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Short and long-term effects of different irrigation and tillage systems on soil properties and rice productivity under Mediterranean conditions

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Abstract

In Mediterranean environments, flood irrigation of rice crops is in danger of disappearance due to its unsustainable nature. The aim of the present study was to determine the short- and long-term effects of aerobic rice production, combined with conventional and no-tillage practices, on soils' physical, physicochemical, and biological properties, as well as on the rice yield components and productivity in the semi-arid Mediterranean conditions of SW Spain. A field experiment was conducted for three consecutive years (2011, 2012, and 2013), with four treatments: anaerobic with conventional tillage and flooding (CTF), aerobic with conventional tillage and sprinkler irrigation (CTS), aerobic with no-tillage and sprinkler irrigation (NTS), and long-term aerobic with no-tillage and sprinkler irrigation (NTS7). Significant soil properties improvements were achieved after the long-term implementation of no-tillage and sprinkler irrigation (NTS7). The short-term no-tillage and sprinkler irrigated treatment (NTS in 2011 and 2012) gave lower yields than CTF, but reached similar yields in the third year (NTS 8229 kg ha^{-1}; CTF 8926 kg ha^{-1}), with average savings of 75% of the total amount of water applied in CTF. The NTS7 data showed that high yields (reaching 9805 kg ha^{-1} in 2012) and water savings are sustainable in the long term. The highest water productivity was with NTS7 in 2011 (0.66 g L^{-1}) and 2012 (1.46 g L^{-1}), and with NTS in 2013 (1.05 g L^{-1}). Thus, mid- and long-term implementation of sprinkler irrigation combined with no-tillage may be considered as a potentially productive and sustainable rice cropping system under Mediterranean conditions.

Keywords: aerobic rice, sprinkler irrigation, no-tillage, water productivity.

1. Introduction

Rice is a staple food for more than 50% of the world's population, reaching up to 80% when considering only the Asian population. Rice production must increase by 70% to meet demand by 2050 as the world population keeps increasing (Wu *et al.*, 2013). This crop takes up to 11% of world farmland (180 million ha). This figure is 88% in the case of Asia which accounts for 90% of global rice production (750 million tons of paddy rice). Besides its importance as a source of food, rice growing is the largest employment sector of rural populations in Asia, and the crop is also widely cultivated in Africa and America, and intensively in some parts of southern Europe, mainly in Mediterranean environments (CGIAR, 2006). In the European Union (EU), 475 000 ha of land are devoted to rice growing, with a production of 3.2 millions of tons of paddy rice. Spain is one of the largest rice producers in the EU, accounting for 20% of total European rice crop farmland, and 30% of total rice production. Within Spain, Extremadura, with an average yield of 7300 kg ha^{-1}, has become consolidated as one of the largest rice producing regions, with the most productive areas concentrated in the River Guadiana's historical floodplains (MAGRAMA, 2013).

World rice production has suffered for years from an important lack of investment regarding research on and development of new management techniques, slowing down the implementation of beneficial innovations (Van Tran, 2002). Environmentally, modern approaches to rice crop intensification have damaged important natural resources, causing significant increases in soil salinity, water pollution, health problems from high pesticide concentrations in water and food, and increased greenhouse gas emissions (Devkota *et al.*, 2015). The agriculture sector is highly exposed to the risks accompanying climate change (Lanfranchi *et al.*, 2014). Therefore, possible global climate changes associated with increased atmospheric concentrations of greenhouse gases are likely to affect the efficiency of agricultural production systems (Porter, 2005). Together with this, one of the major challenges facing rice farming is to produce the same or more with less water, labour, and chemicals, so as to ensure the sector's long-term sustainability (Khumar & Ladha, 2011). In order to avoid long-term supply and demand imbalances, innovations are needed in agronomic management and technology. In particular, the development of alternative rice farming systems may contribute to reduce the aforementioned negative effects and to increase productivity (Mukhopadhyay *et al.*, 2013). Research on these management techniques needs to mainly focus on a rational and sustainable use of two essential resources: soil and water.

Rice crop cultivation in Mediterranean environments traditionally involves intensive and expensive tillage practices. The leveling, ploughing, cross-harrowing, and final puddling may be direct causes of dramatic decreases in soil quality, initiating processes that may change for the worse the soil's original physical properties. These result in organic matter and nutrient depletion, increased penetration resistance due to the creation of plough pan and surface crust, as well as increased acidity and reduced microbial activity (Bezdicek *et al.*, 2003). Furthermore, new studies carried out under Mediterranean conditions (Moreno-Jiménez *et al.*, 2014) show an important increase in heavy metal content in both soil and grain after several years of rice monoculture using conventional tillage practices and flood irrigation.

There are currently many proposals regarding soil conservation in intensive agriculture environments. Most of them are centred on the concept of "conservation agriculture". Conservation agriculture is a modern alternative for resource-saving crop production that strives to achieve acceptable profits from high and sustained production levels while concurrently conserving the environment. It is characterized by three interlinked principles: minimal mechanical soil disturbance, permanent organic soil cover, and diversification of either crop rotations in the case of annual crops or plant associations in the case of perennial crops. These principles reach their greatest expression with the technique known as no-tillage, extensively used to increase soil organic matter, to control soil degradation, and to increase water holding capacity (López-Garrido *et al.*, 2014).

