitored plots over five consecutive seasons (2008-2013) from the Consejería de Agricultura Pesca y Desarrollo Rural (Junta de Andalucía). Approximately 5% of the plots containing annual crops or fallow and that were monitored each year during this period (mean = 6299 plots per year) corresponded to direct seeded crops. Because not all plots were monitored in all years, we focused on a select group of plots that met two conditions: data were available for at least three consecutive years and, of these, at least two years had direct seeded crops (n=177). We then identified which of these plots had not been tilled (n=23), including plots with either direct seeded crops or fallow with spontaneous vegetation or without management. We also noted the sequence of crops in each of the untilled plots.

Additional information on CA crop subsidies was obtained from the Consejería de Agricultura Pesca y Desarrollo Rural (Junta de Andalucía). Within the framework of the National Rural Development Program, the Andalusian government has subsidized farmers since 2010 who practice direct seeding and sunflower residues maintenance in annual crop systems for at least five consecutive years. This subsidy, called Sub-measure 12, is available for plots with a minimum 8% slope. We obtained data on the crop type and number of farmers who requested this subsidy over four seasons (2010-2013).

2.3 Characterization of annual crops under CA in western Andalusia

To describe CA systems in the study area, we conducted a general survey of farmers. Given the lack of official statistics required to accurately estimate the size of the study population, we used snowball sampling, whereby interviewees referred us to other CA practitioners. We also employed purposive sampling to insure the inclusion of small farmers. The total number of conducted surveys was based on information saturation criteria. We identified CA farmers in collaboration with the *Asociación Española de Agricultura de*

Conservación/Suelos Vivos (AEAC/SV) and by phone contact with service providers. A total of 30 farmers from the provinces of Cadiz, Cordoba, Huelva, Malaga and Seville participated in the study (Supplementary Figure S.1). The first part of the questionnaire consisted of a written form that asked farmers for general information about their property, the main rotations used on their farm, and their opinions about the benefits and limitations of CA. The second part consisted of semi-structured interviews in which each farmer was asked to describe the CA techniques applied for each crop, an assessment of those techniques, and priority needs for research. After completing the survey we held a workshop with half of the farmers to discuss preliminary results, validate the main findings, and identify individuals willing to participate in the following case study.

INSERT LINK TO FIGURE S.1 AROUND HERE

2.4 Comparison of CA and conventional systems: wheat-sunflower case study

2.4.1 Selection of paired farm plots and data collection

The most common CA system identified in the study area was rainfed wheat and sunflower rotated in alternate years. To improve our understanding of how CA is practiced in western Andalusia, we compared CA with conventional agriculture using this system as a case study, taking into account agronomic, energetic and economic aspects of management and production. Using a paired plot design to minimize variation in climate, topography, and soil between management systems, we compared 10 pairs of farm plots ≥ 20 ha containing both CA and conventional farming. We designated the CA system as minimum tillage (MT) rather than CA because according to the general survey, residues were removed from the field after wheat harvesting and the soil was tilled prior to sunflower cropping. MT plots were selected according to two criteria: 1) wheat was direct seeded without soil preparation; and 2) records of crop and residues management existed for four consecutive growing seasons (i.e. September – August) between autumn 2007 and summer 2011, hereafter referred to as years. In a given year, half of MT plots were cultivated with wheat and the other half with sunflower, thus the crops were present in equal proportions during all four years. Once a MT farm was chosen, a paired farm plot managed under conventional tillage (CT) was selected according to four criteria: 1) the same wheat-sunflower rotation was implemented in the same order over the four years; 2) soil was tilled and prepared every year; 3) the plot was located within 2 km of the MT plot; and 4) detailed records of crop management were available over the study period. We named pairs according to the nearest town (Supplementary Figure S.1). In structured interviews conducted in person, farmers provided detailed information about tillage and sowing operations, fertilizer and herbicide applications, crop yields, and residues management for each of the four years.

Monthly rainfall was recorded by the nearest meteorological station to the paired farms (Supplementary Table S.1). Mean temperature over the study period was 14.6°C during the winter growing season (November-June) and 21.6°C during the summer growing season (March-August). Most soils in the area are deep vertic soils derived from quaternary terraces and dominated by swelling clays that fracture upon drying. Soils are basic with pH 7.0-7.7.

INSERT LINK TO TABLE S.1 AROUND HERE

2.4.2 Economic and energetic analyses

To compare economic profitability and energy use between MT and CT systems, we used data gathered from the structured interviews with farmers. Parameters were calculated for each plot (n=20) and year (n=4).

Economic analysis consisted of the estimation of production costs (inputs and operating costs of machinery) and crop benefits in each plot and year. We used different prices per year (2008, 2009, 2010 and 2011) for diesel fuel (0.79, 0.76, 0.70, 0.85 € l^{-1}) and grain (wheat: 0.33, 0.14, 0.15, 0.23 € kg $seed^{-1}$; sunflower: 0.38, 0.44, 0.29, 0.42 € kg $seed^{-1}$) according to the public observatory of prices reported by the regional government of Andalusia. We obtained the operating costs of machinery, which included depreciation of value, interest on capital investment, insurance, maintenance, repairs, and hourly costs, from national studies provided by MAGRAMA (2012) (Supplementary Table S.2). All calculations were based on 120 CV-2 + 2WD tractors. Prices of seed, herbicides, fertilizers, and machinery rental for direct-drill and conventional sowing and harvesting operations were estimated based on the average costs charged by three local service providers and three commercial stores. According to these sources, prices were constant over the four years. We did not include subsidies in the analysis because farmers were unwilling to disclose information on this issue.

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Total cost of production (€ ha^{-1}) was calculated as the sum of input costs (fertilizers, seeds, herbicides) and total operating costs of machinery. We calculated crop benefit (€ ha^{-1}) by multiplying crop yield (kg ha^{-1}) by the market price of grain (€ kg^{-1}), and net return (€ ha^{-1}) by subtracting total production cost from crop benefit. Productivity (kg $€^{-1}$) was calculated by dividing crop yield (kg ha^{-1}) by total production cost (€ ha^{-1}).

Energy use analysis was based on studies involving comparable technology in similar agricultural conditions (Hülsbergen et al., 2001; Moreno et al., 2011). Inputs and outputs for each year and plot were converted to energy units (GJ ha^{-1}) using the coefficients presented in Supplementary Table S.2. Total energy input (TEI) was calculated as the sum of direct energy (DE) and indirect energy (IE) input used in crop production (Hülsbergen et al., 2001). DE included diesel fuel used in crop production while IE included the energy required for: the manufacture and maintenance of machinery; herbicide, fertilizer and seed production; and packaging and transport of these products to the farm. Calculation of TEI did not include the energy used in the storage, transport or sale of outputs because these reflect sales rather than production. Other variables excluded from TEI analysis included pesticide management, manpower, and solar energy.

Energy output (EO) was determined as the gross energy content in the grain. In the case of wheat, residues were also included because straw bales were removed from the field and put up for sale. We assumed a harvest index of 0.5 to estimate wheat straw production. Dry weight of harvested grain and bales were converted to energy units using a specific energy coefficient for each crop (Supplementary Table S.2). Energy productivity (EP), which represents the amount of grain produced per GJ of energy invested in the system, was calculated as the coefficient between crop yield and TEI (Rathke et al., 2007).

