Seasonal on-farm irrigation performance in the Ebro basin (Spain): crops and irrigation systems

By

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Abstract

Irrigation performance assessments are required for hydrological planning and as a first step to improve water management. The objective of this work was to assess seasonal on-farm irrigation performance in the Ebro basin of Spain (0.8 million hectares of irrigated land). The study was designed to address the differences between crops and irrigation systems using irrigation district data. Information was only available in districts located in large irrigation projects, accounting for 58 % of the irrigated area in the basin. A total of 1,617 records of plot water application (covering 10,475 ha) were obtained in the basin. Average net irrigation requirements (IR_n) ranged from 2,683 m^3 ha^{-1} in regulated deficit irrigation (RDI) vineyards to 9,517 m^3 ha^{-1} in rice. Average irrigation water application ranged from 1,491 m^3 ha^{-1} in vineyards to 11,404 m^3 ha^{-1} in rice. The Annual Relative Irrigation Supply Index (ARIS) showed an overall average of 1.08. Variability in ARIS was large, with an overall standard deviation of 0.40. Crop ARIS ranged between 0.46 and 1.30. Regarding irrigation systems, surface, solid-set sprinkler and drip irrigated plots presented average ARIS values of 1.41, 1.16 and 0.65, respectively. Technical and economic water productivities were determined for

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the main crops and irrigation systems in the Aragón region. Rice and sunflower showed the lowest productivities. Under the local technological and economic constraints, farmers use water cautiously and obtain reasonable (yet very variable) productivities.

Introduction

All water users share responsibilities in water quantity and quality conservation. Among these users, farmers must obtain adequate irrigation performance standards, since water is a decisive input in their farming operations. Irrigation performance assessments are required for hydrological planning and as a first step to improve water management. The different levels of Public Administration are currently increasing control on water resources, and focusing on the river basin as the primary geographical unit of water policy (Jensen, 2007). At the European level, the implementation of the Water Framework Directive (European Parliament, 2000) requires water application data from all economic sectors. In water-short Mediterranean countries there is a need for structured analyses on irrigation water consumption and irrigation performance.

A number of procedures have been described to assess on-farm irrigation efficiency. The classical work by Merriam and Keller (1978) was one of the first compilations of irrigation performance indicators. Burt et al. (1997) produced an update of irrigation performance indexes, stressing the hydrological implications of irrigation performance. These authors proposed three irrigation performance indexes that could be applied to time intervals exceeding one irrigation event: irrigation efficiency, irrigation consumptive use coefficient, and irrigation sagacity.

In this work, the ARIS index (Annual Relative Irrigation Supply), proposed by Malano and Burton (2001), was used to estimate irrigation performance. This index represents the ratio of irrigation supply to crop irrigation demand as:

$$\mathrm{ARIS} = \frac{\mathrm{IWA}}{\mathrm{IR_n}} \quad [1]$$

where IWA is the irrigation water applied (m^3 ha^{-1}) and IR_n are the seasonal net irrigation requirements (m^3 ha^{-1}).

An ARIS value of 1.00 implies that irrigation water application is equal to the net crop water requirements. This situation can not lead to a fulfilment of water requirements since 100 % irrigation efficiency can not be attained under commercial field conditions. Clemmens and Dedrick (1994) classified irrigation systems according to their potential application efficiency. In an optimistic scenario, the best systems attained 90 % efficiency. If water application is made equal to the net irrigation requirements with an efficiency of 90 %, the resulting ARIS value is 1.11. Under this efficiency hypothesis, any ARIS value below 1.11 implies seasonal underirrigation. Accordingly, ARIS values above 1.11 imply seasonal overirrigation. Since ARIS is a seasonal index, during short periods percolation may happen even with ARIS < 1.11, and deficit may happen even with ARIS ≥ 1.11. A detailed analysis of a particular irrigation system would be required to assess its efficiency, and therefore to establish the specific ARIS value separating seasonal deficit from seasonal excess irrigation.

The ARIS index can be used to estimate the degree of seasonal over- or underirrigation at a given field. If a field is overirrigated, ARIS will be related to irrigation efficiency. Improving irrigation efficiency constitutes a major goal for irrigation engineers and managers, since it means adjusting irrigation to crop water requirements (including salt leaching requirements). However, improving irrigation efficiency does not imply saving water. Lecina et al. (2010), analysing a large irrigation project in the Ebro Basin, concluded that irrigation modernisation (changing from surface to sprinkler irrigation) will result in improved irrigation efficiency, increased water consumption (the sum of estimated beneficial and non-beneficial consumption increased by 19-46 %, depending on the future scenario) and improved quality of the return flows. This reference illustrates with numbers the impact of improving irrigation efficiency in the area of study, and further supports previous analyses (Perry, 1999; Playán and Mateos, 2006; Perry, 2007, Ward and Pulido-Velázquez, 2008).

The Ebro basin, located in NE Spain, is one of the most intensively irrigated river basins in Europe (Wriedt et al., 2008), with about 0.8 million hectares of irrigated land. No work has reported the ARIS index in this area, but the low data requirements that characterize ARIS permit to estimate it from other performance indicators. Thus, Faci et al. (2000) analysed a surface irrigated district in the central Ebro basin grown with field crops, which yielded ARIS values of 2.00 for grain corn and 0.86 for sunflower. Lecina et al. (2005) analysed a similar irrigation district in the Ebro basin, which resulted in average ARIS values of 2.05 for 2000 and 1.51 for 2001. This interseasonal difference was attributed to moderate water scarcity in 2001, which resulted in better irrigation management. Dechmi et al. (2003) analysed a sprinkler irrigated district in the Ebro basin characterized by high energy costs for water pumping. The average crop ARIS were 0.78 for alfalfa and 0.90 for grain corn. In two sprinkler irrigated watersheds Cavero et al. (2003) found ARIS values ranging from 0.94 to 1.12 for corn, from 1.03 to 1.15 for alfalfa and from 0.57 to 1.09 for sunflower. In a wind exposed solid-set irrigation district, Zapata et al. (2009) reported data leading to average estimated ARIS values of 1.25 for grain corn and 1.59 for alfalfa. These authors concluded that the performance of this sprinkler irrigated area was strongly limited by meteorological conditions. The comparison of these works in the Ebro basin suggests that irrigation performance can be related to the irrigation system, to water scarcity and cost and to soil and climatic factors. These limited sources of information do not permit to develop average ARIS information at the basin scale, establishing differences between crops and irrigation systems.

Lorite et al. (2004) applied the ARIS index to the Genil-Cabra irrigation district (7,000 ha), located in the Guadalquivir basin, southern Spain. This area is characterized by annual ET_0 and precipitation of 1,300 and 600 mm, respectively, and a maximum seasonal water availability for irrigation of 5,000 m^3 ha^{-1} (García-Vila et al., 2008). The district was equipped with hand-move sprinkler and drip systems. The authors focused on seven crops and used data from four irrigation seasons. They found ARIS values ranging from 0.22 in sunflower to 1.19 in sugar beets, indicating severe underirrigation and slight overirrigation, respectively. Garcia-Vila et al. (2008) analysed the ARIS index in the same study area, but used 15 irrigation seasons. The average ARIS value for all crops was 0.60. Considering the different crops, these authors found ARIS values ranging from 0.23 (sunflower) and 0.28 (winter cereals) to 0.79 (cotton). Even though the Genil-Cabra area has some similarities with the Ebro basin, there are some relevant differences: 1) on-farm surface irrigation is common in the Ebro basin but this irrigation method is not used in the Genil-Cabra area; 2) water restrictions apply every year at the Genil-Cabra district; and 3) the Ebro basin is much larger in area than the Genil-Cabra district, and therefore more heterogeneous in climate and cropping patterns.

Research results from other parts of the World also permit to estimate ARIS. Thus, data from Molden et al. (1998) corresponding to surface irrigated areas located in different countries, led to regional ARIS values ranging from 0.50 to 4.16. Regarding crops, Molden (1997) collected data in India leading to ARIS values of 1.54 for wheat and 1.64 in cotton.

In the last years, irrigation performance indexes have been extended to include economic terms. Water productivity has gained importance due to the relevance currently given to economic efficiency in water allocation. Playán and Mateos (2006) presented an analysis on water productivity and discussed formulations based on yield (technical productivity, kg m^{-3}) or monetary units (economic productivity, € m^{-3}). When productivity is expressed in monetary units, the gross income or the net benefit can be used in the calculation. The type of crop and the production strategy have a relevant influence on monetary water productivity indexes.

