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Research article

Drip irrigation uptake in traditional irrigated fields: The edaphological impact

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ABSTRACT

Historical and traditional flood-irrigated (FI) schemes are progressively being upgraded by means of drip irrigation (DI) to tackle current water and demographic challenges. This modernization process is likely to foster several changes of environmental relevance at the system level. In this paper we assess the effects derived from DI uptake on soil health and structure in ancient FI systems through the case study of Ricote, SE Spain, first established in the 10-13th centuries CE. We approach the topic by means of physico-chemical analyses (pH, electrical conductivity, available P, carbon analyses, bulk density, soil water content and particle size distribution), Electrical Resistivity Measurements (ERT) and robust statistics. We reach a power of $1\text{-}\beta = 77$ aiming at detecting a large effect size ($f \geq 0.4$). Results indicate that, compared to FI, DI soils present significantly higher water content, a higher proportion of coarse particles relative to fines due to clay translocation, and less dispersion in salt contents. The soils away from the emitters, which were formerly FI and comparatively account for larger extensions, appear significantly depleted in organic matter, available P and N. These results are not affected by departures from statistical model assumptions and suggest that DI uptake in formerly FI systems might have relevant implications in terms of soil degradation and emission of greenhouse gases. A proper assessment of the edaphological trade-offs derived from this modernization process is mandatory in order to tackle undesired environmental consequences.

1. Introduction

The substitution of traditional flood/furrow irrigation (FI) by drip irrigation (DI) is one of the main pathways for the modernization of traditional irrigated systems, which play an important role in regions like Nepal, Indonesia, Morocco, Peru or the Philippines (Pluquellec, 2002). In the Mediterranean, traditional irrigated systems that have been kept steadily operative since ancient times include Andalusi irrigated-terraced fields (Spain, 711–1492 CE), the Ghoutta of Damascus (Syria, c. 2000 BCE), the khettara systems of Tafilalt and the Ziz (Morocco, Middle Ages), or the oases of Timimoun (Algeria, >1000 CE) (Barceló, 1989; Bianquis, 1989; Lightfoot, 1996; Remini et al., 2011). DI uptake is expected to increase water efficiency, crop yields and the attractiveness of irrigated systems in rural areas, ultimately ensuring their sustainability in the current context of water stress, demographic growth and rural depopulation (García-Ruiz et al., 2011; Iglesias et al., 2010; Playán and Mateos, 2006; Wallace, 2000).

From a technological standpoint, DI provides steady amounts of water directly to the root crops through line sources (emitters) on or below the soil surface, mostly at small operating pressures (20–200 kPa) and low discharge rates (1–30 l/h) (Dasberg and Or, 1999). DI and FI are mutually exclusive at the plot level, since DI

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uptake requires discarding the hydraulic infrastructure (e.g. channels, pools) and suspending part of the work related with traditional irrigation (e.g. manuring, levelling, ridge and channel maintenance). This means that large extensions of soils managed and irrigated under FI will be neglected under DI. However, DI in traditional FI schemes is often implemented progressively, with both agro-systems temporarily coexisting within the same irrigation scheme during the upgrading process (see Sese Mínguez, 2012; van der Kooij, 2009). Such situations offer the possibility to assess in coherent settings their contrasting effects in soil health and structure, ultimately gaining an insight into the sustainability of traditional and modern intensive agriculture.

There is a considerable amount of literature on both the particular effects of FI (e.g. Heakal and Al-Awajy, 1989; Hussein et al., 1992; Khokhlova et al., 1997; Ricks Presley et al., 2004) and DI (e.g. Dasberg and Or, 1999; Hannam et al., 2016) in modifying the properties of dry soils. DI and FI have also been compared and their differences assessed in terms of potential water efficiency rates (Maisiri et al., 2005; Playán and Mateos, 2006; van der Kooij et al., 2013), harvest yields (Hussien et al., 2013; Kucukyumuk and Yildiz, 2013; Shrivastava et al., 1995; Yohannes and Tadesse, 1998), emission of greenhouse gases (Kallenbach et al., 2010; Sánchez-Martín et al., 2008; 2010) or social benefits and farmer welfare (Datar and Del Carpio, 2009; Karaa et al., 2009; Narayanamoorthy, 2004; Postel et al., 2001). Much less interest has comparatively been devoted to quantify the impact that DI uptake has on specific physico-chemical features of formerly FI soils (Obbink and Alexander, 1977). To our knowledge, no work has been carried out on assessing the effects derived from withdrawing FI during the modernization process of enduring FI systems.

This paper aims at assessing whether there is a large effect in soils caused by DI uptake in traditional, long-term FI systems. We contribute with quantitative data to the debate on the upgrading of traditional, long-term irrigated systems and its related environmental consequences (FAO, 1999; Lecina et al., 2010a, 2010b; Playán and Mateos, 2006). Unlike former works, which have mostly relied on *p*-values to test the hypothesis of no effect while overlooking other issues of statistical concern [e.g. sample size, effect size, outliers or compositional data (Aitchison, 1986; Ellis, 2010; Filzmoser et al., 2009a,b,c; Maronna et al., 2006; van den Boogaart and Tolosana-Delgado, 2013; Wilcox, 2005)], our work tackles the topic following a robust statistical approach. We use the case of Ricote (SE Spain), an irrigated-terraced area first built between the 10th-13th centuries CE that reached its current extension (120 ha) shortly before 1614 CE (Puy, 2014; Puy and Balbo, 2013; Puy et al., 2016). The system had fully relied on flood irrigation until 2007, when DI was partially introduced. The case of Ricote illustrates the history of many farmers of traditional Mediterranean irrigated fields, who have opted to progressively implement DI in the face of current environmental, social and economical challenges.

1.1. Study area

The historical irrigated-terraced fields of Ricote (38° 09′ 00.82″N, 1° 22′ 04.14″W) are located in Murcia, SE Spain, and extend over 120 ha in a *hoya*, a flat basin surrounded by mountains (Fig. 1). Since the middle of the 20th century, Ricote specializes in the growing of lemon trees, with the production being sold on national and international markets. The climate of the region is semi arid, with summer and winter temperatures ranging between 31 and 34 °C and 1–5 °C respectively, annual rainfall averaging 200–350 mm and evapotranspiration fluctuating between 750 and 900 mm (López Bermúdez, 1973).

The basin is characterized by limestone, Keuper marls, polygenic sandstone and dolostone formations, with soils being mostly Calcisols, Regosols and Leptosols (IUSS, 2006). Xerophytic vegetation dominates, especially *Cistus ciprus*, *Retama sphaerocarpa* and *Rosmarinus officinalis*.

The irrigated terraces at the lowest reaches of the hoya (~235 m asl) are mostly broad (40–60 m wide) cropping surfaces constructed by fill and sustained by stonewalls, while those along the highest reaches (~375 m asl) are narrower (3–20 m wide) and sustained by earth banks (Puy, 2014; Puy et al., 2016). Since their first construction between the 10th-13th centuries CE, the Ricote irrigated-terraced fields have been flood-irrigated with the water provided by a perennial spring located to the SW of the basin (~390 m asl), which supplies a consistent flow of 12–13 l/s (García Avilés, 2000). Before DI uptake in 2007, the water flowed from the spring to the plots through a network of artificial channels, either excavated in the soil or covered by concrete pipes to minimize water losses and siltation. Irrigators opened the gates of the channels and let the water flood in their plots. FI was traditionally performed at least five times per year, and included cleaning of the channels, tilling, fumigation of the weeds twice a year and of the lemon trees once a year, pruning, manuring with P, K and N-based fertilisers, burning of the branches and ridge construction and maintenance. Irrigators who chose to equip their properties with the DI system filled or discarded the traditional hydraulic infrastructure within their plots. Nearly 90% of the parcels included in the historical hydraulic system (1651 out of 1835) are currently equipped with DI, with just some properties still being flood-irrigated by means of the traditional channel network.

DI was first implemented in 2007 after three previous attempts fostered by the Water Council that were turned down by the irrigators. The system consists of 1) two pools of 18.000 m^3 and 45.000 m^3 located on top of two hills to the N and S of the irrigated area, which respectively store water from the Segura River (pool 1) and from the spring and the Segura River (pool 2) (Fig. 1), 2) the network of pipelines, tubes and emitters, whose function is to distribute the water from these pools to the plots, 3) 105 station cabinets spread across the hydraulic system with consumption meters and mechanical and electronic devices to open and close counters and inform the Water Council on possible system breakdowns, 4) the electrical network, which connects the station cabinets with the Water Council computer, and 5) the Water Council computer, which regulates the functioning of the system, controls the station cabinets and stores all the data. The installation of the system cost 2.160.000€, of which 500.000€ (23%) were funded by the Consejería de Agricultura y Agua de la Región de Múrcia (Agriculture and Water Council of the Region of Murcia), 450.000€ (22%) by the Spanish Ministry of Agriculture, and the remaining 1.210.000€ (54%) being directly covered by the landowners themselves. The benefits earned from trading their produces were so low (e.g. c. 300–400€ per person per year) that irrigators had to use their own personal savings to upgrade the irrigated system (García Avilés, personal communication). Agricultural tasks carried out by drip irrigators include pruning, burning of branches, checking of the emitters, fumigation of the lemon trees and the weeds once and twice a year respectively, and replacement of broken devices from the DI system included within their own properties.