2.4.3 Field measurements

To complement the information gathered from farmer interviews, we conducted field measurements of crop residues and soils between October and December 2011. We collected residue and soil samples from six points within each of the paired farm plots according to a stratified random design. Covering a total area of approximately 15,000 m^2, points were separated by 50 m. We collected soil samples at two depths (0-10 and 10-25 cm) and mixed them to obtain a composite sample for each plot and depth. Soil was sieved at 2 mm and separated into two sub-samples. We stored the first subsample immediately at 4^oC to prevent moisture loss prior to assaying for β-glucosidase (β-glu) activity. Enzymatic activity was measured by incubating soil with p-nitrophenyl glucoside and measuring its absorbance at 400 nm with a spectrometer (Tabatabai, 1982). Results were based on the oven-dried weight of the soil. We air-dried and analyzed the second subsample for total organic carbon (TOC) using dichromate oxidation and titration with ferrous ammonium sulphate according to Walkley and Black (1934). We determined sand, silt and clay fractions using the hydrometer method.

We gathered crop residues from an area of 1 m^2 adjacent to each point where soil samples were collected. We calculated residue biomass per unit area after gently washing residue samples to remove soil and drying them to constant weight at 75^{o}C. To determine the fraction of surface area covered by residues, we took digital photos of the 1-m^2 area prior to residue collection and processed the photos with ENVI 4.7 software (Environment for Visualizing Images, Research Systems. Inc, CO, USA).

2.5 Focus group

To identify barriers associated with CA in annual crops, propose management strategies, and highlight research priorities, we convened a focus group of key stakeholders. Participants included four farmers, one machinery dealer, three AEAC/SV members, two researchers, two field technicians, and a CA expert who moderated the group.

2.6 Statistical analyses

We used linear mixed models (LMM) to assess the effect of management system and season on wheat and sunflower yield and to test the effect of management system on soil quality. LMM were also used to evaluate the energy efficiency of each management system separately in wheat and sunflower cropping. All data were analyzed with zone or plot nested within zone as random effects while management system and year were modeled as fixed effects. Year was considered fixed because this variable was replicated only four times. Crop and soil depth were also included as fixed effects in the models analyzing soil quality. Models were constructed applying an information theoretic approach. Akaike's Information Criterion (AIC) and restricted maximum likelihood (REML) estimation were used to select the optimal random effects and variance structure, while the AIC and maximum likelihood (ML) estimation were used to select the optimal fixed effects (Burnham and Anderson, 2002). Structures allowing for different variances per zone or year were included in the models to account for within-group heteroscedasticity (Zuur et al., 2009). Residuals were examined graphically to insure that assumptions of normality and homogeneity of variance were met in the final models. LMM were implemented using the 'nlme' package (Pinheiro et al., 2014) in R version 3.1.2 (R Core Team, 2014).

3. Results

3.1 Examination of official CA data for Andalusia

Evaluation of original data used by MAGRAMA to monitor cereals (C), sunflower (S), cereal fodder crops (CF), and fallow with natural vegetation or without management (F) enabled us to select plots in Andalusia for which data were available for at least three consecutive seasons. We then identified plots planted with direct seeded crops for at least two seasons (consecutive or not). Of the 177 plots that met both criteria, only 23 (13%) were not tilled during the five seasons examined. These included 13, 8 and 2 plots that were not tilled for three, four and five consecutive years, respectively. Conversely, direct seeded crops were alternated with tilled crops or tilled fallow in the remaining 154 (87%) plots.

In the 23 untilled plots, nearly all rotations were combinations of cereal fodder crops, cereal grains and fallow, with cereal grains and fallow dominating. Direct seeded sunflower was only included in the rotation in four instances. The two cases in which soil was untilled over all five seasons followed the sequence F/F/F/C/C. The eight plots that were untilled over four seasons included: 4 x CF/CF/CF/F, CF/CF/CF/C, C/C/C/F, CF/C/CF/F and S/C/F/C. The 13 plots untilled over three seasons included: 6 x C/C/F, 2 x CF/CF/F, 2 x S/C/S, C/S/F, C/C/C, CF/CF/CF. Only 6 % of the 177 plots included a legume crop in the rotation. However, whether the legume was cultivated using direct seeding or conventional methods is unknown because this information was not collected.

An average of 323 (± 18) applications were submitted per year for the Sub-measure 12 subsidy supporting no till and maintenance of sunflower residues in annual crops. After peaking at 5886 ha in the first year (2010), the total amount of land registered in the program decreased to around 4400 ha and stabilized thereafter (by renewal of applications). Cereals (56% wheat) were the dominant crop in the program, covering 79% of the total area subsidized, followed by sunflower, grain legumes, and fodder crops which covered 10%, 9.5% and 0.5% of the area, respectively. Year-to-year differences in these proportions were minor.

3.2 Characterization of annual crop systems under CA

The average CA farmer was male between 40 and 60 years of age. Only 15% of participants were under 40. After an extensive search, we found no female farmers practicing CA in the region. Most farmers possessed a university degree (67%) and their main economic activity was agriculture (78%) or technical agricultural services (15%). Forty-three percent of farms were between 500-1400 ha, indicating that many CA farmers were large landowners. Average farm size was 472 (± 376) ha, 57% of which was dedicated to annual crops and the rest to mostly fruit orchards. Roughly half of the area dedicated to annual crops was managed under CA. Seventy percent of farmers owned their property while 7% leased the land and the rest were cooperatives or associations. Upon implementing CA, 50% of farmers bought new machinery - mainly no-till drills and tractors. Farmers generally owned their own machinery, which on average included six tractors and one no-till drill (single or double disk) per farm. One third of farmers contracted out services for soil preparation and treatments, while all farmers contracted out for crop harvesting.

Many farmers began practicing CA with support from AEAC/SV or other Spanish, Argentinian and Brazilian farmers and technicians with experience in CA. Farmers' initial motivations to adopt CA were improved soil fertility (36%), decreased soil erosion (27%), economic benefits (13%), energy savings (7%), and water conservation (7%). Farms included in the survey had been under CA management for an average of 6 years, with 7% under CA for more than 10 years. A minority of farmers had abandoned CA practices in the case of specific crops (17%) or the whole farm (7%) after two to three years.

The large majority of farms produced CA crops under rainfed conditions (79%) compared to irrigated conditions (21%). Two thirds of farmers applied one CA crop rotation, 26% applied two rotations, and 7% applied three or more. The most common rotation was wheat-sunflower, which was used on 50% of farms, followed by cereal-legume and cereal-cotton, which were implemented on 12 and 10% of farms, respectively. In general, farmers expressed difficulties in finding alternative crops to produce under CA due to low profitability, marketing problems, and lack of familiarity with cultivation requirements.

Farmers practiced a locally adapted form of CA in which direct seeding of cereal crops was combined with tillage in non-cereal crops. A total of 100%, 77%, 33% and 17% of plots cultivated with barley (*Hordeum* vulgare L.), wheat, legumes and sunflower were directly sown without soil disturbance, respectively, while the remaining plots were sown after 1-2 passes with a cultivator. Moreover, although some farmers were aware of the benefits of crop residues for erosion control and improving soil quality, only 33% actually left residues on the ground between plantings.