Water consumption in traditional rice production systems in Spain is on average 24 000 $m^3 ha^{-1} yr^{-1}$. In a semi-arid Mediterranean environment, where water resources are strongly limited, flood irrigation of rice crops is in danger of disappearance due to its unsustainable nature. The continual growth of the population and the consequent growing need for drinking water is a global problem, so that any way to save water is of great importance (Yan *et al.*, 2015). In addition, available water resources for human consumption have been reduced by the competing demands of industry, so that there is a need for the development of new alternatives that allow more efficient water use in agriculture. Rice farming is obviously one of the main objectives to reduce water consumption since it accounts for some 50% of irrigation water used worldwide (Barker *et al.*, 1999). In this context, water productivity has taken on an importance that is even greater than that of yield itself, so that reducing water consumption and increasing its productivity constitute one of the main challenges that the rice sector must face in the near future. Since, however, rice is very sensitive to water stress, a reduction in the total amount of irrigation water used may lead to a major decrease in yield, threatening the economic viability of the crop at its present levels.

Aerobic (non-flooded) rice is one of the new water-saving production systems being developed all over the world. In this, rice is grown on well-drained, unsaturated soils (Rajakumar *et al.*, 2009). Hence, irrigation needs are reduced because of reduced water losses to percolation, evaporation, and surface run-off. This system may be considered an especially interesting alternative for semi-arid Mediterranean environments (Facchi *et al.*, 2013). However, the development of this system is still in its early stages, and more research is needed in order to correctly implement these techniques. Thus, sprinkler irrigation has been proposed as an efficient management technique for aerobic rice systems in semi-arid

Mediterranean conditions. In Europe, research on sprinkler irrigated rice has been limited to the typical paddy fields of northern Italy (Russo & Nardi, 1996) and some irrigated areas of southern Italy and Sardinia (Spanu *et al.*, 1997), giving 50% of irrigation water savings compared with traditional flood irrigation. Recent studies have given promising results when applying no-tillage and different cover crop alternatives to upland aerobic rice in tropical environments (Nascente *et al.*, 2013). But, to the best of our knowledge, there is no information available about rice production in Europe involving sprinkler irrigated aerobic systems combined with different soil management regimes such as no-tillage and conservation agriculture practices.

The aim of the present study was therefore to determine the short- and long-term effects of sprinkler *vs* flood irrigation and no-tillage *vs* conventional tillage on soils' physical, physicochemical, and biological properties, as well as on the yield components and productivity in semi-arid Mediterranean conditions.

2. Materials and Methods

2.1. Description of the study area

A multi-year field experiment was conducted in 2011, 2012, and 2013 on a Hydragic Anthrosol (FAO, 2006) with 16.9% clay, 35.9% silt, and 47.2% sand. The experimental field is located in Extremadura, SW Spain (39°06' N; 5°40' W), with a Mediterranean climate (annual rainfall < 480 mm), with hot, dry summers. This region has serious limitations in developing sustainable agriculture as it has an aridity index of 0.49 (UNESCO, 1977).

2.2. Field experiment

Prior to beginning the study, the experimental area (1800 m^2) was cropped with rice (*Oryza sativa* L.) using the traditional management practices in the region (deep ploughing and waterlogging), and a part of the field had already been devoted to direct seeding and sprinkler-irrigated rice in the 7 years preceding the experiment. After harvesting the rice in November 2010, the field was divided into twelve plots of 140 m² (7×20 m) each, that were subjected to the following four management regimes: (CTF) applying the techniques that are conventional in the region, *i.e.*, tillage to 30 cm and flooding with continuous water flow; (CTS) conventional tillage and sprinkler irrigation; (NTS) conservation agriculture techniques (no-tillage and seeding by direct drilling) and sprinkler irrigation; and (NTS7) the same conservation agriculture techniques (no-tillage and direct drilling) and sprinkler irrigation but where this management regime had already been in use for 7 years in order to observe any long-term changes. Each treatment was replicated thrice in a completely randomized design with two protective buffer zones between adjacent plots (4.5x20 m). Flooded plots were separated with ridges 35 cm high in order to avoid water losses.

2.3. Crop culture

Mouldboard ploughing was applied to 30 cm depth prior to sowing in the CTS and CTF treatments. In the NTS and NTS7 treatments, each year after harvest, the crop residues were left on the soil surface and the soils were left untilled. In contrast, all crop residues were withdrawn from the CTS and CTF plots. The crop was sown in May, using Semeato trailed pneumatic seed drills for the direct drilling of the NTS7 and NTS treatments, conventional pneumatic seed drills for the CTS treatment, and a broadcast seed drill for the CTF treatment after initial flooding. Rice was sown in 0.2 m rows in NTS7, NTS, and CTS. The sowing rate was 160 kg ha^{-1} in all treatments. The seeds were of *Oryza sativa* L. var. *gladio*, a genotype traditionally used in the Extremadura region. For NTS7, NTS, and CTS, a solid-set sprinkler irrigation system was designed to cover the entire plot area. The irrigation water supplied in the different treatments was monitored using a water flow-meter. The total amount of irrigation water applied in 2011 was 7010 m³ ha^{-1} for NTS7, NTS, and CTS, and 24 400 m³ ha^{-1} for CTF. In 2012, it was 6705 m³ ha^{-1} for NTS7, NTS, and CTS, and 34 290 m³ ha^{-1} for CTF. And in

2013, it was 7800 m³ ha^{-1} for NTS7, NTS, and CTS, and 32 235 m³ ha^{-1} for CTF. The amount of irrigation water applied for the sprinkler irrigated treatments was enough to keep soil moisture over 70% of field capacity (Stevens *et al.*, 2012). For the flood irrigation, the aim was to keep the water level constant. In all three years (2011, 2012, and 2013), composite fertilizer 9-18-27 (550 kg ha^{-1}) was applied in April as basal in all treatments, and N was applied in the form of urea in two splits of 200 kg ha^{-1} at tillering and 150 kg ha^{-1} at the panicle initiation stage. Pesticide applications were made using a backpack sprayer. Pre-emergence herbicides were applied yearly – Pendimethalin in the sprinkler irrigated treatments (NTS7, NTS, and CTS) and Oxadiazon in the flooded treatment (CTF). Penoxulam and Cyhalofop were used as post-emergence herbicides in all treatments for first weed generations, and Bispyribac-Sodium for late-emergence weeds. All other recommended culture practices for maximum grain yield were followed.