2. Materials and methods

2.1. Sampling

An *a priori* power test on an omnibus, one-way Anova was carried out with G*Power 3.1 (Faul et al., 2009) in order to assess the sample size needed to detect a large effect size ($f \geq 0.4$)

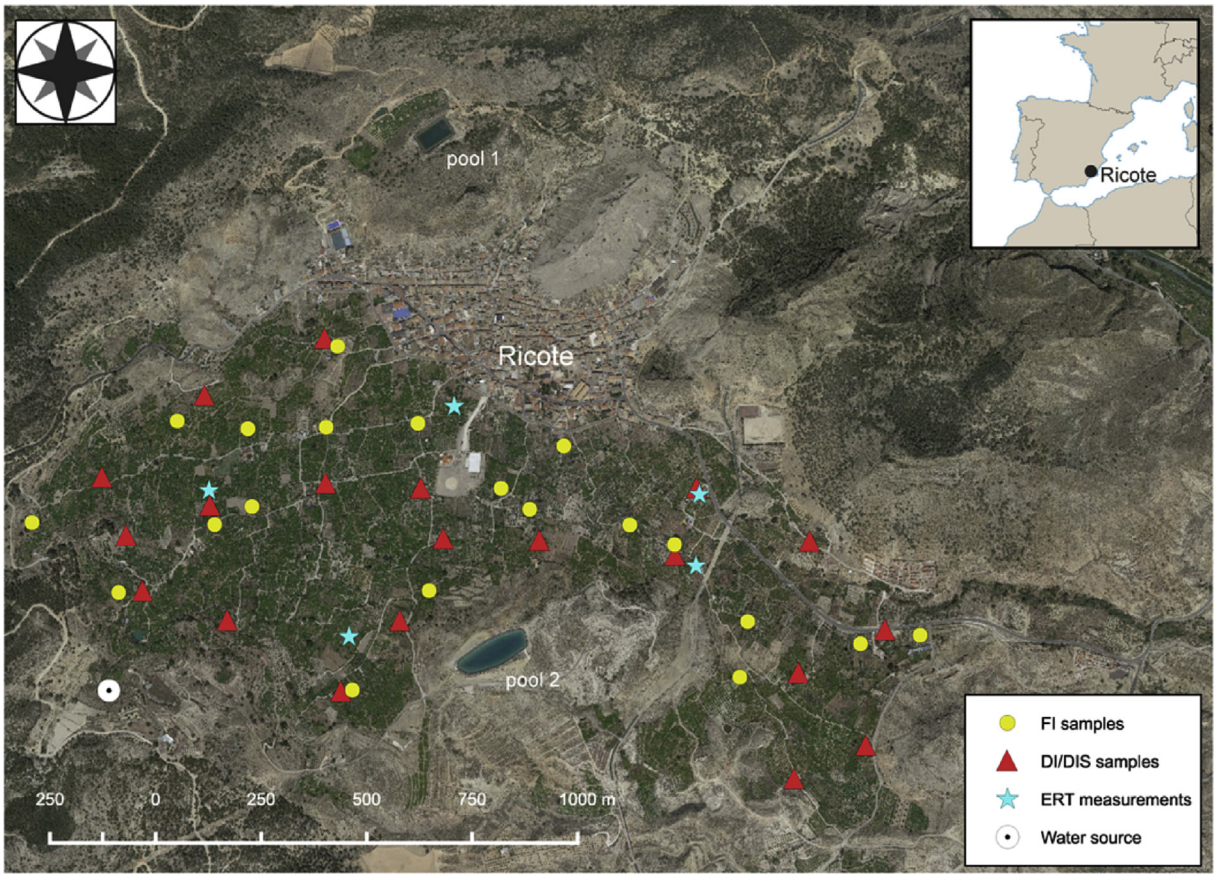

Fig. 1. The village of Ricote, its irrigated area and the sampling locations.

between three groups: FI plots, DI plots and drip irrigation spots (DIS, i.e. the soil spots within DI plots directly wetted by the DI emitters). We decided to focus on seeking a large effect size due to 1) the lack of previously reported effect sizes in the literature on DI/FI uptake and, 2) its higher relevance (compared to small and medium effect sizes) in terms of irrigation management and policy-making. A total sample size of 60 (20 samples per group, $f = 0.4$, $1-\beta = 0.77$, $\alpha = 0.05$) was targeted as a 23% beta risk of failing to detect the sought effect size was considered acceptable due to its proximity to the conventional threshold of 20%, set by Cohen (1988).

Forty plots (20 DI, 20 FI) were selected using a random sampling design (Carter and Gregorich, 2008) and sampled in the course of two field campaigns in September 2014 and 2015 (Fig. 1). Following the results obtained after the *a priori* power test, we focused on the topsoil (upper 30 cm) and collected 1) 20 bulk samples from FI plots, whose physico-chemical features were assumed to reflect the edaphological signature of traditional irrigation, 2) 20 bulk samples from DI plots, whose features were considered to show the short-term edaphological effects (<8 years) of FI withdrawal, and 3) 20 bulk samples from the DI humid spots (DIS) located in the sampled DI plots, which were regarded as a proxy for the conditions of the soil directly wetted by the DI emitters. Comparisons between DI-FI samples aimed at assessing the effects of quitting FI, whereas comparisons between DIS-FI samples aimed at distinguishing the differences between flood and drip irrigation.

We also sampled the water used for DI and FI in order to precise their chemical properties. The FI water was sampled directly from the water spring, whereas the DI water was collected from the drip emitters. A LabQuest2 device, Vernier industries®, was used to carry out in-field measurements of pH, Electrical Conductivity (EC) and temperature of the water. Samples were stored in 0.5 l recipients and kept in cold conditions before analysis.

2.2. Physico-chemical analyses

All soil samples ($n = 60$) were gently crushed with a pestle and a mortar and sieved through a 2 mm mesh after being air-dried at room temperature for 24–48 h. Analyses were carried out on the <2 mm fraction. PH was measured on a 5 ml solution [0.01 M calcium chloride ($CaCl_2$) and 5 ml g of sample] by means of a calibrated glass electrode. Electrical Conductivity (EC) was determined on a solution containing 5 ml of distilled water and 5 ml of sediment using an InoLab pH/ION/EC meter. Particle Size Distribution (PSD) was calculated with a Beckman Coulter LS13 320® on ~0.4 g samples after removing carbonates and organic matter with solutions of 10–15% HCl and 15% of H_2O_2. Total organic carbon (TOC), total carbon (TC), $CaCO_3$, total nitrogen (TN) and total organic nitrogen (TON) were determined with a Vario EL Cube® CN-analyser. Soil bulk density (D_b) was determined as $W_{dry}/90.59$, being W_{dry} the dry weight of the bulk sample and 90.59 the volume (cm^3) of the soil core used to collect the sediment. Soil water content (W) was calculated as $(W_{mst}-W_{dry})/W_{dry}$, being W_{mst} the weight of the soil before being dried out. Soluble, exchangeable phosphates (P) were extracted using the calcium acetate lactate (CAL) method after Schüller (1969). All tests were measured once in all samples and twice in those samples that yielded outliers, identified at this stage by means of boxplots as values falling more than 1.5 box lengths from the lower or upper hinges. This was meant to ensure they reflected legitimate values and not instrumental errors. If the outcomes of the measurements were similar, we retained for analysis

the mean value resulting from both measurements. If they differed, a third measurement was carried out and the mean between the three measurements was retained for analyses. The full dataset can be found in Supplementary Materials I.

The water used for FI and DI was analysed by Eurofins Agroambiental (Lleida, Spain) following established protocols. In this paper we report the results for pH, EC, K, Mg, Ca, H_2PO_4, SO_4, Cl and HCO_3.

2.3. Data analyses

All statistical analyses were performed in the *R* environment (R Core Team, 2015). The dataset resulting from soil physico-chemical analyses included both unconstrained (e.g pH, EC, P, bulk density, water content) and constrained (e.g. PSD, N, C) variables. The latter is known as closed or compositional data (CoDa) and is characterized by vectors formed by positive values that provide portions of a total, thus carrying only relative information (Aitchison, 1986; Buccianti et al., 2006; Pawlowsky-Glahn and Buccianti, 2011). Unlike unconstrained variables, which are able to independently vary, any increase in an individual part of CoDa (e.g. sand in PSD or TOC in carbon tests) leads to a decrease in the rest of the compounds of the dataset, and vice versa. This 'closure effect' implies a special geometry, known as the Aitchison geometry on the simplex (Aitchison, 1986). Correlation coefficients or statistical measures relying in the Euclidean space, such as mean or standard deviation, are inaccurate for CoDa as they assume independence and absence of interaction between data points. Many authors have stressed the need to open CoDa when dealing with environmental data before performing multivariate and univariate analyses to avoid misleading interpretations (Buccianti and Grunsky, 2014; Filzmoser et al., 2009a, 2009b, 2009c, 2010; Reimann et al., 2012; Wang et al., 2014).

Aitchison (1986) and Egozcue et al. (2003) proposed a family of logratio transformations to overcome the closure effect of CoDa: the additive logratio (*alr*), the centered logratio (*clr*) and the isometric logratio (*ilr*). In this paper we opened the PSD [grain size fractions defined by Folk and Ward (1957)] and the C/N datasets (TOC, TC, $CaCO_3$, TON, TN) by means of an *ilr* transformation (Egozcue et al., 2003). The *ilr* transformation generates *D*-1 log-contrasts or balances from a sequential binary partition (SBP) between the components, where components labelled "-1" (denominator) are contrasted with components labelled "+1" (numerator). In this paper we express these contrasts as [denominator | numerator] following Parent et al. (2014). The resulting *ilr* variables no longer represent the original variables but balances between denominators and numerators, and can reliably be used to perform standard statistical tests, such as Anova. A higher negative *ilr* value reflects a higher loading of the *ilr* denominator, while a higher positive *ilr* value indicates a higher loading of the *ilr* numerator. In order to obtain interpretable *ilr* coordinates, we created the SBPs after identifying via robust biplots the balances that had more discriminative power for each CoDa using the "mvoutliers" package (Aitchison and Greenacre, 2002; Filzmoser and Gschwandtner, 2015; Pawlowsky-Glahn and Egozcue, 2011). All compositional analyses were performed with the "compositions" package (van den Gerard van den Boogaart et al., 2014).