Farmers reported that once a crop is established, management under CA and conventional systems is similar except for weed control given that more herbicides are required in CA. They also maintained that CA produced the same yield as conventional farming. Regarding management differences between crops, herbicides were consistently used in wheat but rarely in sunflower or legumes, where mechanical control of weeds was more common. Likewise, wheat was always fertilized whereas only 39% of farmers used fertilizers in sunflower and legumes.

Problems cited by farmers with direct seeded wheat, in order of importance according to the incidence of farms for which each problem was reported relative to total number of farms cultivating wheat, were: weed control (34%), higher pest incidence due to excessive crop residues (27%), and poor crop establishment (20%) due primarily to unsuitable no-till drills in wet Vertisols (Table 1). This last issue was by far the most important problem reported for direct seeded sunflower (92% relative to total number of farms cultivating sunflower), which is planted in the spring when soil moisture is high. In untilled clay soils, seeds of both wheat and sunflower tend to remain uncovered on the soil surface where they are susceptible to predation by birds. Problems with weed control (22%) and higher pest incidence in CA (17%) were also important for sunflower. Approximately 20% of farmers reported no problems with production for either crop. As with sunflower, the most common problems reported for direct seeded legumes were greater presence of weeds and poor performance of no-till drills in wet soils (data not shown).

Results of the general survey were corroborated in a follow-up workshop. In addition to validating the problems cited above, farmers confirmed that they do not follow all three principles of CA as defined by FAO (2013): undisturbed soil, maintenance of ground cover, and crop rotation. Rather, they adjust their practices according to the circumstances at hand while prioritizing the minimization of risk.

INSERT TABLE 1 AROUND HERE

3.3 CA versus conventional agriculture: the wheat-sunflower rotation case study

Wheat yield, soil quality, net return, and energy output and productivity were similar between CA and conventional agriculture in the wheat-sunflower rotation. In contrast, yield and production cost of sunflower were higher in conventional agriculture, while production cost of wheat and residue biomass of both crops were higher in CA. Because wheat residues were removed and the soil was tilled prior to sunflower sowing, we named the CA treatment minimum tillage (MT).

3.3.1. Crop performance and soil quality

MT wheat was directly sown while MT sunflower was sown following soil preparation similar to that used in conventional tillage, which consisted of shallow plowing at 0.15-0.20 m depth with no soil inversion (Table 2). Only one out of 10 plots in MT had directly sown sunflower. CT wheat was sown after one pass of cultivator and of disc harrow. No conventional farmer used moldboard or deep disk harrow.

Although the amount of fertilizer applied to wheat crops was similar in both systems, the type of fertilizer and timing of application differed (Table 2). In MT wheat, farmers generally applied starter fertilizers with microelements at the time of sowing. In CT wheat, farmers applied a basal dressing prior to soil preparation that included phosphorus or nitrogen (diammonium phosphate). Although farmers used herbicides in wheat plots in both systems, a larger range of herbicide types and 25% higher doses of glyphosate were applied in MT.

Unlike wheat, sunflower was cultivated as a low input crop. Farmers applied fertilizer only once in the 10 MT plots and in two of the CT plots during the entire study period. However, the two systems differed with respect to weed management. In CT, weeds were controlled mechanically during early stages of crop growth and herbicides were rarely applied. In contrast, several types of herbicides were applied during both pre- and post-planting stages in MT.

INSERT TABLE 2 AROUND HERE

Average wheat yield over the four seasons was notably similar between management systems: 3312 and 3319 kg ha^{-1} in MT and CT, respectively (Table 2). Year was the only significant variable affecting wheat yield (Table 3). By comparison, sunflower yield was significantly lower in MT (1304 kg ha^{-1}) than in CT (1435 kg ha^{-1}) (Table 2; Table 3).

All farmers baled and sold off their wheat residues every year. Sunflower residues were usually buried during soil preparation prior to wheat sowing in CT, but left on the soil surface in MT (Table 2). In the fall, residue biomass was significantly less in CT than MT for both crops. In CT, mean residue biomass was 70 g m^{-2} for wheat and sunflower. In MT, residue biomass was roughly three times that in CT and was higher after wheat than sunflower cropping (239 and 207 g m^{-2}, respectively). The portion of the ground covered by residues after wheat cropping was 49% (± 26%) in MT and 19% (± 1%) in CT. After sunflower cropping this variable was 23% (± 10%) and 13% (± 4%) in MT and CT, respectively.

Soils were generally clays or clay loams (Table 4). TOC and β-glu were similar between management systems but differed significantly with depth (Table 3). TOC and β-glu were 6 and 26% higher in the top 0.1 m than in the 0.1-0.25 m horizon, respectively.

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3.3.2. Economic profitability

Production costs differed significantly with management system and crop (Table 3). In wheat, mean production costs were 9 € ha^{-1} more in MT than CT, primarily due to higher use of fertilizers and herbicides (Table 5). In sunflower, production costs were 19 € ha^{-1} less in MT than CT due to savings in machinery and diesel fuel. For both crops, herbicide costs were higher in MT. Despite the higher price obtained for sunflower seeds, crop benefit was greater in wheat because of higher yields. Additional income generated from selling wheat straw, which was not included in crop benefit, averaged around 12 € ha^{-1} but rose as high as 40 € ha^{-1} in scarce years.

Net return differed significantly by year but not by management system or crop (Table 3). Higher crop benefits were counterbalanced by higher costs in wheat, resulting in similar net returns for both crops (Table 5). The global mean net return, which was 204 € ha^{-1} y^{-1}, varied widely between seasons due to fluctuations in crop yield and grain price (not shown). When all systems and years were compared, the maximum net return registered was 957 € ha^{-1} for CT wheat and 515 € ha^{-1} for MT sunflower. At the other extreme, some years saw negative net returns for wheat under both management systems (-195 € ha^{-1}) and in MT sunflower (-5.7 € ha^{-1}). CT sunflower was the only system that did not experience a negative net return in any season. It should be noted that absolute values of net return are underestimated because income from European Common Agricultural Policy (CAP) subsidies was not included in the calculations. Crop productivity was similar for both management systems (Table 5). Mean productivity in wheat (7 kg €$^{-1}$) was more than 150% higher than in sunflower (4.5 kg €$^{-1}$).