The technical productivity of irrigation water (WP_T) can be defined as the yield (Y, kg ha^{-1}) obtained per volume of irrigation water application (IWA, m^3 ha^{-1}):

$$WP_T = \frac{Y}{IWA} \qquad [2]$$

WP_T has been reported in a number of research works (Igbadun et al, 2006; Fernández et al., 2007; Kahlown et al., 2007). WP_T has two relevant advantages: 1) it is a direct estimation of water productivity; and 2) it is not subjected to the time and space variability of economic data. Unfortunately, WP_T is not adequate to establish comparisons between crops, because yields, profits and costs can be very different. Alternative approaches to productivity are available to solve this problem. One of these approaches is the gross economic productivity of irrigation water (WP_{Eg}). It can be determined as the ratio between the gross income of a crop (I_g) and the seasonal volume of irrigation water (IWA):

$$WP_{Eg} = \frac{I_g}{IWA} \qquad [3]$$

Molden et al. (1998), Perry (2001), Ahmad et al. (2004) and Jalota et al. (2007) determined WP_{Eg} for rice in different areas of the world, ranging from 0.043 to 0.087 € m^{-3}. Perry (2001) and Jalota et al. (2007) obtained values ranging from 0.106 to 0.053 € m^{-3} for grain corn and from 0.121 to 0.100 € m^{-3} for wheat. Buendía-Espinoza et al. (2004) in pressurized irrigation systems in Mexico found that WP_{Eg} ranged from 1.65 to 2.68 € m^{-3} in tomato and from 2.14 to 2.34 € m^{-3} in pumpkin. In Spain, Lorite et al. (2004) found average values of 0.28 € m^{-3} in winter cereals, 0.23 € m^{-3} in grain corn and 2.21 € m^{-3} in garlic.

An accurate economic assessment of water productivity requires using not only income, but also costs. This is the case of the Net Economic Productivity of irrigation water (WP_{En}, € m^{-3}), which permits to compare the water productivity of different areas or crops. WP_{En} is determined as the ratio of the net crop margin (M_n, € ha^{-1}) to IWA:

$$WP_{En} = \frac{M_n}{IWA} \quad [4]$$

Jalota et al. (2007) and Perry (2001) obtained WP_{En} values from 0.020 € m^{-3} for rice and 0.034 for grain corn to 0.081 € m^{-3} for wheat.

The abovementioned indexes are influenced by factors such as the irrigation system, irrigation scheduling, fertilization, irrigation water quality, crop variety, climate, and soil characteristics. Consequently, large spatial and temporal variability has been reported.

The objectives of this work are 1) To assess seasonal on-farm irrigation performance in the Ebro basin of Spain, studying the differences between crops and irrigation systems; and 2) To determine water productivity where yields and production costs are available. This information can be used to compare the Ebro basin with other irrigated areas in the world and to establish realistic performance benchmarks.

Materials and Methods

Area description

The Ebro basin extends over an area of 85,362 km^2, located mostly in Spain (84,415 Km^2), but also including parts of France and Andorra. In Spain, the Ebro basin partially covers nine autonomous regions, and is divided into 110 districts (Fig. 1) defined by the Water Basin Authority (*Confederación Hidrográfica del Ebro*, CHE). The shape of the Basin is triangular, with mountain ranges running along the three sides, and a depression in the central part where most of the irrigated areas are located. Soil characteristics are related to altitude and to the proximity to the Ebro river or its tributaries. Soils near the rivers can be classified as Fluvisol Eutric (FAO, 1974), while in the rest of the irrigated areas the most common soil types are Xerosol Gypsic and Xerosol Calcic. These soils are often salt-affected (CHE, 2008).

A Mediterranean Continental climate is characteristic of most of the irrigated areas in the Ebro basin. Precipitation concentrates in autumn and spring. The average precipitation in the basin is 622 mm yr^{-1}. Its spatial distribution presents maximum values in the mountain zones and minimum values in the central depression (Martínez-Cob and García-Vera., 2004). At the irrigated areas, the average precipitation is usually in the range of 300-500 mm yr^{-1}.

According to the Moisture Index of the Thornthwaite Classification (Thornthwaite, 1931; Thornthwaite, 1948), the climatic type is humid or subhumid in the North and West of the Ebro basin. In the central part of the basin, the climate is semiarid or arid. According to the Thermal Efficiency index, the climatic type is Megathermal (A' with $ET_0 > 1,140$ mm) or Mesothermal (B'$_4$ with 1,140 mm $\geq ET_0 >$ 997 mm) at the central depression and the East of the basin, respectively. Towards the North or the West, the Thermal Efficiency index decreases to other Mesothermal climatic types such as B'$_3$ (997 mm $\geq ET_0 >$ 855 mm) or B'$_2$ (855 mm $\geq ET_0 >$ 712 mm).

Within the Ebro basin there are approximately 784,000 ha of irrigated land (CHE, 2008), representing one fifth of the irrigated area in Spain (Pinilla, 2002). Four regions located at the centre and East of the basin accumulate about 85 % (670,000 ha) of the irrigated area (Table 1). Surface irrigation is the most common on-farm system in the basin, occupying 69 % of the irrigated area. Sprinkler and drip irrigation follow, with 19 % and 12 % of the irrigated area, respectively (CHE, 2008). Regarding the nature of the water source, virtually all irrigation developments in the Ebro Basin use surface water resources from the Pyrenees or Iberian mountains. These water sources largely depend on snowmelt and winter precipitation. As a consequence, the choice of herbaceous crops (more or less water demanding or drought tolerant) is determined by early indicators of seasonal drought, such as surface water storage at reservoirs and winter precipitation.

The long-term meteorological records from the Zaragoza area, located at the centre of the Ebro basin, can be used to illustrate the local irrigation water requirements (Martínez-Cob and García-Vera, 2004). Average seasonal precipitation amounts to 479 mm, while seasonal reference evapotranspiration amounts to 1,149 mm. For the summer period (May-September), the average values of precipitation and evapotranspiration are 237 and 874 mm, respectively. The dominance of summer evapotranspiration over precipitation is accentuated by the strong interannual variability of precipitation in Mediterranean climates. Rainfall is not relevant for summer crops, but can be very important for winter cereals, thus affecting spring water management.

Table 1 lists the irrigated land occupied by each of the six crop categories established in this work for the four abovementioned regions. Field crops are divided into two categories: winter and summer field crops. Additionally, two typical Mediterranean fruit crops are presented in separate categories: olive trees and vineyards. Field crops are mainly grown in Aragón (81 % of the irrigated area). Summer field crops are predominant in Cataluña and Navarra (47 and

29 % of the irrigated land, respectively), but fruit trees (29 % of the irrigated land in Cataluña) and vegetable crops (21 % of the irrigated land in Navarra) are also relevant. In La Rioja, vegetable and winter field crops are the most relevant categories, each one representing 29 % of the irrigated area. Two summer field crops characterized by high crop water requirements, alfalfa and grain corn, occupy 37 % of the irrigated area (Table 1).

CHE divides the basin irrigated area into large and small irrigation projects (CHE, 2008). Large irrigation projects account for 58 % of the irrigated area. Most of them were developed by the Government, and are characterized by strong users' organizations enforcing water conservation through binomial water billing based on water records. Small irrigation projects (42 % of the irrigated area) correspond to ancient riparian canals where farmers pay water services by the hectare, and water applied is not recorded. Small irrigation projects typically use surface irrigation, and are located on the alluvial terraces of the Ebro river and its tributaries. Given the basin morphology, irrigation return flows resulting from low irrigation efficiency are often reused in downstream irrigation projects. This is particularly important in the case of small irrigation projects, where efficiency is presumed to be low. In large irrigation projects, a public-private modernization effort is currently replacing surface irrigation systems by pressurized systems.

Selecting irrigated plots

Martínez-Cob et al. (2005) set up the database which was used in this study. Cooperation with a number of irrigation districts, farmers' organizations, public water management companies and governmental offices permitted to assemble the data set, which contained information from 1,550 plots (11,528 ha). The largest data source was located in the Aragón region, where irrigation districts often use the Ador software for collective land and water management (Playán et al., 2007). This software records irrigation water application data at the plot level.

The requisite for a plot to be included in the database is that the crop and IWA are known for a given irrigation season. This requisite excluded plots located in small irrigation projects.