Robust mean values were obtained by using 20% trimmed means (Maronna et al., 2006). The spread of the data was assessed through the robust coefficient of variation (rCV), defined as rCV = 100 × MAD (x)/median (x), where MAD is the median absolute deviation and x the variable under study (Varmuza and Filzmoser, 2010). To assess whether DI uptake/FI withdrawal have significantly modified the conditions of the soils we ran 20%-mean-trimmed, t-bootstrapped ($B = 2000$) one-way Anova for DI, DIS and FI soils using the "WRS2" package (Mair et al., 2015). When sample sizes are small and non-normally-distributed, the bootstrap-t method on trimmed means offers protection against outliers and Type I errors, reasonable power and accurate confidence intervals (Wilcox, 2005, 2012). Significant results were followed up with pairwise comparisons through the percentile bootstrap method (Wilcox, 2005), set also at $B = 2000$.

2.4. Electrical Resistivity Tomography (ERT) measurements

In order to complement the quantitative data in terms of water infiltration rates and distribution through the soil profile, we selected three FI and two DI plots to conduct ERT measurements of the subsurface resistivity distribution (Fig. 1). ERT is a geophysical technique that sends electric current into the ground and measures the value of electric resistivity to its conduit. Work by Brunet et al. (2010), Garré et al. (2011, 2013) and Samouëlian et al. (2005) showed that ERT allows identifying spatial and temporal variability of main soil properties (e.g. structure, water content, fluid composition) at a decametric/hectometric scale, as well as retrieving differences between two cropping systems on the same soil and under the same climatic conditions. For the study at hand, stained sticks were inserted into the ground every 30 cm along a straight line 30 m long, drawn parallel and less than 40 cm away from the irrigation channel in FI plots and the pipeline in DI plots. We used a GeoTom MK1E100 1 Channel analog-control ERT unit, the data being recorded and processed with GeoTom and Res2Dinv software (Geotomo Software, 2010) on a Wenner configuration and 20 levels.

3. Results

3.1. Physico-chemical analyses

3.1.1. Constrained data

Fig. 2a and Table 1 respectively show the biplot and the selected SBP for the carbon/nitrogen dataset. TOC and TN had coincident vertices, indicating that their ratio was constant and thus they were redundant (Aitchison and Greenacre, 2002). Since TC and $CaCO_3$ had also nearly aligned rays, we decided to keep only TOC, TON and $CaCO_3$ to create the SBP for the sake of parsimony. Following the first principal axis of the biplot (84.7% of the variability), we first created the balance [$CaCO_3$ | TOC, TON] to obtain a general index for the relative presence of carbonates and organic matter (*ilr* 1A). The balance [TON | TOC] followed the second axis (13% of the variability) and was regarded as a proxy for the C/N ratio (*ilr* 2A).

The resulting *ilrs* are plotted in Fig. 3 and statistically summarized in Table 2. The weight of the numerator in *ilr* 1A is higher in FI soils than in the rest, indicating a higher presence of organic matter and a lower weight of $CaCO_3$. The balance between [TON | TOC] (*ilr* 2A) is similar between DI, DIS and FI soils, suggesting lack of differences between the samples in the C/N ratio. All *ilrs* show a unimodal distribution and similar rCVs for all groups. Pairwise comparisons after a significant Anova ($p = 0.031$, $f = 0.4$) hinted at significant differences between DI-FI soils in their 20% trimmed means for *ilr* 1A ($p = 0.005$, CI = −0.358, −0.027), pointing towards a c. 1–11% lower mean organic matter contents in DI than in FI soils. No significant differences were found between DI, DIS, and FI soils in *ilr* 2A ($p = 0.833$, $f = 0.09$).

Fig. 2b and Table 3 present the biplot and the SBP for the PSD dataset. Since the first principal axis of the biplot accounted for 75.5% of the variability and confronted sand vs silt and clay, we first balanced [sand | silt, clay] to precise the ratio between the coarse and the fine fractions (*ilr* 1B). The balance [clay | silt] followed the second principal axis (24.05%) and aimed at assessing the relative

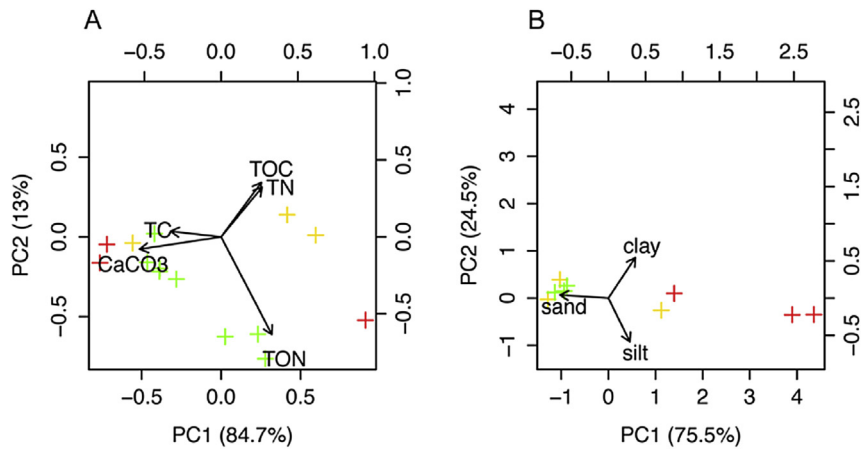

Fig. 2. Biplots of the constrained datasets (*ilr* and *clr* back-transformed). Crosses mark compositional outliers, whose colour reflects the magnitude of the median element concentration of the observations (red = most univariate parts have higher values than average; green = univariate parts with mainly low values) (Filzmoser and Gschwandtner, 2015). A) carbon-nitrogen dataset. B) PSD dataset. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Sequential binary partition (SBP) of (*D*-1) parts made for total organic carbon (TOC), calcium carbonate ($CaCO_3$) and total organic nitrogen (TON); n^+ = number of components at numerator; n^- = number of components at denominator.

ilr	TOC	$CaCO_3$	TON	n^+	n^-
ilr 1A	1	−1	1	2	1
ilr 2A	1	0	−1	1	1

proportion between the finest fractions (*ilr* 2B).

The *ilrs* for the PSD dataset are shown and compiled in Fig. 3 and Table 2 respectively. The mean weight of the coarse relative to the fine fraction (*ilr* 1B) is higher in DIS than in FI and DI soils. No visible differences are found between the groups in their *ilr* 2B scores, which suggest that DI uptake has not significantly modified the balance between the finest fractions. All *ilrs* show a unimodal distribution, and FI soils much lower rCV (12.74%) than DI (32.66%) and DIS (37.22%) soils in *ilr* 1B, indicating that FI homogenises better than DI the ratio between coarses and fines in the irrigated scheme. Pairwise comparisons after a significant Anova ($p = 0.045, f = 0.42$) indicated that significant differences existed in the 20% trimmed means for *ilr* 1B between DIS-FI soils ($p = 0.006$, CI = −0.651, −0.051), pointing towards a c. 3.3–42% reduction in the mean weight of the coarse/fine balance in DIS compared to FI soils.

3.1.2. Unconstrained data

Fig. 4 and Table 4 respectively plot and summarize the results for pH, EC, P, soil water content and bulk density analyses. The mean values for pH (7.7) and EC (593 μs/cm) indicate that the soils within the irrigated area are slightly alkaline and non-saline (Hazelton and Murphy, 2007). DI (7.7), DIS (7.5) and FI (7.8) soils show no relevant differences in their mean pH values, but clearly differ in their mean EC scores, with DIS (323 μs/cm) and FI (1068 μs/cm) soils showing the lowest and highest values respectively. The rCV indicate that DIS soils (40.34%) show much less dispersion in EC values than FI soils (87.43%). Excluding outliers, almost all DIS soils (85%) have EC values equivalent to the lowest EC values for FI soils (<673 μs/cm), pointing towards a relevant role of drip irrigation in reducing and homogenizing salt contents in the irrigated scheme.

Since boxplots and kernel density plots showed a bimodal distribution for EC values in FI soils, we checked the spatial distribution of EC to account for a pattern in the distribution of scores. Plots to the W and E of the irrigated scheme showed the lowest (<673 μs/cm) and highest (>2000 μs/cm) EC scores respectively (Fig. 5a). This trend in FI soils was not related to an uneven distribution of salts from manuring and phosphates ($r = -0.26$), but to carbonates and water, as indicated by the correlation of EC with pH (r=0.6) and soil water contents ($r = 0.48$).

P values average 2.4 mg/l, with FI (2.84 mg/l) and DI (1.81 mg/l) soils respectively showing the highest and lowest means. Bulk density scores average 1.42 g/cm^3, with the differences between the means of the three groups being negligible. As for soil water contents, the average is 0.17 g/g, with DI (0.15 g/g) and DIS (0.24 g/g) soils showing the lowest and highest means respectively. The rCV indicates that DIS soils show much more variation in soil water contents (42.83%) and bulk density (11%) scores than DI (19.76%, 4.71%) and FI (21.8%, 6.24%) soils. Since DIS soils also show a bimodal distribution in their soil water contents (Fig. 4), we checked the distribution of scores along the irrigated scheme to account for a spatial pattern (Fig. 5b). Results do not reveal any clear trend and hint at the bimodality of DIS soils in water content not being linked to topographical variations within the irrigated scheme.