2.4. Soil sampling and analysis

Soil samples from each plot were taken using a manual auger. The depths were: 0-20 cm for physicochemical properties; 0-10 cm for enzymatic activities; and 0-10 and 10-30 cm for aggregate stability. Three subsamples were taken randomly from each of the three replicate plots at the beginning of the study (March 2011), and each year after harvest (October 2011, 2012, and 2013). In October 2011 and 2013, when the soil water content was near field capacity (Bradford, 1986), the soil penetration resistance was measured in the field down to 45 cm depth using a hand penetrometer with 1 cm² conical tip. Texture was determined by sedimentation using the Robinson pipette method (Soil Conservation Service, 1972) after destruction of the organic carbon with H_2O_2 and chemical dispersion using $Na_4P_2O_7$. Total organic carbon (TOC) content was determined by dichromate oxidation (Nelson & Sommers, 1996). Water soluble organic carbon (WSOC) was extracted with de-ionized water at a 3:1 water-to-soil ratio. Humic acids (HA) and fulvic substances (fulvic acids + humins, FA) were extracted with a solution of 0.1 M $Na_4P_2O_7$ + NaOH at a 10:1 extractant-to-sample ratio, and, to precipitate humic acid, the supernatant was acidified to pH 2 with H_2SO_4. The WSOC and the TOC associated with each fraction of HA and FA were determined by dichromate oxidation and measurement of the absorbance at 590 nm (Sims & Haby, 1971). A combination electrode was used to measure electrical conductivity (EC) in a saturated soil extract and the pH in a 1:1 (w/v) soil/water mixture. Total nitrogen (N) was determined by the Kjeldahl method (Bremner & Mulvaney, 1982), and phosphorus (P) by the Olsen method (Olsen *et al.*, 1954). Aggregate stability (AS) was determined following the Sun method (Sun *et al.*, 1995) which uses a single 0.250 mm sieve and an apparatus with a stroke length of 1.3 cm and frequency of 35 cycles min^{-1}, and sodium hydroxide as dispersant. Table 1 gives some selected properties of the soil samples taken at the beginning of the study (March 2011).

Table 1. Soil physicochemical properties prior to the trial.

	TOC (g kg^{-1})	**HA (g kg^{-1})**	**FA (g kg^{-1})**	**EC (µS cm^{-1})**	**pH**	**N (%)**	**P (mg kg^{-1})**
NTS7	15.3	1.22	1.03	0.472	6.24	0.119	20.6
NTS	8.56	0.481	0.626	0.733	5.54	0.101	19.2
CTS	8.68	0.459	0.594	0.740	5.46	0.097	19.5
CTF	8.50	0.460	0.605	0.739	5.53	0.098	19.3

TOC: Total organic carbon; **HA**: Humic acid; **FA**: Fulvic acid; **EC**: Electrical conductivity; **N**: Total nitrogen; **P**: Phosphorus.

2.5. Enzyme activities

Dehydrogenase (DH) activity was determined by the method of Trevors (1984) as modified by García *et al.* (1993). An aliquot of 1 g of soil was incubated for 20 h at 20°C in darkness with 0.2 mL of 0.4% 2-(4-iodophenyl)-3-(4-nitrophenyl)-5-phenyl-2*H*-tetrazolium (INT) chloride as substrate. At the end of the incubation the iodonitrotetrazolium formazan produced was extracted with 10 mL of methanol, and the absorbance measured at 490 nm. The DH and other activities were determined in triplicate. To assay the urease (UR) activity, 2 mL of 0.1 M pH 7.0 phosphate buffer and 0.5 mL of 1.066 M urea were added to 0.5 g of soil and incubated for 1.5 h at 30°C. The ammonia released in the hydrolytic reaction was measured spectrophotometrically at 636 nm (Kandeler & Gerber, 1988; Nannipieri *et al.*, 1980). The activity of β-glucosidase (GLU) was determined by incubating 1 g of soil with 4 mL of 25 mM 4-nitrophenyl-β-D-glucopyranoside in 0.1 M modified universal buffer (MUB) pH 6.0 (Tabatabai, 1982). For the determination of phosphatase (PHO) activity, 4 mL of 25 mM 4-nitrophenyl phosphate MUB pH 11 was added to 1 g of soil (Tabatabai & Bremner, 1969). For the determination of arylsulfatase (ARS) activity, 4 mL of 5 mM 4-nitrophenyl sulfate in 0.5 M acetate buffer pH 5.8 was added to 1 g of soil (Tabatabai & Bremner, 1970). The soil samples were incubated for 1 h at 37°C, then cooled to 2°C for 15 min to halt the reaction. The p-nitrophenol produced in the enzymatic reactions was determined at 400 nm, 398 nm, and 410 nm for GLU, PHO, and ARS, respectively. Blank assays without soil or substrate were performed at the same time as the controls.