Irrigation water application data

The original data set contained 2,754 records of seasonal irrigation water application on the abovementioned 1,550 plots. The irrigation seasons ranged from 1982 to 2005. A subset of 1,617 records of seasonal irrigation water application were analysed in this paper. These are the records for which meteorological data was available to estimate crop water requirements using the FAO Penmann-Monteith method (Allen et al., 1998). The selected records correspond to 1,077 plots (10,475 ha), and to the irrigation seasons 1990-2005. Each record consisted of a combination of the plot characteristics (location, CHE district and area), the seasonal application of irrigation water, the crop, the year, and the irrigation system. These plots were located in 20 different CHE districts (Fig. 1). The average number of records per district was 81. The largest number of records was obtained at the *Ribera Baja de Navarra* CHE district, with 420. The CHE districts with the lowest number of records were *Plà d'Urgell* (2), *Angüés* (4) and *Alagón* (4). The irrigation season with the largest number of records was 2004 (665 records). Regarding the crops, the largest number of records corresponded to grain corn (944), alfalfa (236) and vineyards (99), while the lowest number of records corresponded to wheat (5), cherry (8) and potato (10).

Net irrigation requirements and irrigation performance

Most of the meteorological data used to estimate crop water requirements were obtained from the SIAR network of agrometeorological stations installed by the *Ministerio de Medio Ambiente, Medio Rural y Marino*, Government of Spain (MARM, 2003). Additional data were obtained from the regional agrometeorological networks of Navarra (Gobierno de Navarra, 2003) and Cataluña (Generalitat de Catalunya, 2002). These networks publish daily

FAO Penman-Monteith reference evapotranspiration (ET_0, mm day^{-1}) and precipitation (P, mm day^{-1}), among other variables. Only in the case of Navarra it was necessary to determine FAO Penman-Monteith ET_0 (Allen et al., 1998) from the supplied meteorological variables. Effective precipitation was determined following Cuenca (1989).

Crop ET (ET_c) was determined as the product of ET_0 and the corresponding crop coefficient K_c (Allen et al., 1998). K_c values were obtained from local phenology (Martínez-Cob and García-Vera, 2004) and tabulated values (Allen et al., 1998). For olive trees the monthly K_c values proposed by Pastor and Orgaz (1994) for the conditions of Andalucía (southern Spain) were used. For alfalfa, K_c curves were determined for each period between hay harvests. For fruit trees, the four phenological stages defined by Allen et al. (1998) were slightly modified to adapt them to the phenological stages defined by agronomists and physiologists, following Girona (1996). The criteria adopted by this author were also followed to estimate ET_c under Regulated Deficit Irrigation (RDI) orchard management conditions for cherry, peach and vineyards. Finally, net irrigation requirements (IR_n) were determined for each crop as the difference between ET_c and effective precipitation.

The ARIS index was selected as an indicator of irrigation performance because: 1) It was proposed in the frame of a standardization effort led by IPTRID (Malano and Burton, 2001); 2) the variables required to estimate ARIS can be easily obtained in a large number of plots within a large area of study; and 3) ARIS has been successfully used to characterize irrigation performance in Mediterranean environments (Lorite et al., 2004; García-Vila et al., 2008). In this work ARIS was determined following Eq. [1].

The three abovementioned water productivity indexes (WP_T, WP_{Eg} and WP_{En}) were used in this work (Eqs. [2], [3] and [4]). For field crops, different yields were used for surface and solid-set irrigation (Cavero et al, 2003; Sisquella et al, 2004 and Lecina et al, 2010). The average farm economic data required to determine the WP_{En} index could only be obtained for

Aragón and Navarre. Economic data for Aragón in seasons 2001 to 2005 was used (MAPA, 2002; MAPA, 2003; MAPA, 2004; MAPA, 2005; MAPA, 2006). In the determination of WP_{En}, European Union subsidies (only affecting field crops) were considered in all cases. Irrigation water costs are typically charged by the cubic meter and by the hectare. These costs were available in Aragón due to the common use of the Ador software for irrigation district management (Playán et al. 2007). Average irrigation water costs resulted different in Aragon in pressurized irrigation districts (0.03 € m^{-3} and 40 € ha^{-1}) and in surface irrigation districts (0.01 € m^{-3} and 50 € ha^{-1}). In the case of pressurized irrigation the high cost per cubic meter is associated to the energy used at the pumping stations. Economic water productivity could only be determined for the database plots located in Aragón.

Statistical analysis

The statistical analysis of the dataset was performed using the SPSS software (Statistical Package for the Social Sciences, version 15 for Windows, SPSS Inc, Chicago, USA). The analytical procedures involved ANOVA and cluster analyses.

Results and discussion

ET_0, IR_n and IWA

Annual ET_0 values for the different CHE districts are presented in Figure 2. Annual ET_0 presented a large variability among the different districts and years of study (840-1,436 mm), with an overall average value of 1,150 mm. Districts located at the Central Ebro Basin area (numbers 3, 4, 12, 14, 16 and 18) generally showed higher ET_0 values than the districts located at the North and South river basin boundaries. The Figure also presents precipitation data for the same years and locations, with an average of 398 mm. Interannual variation in P was much more important than for ET_0, although P had a relatively low weight on the determination of irrigation requirements. The variability in ET_0, precipitation and irrigation water availability within the basin did not permit to analyse seasonal irrigation performance trends responding to dry/wet years. However, it is known that precipitation events reduce ARIS even in well managed irrigation systems (Cavero et al., 2003).

The 1,617 records of IR_n were classified by crop type (Table 2). The total area occupied by crops in the database was 10,475 ha, with grain corn and alfalfa occupying the largest areas (6,342 and 1,994 ha, respectively). The average area of plots in each crop ranged between 0.6 ha in apple and 14.4 ha in cherry. The average plot area was 6.5 ha.

The overall average value of IR_n in the dataset was 5,693 $m^3\ ha^{-1}$. By crops, the average IR_n ranged (among the CHE districts and years) between 2,683 $m^3\ ha^{-1}$ for vineyards RDI and 9,517 $m^3\ ha^{-1}$ for rice. Vineyards and winter field crops showed very low IR_n, whereas alfalfa, grain corn and fruit trees with standard irrigation presented very high IR_n. In the crops where RDI was considered (cherry, peach and vineyards), the average IR_n reduction under RDI management was about 18 %.

Table 3 presents values of IWA for each crop stratified by irrigation system. Only 6 of the 18 studied crops used more than one irrigation system, since a clear association between crop and irrigation system could often be observed in the studied area. A few crops (6) had surface irrigated records, being the most important alfalfa, rice and grain corn, with respective percentages of the analysed area under surface irrigation of 38, 28 and 23 %. In sprinkler irrigated plots, grain corn and alfalfa occupied most of the area, with 69 % and 20 % of the land, respectively. In drip irrigated plots, olive trees were present in 33 % of the area, followed by vineyards (22 %).

The overall average IWA was 6,637 m^3 ha^{-1} (Table 3). The crop with the largest average IWA was rice. Other crops with high average IWA were surface irrigated alfalfa and pepper. Sprinkler irrigation records were available in these two crops, and their average IWA were noticeably lower than for surface irrigation (20 and 47 % lower, respectively). The lowest average IWA was found in vineyards (1,494 m^3 ha^{-1}) and surface irrigated barley (1,936 m^3 ha^{-1}). Standard deviations (SD) were relatively high in all cases, with rice (3,847 m^3 ha^{-1}) and pepper (2,423 m^3 ha^{-1}) showing the largest values.

Irrigation performance: Basic ARIS Statistics

Figure 3 presents the average value of ARIS ± SD for the different crops. The line ARIS = 1.00 is presented for reference. The overall average ARIS was 1.08. As previously indicated, this average value indicates slight underirrigation for any irrigation system (even with efficiencies as high as 90 %). This value is much higher than the average value reported by García-Vila et al. (2008) for the Genil-Cabra district (0.60).

The ARIS value was lower than 1.00 in 12 crops. Summer field crops (with the exception of sunflower) had ARIS values higher than 1.00. Fruit trees ARIS presented high variability, with standard management closer to unit values than RDI management. In the case of vineyards, IWA was lower than the IR_n corresponding to RDI management. This seems to correspond to a production strategy related to wine quality, since in the Ebro basin water restrictions are not applied every year, and irrigation water costs in vineyards are not relevant. Olive trees, vineyards and most vegetable crops presented ARIS values clearly indicating underirrigation.