Pairwise comparisons after a significant Anova for pH ($p = 0.002, f = 0.76$), P ($p = 0.012, f = 0.50$) and soil water content ($p = 0.018, f = 0.79$) allowed specifying the significant differences existing between the groups on their 20% trimmed means. DIS samples have a lower pH mean than DI ($p = 0.003$, CI = −0.328–0.037) and FI ($p = 0.000$, CI = −0.395, −0.108), but a higher soil water content mean than DI ($p = 0.000$, CI = 0.035, 0.134) and FI ($p = 0.001$, CI = 0.010, 0.118). As for DI samples, they show a lower mean P content than DIS ($p = 0.015$, CI = −1.75, −0.035) and FI ($p = 0.01$, CI = −2.00, −0.115) soils. These results suggests that FI withdrawal has lowered the average P contents between c. 4–71%, whereas drip irrigation uptake has reduced the mean pH values by 0.1–0.4 points and increased by c. 5–68% the mean water content compared to DI and FI plots respectively.

3.1.3. Water chemistry

Table 5 presents the values of the physico-chemical analysis of the water used for FI and DI. They mainly differed in their values for pH (FI = 7.3, DI = 6.7), H_2PO_4 (FI=<50 μg/l, DI = 95 μg/l) and HCO_3 (FI = 2.71 meq/l, DI = 1.46 meq/l).

3.2. ERT measurements

Fig. 6 shows two representative ERT profiles of FI and DI plots.

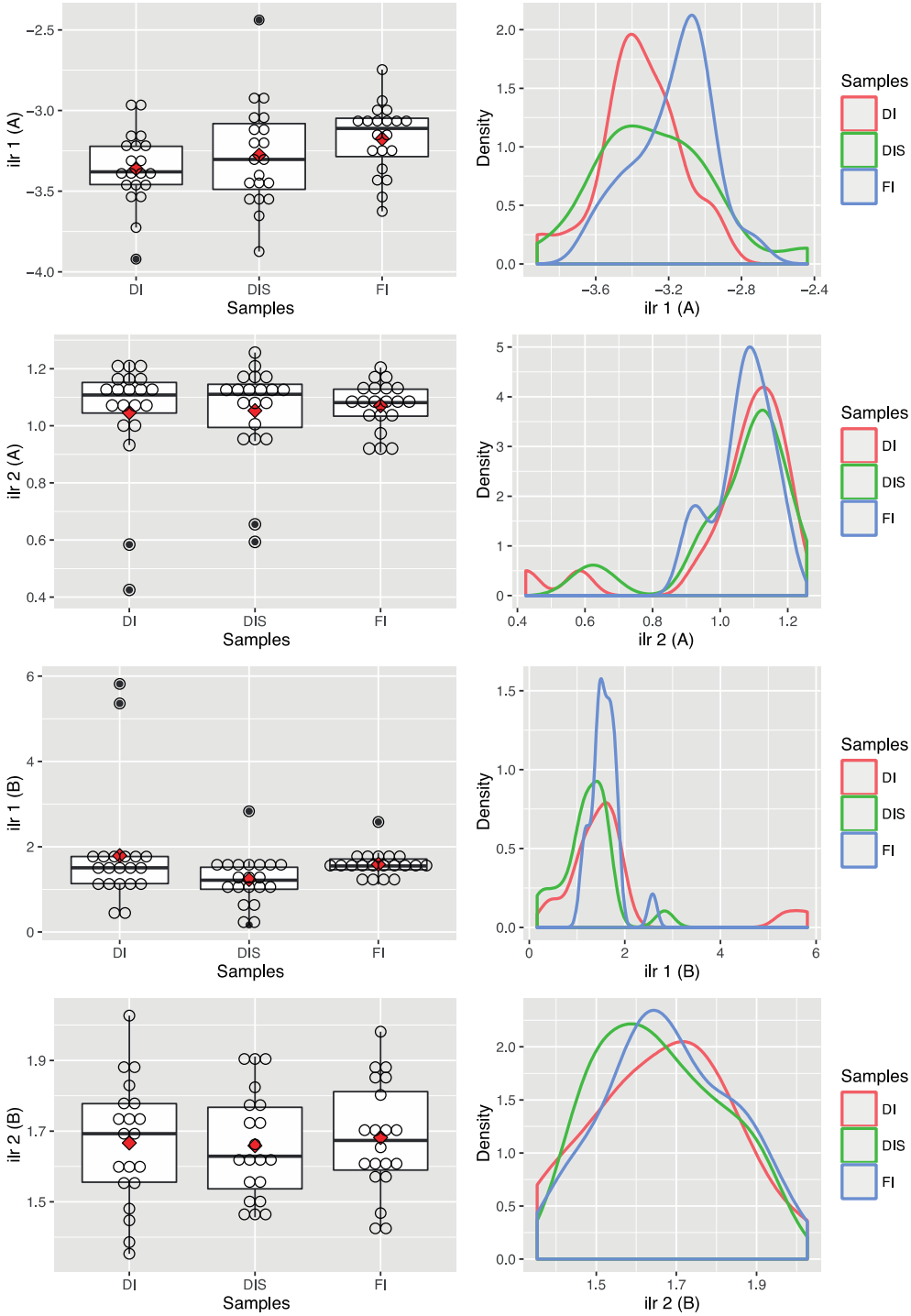

Fig. 3. Boxplots and kernel density plots for the *ilr*-transformed datasets (*ilr* A = carbon-nitrogen; *ilr* B = PSD). DI = Drip Irrigation, DIS = Drip Irrigation Spots, FI = Flood Irrigation. The red diamonds in the boxplots show the mean value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

After irrigation, water in FI plots reached a depth of 60 cm on each lot between ridges (Fig. 6a). The lower resistivity detected in the layer between 60 and 120 cm bgl in the FI plot marks the dry soil profile where water has not infiltrated yet. Five hours after FI, the wetting front reached a depth of c. 60–100 cm and >120 cm in the stretch between 20 and 28 m (Fig. 6b). As for DI plots, the water concentrated around the drip spots and reached depths of c. 30–40 cm (Fig. 6c). No relevant differences were found in the distribution of water immediately after irrigation and 5 h after irrigation, although stretches at 1.2 m, 16.6 m and 27 m along the transect suggest a deeper water percolation, probably due to locally higher permeability (Fig. 6d).

4. Discussion

4.1. The statistical framework

A robust quantitative analysis of the edaphological trade-offs

Table 2
Descriptive statistics for the *ilr*-transformed carbon/nitrogen (*ilr* A) and PSD (*ilr* B) datasets.

	Sample	n	*ilr* 1A	*ilr* 2A	*ilr* 1B	*ilr* 2B
Min	DI	20	−2.96	1.22	0.39	1.35
	DIS	20	−2.43	1.25	0.16	1.45
	FI	20	−2.74	1.20	1.11	1.42
Max	DI	20	−3.92	−0.42	5.81	2.02
	DIS	20	−3.87	−0.59	2.83	1.91
	FI	20	0.3.62	−0.90	2.58	1.98
Tr. mean (20%)	DI	20	−3.35	1.09	1.48	1.66
	DIS	20	−3.29	1.08	1.22	1.65
	FI	20	−3.15	1.08	1.56	1.68
rCV	DI	20	5.79	6.95	32.66	10.57
	DIS	20	9.93	7.38	37.22	11.26
	FI	20	6.20	6.66	12.74	9.1

Table 3
Sequential binary partition (SBP) of (*D*-1) parts made for sand, silt and clay; n^+ = number of components at numerator; n^- = number of components at denominator.

ilr	Sand	Silt	Clay	n^+	n^-
ilr 1B	−1	1	1	2	1
ilr 2B	0	1	−1	1	1

derived from the modernization of traditional irrigated fields is critical to ensure their future sustainability. The effects of DI uptake/FI withdrawal and their magnitude need to be identified and potential drawbacks of the upgrading process addressed based on robust data collected in the field. Several authors have shown the pitfalls of not considering power (the probability of identifying a genuine effect when there is an effect to be identified) or the relationship between power, alpha (α), effect size and sample size when designing agronomical/soil research and sampling (Karamanos et al., 2014; Kravchenko and Robertson, 2011; Necpalova et al., 2014; Pennock, 2004). Studies with such caveat might fail to reject the null hypothesis of no effect simply because they are underpowered to detect any effect due to a too small sample size. For conservative research this can be highly pernicious as it might cause unwanted or harming effects to be overlooked (Peterman, 1990). In case significant differences are found, it will be hard to argue for an underpowered study that such differences relate to a real phenomenon and do not result from randomness (Ellis, 2010). To our knowledge, work on DI/FI uptake has reported both significant (e.g. total soluble salts and chloride, Obbink and Alexander, 1977; total clay, Ricks Presley et al., 2004) and non-significant (e.g. soil moisture, Obbink and Alexander, 1977; organic C and calcium carbonate equivalent, Ricks Presley et al., 2004) results, but fully lacked details on the power achieved or the effects being sought. Being a breeding ground for Type I and II errors, these approaches might lead to flawed managerial or regulatory practices with undesired consequences at the system level.