2.6. Agronomic parameters

All agronomic parameters were determined from a 2 m² sampling area within each plot (three plots per treatment), and all production parameters were standardized to a moisture content of 14% fresh weight. The total number of grains per panicle and the ripening ratio were determined by direct counting on 20 representative panicles. The 1000 grain weight was determined by direct weighing of 1000 grains counted by an electronic seed counter (Swantech-SC2). Grain production was determined as the direct weight of all filled grains per panicle collected in the trial area. Biomass production was determined by the direct weight of the aerial part of the plant after grain removal. The harvest index (HI) was taken to be the ratio between the yield and the total biomass (yield + straw yield), and water productivity was taken to be the ratio between yield and the applied amount of irrigation water.

2.7. Statistical analyses

Statistical analyses were performed using the IBM SPSS Statistics 22.0 program package. The data were checked for normality and homoskedasticity. A one-way ANOVA was used to analyse soil and agronomic properties, the Duncan test to determine significant parameter differences between treatments and years, and the Pearson correlation coefficient to study possible correlations between different parameters. Differences were considered statistically significant at a p-value of less than 0.05.

3. Results and Discussion

3.1. The soils' physicochemical properties

The soils' physicochemical parameters at 0-20 cm depth for the years 2011, 2012, and 2013 are listed in Table 2. All the TOC values were low, as is usual for agricultural soils in Mediterranean environments (López-Garrido *et al.*, 2012). The highest values were for NTS7 in all three years (15.6, 15.5, and 16.2 g kg^{-1}), reflecting a major effect of long-term no-tillage practices on this parameter. Although increases in TOC have been observed in rice cultivation under flood irrigation (Hao *et al.*, 2013), in the present case there were no significant variations of the TOC content in the NTS treatment over the three years studied (Table 2). Indeed, the short-term effects of no-tillage practices on TOC are complex, with widely varying results being reported that depend on such factors as climate, crop residue, and the crop management regime itself (Muñoz *et al.*, 2007). On the other hand, the CTS and CTF treatments showed significant declines (by 23.9% and 13.4%, respectively) in TOC content for 2013 compared to 2011. The irrigation method is an important factor that may help explain the differences in TOC losses between the CTS and CTF treatments. In this sense, it is important to note that organic matter mineralization is related to soil moisture balance, in particular, to the air-water ratio. Aerobic microbial activity in soil rises with increasing moisture content up to limits at which the amount of water reduces oxygen availability. The anaerobic conditions caused by the flooding in the CTF treatment may have resulted in a slower rate of organic matter decomposition than in the CTS treatment, in which the conditions for faster organic matter mineralization were more favourable.

Table 2. Effect of different management regimes on soil physicochemical properties.

	TOC ($g\ kg^{-1}$)	**HA ($g\ kg^{-1}$)**	**FA ($g\ kg^{-1}$)**	**EC ($\mu S\ cm^{-1}$)**	**pH**	**N (%)**	**P ($mg\ kg^{-1}$)**
				2011			
NTS7	15.6cA	1.60cB	1.03cA	1.51dC	5.84cA	0.143bB	16.4bA
NTS	7.93aA	0.833bB	0.532aA	0.906bB	5.91cB	0.081aA	11.5aA
CTS	9.23abC	0.604aB	0.676bB	0.698aA	5.63bA	0.074aA	9.26aA
CTF	9.92bB	0.627aB	0.634bA	1.26cB	5.15aA	0.086aB	11.1aA
				2012			
NTS7	15.5cA	1.33bA	0.993cA	0.490aA	5.92dA	0.106bA	19.0bB
NTS	6.80aA	0.514aA	0.579aB	0.857bA	5.92cB	0.072aA	18.0aB
CTS	8.22bB	0.515aA	0.685bB	1.09cB	5.84bB	0.078aA	21.6cC
CTF	8.25bA	0.481aA	0.661bA	1.27dB	5.21aB	0.079aA	26.0dC
				2013			
NTS7	16.2dA	1.76dC	0.998dA	1.26cB	5.84cA	0.173dC	20.8cC
NTS	7.67bA	1.13cC	0.764cC	1.38dC	5.22aA	0.104bB	21.9dC
CTS	7.03aA	0.908aC	0.586aA	0.753aA	6.24dC	0.094aB	12.5aB
CTF	8.60cA	0.984bC	0.639bA	1.08bA	5.33bC	0.114cB	17.2bB
Y	**	***	**	***	*	***	***
T	***	***	***	***	***	***	***
Y*T	***	***	***	***	***	***	***

TOC: Total organic carbon; **HA**: Humic acid; **FA**: Fulvic acid; **EC**: Electrical conductivity; **N**: Total nitrogen; **P**: Phosphorus. ANOVA factors are **Y**: Year; **T**: Treatment; **Y*T**: Interaction Year*Treatment; *, ** and *** significant at α levels of 0.05, 0.01 and 0.001, respectively; **NS**: not significant. Different letters show significant differences ($p<0.05$) between treatments in the same year (lower case letters) and between years within the same treatment (upper case letters).

The greatest FA content throughout the trial corresponded to NTS7. There were no significant changes in this parameter between years for the NTS7 or CTF treatments (Table 2). It is important to recall that the management techniques applied in these two treatments did not differ from those applied prior to the experiment, reflecting a long-term stabilization. But the NTS and CTS treatments showed contrasting trends: while the FA content in NTS increased by 43.6% in 2013 relative to 2011 due to the annual input of organic matter, the FA content in CTS fell by 13.3% over the same period.