High variability was found in ARIS, affecting all crop groups (Figure 3). The ARIS standard deviation (Table 4) was 0.29 in average, with the minimum (0.11) corresponding to drip irrigated olive trees and the maximum (0.65) corresponding to solid-set irrigated barley. ARIS variability within each crop was generally high, and could be primarily attributed to variability in irrigation management.

Table 4 also presents basic ARIS statistics for the combination of crops and irrigation systems. Average ARIS exceeded 1.00 only in 12 of 28 combinations. The lowest average ARIS values were found in drip irrigated vineyards (0.46) and solid-set irrigated asparagus (0.47). The adoption of RDI in fruit trees can be assessed from Table 4. Concentrating on drip irrigated cherry and peach, and adopting the 1.11 threshold for ARIS, RDI management results in moderate overirrigation (1.21 for peach and 1.30 for cherry), while standard management results in slight underirrigation (0.99 for peach and 1.08 for cherry). Standard management seems to prevail in these two crops, although RDI seems to be a common practice in the area.

Considering previous work in the area, our results for surface irrigation show lower ARIS than reported by Faci et al. (2000) for 1994 in corn and sunflower. Recent improvements in local surface irrigation management can explain these differences, as evidenced by Lecina et al. (2005). In solid-sets, however, results from the literature (Cavero et al., 2003; Dechmi et al., 2003 and Zapata et al., 2009) fit in the reported distribution of ARIS values. Improved control of water application and relevant energy costs contribute to the fact that ARIS values in the area are lower for solid-set irrigation than for surface irrigation.

ARIS in the Ebro basin and in the Genil-Cabra area can be compared for the four crops in present in both studies (Lorite et al., 2004). Winter cereals ARIS in Genil-Cabra was 0.39 compared to 0.79 for barley and 0.58 for wheat in the Ebro basin; grain corn was 0.73 compared to 1.21 in the Ebro basin; sunflower was 0.28 compared to 0.68 in the Ebro basin; and olive trees was 0.37 compared to 0.64 in the Ebro basin. The lower ARIS values reflect more water scarcity at the Genil-Cabra district. Larger ARIS variability could be expected at the Ebro basin than at the Genil-Cabra district, owing to the differences in geographic extension, climate, soils and irrigation technologies. However, clear differences in ARIS variability between both areas could not be established, with crop ARIS SD ranging between 0.18 and 0.31 at the Genil-Cabra district and between 0.11 and 0.57 at the Ebro basin.

Figure 4 presents three scatter plots where IR_n and IWA are compared for a) all data set records; b) crop types; and c) irrigation systems. Considering all data set records, most of the points showing low IR_n are located below the diagonal line, while points with high IR_n are generally located above it (Fig. 4a). All crop types excepting summer field crops are located below the 1:1 line, with olive trees and vineyards clearly deviating from it on the underirrigation side (Fig. 4b). Clear differences between the three irrigation systems were found (Fig. 4c). Surface irrigated plots presented IWA clearly higher than IR_n (ARIS = 1.41). Solid-set and drip systems were located closer to the 1:1 line. Solid-set irrigated plots showed slightly higher IWA than IR_n (ARIS = 1.16), and drip irrigated plots showed clear underirrigation (ARIS = 0.65).

The relationship between irrigation systems and crops is further explored in Figure 5. Four surface irrigated crops (rice, alfalfa, pepper and grain corn) showed higher IWA than IR_n (Fig. 5a). For solid-set sprinkler irrigation, only summer field crops and onion showed IWA higher than IR_n (Fig. 5b). For drip irrigation, only peach RDI and cherry (both standard and RDI) presented IWA higher than IR_n (Fig. 5c), and in all cases near of the 1:1 line.

Irrigation performance: Classification of ARIS results

A cluster classification analysis was performed for each combination of crop – irrigation system using IR_n and IWA as independent variables (Figure 6). Four main groups (A, B, C and D) were obtained, two of which (B and C) were divided in two subgroups (1 and 2). Figure 7 presents a scatter plot of IR_n and IWA for the crop – irrigation system combinations belonging to each subgroup resulting from the cluster analysis. Group A presented very high values of IWA and IR_n. Group B was characterized by medium-high IR_n, and was divided in two subgroups: B1 with very high IWA and B2 with high IWA. Group C was characterized by medium-high IR_n and medium (C1) or low (C2) IWA. Group D included combinations of crop-irrigation system showing low IR_n and very low IWA.

Irrigation Water Productivity

Irrigation water productivity in the Aragón region was determined for ten crop – irrigation system combinations (Table 5). The variability in productivity between crops and irrigation systems was large, and increased from WP_T to WP_{Eg} and to WP_{En}. The ratios of maximum to minimum productivity were 14, 16 and 24, respectively. Transition from WP_T to WP_{En} increased the observed differences between crops and irrigation systems. In the case of barley, alfalfa, grain corn and sunflower, solid-set irrigated crops had higher water productivities than surface irrigated crops, due to the fact that irrigation depth was lower and yield was higher in sprinkler irrigation than in surface irrigation.

WP_{Eg} and WP_{En} showed similar trends as WP_T regarding crops and irrigation systems, although costs were higher for solid-set sprinkler systems than for surface irrigation systems. Comparing the two most frequent crops in the Ebro basin, grain corn showed higher economic productivities than alfalfa. Rodrigues and Pereira (2009) presented results of water productivity for three crops in a sprinkler irrigated area near Évora (south of Portugal). Different deficit irrigation scenarios, locations, dry/wet years and potential application efficiencies were considered. Comparisons with the present study could be established in terms of WP_T. Technical productivity was higher in Portugal, with ranges of 1.11-2.75 kg m^{-3} for corn, 0.61-2.46 kg m^{-3} for sunflower, and 1.48-15.44 kg m^{-3} for wheat. The comparatively low crop water requirements at Évora and the use of deficit irrigation contributed to these high productivity figures. When comparisons in WP_{Eg} were established between the Genil-Cabra district (period 1997 - 2000) (Lorite et al., 2004) and the Aragón region (period 2001 - 2005), irrigation water productivity was higher in the Genil-Cabra district for the four common crops: sprinkler irrigated winter cereals (0.91 € m^{-3} vs. 0.26 € m^{-3} for barley and 0.19 € m^{-3} for wheat), sprinkler irrigated grain corn (0.28 € m^{-3} vs 0.16 € m^{-3}), sprinkler irrigated sunflower (0.56 € m^{-3} vs. 0.11 € m^{-3}), and drip irrigated olive trees (2.34 € m^{-3} vs. 0.52 € m^{-3}). These differences were heavily influenced by irrigation water application: deficit irrigation in Genil-Cabra increased economic productivity. Although the Ebro basin and the Genil-Cabra district are similar in many aspects, differences in the agricultural and economic context, and in the analysed period, make comparisons difficult.

Conclusions

The reported results permitted to analyse irrigation water application in large irrigation projects of the Ebro basin, in which irrigation districts keep crop and water records. The analysis of the data set has revealed that in the period of study farmers used water cautiously.

For each crop, data variability was higher in IWA than in IR_n since IWA is subjected to farmer's economic decisions and water management practices. The crops with minimum and maximum IWA (vineyards and rice) adequately illustrate this variability. While irrigation of vineyards is mostly driven by market preferences, irrigation of rice is mainly influenced by soil infiltration.

The overall average ARIS was 1.08. This value suggests that on the average, Ebro basin crops suffered slight underirrigation. Summer field crops (except sunflower) and fruit trees under RDI management presented the highest ARIS values. Drip irrigation of fruit trees under RDI management resulted in moderate overirrigation, while consideration of standard management resulted in slight underirrigation. Standard management prevails in the Ebro basin, although RDI seems to be a common practice. In the case of vineyards, farmers used less water than the considered RDI strategy, apparently searching for higher wine quality.

For a given crop, ARIS was generally lower under solid-set irrigation than under surface irrigation. The differences averaged 0.20 in grain corn (14 % lower) and 0.39 in alfalfa (24 % lower). The cluster analysis performed on IWA and IR_n identified four significantly different groups, stressing the need to consider the association between crops and irrigation systems. In fact, the reported differences on irrigation systems were very relevant to explain the differences among crops. The standard deviation of ARIS values was large (0.29 on the average) even for the combinations of crop and irrigation system.

In general, water productivity was higher in solid-set sprinkler than in surface irrigation. Differences among the three indicators in the ranking of associations of crop - irrigation system were moderate.