In this paper we achieved a power of 77 for $\alpha = 0.05$ and $f > 0.4$, meaning we had 77% chances of detecting a large effect linked to DI uptake, in case this effect was real, by means of a one-way Anova. We used trimmed means, which drain power compared to means when samples are normally distributed. However, Wilcox (1994, 2010) stated that they also allow sticking closer to the desired power level in case of slight departures from normality and outliers, as was the case. Our results are thus robust and not affected by departures from model assumptions. With this statistical basis we detected a large effect in five out of the nine variables considered (55.5%), with two (organic matter/$CaCO_3$, available P) reflecting the changes undergone by the soils away from the emitters, and three (pH, soil water content, coarse/fines ratio) reflecting the different edaphological impact of FI and DI. According to the confidence intervals, the largest effects were found for organic matter, available phosphates and soil water content. Although the mean pH values in DIS soils were significantly lower than in FI soils ($p = 0.003$, CI = −0.328, −0.037), the effect is irrelevant in terms of soil management and we will not include the variable in the following discussion.

4.2. Effects derived from FI withdrawing

Changes in available P, organic matter and the balance between organic/inorganic carbon stocks due to DI uptake in former FI systems might affect greenhouse emission rates and the carbon cycle, as well as soil quality, at the system level. Compared to FI, water inputs and fertilisers such as P and reactive N compounds are applied to a considerable smaller area under DI, thus likely reducing the amount of soil that undergoes wet and dry cycles, the amplitude of CO_2 pulses and the release of N_2O (Huth et al., 2010; Kallenbach et al., 2010; Sanchez-Martín et al., 2010; Trost et al., 2013). This might be at the expense of depleting the rest of the scheme from nutrients and organic carbon while decreasing its overall potential as an atmospheric carbon sink.

The functions of organic matter and carbon in soils are well known and include increasing soil aggregation, stability, water retention, soil biodiversity and nutrient availability, as well as buffering greenhouse emissions from soil to the atmosphere (Lal, 2004a). Although cultivation has been regarded as an activity that depletes organic carbon from the soil (Davidson and Ackerman, 1993), in arid and semi-arid environments it might actually have the opposite effect, especially when irrigation is applied (Amundson, 2001; Trost et al., 2013). The combination of water with P and N inputs favours biomass productivity (Ercoli et al., 1999; Lal, 2004b), likely enhancing weed growth also by dispersing weed seeds through the channels of the hydraulic network (Kelley and Bruns, 1975). Although they compete with crops for light, space and soil nutrients, a proper management of weeds might increase the rate of carbon sequestered in the soil (Schonbeck, 2013). However, weed growth, as well as biological activity, is seriously limited in DI compared to FI systems due to the exclusion of large portions of the plot from regular nutrient and water inputs. The combination with high temperatures and water stress characteristic of arid and semi-arid environments creates conditions that favour organic carbon outputs rather than inputs, with those areas excluded from the emitters exposing organic carbon accumulated during years of irrigation to oxidation and eventual loss as atmospheric CO_2.

Our results also suggest that the areas excluded from the drip emitters might increase their $CaCO_3$ contents due to FI withdrawal and the drying of the soil. It has been argued that a change in the soil carbonate content can either act as a source or as a sink of CO_2 depending on the main source of HCO_3 (e.g. soil biota, water used for irrigation) and calcium (e.g. cations, weathering of Ca/Mg-bearing minerals), as well as on the degree of soil leaching (Sanderman, 2012). In Ricote, values for HCO_3, Ca and Mg are high for DI and even higher for FI water (Table 5) and soils are naturally rich in Ca^{2+} (Puy and Balbo, 2013), thus creating the conditions for the formation of carbonates in the soils excluded from the emitters being a source of atmospheric CO_2. Although no significant differences were found in terms of $CaCO_3$ between the soils under the drip emitters and those FI, it is worth noting that in semi-arid environments carbonates might be re-precipitated lower in the soil profile (Khokhlova et al., 1997). Here we could not detect carbonate leaching as we focused on the topmost 30 cm of the soil profile. Nevertheless, ERT measurements suggest that much more water is

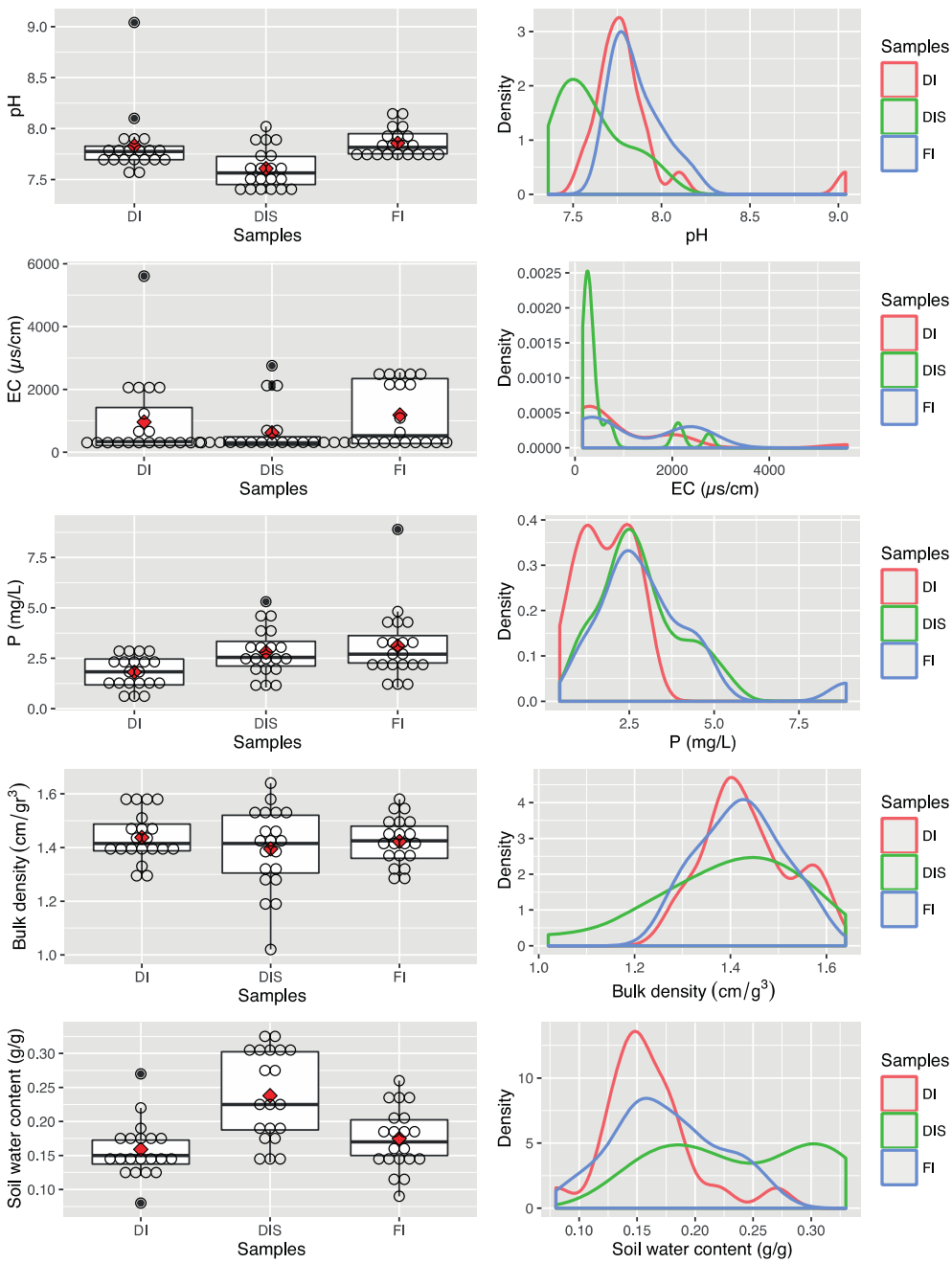

Fig. 4. Boxplots and kernel density plots for pH, EC, available P, bulk density and soil water content. DI = Drip Irrigation, DIS = Drip Irrigation Spots, FI=Flood Irrigation. The red diamonds in the boxplots show the mean value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

likely to be leached down to the groundwater system under FI compared to DI (a partially carbon-sinking process). Under DI, most of the HCO_3 provided by irrigation water might re-precipitate in the upper soil profile. In that sense, Hannam et al. (2016) showed that the carbonates precipitated under the drip emitters are a relevant source of CO_2 and strongly influence the amount of $^{13}CO_2$ released from the soil.

4.3. Differences between DI and FI

Irrigated schemes might extend over heterogeneous terrains with contrasting features in terms of soil quality, sun exposure and elevation. These differences are likely to be exacerbated as a consequence of uneven FI. The amount of water reaching the fields

Table 4
Descriptive statistics for pH, EC, P, bulk density and soil water content.