With respect to the HA content, all the treatments presented significant decreases in 2012 relative to 2011 (Table 2), and reached their highest values in 2013. That this pattern is independent of the type of management and irrigation technique points to the influence of external factors. In particular, high rainfall was recorded in autumn 2012, with very wet months of September, October, and November months (AEMET, 2012). There was some 40 mm of rainfall prior to the 2012 soil sampling, which may have slowed down organic matter humification in all the treatments. Then, the more favourable weather conditions in 2013 generated the major rise in HA content due to the cumulative humification of organic matter left over from 2012 as well as that of 2013.

The EC values were highly variable, reflecting the great spatial variability of this parameter in field conditions. In 2013, after three years of the trial, the lowest value of this parameter corresponded to the CTS soil and the highest to the two no-tillage treatments (NTS7 and NTS). The TOC accumulation in the no-tillage treatments and the organic matter depletion in CTS may help to explain these contrasting trends. In the literature, there is no consistent pattern in the effects of no-tillage practices on EC. While in a long-term experiment (13 years) Dalal (1989) observed EC values that were lower in soils under no-tillage than under conventional tillage, Pérez-Brandán *et al.* (2012) observed the contrary, although neither of those works studied the influence of the irrigation system.

The treatments greatly influenced the pH levels. There was acidification of the NTS7 and NTS soils in 2013 relative to 2012. This was probably because of a build-up of organic residues on the surface as was noted by Limousin & Tessier (2007) in studying topsoil acidification in no-tillage maize and wheat plots. On the other hand, the pH of the CTS soil rose (by 10.8%) from 5.63 in 2011 to 6.25 in 2013. The CTF soil showed a similar trend, but with a much smaller increase in pH (by 3.50%). This behaviour in the two conventionally tilled treatments is related to the changes in TOC content discussed above, with the rises in pH being explicable by the losses of organic matter in these treatments (Table 2).

The total nitrogen (N) was significantly correlated with the TOC content (r=0.769; p<0.001), with, in all three years, the highest values corresponding to the NTS7 treatment and the lowest to CTS. This effect of long-term no-tillage on soil nitrogen is coherent with the observations of other workers (Heenan *et al.*, 2004; Pérez-Brandán *et al.*, 2012) for different crops and environmental conditions, with, in all cases, there being significant increases in N under no-tillage relative to conventional tillage systems.

In 2011, NTS7 had the highest P levels, while there were no significant differences between the rest of the treatments. In 2012, the highest levels corresponded to the conventional tillage soils (CTS and CTF). This trend was reversed in 2013, however, when the highest values corresponded to the no-tillage treatments (NTS7 and NTS). While a study involving sprinkler irrigated corn (Essington & Howard, 2000) found no significant differences in the P content of soils under conventional and no-tillage practices, the present results are coherent with those of a study of agricultural soils in southern Spain (Bravo *et al.*, 2006) in that, in the mid to long term, no-tillage practices may enhance the P content in Mediterranean soils.

Aggregate stability (AS), expressed as the stable fraction percentage (Figure 1), is a key factor in soil fertility (Hernanz *et al.*, 2002). It has been found to be significantly correlated with TOC (r=0.935; p<0.001), FA (r=0.773; p<0.001), and HA (r=0.891; p<0.001) for the 0-10 cm depth, and with TOC (r=0.656; p<0.01), FA (r=0.907; p<0.001), and HA (r=0.867; p<0.001) for the 10-30 cm depth. These results highlight the importance of organic matter and humic substances in stabilizing soil structure. For this reason, the highest values of AS corresponded to NTS7 for all three years and for both depths. In the NTS treatment, there was a significant increase in AS in 2013 in the 0-10 depth, and even more importantly in the 0-30 depth. The CTS and CTF treatments also showed increases in AS in 2013 reflecting the greater HA content, but these increases were not comparable to those of the no-tillage treatments.

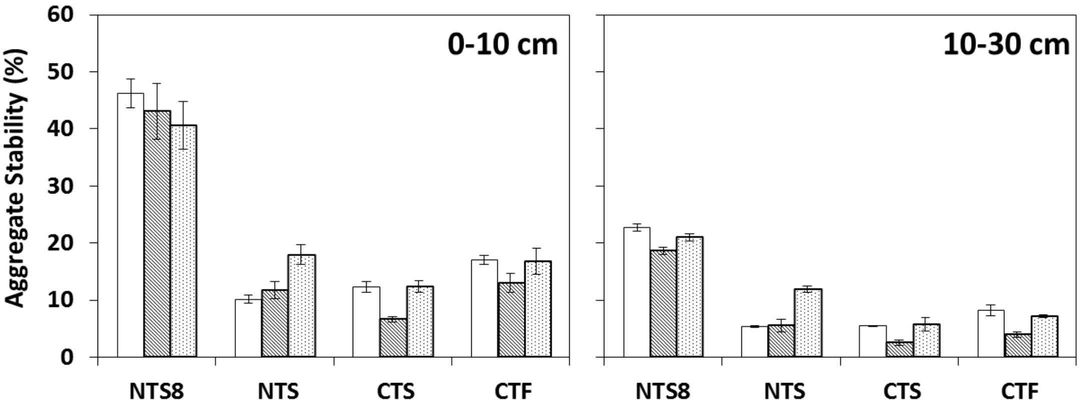

Figure 1. Effect of different management regimes on soil aggregate stability in 2011 (□), 2012 (▨), and 2013 (░).