The results of this study have permitted to identify structural and managerial problems associated to current on-farm irrigation performance in the study area. Structural problems are currently being addressed *via* irrigation modernization (from surface to sprinkler irrigation). These projects are reducing on-farm water application. In the case of grain corn and alfalfa, the change of irrigation system will lead to average reductions in water application of 11 and 20 %, respectively. Managerial problems are related to specific crops showing poor irrigation performance. Additionally, the large variability in water applied to a given crop and irrigation system requires actions to improve farmers' water management via a combination of irrigation advisory services and policy measures.

Reductions in crop water application will permit to benefit more from water storage at the reservoirs and to control on-farm nutrient leaching. However, basin-wide water consumption will probably increase owing to the combination of improved uniformity, improved irrigation scheduling, increased evaporation losses (associated to sprinkler irrigation) and maybe to increased cropping intensity. In addition to these hydrologic effects, adjusting water application to water requirements will strongly increase the sustainability of irrigation in the valley. Productivity per unit land area and unit water applied (technical and economical) will increase, but according to local studies (Lecina et al., 2010) productivity based on water consumption is likely to remain constant. As a consequence, improving irrigation performance and maintaining the current irrigated area would result in increased water consumption and water scarcity in the basin. Decisions will have to be made regarding the target Ebro valley production and water depletion associated to irrigated agriculture.

ARIS has resulted adequate to assess on-farm irrigation performance. Its low data requirements permit applications to large areas with moderate effort. However, ARIS significance is affected by the use of net irrigation requirements instead of actual crop consumptive use. This is a major limitation when comparing crop ARIS under different management schemes or irrigation systems, since crop evapotranspiration is likely to change owing to varying degrees of crop water stress. On the other hand, ARIS does not permit to account for the hydrological interdependencies between different irrigated areas and types of water uses in a basin (i.e., water reuse). As a consequence, ARIS is clearly insufficient to judge system performance at a basin scale. Water accounting provides the necessary insight on water consumption in large hydrological systems. Minimising non-beneficial consumption and limiting water consumption to sustainable levels are key objectives at the basin scale, which can not be attained through the analysis of on-farm performance indicators such as ARIS.

Acknowledgements

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Table 1.

	Aragón 2003 (thousand ha)	**Cataluña 1999 (thousand ha)**	**Navarra 2003 (thousand ha)**	**La Rioja 2003 (thousand ha)**	**Total - (thousand ha)**
Winter field crops	100	28	16	9	**153**
Summer field crops	207	81	32	5	**325**
Fruit trees	42	50	4	5	**101**
Vegetable crops	11	4	17	9	**41**
Olive trees	11	8	2	1	**22**
Vineyards	9	3	11	5	**28**
Total	**380**	**174**	**82**	**34**	**670**

Table 2.

Crop type	Crop	Number of records	Area: Total (ha)	Area: Average (ha)	IR_n: Average (m^3 ha^{-1})	IR_n: Maximum (m^3 ha^{-1})	IR_n: Minimum (m^3 ha^{-1})
Winter field crops	Barley	12	122	10.2	3,335	4,213	2,405
	Peas	21	112	5.3	3,068	3,681	1,844
	Wheat	5	47	9.3	3,992	5,176	2,640
Summer field crops	Alfalfa	236	1,994	8.4	6,992	8,935	4,740
	Grain corn	944	6,342	6.7	5,990	7,345	4,389
	Rice	21	147	7.0	9,517	10,223	8,575
	Sunflower	12	50	4.1	5,300	6,355	4,587
Fruit trees	Apple	11	6	0.6	5,865	6,663	5,707
	Cherry	8	58	14.4	5,533	6,236	4,657
	Cherry RDI	8	58	14.4	4,599	5,162	3,861
	Peach	22	90	6.0	6,045	7,046	5,095
	Peach RDI	22	90	6.0	4,884	5,734	4,136
	Pear	22	36	1.9	5,899	6,807	5,535
Vegetable crops	Asparagus	16	68	4.2	4,860	5,201	4,349
	Onion	34	190	5.6	6,683	7,632	5,942
	Pepper	26	100	3.8	5,528	6,677	4,579
	Potato	10	31	3.1	5,140	5,409	4,737
	Tomato	69	340	4.9	6,063	7,306	5,418
Olive trees	Olive trees	49	447	9.1	4,514	5,053	2,048
Vineyards	Vineyards	99	296	3.0	3,309	4,591	2,640
	Vineyards RDI	99	296	3.0	2,683	3,790	2,098

Table 3.

Crop type	Crop	Irrigation system	Number of records	Total area (ha)	IWA Average ($m^3\ ha^{-1}$)	IWA SD ($m^3\ ha^{-1}$)
Winter field crops	Barley	Solid-set	9	79	2,602	1,687
		Surface	3	43	1,936	490
		All	**12**	**122**	**2,436**	**1,484**
	Peas	Solid-set	**21**	**112**	**3,526**	**1,609**
	Wheat	Solid-set	**5**	**47**	**2,228**	**920**
Summer field crops	Alfalfa	Solid-set	211	1,791	8,597	1,793
		Surface	25	202	10,731	1,990
		All	**236**	**1,994**	**8,823**	**1,926**
	Grain corn	Solid-set	917	6,218	7,173	1,827
		Surface	27	124	8,077	1,664
		All	**944**	**6,342**	**7,199**	**1,828**
	Rice	Surface	**21**	**147**	**11,404**	**3,847**
	Sunflower	Solid-set	9	43	3,460	1,589
		Surface	3	7	3,795	1,229
		All	**12**	**50**	**3,544**	**1,461**
Fruit trees	Apple	Drip	**11**	**6**	**3,345**	**1,425**
	Cherry	Drip	**8**	**58**	**6,007**	**1,609**
	Peach	Solid-set	3	13	4,492	720
		Drip	19	77	5,865	1,035
		All	**22**	**90**	**5,678**	**1,096**
	Pear	Drip	**22**	**36**	**4,541**	**1,498**
Vegetable crops	Asparagus	Solid-set	**16**	**68**	**2,303**	**1,221**
	Onion	Solid-set	**34**	**190**	**6,972**	**1,349**
	Pepper	Solid-set	20	93	5,510	1,193
		Surface	6	7	10,409	1,340
		All	**26**	**100**	**6,641**	**2,423**
	Potato	Solid-set	**10**	**31**	**3,933**	**1,246**
	Tomato	Solid-set	**69**	**340**	**5,394**	**1,362**
Olive trees	Olive trees	Drip	**49**	**447**	**2,878**	**619**
Vineyards	Vineyards	Drip	**99**	**296**	**1,494**	**764**
(*)		**-**	**1,617**	**10,475**	**6,637**	**1,418**

(*) Data represent summation in columns “number of records” and “total area”, average in columns “average IWA” and “SD IWA”.

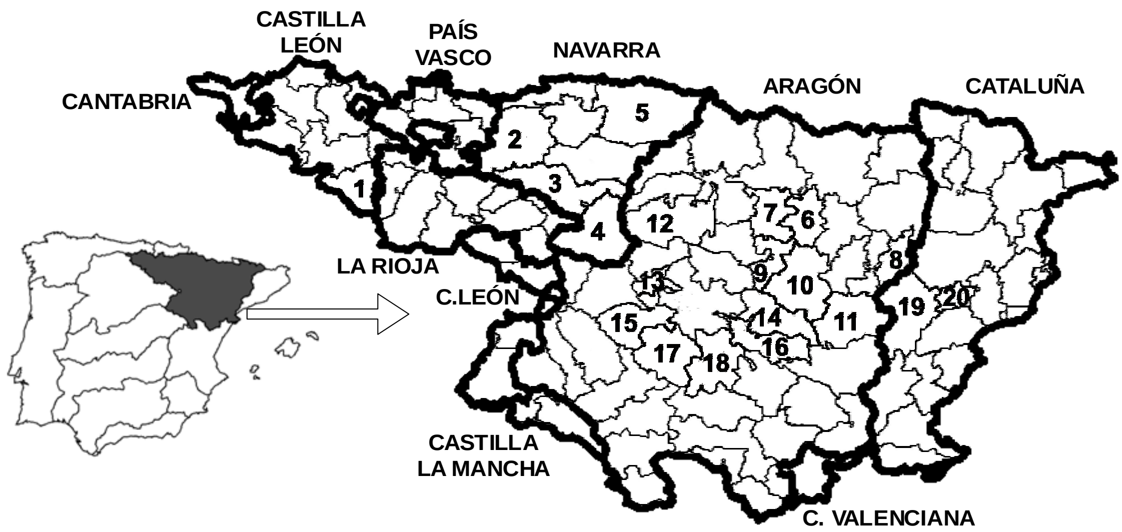
Table 4.