	Sample	n	pH	EC (μS/cm)	P (mg/L)	D_b (g/cm^3)	W (g/g)
Min	DI	20	7.6	157	0.45	1.29	0.08
	DIS	20	7.4	190	1.04	1.02	0.14
	FI	20	7.7	204	1.03	1.28	0.9
Max	DI	20	9.0	5605	3.00	1.59	0.27
	DIS	20	8.0	2755	4.88	1.64	0.33
	FI	20	8.2	2550	8.88	1.58	0.26
Tr. mean (20%)	DI	20	7.7	568	1.81	1.42	0.15
	DIS	20	7.5	323	2.67	1.41	0.24
	FI	20	7.8	1068	2.84	1.42	0.17
rCV	DI	20	1.62	73.91	52.80	4.71	19.76
	DIS	20	2.25	40.34	35.75	11	42.83
	FI	20	1.61	87.43	35.56	6.24	21.8

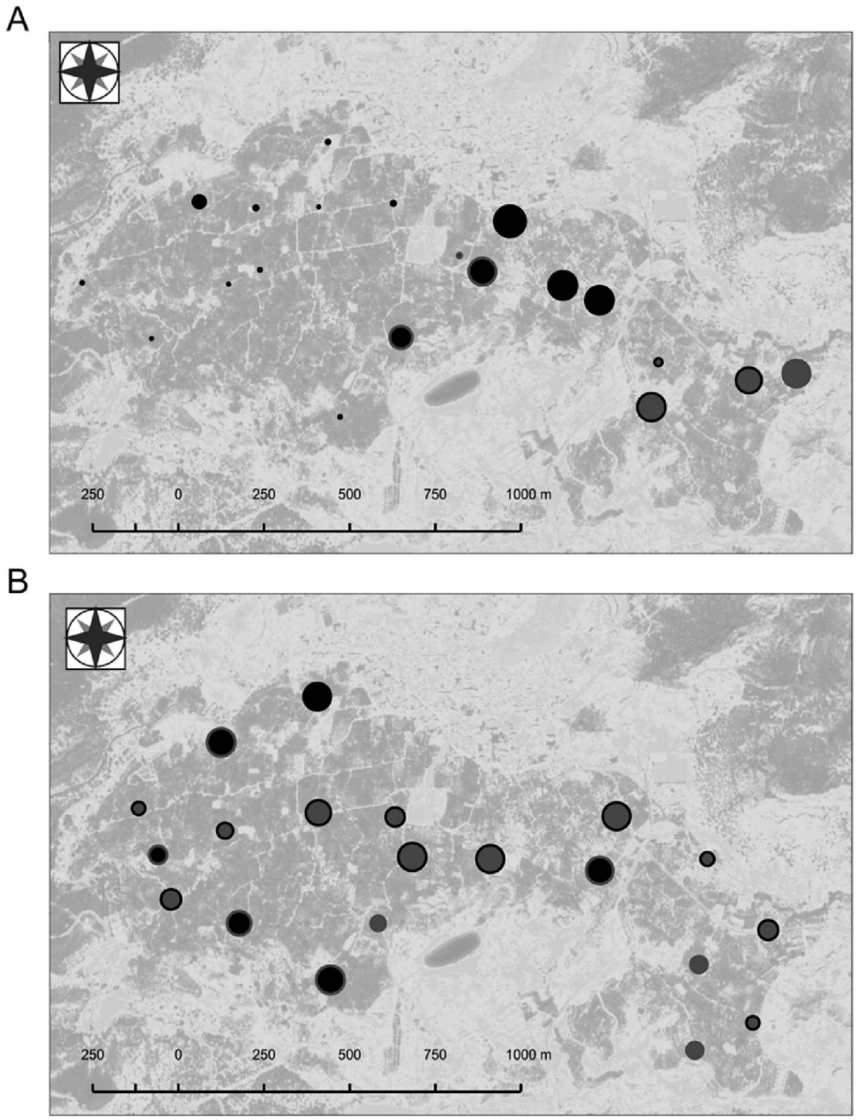

Fig. 5. Spatial distribution of A) EC scores in FI plots; B) soil water content scores in DIS plots. Bigger circles indicate higher scores.

Table 5
Physico-chemical results for the analysis of the FI and DI water. EC is in μs/cm; K, Mg, Ca in meq/l; H_2PO_4 in μg/l; SO_4, Cl and HCO_3 in meq/l.

	FI	DI
pH	7.3	6.7
EC	1710	1710
K	0.064	0.092
Mg	6.19	5.84
Ca	11.7	10.5
H_2PO_4	<50	95
SO_4	14.3	13.4
Cl	4.8	4.2
HCO_3	2.71	1.46

is a function of their location, with the plots further from the water source being more prone to experience water stress and shortages due to water leakage and evaporation (Farrington, 1980; Mateu, 1989). In the northern hemisphere, plots facing south may get up to six times much solar radiation than those oriented north (Auslander et al., 2003; Nevo, 1997), thus leading to higher evaporation rates. Those located in lower grounds are more likely to have the water table reach the surface (Jordán et al., 2004). All these factors promote the accumulation of salts in the soil profile, which degrade the soil health by altering its structure, increasing the swelling and dispersing clay aggregates (Postiglione, 2002). The easternmost reaches of the Ricote irrigated scheme are located in the lowest grounds, face south, and suffer from water shortages due to their distance (1.2 km) from the water source (Puy, 2014; García Avilés, personal communication). Their location explain their higher EC values compared with the terrains located to the west (Fig. 5a), as the volume of FI water reaching the area is not sufficient to leach the salts down the soil profile. DI has diminished the effects of locational impairment by providing steady water inputs directly to the main root zone of lemon trees (c. 30–60 cm below ground level) (Domingo et al., 1996), dissolving salts and homogenizing EC values in the upper 30 cm all across the irrigated scheme. However, this has been in exchange of coarsening the topsoil. Unlike FI, characterised by periodical, low-energy flooding, the concentrated and highly localized water inputs under DI have fostered clay translocation and increased the presence of sand compared to the fine fraction. This coarsening process, which might degrade soil

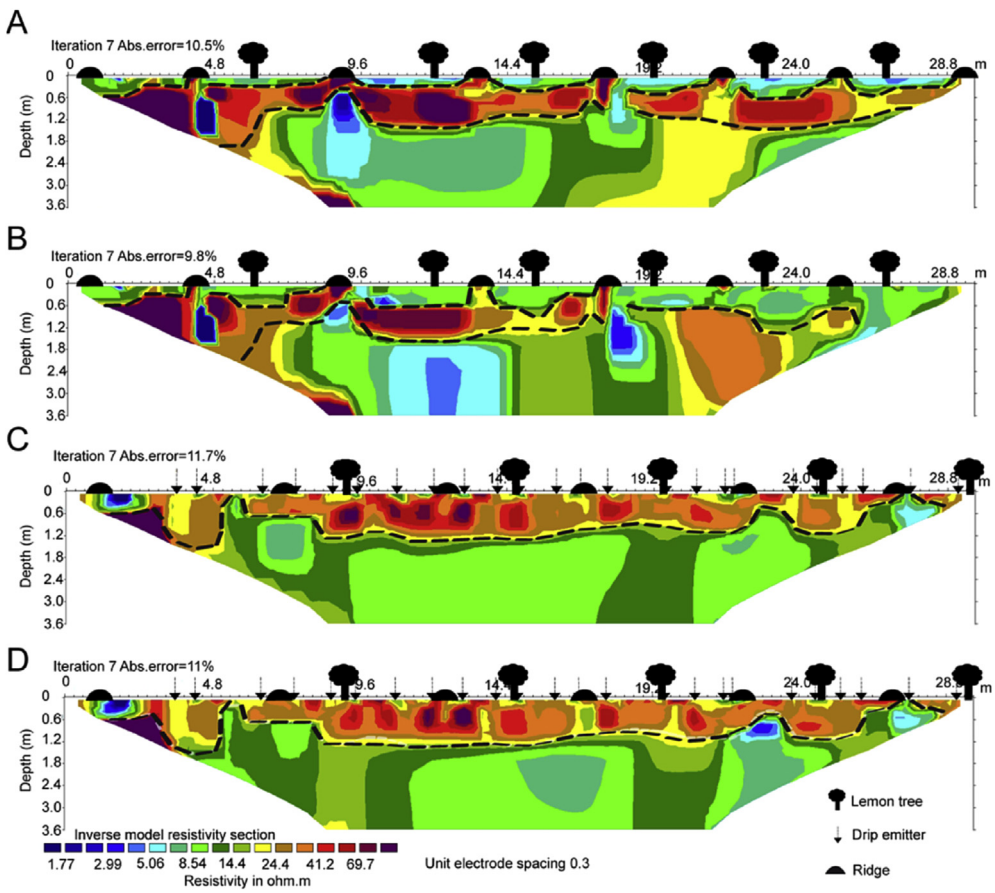

Fig. 6. ERT measurements. A) Immediately after FI. B) Same plot five hours after FI. C) Immediately after DI. D) Same plot five hours after DI.

structural stability and create illuviated layers leading to drainage problems (Warrington et al., 2007), has been widely identified as a symptom of soil degradation potentially leading to desertification (Geeson et al., 2002).

5. Conclusions

We have analysed the effects of drip irrigation (DI) uptake in formerly long-term flood-irrigated (FI) plots through the case study of Ricote (SE Spain, 120 ha, 10-13th centuries). Our results are supported by a robust statistical approach and indicate that eight years of DI are enough to modify several soil physico-chemical features. Firstly, organic matter, available P and N contents have significantly decreased in those soils that were formerly FI but are not directly irrigated in the new irrigation system. Secondly, the soils that receive direct water inputs from the DI system show significantly higher water contents, lower EC values and a higher coarse/fine ratio than FI soils. Such changes might have relevant implications in terms of greenhouse emissions, soil quality and water conservation policies, and further studies are needed in order to properly and robustly assess their environmental trade-offs. In any case, our work argues that DI uptake in formerly FI schemes might foster the degradation of the soils that are not directly drip-irrigated, which comparatively account for much larger extensions. Monitoring is suggested in order to acknowledge and tackle potential negative trends as early as possible and establish appropriate compensative strategies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2016.07.017.

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References

Aitchison, J., 1986. The Statistical Analysis of Compositional Data. Chapman & Hall, London.