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3.3.3. Energy use efficiency

TEI differed significantly by crop but not by management system (Table 3). TEI_W (18.4 GJ $ha^{-1} yr^{-1}$) was more than five times greater than TEI_S (3.4 GJ ha^{-1} yr^{-1}) (Table 6). However, the five components of TEI (fertilizers, diesel, machinery use, seed and herbicide), differed with respect to management and crop (Figure 1):

- In wheat, fertilizers accounted for 68% of TEI_w in both MT (12.1 GJ ha^{-1} yr^{-1}) and CT (12.7 GJ ha^{-1} yr^{-1}), whereas fertilizer was rarely applied in sunflower.
- In wheat, diesel fuel consumption was lower in MT (2.22 GJ ha^{-1} yr^{-1}) compared to CT (3.42 GJ ha^{-1} yr^{-1}). In sunflower, mean diesel use was 2.09 and 2.69 GJ ha^{-1} yr^{-1} in MT and CT, respectively. The energy input corresponding to diesel consumption represented only 15% of TEI_W in wheat, but comprised 70% of TEI_S in sunflower.
- The energy corresponding to seed varied with crop: 2.50 GJ ha^{-1} yr^{-1} in wheat (14% TEI_W) and 0.20 GJ ha^{-1} yr^{-1} in sunflower (6% TEI_S). Although sunflower seeds have a higher caloric content than wheat seeds (Supplementary Table S.2), the energy cost of the latter was 13 times higher due to the larger amount of seed required during cultivation.
- The energy corresponding to machinery use was lower in MT compared to CT and in sunflower compared to wheat: 0.30 and 0.35 GJ ha^{-1} yr^{-1} in MT and CT in wheat, and 0.18 and 0.20 GJ ha^{-1} yr^{-1} in MT and CT in sunflower. Energy input corresponding to this component represented 2% and 6% of TEI_W and TEI_S, respectively. Harvesting was the most costly operation in wheat, consuming 0.22 GJ ha^{-1} (17% of which corresponded to baling), but was only 0.08 GJ ha^{-1} in sunflower.
- Energy consumption due to herbicides was similar between systems in wheat despite higher glyphosate use in MT. This component was highly variable among farmers in sunflower. Mean energy inputs were 0.40 GJ ha^{-1} yr^{-1} in wheat (2.2% TEI_W) and 0.25 GJ ha^{-1} yr^{-1} in sunflower (7.4% TEI_S).

INSERT FIGURE 1 AROUND HERE

Energy output (EO) was calculated from grain yield and baled straw in wheat and from grain yield in sunflower. Like TEI, EO was significantly different between crops but not management systems (Table 3; Table 6). In wheat, mean EO was 103 GJ ha^{-1} yr^{-1}, 43% of which corresponded to grain yield and 57% to baled straw. In sunflower, mean EO was 29.4 GJ ha^{-1} yr^{-1}. Sunflower seeds have a higher caloric content than wheat but grain yield was less than half (Table 2).

Energy productivity (EP), which is the weight of harvested grain per unit of energy invested, also differed significantly with crop (Table 6). Mean EP in sunflower (0.47 tons GJ^{-1}) was double that in wheat (0.19 tons GJ^{-1}).

INSERT TABLE 6 AROUND HERE

3.4 Strategies for increasing CA adoption in Andalusia

The most important barriers to CA adoption cited in the general survey (Table 1) were validated in a focus group at the end of the study. Some problems, such as fertilization and residues management, were not mentioned while others dominated the discussion. Most of the conversation focused on the lack of suitable no-till drills for sowing in wet, undisturbed Vertisols. This problem was especially acute for sunflower. Farmers, researchers, and the machinery dealer proposed technical modifications to the drill to improve its performance in these conditions (Table 1). Development of strip-till systems was also proposed. In contrast, representatives from AEAC/SV asserted that such technical problems could be avoided if farmers implemented all three components of CA. Farmers proposed to increase planting density and encourage rapid coverage by wheat to suppress weeds. They also suggested applying granular insecticides at the time of sowing to control pests during crop establishment. Further research to address these problems was unanimously called for by stakeholders.

4. Discussion

4.1 CA in annual crop systems as practiced by Andalusian farmers

We found that farmers selectively implemented certain components of CA while disregarding others as a strategy to adapt to complex and dynamic local conditions. The large majority of farmers in our study practiced a form of CA that combined direct seeding of cereal crops with tillage in non-cereal crops, without incorporating residues into the system or rotations that included no-till legumes or other crops. Although these practices deviate from the internationally accepted concept that CA should integrate minimum soil disturbance, permanent ground cover, and crop rotation (FAO, 2013), they represent rational adaptations to local socioeconomic, agronomic, and environmental conditions. Understanding how and why farmers selectively apply some aspects but not others will help researchers, farmers, and other stakeholders address key problems and maximize the environmental and economic benefits of CA.

Farmers used tillage in non-cereal crops, particularly sunflower, because suitable technology for no-till soil preparation was unavailable. In 13% of the selected CA plots monitored by MAGRAMA in Andalusia and 23% of the identified CA rotations in our general survey, farmers did not till the soil in consecutive rotations during the study period. These two sources of information as well as the Sub-measure 12 applications showed that combinations of cereal crops (grain and fodder) and fallow dominated no-till CA rotations. In the majority of the remaining rotations, soil was prepared prior to sunflower or legume cropping. Regular soil disturbance resulting from tillage disrupts the biochemical pathways for long-term soil improvement associated with CA (Verhulst et al., 2010) and cancels potential yield gains (Brouder and Gómez-Macpherson, 2014).

Despite the environmental advantages of maintaining crop residues on the ground, farmers in our study sold them off to earn additional income. Average revenue from wheat residues earned 5.5% above net return, reaching as high as 18.5% in scarce years. However, removing crop residues devoids microorganisms of valuable carbon and other nutrients, leading to lower soil fertility (Erenstein, 2002) and increased erosion by directly exposing the soil surface to raindrops and runoff (Boulal et al., 2011). In northeastern Spain, removal of cereal residues from CA fields resulted in a 20% reduction of soil organic carbon in the top 0.2-m layer (López et al., 2012).

4.2 Overcoming barriers to CA adoption and implementation

The large size of CA farms compared to conventional farms in Andalusia (mean: 472 vs. 18 ha) underscores a fundamental socioeconomic barrier to CA adoption (INE, 2009). Large farms are associated with better access to economic resources and education. Not only can large landowners invest in the costly machinery necessary to practice CA, they can assume yield losses which are common during the early stages of conversion to CA (Andersson and D'Souza, 2014; Bolliger et al., 2006). Even farmers who had been implementing CA for several years dedicated only half of their annual cropping area to CA, which likely represents a strategy to minimize risk in case of crop failure. Moreover, the fact that no CA farmers were women, even though 22% of farms in Andalusia are managed by women, may reflect gender inequalities in land and economic resources. Despite the high education level of CA farmers, 67% of whom held a university degree compared to 2% of Andalusian farmers generally, nearly all agreed that specialized training is needed to implement CA successfully. The positive relationship between external training and CA adoption in Spain (Rodríguez-Entrena and Arriaza, 2013) and elsewhere (Baumgart-Getz et al., 2012) provides a potential strategy to promote CA adoption among underrepresented groups like middle-income farmers and women. Another promising strategy is cost sharing to enable individual farmers and cooperatives access to specialized machinery. Although the socioeconomic profile of most farmers practicing CA in Andalusia suggests significant economic limitations to adoption, participatory research and educational outreach offer ways to promote CA among a broader range of farmers.