Crop type	Crop	Irrigation system	ARIS Average	ARIS SD
Winter field crops	Barley	Solid-set	0.87	0.65
		Surface	0.55	0.14
		All	**0.79**	**0.57**
	Peas	Solid-set	**1.18**	**0.63**
	Wheat	Solid-set	**0.58**	**0.18**
Summer field crops	Alfalfa	Solid-set	1.25	0.31
		Surface	1.64	0.52
		All	**1.30**	**0.36**
	Grain corn	Solid-set	1.20	0.30
		Surface	1.40	0.38
		All	**1.21**	**0.30**
	Rice	Surface	**1.21**	**0.43**
	Sunflower	Solid-set	0.63	0.28
		Surface	0.81	0.26
		All	**0.68**	**0.28**
Fruit trees	Apple	Drip	**0.56**	**0.21**
	Cherry	Drip	**1.08**	**0.20**
	Cherry RDI	Drip	**1.30**	**0.24**
	Peach	Solid-set	0.74	0.19
		Drip	0.99	0.20
		All	**0.95**	**0.22**
	Peach RDI	Solid-set	0.97	0.27
		Drip	1.21	0.25
		All	**1.18**	**0.26**
	Pear	Drip	**0.77**	**0.26**
Vegetable crops	Asparagus	Solid-set	**0.47**	**0.24**
	Onion	Solid-set	**1.05**	**0.19**
	Pepper	Solid-set	1.00	0.22
		Surface	1.93	0.32
		All	**1.21**	**0.47**
	Potato	Solid-set	**0.76**	**0.24**
	Tomato	Solid-set	**0.89**	**0.21**
Olive trees	Olive trees	Drip	**0.64**	**0.11**
Vineyards	Vineyards	Drip	**0.46**	**0.26**
	Vineyards RDI	Drip	**0.58**	**0.33**

Table 5.

Crop type	Crop	Irrigation system	Water Productivity WP_T (Kg m^{-3})	WP_{Eg} (€ m^{-3})	WP_{En} (€ m^{-3})
Winter field crops	Barley	Solid-set	2.5	0.26	0.20
		Surface	2.3	0.28	0.19
	Wheat	Solid-set	1.6	0.19	0.043
Summer field crops	Alfalfa	Solid-set	1.8	0.11	0.083
		Surface	1.1	0.077	0.052
	Grain corn	Solid-set	1.6	0.16	0.13
		Surface	1.2	0.13	0.10
	Rice	Surface	0.45	0.081	0.059
	Sunflower	Solid-set	0.68	0.11	0.068
		Surface	0.53	0.089	0.045
Fruit trees	Apple	Drip	6.4	1.2	1.0
	Peach	Drip	4.1	0.91	0.74
	Pear	Drip	4.2	1.1	0.91
Olive trees	Olive trees	Drip	1.1	0.52	0.42

Figure 1:

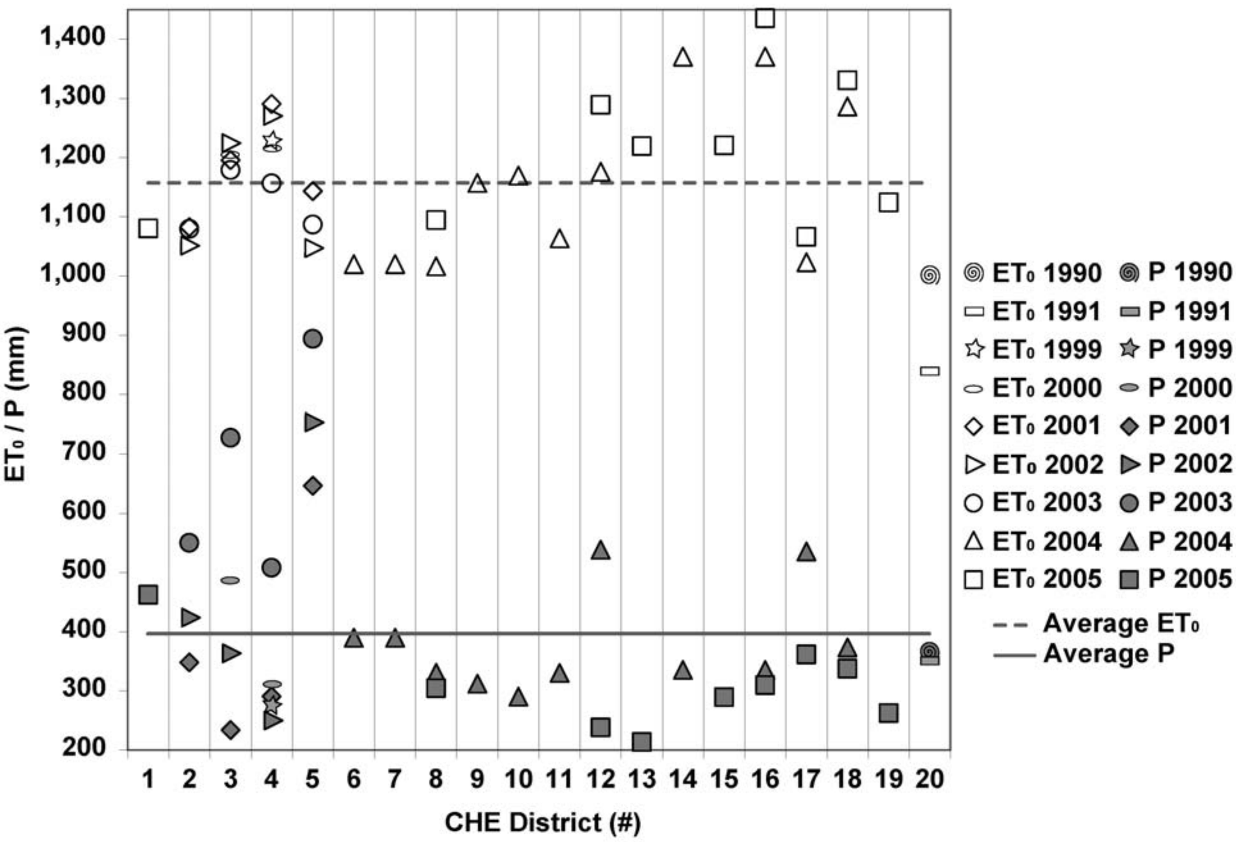


#	CHE District	Records
1	BELORADO	6
2	TIERRA ESTELLA	96
3	RIBERA ALTA-ARAGÓN	288
4	RIBERA BAJA NAVARRA	420
5	NAVARRA PIRINEOS	37
6	ANGÜÉS	4
7	HUESCA	14

#	CHE District	Records
8	TAMARITE DE LITERA	29
9	GRAÑÉN	107
10	SARIÑENA	220
11	FRAGA	91
12	EJEA DE LOS CABALLEROS	85
13	ALAGÓN	4
14	PINA DE EBRO	133

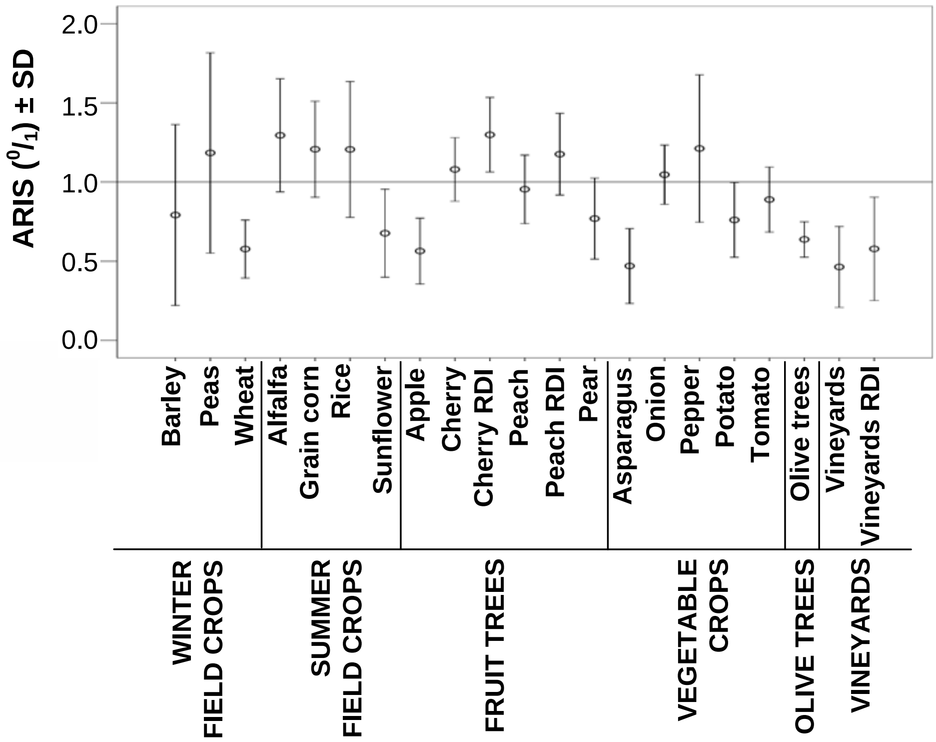
#	CHE District	Records
15	ÉPILA-LA ALMUNIA	5
16	QUINTO DE EBRO	18
17	CARIÑENA	8
18	BELCHITE	43
19	SEGRIÀ	7
20	PLÀ D'URGELL	2