Aitchison, J., Greenacre, M., 2002. Biplots of compositional. Data. Appl. Stat. 51, 375–392.
Amundson, R., 2001. The carbon budget in soils. Annu. Rev. Earth Planet. Sci. 29, 535–562.
Auslander, M., Nevo, E., Inbar, M., 2003. The effects of slope orientation on plant growth, developmental instability and susceptibility to herbivores. J. Arid. Environ. 55, 405–416.
Barceló, M., 1989. El diseño de espacios irrigados en al-Andalus: un enunciado de principios generales. In: Cara Barrionuevo, L. (Ed.), El Agua En Zonas Áridas. Arqueología E Historia. Actas Del I Coloquio de Historia Y Medio Físico, I. Instituto de Estudios Almerienses, Almería, pp. 15–47.
Bianquis, A.-M., 1989. La Reforme Agraire dans la Ghouta de Damas. OpenEdition Books, Damasc.
Brunet, P., Clément, R., Bouvier, C., 2010. Monitoring soil water content and deficit using Electrical Resistivity Tomography (ERT) – A case study in the Cevennes area, France. J. Hydrol. 380, 146–153.
Buccianti, A., Mateu-Figueras, G., Pawlowsky-Glahn, V. (Eds.), 2006. Compositional Data Analysis in the Geosciences. Geological Society, London. Special Publications 264.
Buccianti, A., Grunsky, E., 2014. Compositional data analysis in geochemistry: are we sure to see what really occurs during natural processes? J. Geochem. Explor 141, 1–5.
Carter, M.R., Gregorich, E.G. (Eds.), 2008. Soil Sampling and Methods of Analysis,, second ed. Canadian Society of Soil Science, Boca Raton.
Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences. Lawrence Erlbaum Associates, Hillsdale.
Dasberg, S., Or, D., 1999. Drip Irrigation. Springer, Berlin.
Datar, G., Del Carpio, X.V., 2009. Are Irrigation Rehabilitation Projects Good for Poor Farmers in Peru?, Policy Research Working Paper 5154. The World Bank (accessed 30.06.16). http://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-5154.
Davidson, E.A., Ackerman, I.L., 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochem 20, 161–193.
Domingo, R., Ruiz-Sánchez, M.C., Sánchez-Blanco, M.J., Torrecillas, A., 1996. Water relations, growth and yield of Fino lemon trees under regulated deficit irrigation. Irrig. Sci. 16, 115–123.
Egozcue, J.J., Pawlowsky-Glahn, V., Mateu-Figueras, G., Barceló-Vidal, C., 2003. Isometric logratio transformations for compositional data analysis. Math. Geol. 35, 279–300.
Ellis, P.D., 2010. The Essential Guide to Effect Sizes. Cambridge University Press, Cambridge.
Ercoli, L., Mariotti, M., Masoni, A., Bonari, E., 1999. Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of Miscanthus. F. Crop. Res. 63, 3–11.
FAO, 1999. In: Modernization of irrigation system Operations: Proceedings of the 5th ITIS Network international Meeting, Aurangabad, 28–30 October 1998. Bangkok (accessed 30.06.16). http://www.fao.org/3/a-x6626e/x6626e00.htm.
Farrington, I.S., 1980. The archaeology of irrigation canals, with special reference to Peru. World Archaeol. 11, 287–305.
Faul, F., Erdfelder, E., Buchner, A., Lang, A.G., 2009. Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behav. Res. Methods 41, 1149–1160.
Filzmoser, P., Gschwandtner, M., 2015. Mvoutlier: Multivariate Outlier Detection Based on Robust Methods. R package version 2.0.6.
Filzmoser, P., Hron, K., Reimann, C., 2009a. Univariate statistical analysis of environmental (compositional) data: problems and possibilities. Sci. Total Environ. 407, 6100–6108.
Filzmoser, P., Hron, K., Reimann, C., 2009b. Principal component analysis for compositional data with outliers. Environmetrics 20, 621–632.
Filzmoser, P., Hron, K., Reimann, C., Garrett, R., 2009c. Robust factor analysis for compositional data. Comput. Geosci. 35, 1854–1861.
Filzmoser, P., Hron, K., Reimann, C., 2010. The bivariate statistical analysis of environmental (compositional) data. Sci. Total Environ. 408, 4230–4238.
Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. J. Sediment. Petrol 27, 3–26.
García Avilés, J.M., 2000. El Valle de Ricote: Fundamentos Económicos de la Encomienda Santiaguista. Real Academia Alfonso X el Sabio, Murcia, pp. 1740–1780.
García-Ruiz, J.M., López-Moreno, J.I., Vicente-Serrano, S.M., Lasanta–Martínez, T., Beguería, S., 2011. Mediterranean water resources in a global change scenario. Earth-Science Rev. 105, 121–139.
Garré, S., Günther, T., Diels, J., Vanderborght, J., 2011. Sensitivity and resolution of ERT for soil moisture monitoring in contour hedgerow intercropping systems: a methodological analysis. Appl. Hydrol. 221–227.
Gerard van den Boogaart, K., Tolosana, R., Bren, M., 2014. Compositions: Compositional Data Analysis. R package version 1.40-1.
Hannam, K.D., Kehila, D., Millard, P., Midwood, A.J., Neilsen, D., Neilsen, G.H., Forge, T.A., Nichol, C., Jones, M.D., 2016. Bicarbonates in irrigation water contribute to carbonate formation and CO_2 production in orchard soils under drip irrigation. Geoderma 266, 120–126.
Hazelton, P., Murphy, B.W., 2007. Interpreting Soil Test Results: what Do All the Numbers Mean? CSIRO Publishing, Collingwood, Victoria.
Heakal, M.S., Al-Awajy, M.H., 1989. Long-term effects of irrigation and date-palm production on Torripsaments, Saudi Arabia. Geoderma 44, 261–273.
Hussein, J., Adey, M.A., Elwel, H.A., 1992. Irrigation and dryland cultivation effects on the surface properties and erodibility of a Zimbabwe vertisol. Soil Use Manag. 8, 97–103.
Hussien, S.M., Fathi, M.A., Eid, T.A., 2013. Effect of shifting to drip irrigation on some plum cultivars grown in clay loamy soil. Egypt. J. Agric. Res. 91, 217–233.
Huth, N.I., Thorburn, P.J., Radford, B.J., Thornton, C.M., 2010. Impacts of fertilisers and legumes on N_2O and CO_2 emissions from soils in subtropical agricultural systems: a simulation study. Agric. Ecosyst. Environ. 136, 351–357.
Iglesias, A., Mougou, R., Moneo, M., Quiroga, S., 2010. Towards adaptation of agriculture to climate change in the Mediterranean. Reg. Environ. Chang. 11, 159–166.
IUSS Working Group WRB, 2006. World reference base for soil resources 2006. World Soil Resources Reports No.103, second ed. FAO, Rome.
Jordán, M.M., Navarro-Pedreño, J., García-Sánchez, E., Mateu, J., Juan, P., 2004. Spatial dynamics of soil salinity under arid and semi-arid conditions: geological and environmental implications. Environ. Geol. 45, 448–456.
Kallenbach, C.M., Rolston, D.E., Horwath, W.R., 2010. Cover cropping affects soil N_2O and CO_2 emissions differently depending on type of irrigation. Agric. Ecosyst. Environ. 137, 251–260.
Karaa, K., Karam, F., Raad, R., 2009. Modernization of irrigation systems: measures to reduce pressure on water demand in Lebanon. In: El Moujabber, M., Mandi, L., Trisorio-liuzzi, G., Martín, I., Rabi, A., Rodríguez, R. (Eds.), Technological Perspectives for Rational Use of Water Resources in the Mediterranean Region. CIHEAM (Óptions Mediterranéennes: Série A), Marrakesh, pp. 241–254.
Karamanos, R.E., Flaten, D.N., Stevenson, F.C., 2014. Real differences – a lesson from an agronomist's perspective. Can. J. Plant Sci. 94, 433–437.
Kelley, A.D., Bruns, V.F., 1975. Dissemination of weed seeds by irrigation water. Weed Sci. 23, 486–493.
Khokhlova, O.S., Arlashina, E.A., Kovalevskaya, I.S., 1997. The effect of irrigation on the carbonate status of Chernozems of Central Precaucasus (Russia). Soil Technol. 11, 171–184.
Kravchenko, A.N., Robertson, G.P., 2011. Whole-profile soil carbon stocks: the danger of assuming too much from analyses of too little. Soil Sci. Soc. Am. J. 75, 235.
Kucukyumuk, C., Yildiz, H., 2013. The impacts of transition from flood irrigation to drip irrigation method on plant water consumption and yield in apple growing. Bulg. J. Agric. Sci. 19, 1018–1026.
Lal, R., 2004a. Soil carbon sequestration to mitigate climate change. Geoderma 123, 1–22.
Lal, R., 2004b. Soil carbon sequestration impacts on global climate change and food security. Science 304 (5677), 1623–1627.
Lecina, S., Isidoro, D., Playán, E., Aragüés, R., 2010a. Irrigation modernization in Spain: effects on water quantity and quality—a conceptual approach. Int. J. Water Resour. Dev. 26, 265–282.
Lecina, S., Isidoro, D., Playán, E., Aragüés, R., 2010b. Irrigation modernization and water conservation in Spain: the case of Riegos del Alto Aragón. Agric. Water Manag. 97, 1663–1675.
Lightfoot, D., 1996. Moroccan khettara: traditional irrigation and progressive desiccation. Geoforum 21, 261–273.
López Bermúdez, F., 1973. La Vega Alta del Segura. Universidad de Murcia, Murcia.
Mair, P., Schoenbrodt, F., Wilcox, R., 2015. WRS2: Wilcox Robust Estimation and Testing. R Package.
Maisiri, N., Senzanje, A., Rockstrom, J., Twomlow, S.J., 2005. On farm evaluation of the effect of low cost drip irrigation on water and crop productivity compared to conventional surface irrigation system. Phys. Chem. Earth 30, 783–791.
Maronna, R.A., Martin, R.D., Yohai, V.J., 2006. Robust Statistics. John Wiley & Sons, Chichester.
Mateu, J.F., 1989. Assuts i vores fluvials regades al País Valencià medieval. Los Paisajes Del Agua. Universitat de València, Universitat d'Alacant, València, pp. 165–185.
Narayanamoorthy, A., 2004. Impact assessment of drip irrigation in India: the case of sugarcane. Dev. Policy Rev. 22, 443–462.
Necpalova, M., Anex, R.P., Kravchenko, A.N., Abendroth, L.J., Del Grosso, S.J., Dick, W.A., Helmers, M.J., Herzmann, D., Lauer, J.G., Nafziger, E.D., Sawyer, J.E., Scharf, P.C., Strock, J.S., Villamil, M.B., 2014. What does it take to detect a change in soil carbon stock? A regional comparison of minimum detectable difference and experiment duration in the north central United States. J. Soil Water Conserv. 69, 517–531.
Nevo, E., 1997. Evolution in action across phylogeny caused by microclimatic stresses at Evolution Canyon. Theor. Popul. Biol. 52, 231–243.
Obbink, J.G., Alexander, D.M., 1977. Observations of soil water and salt movement under drip and flood irrigation in an apple orchard. Agric. Water Manag. 1, 179–190.
Parent, L.E., Parent, S.É., Ziadi, N., 2014. Biogeochemistry of soil inorganic and organic phosphorus: a compositional analysis with balances. J. Geochem. Explor 141, 52–60.
Pawlowsky-Glahn, V., Buccianti, A. (Eds.), 2011. Compositional Data Analysis: Theory and Applications. John Wiley & Sons, Chichester.
Pawlowsky-Glahn, V., Egozcue, J., 2011. Exploring compositional data with the CoDa-Dendrogram. Austrian J. Stat. 40, 103–113.
Pennock, D.J., 2004. Designing field studies in soil science. Can. J. Soil Sci. 84, 1–10.
Peterman, R.M., 1990. Statistical power analysis can improve fisheries research and management. Can. J. Fish. Aquat. Sci. 47, 2–15.
Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manag. 80, 100–116.
Pluquellec, H., 2002. How Design, Management and Policy Affect the Performance of Irrigation Projects -emerging Modernization Procedures and Design