The solution to the lack of suitable drills, the principal technical problem impeding farmers from practicing no till in non-cereal crops, appears simpler. Collaboration between farmers, researchers, and manufacturers is needed to develop a drill that can perform well in wet Vertisols and facilitate direct seeding of crops like sunflower. A model solution is provided by Brazil and Argentina, where the rapid adoption of CA was possible in part because local companies manufactured machinery adapted to the demands of local farmers (Derpsch and Friedrich, 2009). Although approximately 20% of no-till drills owned by farmers in our study were manufactured in Spain, the manufacturers are located in the central and northeastern parts of the country where soil types and conditions are different from those of Andalusia. The small market for such technology in Andalusia, where the number of no-till drills registered between 2007 and 2013 comprised only 2.4% of the national total (MAGRAMA, 2014b), may contribute to the lack of interest on the part of manufacturers. These results contradict the argument that CA machinery is well-adapted to local conditions in Spain (Friedrich et al., 2014), which may only be true for the cereal-fallow and cereal-cereal rotations in the north where direct seeding has been implemented successfully (López et al., 2012). In the south, development of suitable drill technology, including strip-till systems, would reduce soil disturbance in non-cereals and likely facilitate CA expansion.

As with developing appropriate technology, addressing most problems in CA requires collaboration between farmers, researchers, and other key stakeholders to establish management strategies in accordance with local conditions. For example, farmers should be made aware that maintaining residues on the ground mitigates the negative effects of sowing in undisturbed soil on long-term crop performance and soil quality (Brouder and Gómez-Macpherson, 2014). However, research is needed to help farmers maximize the environmental and economic benefits of this practice, particularly to determine the optimal amount of straw for protecting and improving the soil under different conditions, cut height at harvest, and timing of partial removal of residues. CA should not follow a rigid recipe, but rather remain flexible by incorporating local adaptations to meet farmers' needs. For example, innovative systems could include sporadic or precision tillage to improve sustainability and economic viability (Kirkegaard et al., 2014; López-Fando et al., 2007). The challenge is to find ways to integrate minimum soil disturbance, maintenance of residues, and crop rotation into a functional system that can be adapted to different agricultural contexts while optimizing the synergistic benefits of these components.

4.3. Costs and benefits of CA as practiced in western Andalusia: wheat-sunflower rotation

Compared to conventional agriculture, the CA treatment of the wheat-sunflower rotation or minimum tillage (MT), failed to achieve the most commonly claimed benefits of CA at the farm scale: improved soil quality, increased crop productivity, reduced production costs, and decreased energy inputs. Most of the variables examined were not significantly different given the similar management practices between the two systems.

4.3.1 Crop management and soil quality

Compared to CT, the main differences in MT management were direct seeding of wheat, use of different fertilizers and more herbicides in wheat, and delayed soil preparation in sunflower. The fact that no CT farmer used the moldboard contrasts with studies in southern

Spain showing that conventional farming generally involves deep tillage with a moldboard (López-Garrido et al., 2011; Madejón et al., 2007; Ordóñez-Fernández et al., 2007). Farmers in the initial workshop confirmed that deep tillage is seldom applied in the study region.

Nearly all farmers removed wheat residues from their fields (Table 2). In 2011, differences between MT and CT in the amount of residues on the ground were due to the time of sampling (autumn). Conventional farms had fewer residues in this season because fields were plowed in the summer, whereas MT plots were cultivated in the following spring. Residues in MT thus protected the soil surface during the rainy autumn and winter better than in CT plots, after both the wheat (49 vs. 19% of soil surface covered in MT and CT, respectively) and sunflower harvest (23 vs. 13% in MT and CT). As indicators of soil quality change resulting from tillage in the clay soils common to this region - in both rainfed and irrigated conditions (Madejón et al., 2007; Panettieri et al., 2013) - TOC and β-glu enzyme activity did not differ between MT and CT (Table 3). As discussed in the previous section, regular soil disturbance in sunflower cropping and removal of residues likely reduced any positive impact of CA on soil quality.

Apart from the lack of appropriate drill technology and residues management, weed control was a major problem cited by farmers for both crops in MT. Greater weed incidence in wheat plots under CA has been associated with increased herbicide use and appearance of herbicide resistance in CA systems (Soane et al., 2012; Trichard et al., 2013). In Spain, 33 cases of herbicide-resistant weeds have been registered during the last 40 years (Heap, 2014) and the rate of resistance could increase with CA expansion. Herbicide-resistant GM cultivars have been a key element for CA adoption in the United States, Brazil, Argentina and Canada. These countries have the largest area under no till and GM cultivation (ISAAA, 2011), although several cases of glyphosate resistance have already been registered in the last decade (Heap, 2014). Moreover, higher herbicide use in CA increases the risk of groundwater contamination, if leaching occurs, and of adverse effects on human health (Alleto et al., 2010; Gasnier et al., 2009). To improve weed control, our focus group proposed promoting intraspecific competition by reducing row spacing and increasing sowing density in wheat, and using available herbicide-resistant cultivars (non-GM) in sunflower (Table 1). Weed control strategies used in organic agriculture also provide a template to design practices that may reduce herbicide dependence in CA, such as more diverse crop rotations that incorporate legumes and industrial crops, higher seed density, and grouped sowing lines (Lacasta, 2007). Further research is needed to develop integrated management that controls weeds while reducing herbicide use in annual crop systems under CA.

4.3.2 Crop yield and economic assessment

Any detectable effect of management on wheat yield was likely overwhelmed by seasonal differences in rainfall (Hernanz et al., 2014). Significantly lower sunflower yield in MT relative to CT was probably due to subsoiling compaction in MT (Botta et al., 2006). Although soil preparation was similar between the two management systems in the sunflower phase of the rotation, tillage applied during the wheat phase probably alleviated subsoiling compaction in CT, conferring the benefit to the sunflower phase. Other studies found no differences in sunflower grain yield between tillage techniques, including no till, but rather concluded that spring rainfall is the major determinant of crop yield (Aubraudare et al., 2006; Ordóñez-Fernández et al., 2007).

In economic terms, production costs varied significantly with crop and management system, crop benefits varied with crop and year, and net return varied only with year (Table 3). Wheat cropping resulted in higher benefits but also required higher investments whereas sunflower, a low input crop, required practically no investment but produced enough yield to nearly equal the net return of wheat. Regarding production costs, higher investment in herbicides and more expensive fertilizers in MT wheat canceled out the savings from less diesel fuel used in no till. In sunflower, even though the savings in diesel fuel and machinery in

MT were partially offset by the higher use of herbicides, overall production costs were lower in MT (Table 5). However, the end result was lower yield compared to CT plots. It is important to remember that the high volatility of input prices makes the results such short-term economic assessments tentative. For example, a decrease in the price of glyphosate resulting from patent expiration and high diesel fuel prices significantly impacted the profitability of CA systems in the U.S. (Nail et al., 2007). Longer-term economic studies of CA are needed to improve our understanding of the profitability, sensitivity to external costs, and farmers' responses to changing costs in the context of high price volatility.