Figure 2:



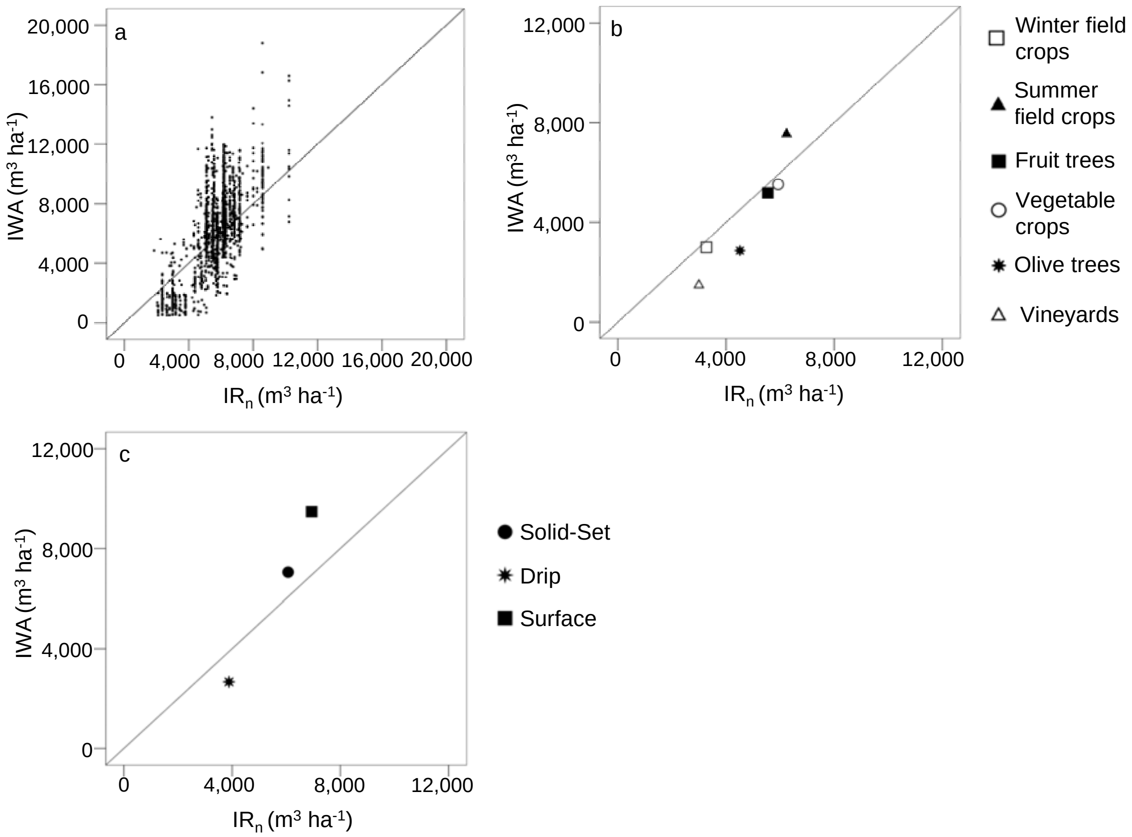
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
ET0 / P (mm)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
CHE District (#)
ET0 1990 P 1990
ET0 1991 P 1991
ET0 1999 P 1999
ET0 2000 P 2000
ET0 2001 P 2001
ET0 2002 P 2002
ET0 2003 P 2003
ET0 2004 P 2004
ET0 2005 P 2005
Average ET0
Average P

Figure 3:



ARIS (⁰/₁) ± SD
2.0
1.5
1.0
0.5
0.0
Barley
Peas
Wheat
Alfalfa
Grain corn
Rice
Sunflower
Apple
Cherry
Cherry RDI
Peach
Peach RDI
Pear
Asparagus
Onion
Pepper
Potato
Tomato
Olive trees
Vineyards
Vineyards RDI
WINTER FIELD CROPS
SUMMER FIELD CROPS
FRUIT TREES
VEGETABLE CROPS
OLIVE TREES
VINEYARDS

Figure 4:



a
20,000
16,000
12,000
8,000
4,000
0
IWA (m3 ha-1)
0
4,000
8,000
12,000
16,000
20,000
IRn (m3 ha-1)
b
12,000
8,000
4,000
0
IWA (m3 ha-1)
0
4,000
8,000
12,000
IRn (m3 ha-1)
Winter field crops
Summer field crops
Fruit trees
Vegetable crops
Olive trees
Vineyards
c
12,000
8,000
4,000
0
IWA (m3 ha-1)
0
4,000
8,000
12,000
IRn (m3 ha-1)
Solid-Set
Drip
Surface

Figure 5.