Standards.
Postel, S., Polak, P., Gonzales, F., Keller, J., 2001. Drip irrigation for small farmers. A new initiative to alleviate hunger and poverty. Water Int. 26, 3–13.
Postiglione, L., 2002. Soil salinization in the Mediterranean, Soils. processes and implications. In: Geeson, N.A., Brandt, C.J., Thornes, J.B. (Eds.), Mediterranean Desertification: a Mosaic of Processes and Responses. John Wiley & Sons, Ltd., pp. 163–173
Puy, A., 2014. Land selection for irrigation in al-Andalus, Spain (8th century AD). J. F. Archaeol. 39, 84–100.
Puy, A., Balbo, A.L., 2013. The genesis of irrigated terraces in al-Andalus. A geo-archaeological perspective on intensive agriculture in semi-arid environments (Ricote, Murcia, Spain). J. Arid. Environ. 89, 45–56.
Puy, A., Balbo, A.L., Bubenzer, O., 2016. Radiocarbon dating of agrarian terraces by means of buried soils. Radiocarbon 58, 345–363.
R Core Team, 2015. R: a Language and Environment for Statistical Computing.
Reimann, C., Filzmoser, P., Fabian, K., Hron, K., Birke, M., Demetriades, A., Dinelli, E., Ladenberger, A., Albanese, S., Andersson, M., Arnoldussen, A., Baritz, R., Batista, M.J., Bel-lan, A., Cicchella, D., De Vivo, B., De Vos, W., Duris, M., Dusza-Dobek, A., Eggen, O.A., Eklund, M., Ernstsen, V., Finne, T.E., Flight, D., Forrester, S., Fuchs, M., Fugedi, U., Gilucis, A., Gosar, M., Gregorauskiene, V., Gulan, A., Halamic, J., Haslinger, E., Hayoz, P., Hobiger, G., Hoffmann, R., Hoogewerff, J., Hrvatovic, H., Husnjak, S., Janik, L., Johnson, C.C., Jordan, G., Kirby, J., Kivisilla, J., Klos, V., Krone, F., Kwecko, P., Kuti, L., Lima, A., Locutura, J., Lucivjansky, P., Mackovych, D., Malyuk, B.I., Maquil, R., McLaughlin, M.J., Meuli, R.G., Miosic, N., Mol, G., Négrel, P., O'Connor, P., Oorts, K., Ottesen, R.T., Pasieczna, A., Petersell, V., Pfleiderer, S., Ponavic, M., Prazeres, C., Rauch, U., Salpeteur, Schedl, A., Scheib, A., Schoeters, I., Sefcik, P., Sellersjö, E., Skopljak, F., Slaninka, I., Šorša, A., Srvkota, R., Stafilov, T., Tarvainen, T., Trendavilov, V., Valera, P., Verougstraete, V., Vidojevic, D., Zissimos, A.M., Zomeni, Z., 2012. The concept of compositional data analysis in practice - total major element concentrations in agricultural and grazing land soils of Europe. Sci. Total Environ. 426, 196–210.
Remini, B., Achour, B., Albergel, J., 2011. Timimoun's foggara (Algeria): an heritage in danger. Arab. J. Geosci. 4, 495–506.
Ricks Presley, D.R., Ransom, M.D., Kluitenberg, G.J., Finnell, P.R., 2004. Effects of thirty years of irrigation on the genesis and morphology of two semi-arid soils in Kansas. Soil Sci. Soc. Am. J. 68, 1916–1926.
Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005. Electrical resistivity survey in soil science: a review. Soil Tillage Res. 83, 173–193.
Sánchez-Martín, L., Arce, A., Benito, A., Garcia-Torres, L., Vallejo, A., 2008. Influence of drip and furrow irrigation systems on nitrogen oxide emissions from a horticultural crop. Soil Biol. Biochem. 40, 1698–1706.
Sanchez-Martín, L., Meijide, A., Garcia-Torres, L., Vallejo, A., 2010. Combination of drip irrigation and organic fertilizer for mitigating emissions of nitrogen oxides in semiarid climate. Agric. Ecosyst. Environ. 137, 99–107.
Sanderman, J., 2012. Can management induced changes in the carbonate system drive soil carbon sequestration? A review with particular focus on Australia. Agric. Ecosyst. Environ. 155, 70–77.
Schonbeck, M., 2013. An Ecological Understanding of Weeds (accessed 4.6.16). http://articles.extension.org/pages/18529/an-ecological-understanding-of-weeds.
Schüller, H., 1969. Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. Z. für Pflanzenernährung Bodenkd 123, 48–63.
Sese Mínguez, S., 2012. Perspectives of different stakeholders to implement drip irrigation systems and its consequences for land and water use. A Case Study in Cànyoles River Basin, Valencia (Spain). Universidad Pública de Navarra. MSc Thesis.
Shrivastava, P.K., Parikh, M.M., Sawani, N.G., Ramam, S., 1995. Effect of drip irrigation and mulching on tomato yield. Int. Water Irrig. 15, 17–19.
Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., Baumecker, M., 2013. Irrigation, soil organic carbon and N_2O emissions. A review. Agron. Sustain. Dev. 33, 733–749.
van den Boogaart, K.G., Tolosana-Delgado, R., 2013. Analyzing Compositional Data with R. Springer, New York.
van der Kooij, S., 2009. Why Yunquera Will Get Drip Irrigation. Social Groups Identity and Construction of Meanings as an Approach to Understand Technological Modernization. Wageningen University, Wageningen. MSc Thesis.
van der Kooij, S., Zwarteveen, M., Boesveld, H., Kuper, M., 2013. The efficiency of drip irrigation unpacked. Agric. Water Manag. 123, 103–110.
Varmuza, K., Filzmoser, P., 2010. Introduction to Multivariate Statistical Analysis in Chemometrics. Taylor and Francis, Boca Raton.
Wallace, J., 2000. Increasing agricultural water use efficiency to meet future food production. Agric. Ecosyst. Environ. 82, 105–119.
Wang, W., Zhao, J., Cheng, Q., 2014. Mapping of Fe mineralization-associated geochemical signatures using logratio transformed stream sediment geochemical data in eastern Tianshan, China. J. Geochem. Explor 141, 6–14.
Warrington, D., Goldstein, D., Levy, G.J., 2007. Clay translocation within the soil profile as affected by intensive irrigation with treated wastewater. Soil Sci. 172, 692–700.
Wilcox, R., 1994. A one-way random effects model for trimmed means. Psychometrika 59, 289–306.
Wilcox, R., 2005. Introduction to Robust Estimation and Hypothesis Testing. Elsevier, Burlington.
Wilcox, R., 2010. Fundamentals of Modern Statistical Methods: Substantially Improving Power and Accuracy. Springer, London.
Wilcox, R., 2012. Modern statistics for the social and Behavioral Sciences. A Practical Introduction. Taylor & Francis, Boca Raton.
Yohannes, F., Tadesse, T., 1998. Effect of drip and furrow irrigation and plant spacing on yield of tomato at Dire Dawa, Ethiopia. Agric. Water Manag. 35, 201–207.