Although the lack of clear economic benefits is probably a major reason for the limited adoption of CA in southern Spain, important opportunities exist for improving the net return of CA through better management and production of a greater variety of crops. Maintenance of residues on the ground and reduced tillage can improve long-term soil fertility and decrease fertilizer costs in wheat. However, a critical question is whether sunflower should be replaced by other non-cereal crops that are better adapted to CA but also profitable to farmers. The new Common Agricultural Policy (CAP) framework encourages European farmers to cultivate economically viable legumes such as faba bean and industrial rapeseed, which can be cultivated in the winter to take advantage of the rainy season and avoid sowing in wet soils in the spring. One farmer in the general survey claimed higher profits and significant reductions in nitrogen fertilization over six years by rotating no-till wheat with no-till legumes (faba bean or vetch) and maintaining residues on his 73-ha farm. In central Spain, economic performance was highest in no-till rainfed wheat rotated with a forage legume on farms ≥ 400 ha while minimum tillage systems were most profitable on farms < 100 ha (Sánchez-Girón et al., 2007). Further research is necessary to evaluate the best crops and management options under different socioeconomic and environmental conditions.

4.3.3 Energy use efficiency

Although differences in TEI, EO and EP were not significant between MT and CT in agreement with Hernanz et al. (2014), differences between crops were significant. Given that sunflower is typically produced with low inputs in southern Spain (López-Bellido et al., 2002), TEI_S and EO_S were lower but EP_S was higher in sunflower than in wheat (Table 6). TEI_S was also lower and EP_S was higher than that in studies where sunflower was produced to maximize yields (Kallivroussis et al., 2002; Nassi o Di Nasso et al., 2011). Moreover, EO_S and EP_S were higher than values reported by Moreno et al. (2011) under similar rainfed conditions because of the higher yields obtained by farmers participating in our study. EO_w was comparable with values obtained in studies that also considered crop residues in Mediterranean environments (Nassi o Di Nasso et al., 2011). However, if residues had been retained on farm as prescribed for CA systems, EO_w would have decreased by roughly 50%.

As the largest energy inputs in the wheat-sunflower rotation, fertilizer and diesel should be the focus of efforts to improve energy efficiency. Fertilizers and diesel represented 68% and 15% of TEI_w in wheat, respectively, while diesel represented 70% of TEI_s in sunflower - although the absolute value was low. These results agree with those obtained in other energy balance studies of no-till rainfed wheat in Spain and France, where energy consumption corresponding to fertilizer and diesel accounted for 60-80% of $TEI_{W,}$ with fertilizers constituting the largest input at 40-65% (Hernanz et al., 2014; Khaledian et al., 2010). Given that the contribution of herbicides to TEI was small relative to other energy inputs in our study, improving weed control may have little impact on energy efficiency at the crop level.

The Second Spanish Plan of Action for Energy Saving and Efficiency (2011-2020) includes a strategy to promote CA techniques in order to reduce energy consumption in the agricultural sector (IDAE, 2011). While the strategy focuses on reducing machinery use and diesel fuel inputs, it does not consider fertilizer reduction. Measures to reduce machinery use and diesel fuel could be applied to sunflower, but TEI_S are so low that even if this crop were successfully cultivated under no till, energy savings would be minimal. On the other hand, any change in wheat management that results in lower chemical fertilizer use without affecting yields will more effectively reduce TEI and increase EP than lower diesel consumption (Alluvione et al., 2011). Promising techniques to achieve this reduction include precision fertilizer application using GPS-guided tractors to avoid overlapping and calculation of optimal fertilization rates based on soil analysis and target yield. In general, implementing all CA components can reduce the need for external fertilizer inputs in the long term depending on local conditions (Govaerts et al., 2006).

Whole or partial replacement of chemical fertilizers by organic fertilizers provides another means to reduce energy inputs. We identified two farmers from the general survey who combined organic fertilizers with chemical fertilizers in cereal cropping. One farmer integrated crops and livestock while the other bought commercial organic fertilizers to provide phosphorous. Government guidelines for organic production of rainfed cereals and energy-efficient N fertilization recommend an approach that integrates maintenance of crop residues, rotations with legumes, minimum soil disturbance, and sporadic manure application (IDAE, 2007; Lacasta, 2007). In northeast Spain, applications of pig slurry from industrial swine production at rates of 75 kg N ha^{-1} in continuous no-till barley cropping represents a viable option (Plaza-Bonilla et al., 2014). Another strategy is the incorporation of legumes in the rotation, which can limit the need for nitrogen fertilizers on the order of 5 kg N t^{-1} grain (IDAE, 2007). A wheat-legume rotation produced better wheat yields than wheat-sunflower and wheat monocrops at the same rate of fertilization in rainfed Vertisols (López-Bellido et al., 2000). The development of such integrated approaches to improve energy efficiency under different conditions at the farm level is another research priority in CA.

4.4 Need for international standardized methods for generating statistics on CA

Accurate data about conservation agriculture are important to guide policy decisions related to agricultural production, land management, and natural resources protection. Spain is one of the few European countries that monitors and generates official statistics about CA whereas in most countries, statistics about these systems are generated and reported by national CA associations (E. González-Sánchez, pers. communication). Spain has taken the first important step to obtain reliable and timely data by collecting annual data on direct seeded cereals and sunflower (MAGRAMA, 2014a). However, as discussed by others and as we have shown, direct seeding is not equivalent to CA if other essential components are not implemented (Derpsch et al., 2014). For example, our surveys and examination of the original data used to generate official statistics revealed that most CA farmers in Andalusia remove wheat residues and till the soil before establishing non-cereal crops (every other year in the wheat-sunflower rotation). Despite these discrepancies, official data on the area of direct seeded crops is considered equivalent to the area of CA in published studies (González-Sánchez et al., 2015) and included in the FAO database (FAO, 2015). Given the widespread use of FAO statistics, we recommend that current figures for Spain be reviewed.

Different interpretations of CA among farmers, researchers and institutions have been found elsewhere (Uri, 2000). In the case of published research, the standardization of methods and reporting on CA were recently claimed to improve transparency and facilitate comparative studies (Brouder and Gómez-Macpherson, 2014; Derpsch et al., 2014). This is especially relevant given the publication of a global meta-analysis on CA principles which compared many experimental studies with different designs (Pittelkow et al., 2015; and reply letters #64947 and #65029 by Bing-So et al. and Buffett et al., respectively). Similarly, standardization of methods used for collecting national data on CA crop area in each country is desirable. The methods currently used by MAGRAMA (2014a) could easily be expanded to include information on residues management, crop rotations, and establishment of annual crops, including legumes. This new methodology could provide a model to other European countries that currently rely on national CA associations to generate and report statistics. The European Conservation Agriculture Federation (ECAF) could be an effective leader in this effort given their role in coordinating these associations around CA promotion.

5. Conclusions

Full implementation of CA based on the principles of minimum soil disturbance, permanent ground cover, and crop rotation as defined by FAO (2013) was virtually nonexistent in southern Spain. Rather, farmers adjust their practices according to dynamic local conditions, placing high priority on minimizing economic and agronomic risks. Locally adapted CA combined direct seeding of cereal crops with tillage in non-cereal crops, without incorporating residues or rotations that included no-till legumes or other crops. In comparison with conventional tillage systems, direct seeded wheat without maintenance of crop residues and rotated with tilled sunflower resulted in similar soil quality, wheat yield, economic net return, and energy use. This lack of substantial differences can be attributed to similar management of residues, recurrent soil disturbance, and disuse of deep tillage in both systems. Only sunflower yield, residues biomass, and production cost of both crops differed significantly between the two systems.