Figure 2 shows the penetration resistance results for 2011 and 2013. One observes that, for both years, there was greater compaction in the upper layers of soil for the no-tillage treatments (NTS7 and NTS), and that the compaction of the conventionally tilled treatments (CTS and CTF) increased with depth to surpass that of the no-tillage soils, until reaching a maximum at 20-25 cm. Beyond this depth, the CTS and CTF values decreased down to levels similar to those for NTS7 and NTS. This pattern suggests that the conventional tillage generated a plough pan, and highlights the importance of taking depth into account when considering variations in penetration resistance (Afzalinia & Zabihi, 2014). The pattern of the two no-tillage curves is also coherent with the finding of a study on rainfed wheat cropping with a no-tillage regime (Ferreras *et al.*, 2000) that penetration resistance increased faster with depth in the top layers of the soil than in deeper layers.

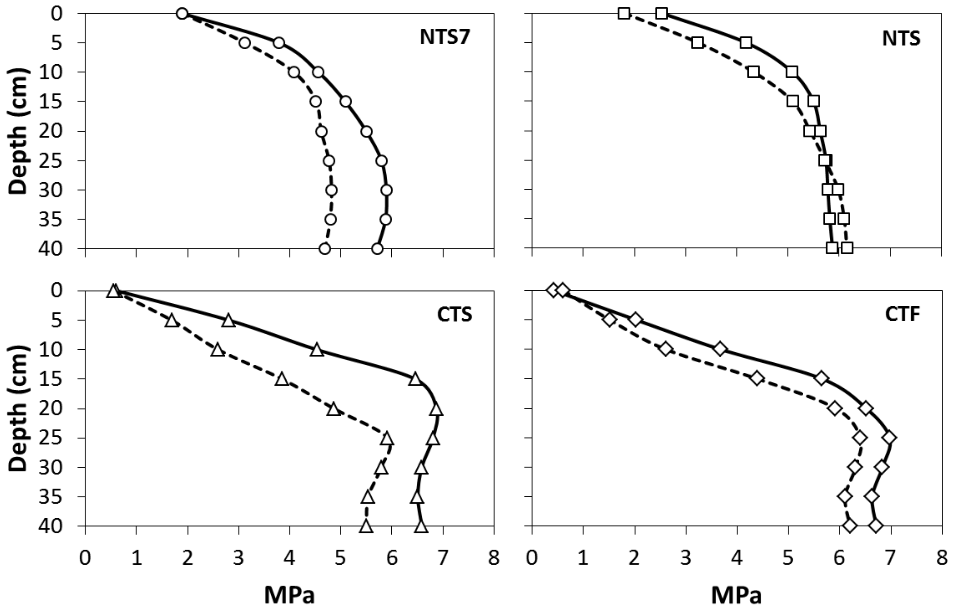

Figure 2. Effect of different management regimes on soil penetration resistance. Treatments are: NTS7 (○), NTS (□), CTS (△) and CTF (◇). Years are: 2011 (—) and 2013 (‥).

3.2. Enzymatic activities

Dehydrogenase activity (DH) is a good indicator of the microbial redox system, and is also regarded as a good measure of soil microbial activity (Moreno *et al.*, 2008). It was found to be greatest in all years in the NTS7 soil (Table 3), with there being no significant differences between the rest of the treatments in 2012 and 2013. The TOC content of NTS7 may have influenced this behaviour as it showed a significant correlation with DH activity ($r=0.709$; $p<0.01$).

A soil's β-glucosidase activity (GLU) plays an important part in hydrolytic processes during organic matter degradation (Pandey *et al.*, 2014). The highest values corresponded to the NTS7 treatment (Table 3), and they were significantly correlated with the TOC content ($r=0.808$; $p<0.01$), indicating that the addition of crop residues is a good strategy with which to increase GLU in soils.

Urease activity (UR) is of major importance since it is related to the nitrogen cycle, and also because of the extensive use of urea as a nitrogen fertilizer. A significant decrease in UR was observed in 2013 relative to 2012 for all treatments except NTS7. The increase in N contents in 2013 as a consequence of applications of urea to the crop may have had an inhibitory effect on UR, in coherence with the findings of Pandey *et al.* (2014) in aerobic rice fields under no-tillage and conventional tillage management.

Table 3. Effect of different management regimes on soil enzyme activities.

	DH (μg INTF g^{-1} h^{-1})	**GLU** (μmol pNP g^{-1} h^{-1})	**UR** (μmol NH_4^+ g^{-1} h^{-1})	**PHO** (μmol pNP g^{-1} h^{-1})	**ARS** (μmol pNP g^{-1} h^{-1})
			2011		
NTS7	0.948cA	0.522bA	3.09bA	1.71bA	0.150bA
NTS	0.854bB	0.119aA	1.23aB	1.30aA	0.072aA
CTS	0.750bB	0.156aA	1.22aB	1.40aA	0.088abA
CTF	0.645aB	0.196aA	1.49aB	1.23aA	0.096abA
			2012		
NTS7	0.781bA	0.846bAB	3.27cA	1.84bA	0.138bA
NTS	0.455aA	0.288aB	1.49bB	1.31aA	0.041aA
CTS	0.466aA	0.270aB	1.02aAB	1.41aA	0.060aA
CTF	0.516aA	0.287aAB	1.54bB	1.31aA	0.049aA
			2013		
NTS7	0.884bA	1.11bB	3.13bA	1.62bA	0.207bA
NTS	0.527aA	0.298aB	0.766aA	1.07aA	0.068aA
CTS	0.689aB	0.340aB	0.809aA	1.11aA	0.080aA
CTF	0.481aA	0.372aB	0.782aA	1.21aA	0.109aA
Y	***	***	***	***	**
T	***	***	***	***	***
Y*T	**	*	*	**NS**	**NS**

ARS: Arylsulfatase activity; **GLU**: β-glucosidase activity; **DH**: Dehydrogenase activity; **PHO**: Phosphatase activity; **UR**: Urease activity. ANOVA factors are **Y**: Year; **T**: Treatment; **Y*T**: Interaction Year*Treatment; *, ** and *** significant at α levels of 0.05, 0.01 and 0.001, respectively; **NS**: not significant. Different letters show significant differences ($p<0.05$) between treatments in the same year (lower case letters) and between years within the same treatment (upper case letters).