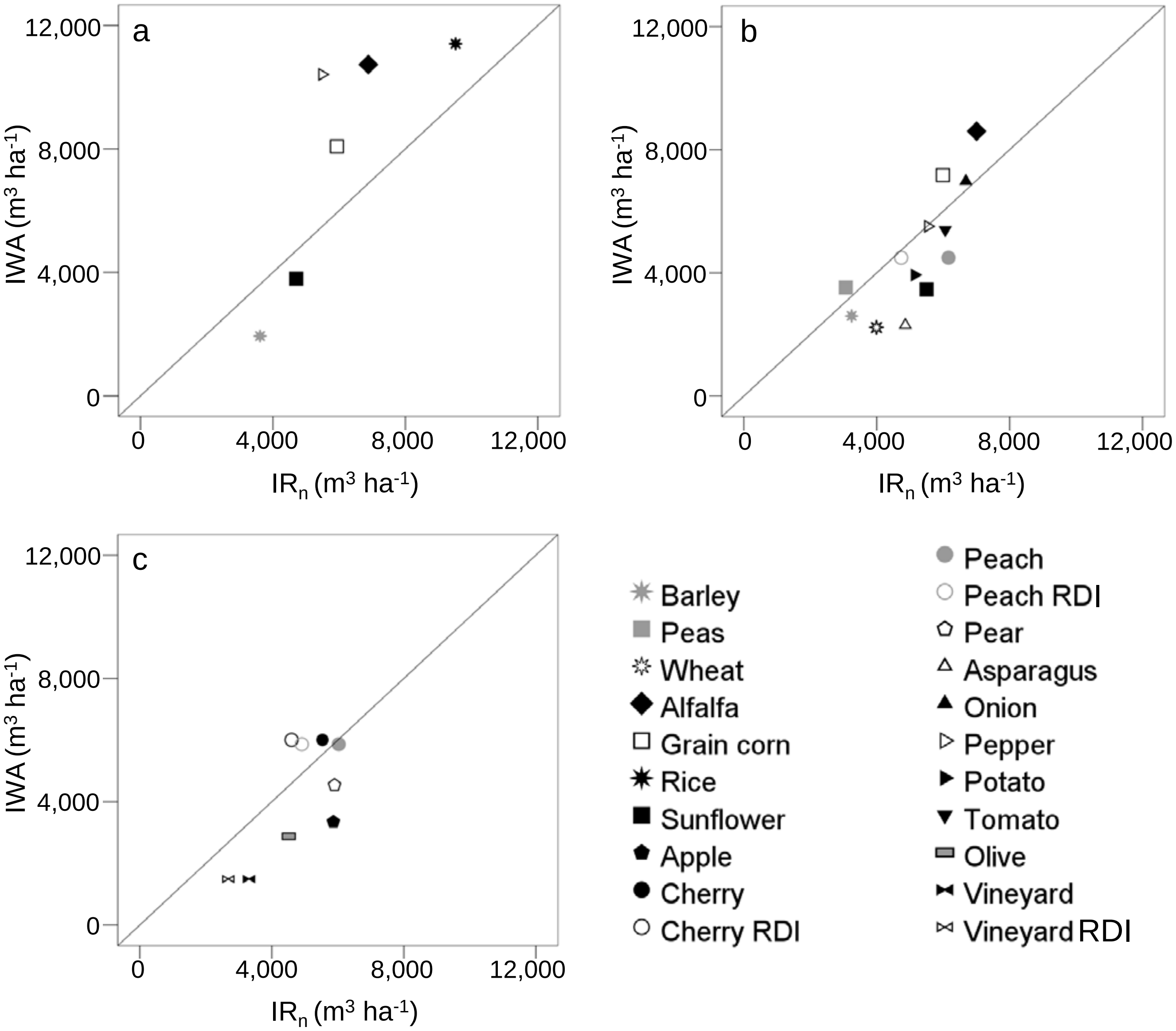

a
b
c
IWA (m3 ha-1)
IRn (m3 ha-1)
0
4,000
8,000
12,000
Barley
Peas
Wheat
Alfalfa
Grain corn
Rice
Sunflower
Apple
Cherry
Cherry RDI
Peach
Peach RDI
Pear
Asparagus
Onion
Pepper
Potato
Tomato
Olive
Vineyard
Vineyard RDI

Figure 6:

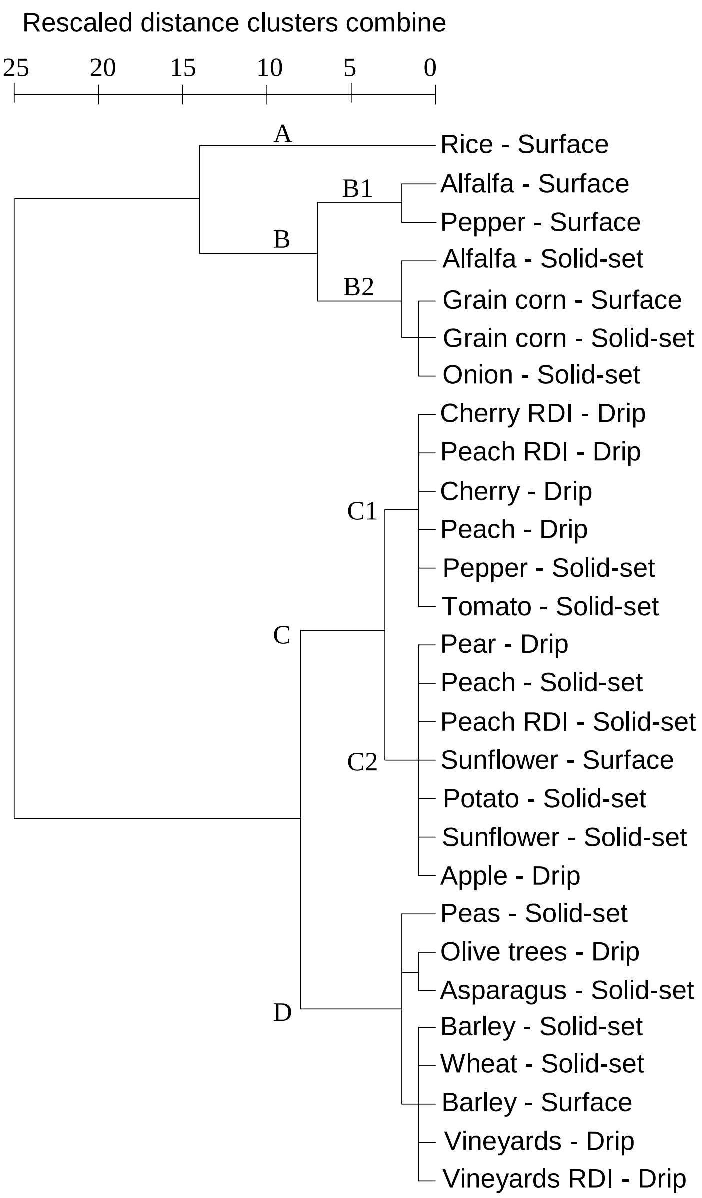
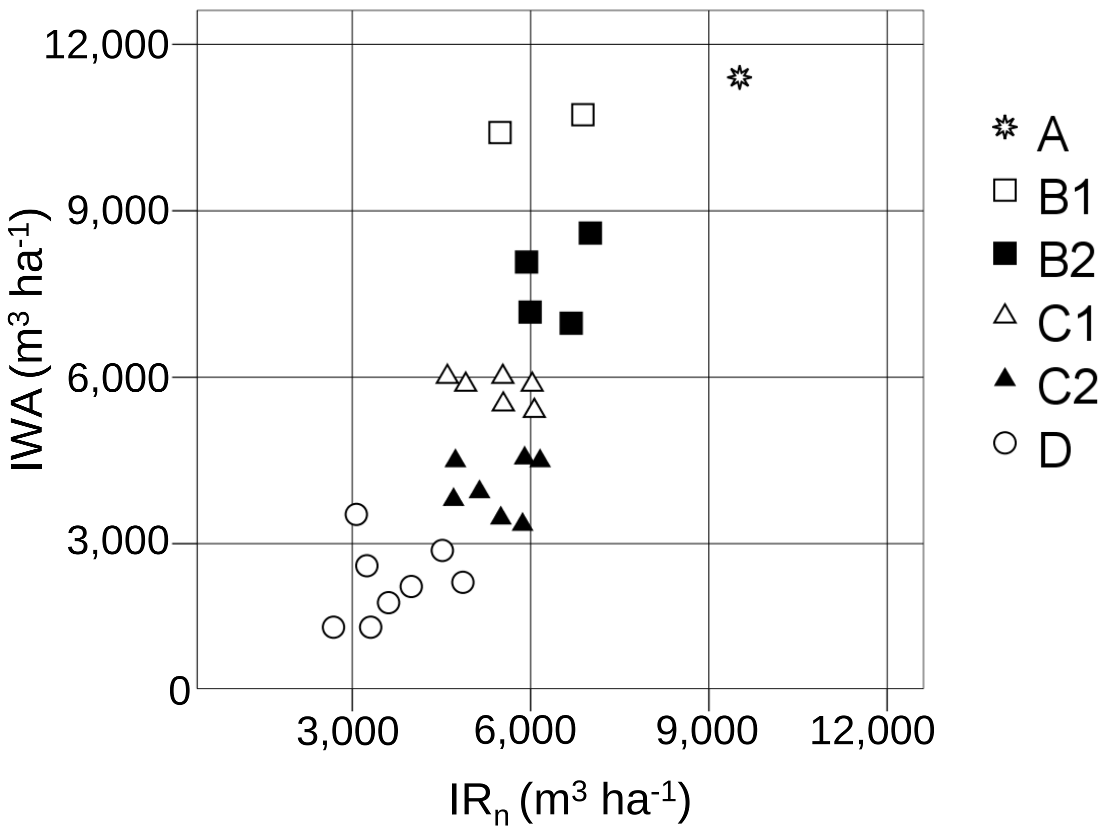

Rescaled distance clusters combine
25
20
15
10
5
0
A
B
B1
B2
C
C1
C2
D
Rice - Surface
Alfalfa - Surface
Pepper - Surface
Alfalfa - Solid-set
Grain corn - Surface
Grain corn - Solid-set
Onion - Solid-set
Cherry RDI - Drip
Peach RDI - Drip
Cherry - Drip
Peach - Drip
Pepper - Solid-set
Tomato - Solid-set
Pear - Drip
Peach - Solid-set
Peach RDI - Solid-set
Sunflower - Surface
Potato - Solid-set
Sunflower - Solid-set
Apple - Drip
Peas - Solid-set
Olive trees - Drip
Asparagus - Solid-set
Barley - Solid-set
Wheat - Solid-set
Barley - Surface
Vineyards - Drip
Vineyards RDI - Drip

Figure 7.



12,000
9,000
6,000
3,000
0
IWA (m3 ha-1)
3,000
6,000
9,000
12,000
IRn (m3 ha-1)
A
B1
B2
C1
C2
D