Understanding why farmers choose not to adopt all three principles and how they adapt their practices to local conditions is a first step in improving CA systems. Cereals appeared well suited to direct seeding while sunflower, the second most important annual crop in southern Spain, performed poorly due to a lack of suitable direct drills for use in wet clay soils. Other key problems identified by farmers were weed control and increasing pest incidence due to crop residues management. Beyond the specific problems reported by farmers, our study suggests socioeconomic barriers to CA adoption. Lack of sufficient land and financial resources to buy specialized equipment and endure initial yield losses likely exclude most middle-income farmers and women.

Overcoming these challenges requires research and development of strategies that maximize the long-term environmental and agro-economic benefits of CA. Participatory research involving farmers, researchers, equipment manufacturers, and other stakeholders is needed to develop integrated management that enables annual crop farmers to adapt to changing local and external conditions. Priorities for agronomic research in southern Spain include development of no-till drills for establishing spring crops, identification of alternative crops to sunflower, optimization of residues management, and development of effective fertilization techniques. Strategies to improve energy efficiency in CA wheat-sunflower systems should focus on improving fertilizer management. To overcome socioeconomic barriers to CA adoption, participatory research and external training can to promote CA among groups of farmers that may be excluded by lack of resources and support.

Examination of government data on the area of annual crops cultivated under CA in Spain underscores the need for international standardized methods for generating statistics on CA. Although FAO (2013) clearly defines CA, it is important that countries follow similar methods so that the data collected are comparable. We do not advocate an orthodox definition of CA, which can mean different things to different stakeholders, but rather argue for transparent guidelines on how data are collected and analyzed to facilitate comparative analysis and collaborative problem-solving.

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Figure caption

Figure 1. Energy inputs (GJ ha^{-1}) corresponding to a) fertilizer, b) diesel fuel consumption, c) seed at time of sowing, d) machinery use, and f) herbicides in wheat and sunflower production under minimum (MT) and conventional (CT) tillage systems according to the case study. The horizontal line in the middle of the box represents the median. The lower and upper ends of the rectangles represent 25 and 75% quartiles respectively and vertical lines extend to 1.5 times the difference between these percentiles.

Table captions

Table 1 Problems with conservation agriculture reported by farmers in the general survey for wheat (W) and sunflower (S) cropping and strategies proposed by stakeholders in the focus group to overcome each problem. Farms reporting the problem relative to total number of farms cultivating each crop (%) and importance (I) scored by farmers (1 = very important, 2 = important, 3 = least important).

Table 2 Crop management in minimum (MT) and conventional (CT) tillage systems in the wheat-sunflower case study. Numbers represent mean values (n = 20). Values with asterisk (*) indicate occasional use or application.

Table 3 Results of linear mixed models (fixed effects: Year, Crop, Management System (MS), Depth; random effects: Zone, Plot) explaining the variance in variables describing crop performance, soil quality, economic balance, and energy analysis in the wheat-sunflower case study.

Table 4 Soil texture, particle size distribution (%; clay, silt and sand), total organic carbon (TOC; g kg^{-1}) and β-glucosidase activity (β-glu; mg p-nitrophenol kg^{-1} dw soil) in the top 0.1-m horizon of paired farm plots compared in the wheat-sunflower case study. Plots are grouped by the most recent cultivated crop, geographical zone, and tillage system (MT = minimum tillage; CT = conventional tillage).

Table 5 Mean production cost (€ ha^{-1}), crop benefit (€ ha^{-1}), net return (€ ha^{-1}), and economic productivity (kg €$^{-1}$) of wheat and sunflower cropping by management system (MT = minimum tillage; CT = conventional tillage) according to the case study. Mean, maximum and minimum values during the period of study (2007-2011) are shown for each variable (n=20).

Table 6 Energy use indicators (mean ± standard deviation) of wheat and sunflower by management system (MT = minimum tillage; CT = conventional systems) according to the case study. Values with the same letter within a row are not significantly different at $P < 0.05$.

Supplementary Data caption

Figure S.1 Maps of areas sampled for the general farmer survey and locations of paired farm plots (two paired plots per location) in case study.

Table S.1 Monthly and seasonal rainfall (mm) during the four growing seasons (“year”) of the study as recorded by the closest meteorological station (UTM coordinates provided) to the sampled farm plots.

Table S.2 Energy and economic coefficients and fuel consumption rates used in paired farm analysis of minimum (MT) and conventional (CT) tillage systems in the wheat-sunflower case study.

Table 1 Problems with conservation agriculture reported by farmers in the general survey for wheat (W) and sunflower (S) cropping and strategies proposed by stakeholders in the focus group to overcome each problem. Farms reporting the problem relative to total number of farms cultivating each crop (%) and importance (I) scored by farmers (1 = very important, 2 = important, 3 = least important).

General Survey					**Focus group**	
Problems identified by farmers		Crop	Farms (%)	I	Proposed strategies	Stakeholder
Weed control	Greater weed presence	W	27	1.9	• Reduce row spacing	F
					• Higher seed densities	F
		S	22	2.6	• Use of herbicide-resistant sunflower cultivars (Crearfield® and ExpressSun®)	F, AEAC/SV
	Herbicide resistance	W	7	1	• More research in weed control	F
	High price of herbicides	S	13	2.7		
Machinery	Soil compaction	W	7	1	• Use high flotation tires or reduce tire inflation pressure	F
					• Avoid planting in wet soils	F
	Inadequate zero-till drill technology in wet clay soils (Vertisols)	W	13	1.3	• Evaluate sporadic tillage	F
					• Fast harrow pass to improve the seedbed tilth	F, MD
					• Zero-till drill with coulter followed by tines, which replaces double disks	F, MD
					• Increase availability of zero-till drill services	F
		S	92	1.3	• More research on zero-till drill technology for sunflower	F, MD, R
					• Simplify the zero-till drill (fewer bearings, remove the depth limit on discs, set sowing depth with rings)	F, R
					• Remove the coulter to increase pressure on sowing discs	F
					• Incorporate fluted coulters	F, MD
					• Use strip tillage	F, MD
Crop residues management	Higher pest incidence:					
	• Beetle (Zabrus tenebrioides), slugs and fungal pathogen	W	20	1.7	• Granular insecticide applied with no-till drill	F
	• Slugs and beetle larvae (Agriotes spp.)	S	17	2.3		
	Optimal management unknown	W	7	1	Problem not discussed	
	Low soil temperature	S	9	2	Problem not discussed	
Fertilization	Phosphorus deficiency during planting	W	10	1.3	Problem not discussed	
	Higher dose requirement	W	7	2	Problem not discussed	
	Optimal dose unknown	W	3	2	Problem not discussed	
	High price of fertilizer used in no-till drill	W	3	2	Problem not discussed	
No problems reported		W	20		Problems with CA can be solved if all three components are adopted	AEAC/SV
		S	17			

F = farmer, MD = machinery dealer, AEAC/SV = members of the Spanish Association of Conservation Agriculture, R = researcher

Table 2 Crop management in minimum (MT) and conventional (CT) tillage systems in the wheat-sunflower case study. Numbers represent mean values (n = 20). Values with asterisk (*) indicate occasional use or application.