An apparently similar trend was observed for the phosphatase activity (PHO), but the decreases in 2013 for all treatments did not reach statistical significance. But the NTS7 values were indeed significantly higher than the rest, reflecting that there is more substrate available for microbial activity in this treatment than in other treatments with less time of no-tillage management (Shi *et al.*, 2013).

Arylsulfatase activity (AR) is one of the commonest enzymatic activities in soils. Besides satisfying microbial and plant needs for sulfate ion, it takes part in the processes of degrading xenobiotic compounds in soils (Kertesz *et al.*, 1994). For this reason, it is important to try to gain some insight into how AR varies in response to different management techniques. Coherent with the findings of Lin (2007) in comparing AR between flooded and upland aerobic rice crops, we found no significant differences between the flooded and sprinkler irrigated treatments (Table 3). For the NTS7 soil, there was an increase in AR in 2013. This may have been related to the pH value (6.1 from 0 to 10 cm) which is in the range for this enzyme's greatest activity. This is supported by the significant correlation found between AR and pH ($r=0.623$; $p<0.01$).

3.3. Yield, yield attributes, and water productivity

Table 4 presents the results for the yield, yield attributes, and water productivity. It is important to note that reductions in yield due to weed competition have been recognized as one of the main threats for sprinkler irrigated rice since the first field experiments of Westcott & Vines (1986) and McCauley (1990). Given the abnormal circumstances of 2011 when there was a very high level of weed infestation over the entire area of the Guadiana River lowlands, our discussion will mainly focus on the 2012 and 2013 results.

For these two years, NTS7 had the greatest number of grains per panicle (GP), although the difference was statistically significant only in 2012. There were no significant differences between the other treatments, irrespective of the irrigation and tillage methods applied. The values of GP were significantly correlated with TOC ($r=0.469$; $p<0.01$) and HA ($r=0.664$; $p<0.001$). This latter correlation was also found by Saha *et al.* (2013) in studying the influence of a soil's humic acids on rice plant growth, and may explain the greater value of GP in the NTS7 treatment.

Table 4. Effect of different management regimes on yield and yield components of rice.

	GP	RR (%)	1000W (g)	Y (kg ha^{-1})	HI	WP (g L^{-1})
2011						
NTS7	101bA	82.4aA	22.5aA	4 621bA	0.49abA	0.66cA
NTS	70.3aA	79.0aA	21.5aA	2 519aA	0.44aA	0.36bA
CTS	82.5aA	83.3aC	22.8aB	2 328aA	0.50bB	0.33bA
CTF	65.4aA	85.2aA	21.9aA	4 550bA	0.45aA	0.19aA
2012						
NTS7	121cA	74.8bA	22.0bA	9 805eC	0.53dA	1.46dC
NTS	94.8abB	69.7bA	21.4abA	4 844bB	0.46bA	0.72cB
CTS	82.7aA	60.6aA	20.4aA	3 590aB	0.35aA	0.53bB
CTF	88.4aB	83.8cA	25.4cB	6 556cB	0.49cB	0.19aA
2013						
NTS7	109aA	84.4bcA	23.8cA	7 397cB	0.60aA	0.94cB
NTS	99.5aB	81.8bB	23.0bcB	8 229dC	0.61aB	1.05dC
CTS	106aB	75.9aB	21.9aB	4 784aC	0.57aB	0.61bB
CTF	95.3aB	89.9dA	24.9dB	8 926eC	0.68bC	0.27aB
Y	***	***	**	***	***	***
T	**	***	***	***	**	***
Y*T	**NS**	**	***	***	***	***

GP: Grains per panicle; **RR**: Ripening ratio; **1000W**: 1000 grain weight; **Y**: Yield; **HI**: Harvest index; **WP**: Water productivity. ANOVA factors are **Y**: Year; **T**: Treatment; **Y*T**: Interaction Year*Treatment; ****,** and *** significant at α levels of 0.01, and 0.001, respectively; **NS**: not significant. Different letters show significant differences ($p<0.05$) between treatments in the same year (lower case letters) and between years within the same treatment (upper case letters).

The ripening ratio (RR) (Table 4) was significantly greater ($p<0.05$) under flooded conditions (CTF) in both years. Any reduction in the amount of water available may turn into a situation of moisture stress for the rice plant, and hence affect grain ripening in the aerobic treatments (NTS7, NTS, and CTS) relative to flooded conditions (Wei *et al.*, 2011). The lowest ripening ratio in both 2012 and 2013 corresponded to CTS, indicating that, under aerobic conditions, no-tillage gives the soil a greater moisture retention capacity, therefore reducing the frequency and intensity of moisture stress situations in the NTS7 and NTS treatments relative to CTS.

The pattern of the 1000 grain weight results for both years (2012 and 2013) was similar to that of RR, with significantly ($p<0.05$) greater weights in the flooded treatment (CTF) than in the aerobic treatments, and with CTS being the treatment presenting the lowest weight.