	Wheat		Sunflower	
	MT	CT	MT	CT
PRE-SOWING				
Tillage operations	No-till	Cultivator + disc harrow	2 x cultivator or disc harrow	2 x cultivator + disc harrow
Fertilization[a] (UF)	0	20-30 N 50-70 P 17-20 K*	0	0
Herbicides applications	1-2	1-2	1-2	0-1
SOWING				
Drill type	No-till	Conventional	Conventional; No-till*	Conventional
Seed (kg ha^{-1})	190-220	190-220	5-7	5-7
Fertilization[a] (UF)	4-45 N 8-110 P 24 K*	0	7 N* 18 P*	0
CROP GROWTH				
Fertilization[a]	64-180 N 46 P*	74-180 N	0	0
Herbicides applications	2-3	2	1	Mechanical (cultivator)
HARVEST				
Crop yield (kg ha^{-1})	3312	3319	1304	1435
Residues management	Baled	Baled	Left on ground	Buried

[a] Seed rates and fertilizer units (UF) of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) correspond to the minimum and the maximum applied amount

Table 3 Results of linear mixed models (fixed effects: Year, Crop, Management System (MS), Depth; random effects: Zone, Plot) explaining the variance in variables describing crop performance, soil quality, economic balance, and energy analysis in the wheat-sunflower case study.

Response variable	Fixed Effects	Random Effects	Variance differs by
CROP PERFORMANCE			
Wheat yield (kg ha^{-1})	Year	Zone	-
Sunflower yield (kg ha^{-1})	MS	Zone	-
Biomass crop residues (g m^{-2})	MS + Crop	Zone	-
SOIL QUALITY			
β-glucosidase activity (mg pnitrophenol kg^{-1} dw soil)	Depth	Zone	-
Total organic carbon (TOC) (g kg^{-1})	Depth	Zone	-
ECONOMIC BALANCE			
Production cost (€ ha^{-1} y^{-1})	MS + Crop	Zone/plot	Zone
Crop benefit (€ ha^{-1} y^{-1})	Year + Crop	Zone/plot	Zone
Net return (€ ha^{-1} y^{-1})	Year	Zone/plot	-
ENERGY ANALYSIS			
Total energy input (GJ ha^{-1} y^{-1})	Crop	Zone/plot	Zone
Energy output (GJ ha^{-1} y^{-1})	Crop	Zone/plot	Year
Energy productivity (tons GJ^{-1})	Crop	Zone/plot	-

Table 4 Soil texture, particle size distribution (%; clay, silt and sand), total organic carbon (TOC; g kg^{-1}) and β-glucosidase activity (β-glu; mg p-nitrophenol kg^{-1} dw soil) in the top 0.1-m horizon of paired farm plots compared in the wheat-sunflower case study. Plots are grouped by the most recent cultivated crop, geographical zone, and tillage system (MT = minimum tillage; CT = conventional tillage).

Crop	Zone	Tillage system	Soil texture	Clay	Silt	Sand	TOC	β-glu
Wheat	La Palma	MT	Clay	55.1	37.5	7.3	12.4	211
		CT	Clay loam	23.6	45.2	31.1	11.2	150
	Ecija	MT	Clay	79.3	18.6	2.1	9.3	269
		CT	Clay	89.2	7.5	3.3	8.2	224
	Santa Cruz	MT	Clay loam	32.9	36.2	30.8	9.7	108
		CT	Clay	55.3	20.1	24.5	6.1	113
	La Montiela	MT	Clay	52.2	33.9	13.9	11.0	177
		CT	Clay	76.5	18.5	5.0	11.1	229
	La Rambla	MT	Clay loam	37.1	36.9	25.9	12.9	169
		CT	Loam	25.6	35.2	39.1	14.3	160
Sunflower	La Palma	MT	Clay	60.7	32.9	6.3	10.8	256
		CT	Clay	54.2	38.8	7.0	9.2	176
	Ecija	MT	Clay	81.4	14.4	4.1	9.8	263
		CT	Clay	79.3	14.8	5.8	9.4	211
	Santa Cruz	MT	Clay	49.6	32.3	18.0	9.1	136
		CT	Clay	50.0	25.2	24.8	10.0	205
	La Montiela	MT	Clay	67.2	15.3	17.4	11.2	160
		CT	Clay	89.8	7.5	2.6	11.3	179
	La Rambla	MT	Clay loam	39.2	39.2	21.5	7.0	200
		CT	Clay loam	31.3	38.5	30.1	12.9	117

Table 5 Mean production cost (€ ha^{-1}), crop benefit (€ ha^{-1}), net return (€ ha^{-1}), and economic productivity (kg €$^{-1}$) of wheat and sunflower cropping by management system (MT = minimum tillage; CT = conventional tillage) according to the case study. Mean, maximum and minimum values during the period of study (2007-2011) are shown for each variable (n=20).

	wheat		sunflower	
	MT	CT	MT	CT
	Mean (min-max)	Mean (min-max)	Mean (min-max)	Mean (min-max)
Machinery	136 (124-154)	139 (129-145)	166 (146-188)	183 (151-228)
Diesel	32.8 (26-55)	54.9 (39-72)	37.2 (17-62)	47.2 (26-75)
Fertilization	185 (84-272)	160 (68-290)	4.65* (0-24)	4.98* (0-96)
Herbicide	46.0 (17-79)	38.0 (17-89)	26.4* (0-48)	14.1* (0-36)
Seed	88.4 (80-98)	87.4 (84-98)	72.6 (57-86)	76.6 (63-86)
PRODUCTION COST	488 (386-608)	479 (391-652)	307 (241-349)	326 (258-430)
CROP BENEFIT	705 (320-1214)	693 (250-1433)	492 (267-839)	525 (343-763)
NET RETURN	217 (-193-781)	214 (-196-957)	185 (-5.75-515)	199 (39-398)
PRODUCTIVITY	6.9 (4.6-9.7)	7.0 (4-11)	4.3 (3-7)	4.8 (3-6)

* Fertilizer and herbicide were applied in only a few plots.
Mean cost of fertilization in MT (n=5) and CT (n=2) was 18.6 and 52.3 € ha^{-1}, respectively.
Mean cost of herbicide in MT (n=16) and CT (n=15) was 33.3 and 19.8 € ha^{-1}, respectively.

Table 6 Energy use indicators (mean ± standard deviation) of wheat and sunflower by management system (MT = minimum tillage; CT = conventional systems) according to the case study. Values with the same letter within a row are not significantly different at *P* < 0.05.

	Wheat		Sunflower	
	MT	CT	MT	CT
Total energy inputs (GJ ha^{-1} y^{-1})	17.6 ± 3.50 a	19.3 ± 4.04 a	3.0 ± 0.68 b	3.7 ± 2.06 b
Energy outputs (GJ ha^{-1} y^{-1})	103 ± 22.7 a	103 ± 24.2 a	28 ± 7.3 b	31 ± 5.3 b
Energy productivity (tons GJ^{-1})	0.20 ± 0.06 a	0.19 ± 0.07 a	0.46 ± .16 b	0.44 ± 0.14 b

Figure

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