In 2011, the yields for each treatment were lower than in the other two years. There was no significant difference between the NTS7 (4621 kg ha^{-1}) and the CTF (4550 kg ha^{-1}) yields, indicating that long-term implementation of no-tillage and sprinkler irrigation management may achieve yields that are similar to those obtained under traditional management techniques, but, in the present case, with the benefit of 71.2% of water savings.

In 2012, the NTS7 treatment gave the highest yield (9805 kg ha^{-1}), 49.5% higher than that of the CTF treatment (6556 kg ha^{-1}) while using 80.4% less water. It is important to note that the CTF treatment was on a paddy soil with relatively high percolation losses. This NTS7 yield was also greater than the yields recorded by Stevens *et al.* (2012) for different rice varieties under sprinkler irrigation and conventional tillage. The NTS and CTS yields were lower than that of CTF. In the short term, no-tillage may lead to significant yield reductions in maize and other crops (Linden *et al.*, 2000), so that similar reductions could be expected in aerobic rice too.

In 2013, there was a significant reduction in the NTS7 yield, while the yields of the other three treatments each attained their greatest values of the three years. This may have been a sign of negative effects of long-term rice monoculture, in which case crop rotation would be necessary in order both to avoid the selection of herbicide-resistant weeds and to improve the soil's fertility. Nevertheless, the NTS7 yield of 7397 kg ha^{-1} was still very close to the Spanish average under flooded conditions (7600 kg ha^{-1}). Although the CTF treatment gave the greatest yield (8926 kg ha^{-1}), it required more than four times the amount of water that was applied in the sprinkler irrigated treatments. The NTS yield was far greater than in the previous two years, reaching 8229 kg ha^{-1}. These results show that no-tillage combined with sprinkler irrigation has the potential of providing good yields in the mid-term, and that this potential may be maintained in the long term. Although the CTS yield was also greater in 2013 (4784 kg ha^{-1}), this was significantly ($p<0.05$) less than the yields obtained with the other treatments, and even less than the Regional average, indicating that the combination of sprinkler irrigation and conventional tillage is poorly suited to the environmental conditions of the study. A correlation analysis for the 2012 and 2013 data showed yield to be significantly correlated with TOC ($r=0.542$; $p<0.01$), FA ($r=0.583$; $p<0.01$), HA ($r=0.622$; $p<0.01$), and N ($r=0.476$; $p<0.01$), indicating the important influence of the quantity and quality of soil organic matter on rice crop productivity.

The harvest index (HI) values for 2011 were low due to the low yields achieved by all four treatments. For 2012, the values were within the mean value ranges reported by Bueno & Lafarge (2009) for different rice varieties and genotypes. For 2013, there was a significant ($p<0.05$) increase in the HI values for all the treatments (Table 4). While there were no significant differences between the sprinkler irrigated treatments, the CTF value was the highest of the entire experiment, close to the limits indicative of a high risk of lodging.

The management regimes significantly influenced the waterproductivity (WP) values in the three years (Table 4), but the effectswere different from year to year as determined by the significanttreatment × year interaction ($p < 0.001$; Table 4). One of the main goals of rice-based cropping systems worldwide is to increase water productivity (WP). In all three years, the CTF plot had the lowest WP. The mid-term effect of implementing no-tillage for sprinkler irrigated treatments was clearly noticeable in 2012, with NTS7 having the greatest WP (1.46 g L^{-1}), followed by NTS (0.72 g L^{-1}), and then CTS (0.53 g L^{-1}). In the third year of study, the greatest

WP corresponded to NTS (1.05 g L^{-1}), followed by NTS7 (0.94 g L^{-1}), whereas CTF showed the lowest value (0.27 g L^{-1}). These results were consistent with findings of previous studies by Lampayan et al. (2015) who reported that water productivities in aerobic rice managements (0.86-1.24 g L^{-1}) were higher than anaerobic rice (0.50-0.63 g L^{-1}). There were significant correlations ($p<0.01$) of WP with the soils' TOC ($r=0.615$), HA ($r=0.632$), FA ($r=0.730$) contents. These results suggest that conservation agriculture practices such as no-tillage, which increase the soil's organic matter content, may have a boosting effect on rice crops' WP under Mediterranean environmental conditions. With regard to other studies carried out in Mediterranean environments, the 2012 NTS7 WP was greater than the values reported by Spanu *et al.* (1997) for conventionally tilled and sprinkler irrigated rice, and the 2013 NTS7 and NTS WP values were in the range of the most productive varieties tested by Guiducci *et al.* (1998) when comparing the adaptation of different rice varieties to sprinkler irrigation (0.79-1.15 g L^{-1}), although neither of these studies applied conservation agriculture techniques. The 2013 CTS WP value was below the range reported by Guiducci *et al.* (1998) for the least productive varieties they tested (0.72-0.78 g L^{-1}). An explanation might be the TOC depletion in this soil during the course of the present study.

4. Conclusions

This study has shown that aerobic rice production combined with no-tillage practices may induce important transformations in the soil, leading to major improvements in its physical, physicochemical, and biological properties. This is especially so after long-term implementation of the strategy. Although, in the short-term, sprinkler irrigation gave lower yields, in the mid-term, the combination of this irrigation method with no-tillage practices gave yields similar to those observed in the conventional tillage plus flood irrigation treatment, but with water savings that averaged 75% of the total amount of water used in the flood irrigation. Moreover, these yields, water savings, and soil improvements are sustainable in the long-term.

The greatest water productivity values corresponded to the no-tillage, aerobic rice systems. In sum, the mid- and long-term implementation of no-tillage combined with sprinkler irrigation may be considered to be a productive and sustainable management system for rice farming under semi-arid Mediterranean conditions.

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