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Title

Plot level assessment of irrigation water savings due to the shift from sprinkler to localized irrigation systems or to the use of soil hydric status probes. Application in the French context

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Abstract

In order to reduce irrigation water withdrawal, the European Commission provides grants to farmers for investments in irrigation techniques that save water. However, little is known about the real extent of water savings at plot scale resulting from change in irrigation application equipment or the adoption of scheduling devices in a given agro-pedo-climatic context.

The aim of this study was to evaluate irrigation water savings achievable by switching from sprinkler to localized irrigation system or by using soil hydric status probes. For this purpose,

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we used the French metropolitan context for our case study and compiled all available studies conducted over the past 30 years. A total of 93 records were collected from experimental field trials representative of a wide range of pedo-climatic conditions (25 different sites) and crops (field crops, fruit and vegetable production). Each record represents the water consumption of two different irrigation systems (sprinkler system vs localized system) or two scheduling systems (without soil probe vs with soil probe) at plot scale and is used to assess the water saving made when comparing the most water consuming system to the least consuming one.

Results show that water savings are highly variable, ranging from 0% to more than 75% of the initial consumption. They originate in both irrigation technology and management. Their key features are the following. (1) Water savings made with localized systems, when compared to sprinkler irrigation, significantly decrease when the hydric deficit of the cropping season increases and when soil water holding capacity rises. Moreover, they tend to be higher when irrigation is managed with soil probes. (2) Water savings obtained with irrigation scheduling using soil probes (when compared to scheduling without probes) seem, on the contrary, not to be influenced by hydric deficit and soil water holding capacity. The type of soil probe (tensiometric or capacitive) used has no influence on the water savings obtained. (3) Water savings achieved with either localized systems or soil probes result in increased irrigation water productivity and are only marginally influenced by crop type.

This frame of reference for irrigation water savings can guide public policies encouraging and financially supporting the implementation of water saving systems, not only on the subject of irrigation devices, but also on irrigation scheduling tools.

Highlights

- Water savings due to localized systems decrease when the hydric deficit increases.
- Water savings due to localized systems decrease when soil water holding capacity rises.
- Water savings due to scheduling with soil probes are not influenced by hydric deficit.
- Water savings due to soil probes are not influenced by soil water holding capacity.
- Irrigation water savings increase irrigation water productivity

Keywords

Drip; microsprinkler; irrigation scheduling; climatic hydric deficit; soil water holding capacity; irrigation water productivity

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Declarations of interest

None

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1. Introduction

Agriculture is a sector often criticized for its excessive water consumption. Indeed, agriculture is responsible for approximately 70 % of total freshwater withdrawal in the world, mostly through irrigation (FAO, 2015). This water abstraction rate is highly variable among countries as it is estimated at 24% for the whole European Union (European Environment Agency, 2009), 73% for Portugal, 61% for Spain and 12 % for France (Gleick, 2014).

As water scarcity intensifies in most countries due to climate change, water savings are of increasing concern and European water-resource policy targets sustainable water management and water savings. For this purpose, it supports investments in efficient irrigation equipment via the European Agricultural Fund for Rural Development (EAFRD). In this context, “an investment in an improvement to an existing irrigation installation or element of irrigation infrastructure shall be eligible only if it is assessed *ex ante* as offering potential water savings of a minimum of between 5% and 25% according to the technical parameters of the existing installation or infrastructure” (European Union (2013), Article 46, point 4).

Water savings can be achieved, through proper design and management of the irrigation system, by optimizing water allocation over crop cycle and reducing irrigation water losses, whose definition and estimation vary among approaches (Seckler et al, 2003; Jensen, 2007; Perry, 2007; Lankford, 2012; Van Halsema and Vincent, 2012). The first approach, linked with the concept of “classical irrigation efficiency”, focuses on the ratio of water beneficially used by the crop (evapotranspiration) to the water delivered, or the ratio of yield to water delivered. The second one, called the “neoclassical” approach, takes into account the part of delivered water potentially available for downstream reutilization. The classical approach is appropriate at plot scale and considers that water leaving the plot is lost (Hsiao, 2007). The neoclassical one is relevant for water resource management at the basin scale, as it values the reuse of return flow, which is useful for the monitoring of water table levels (Richter et al, 2017). However, in this case one must take into account that the quality of reused water may be lower than the quality of the first use water.

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In the above-mentioned European regulatory context, water savings are basically considered at plot or farm scale, in keeping with the "classical efficiency" approach. In this case, irrigation water losses include direct evaporation and wind drift during sprinkler irrigation, interception and storage by the crop canopy, run-off and drainage related to excessive or non-uniform application, soil evaporation, weed transpiration, and residual soil water after harvest (for a comprehensive review, see Hsiao et al, 2007). There are several types of levers used to save water by limiting irrigation water losses (BIO Intelligence Service, 2012; Jensen et al, 2014) including soil and crop management (no-till farming, mulching, weeds' management), as well as the improvement of irrigation technology (efficient irrigation application) and management (scheduling, deficit irrigation).

Irrigation upgrades at the technology level can be achieved by adding some devices to an existing system. For instance, a variable rate irrigation system (VRI) can be adapted to center pivots. Zhao et al (2017) report 14% water savings with VRI when compared to uniform rate irrigation on maize. Ghinassi and Pezzola (2014) describe a controller used to manage sprinkler rotation speeds, the use of which allows up to 15% water savings. Another way to take advantage of technology is to adopt systems that are more efficient, i.e. by switching from flood or sprinkler irrigation to localized irrigation (surface drip, subsurface drip or microsprinkler). All localized systems are likely to eliminate drift and direct evaporation normally occurring during sprinkler irrigation. They also reduce run-off and drainage, as they lessen the amounts of water applied (typically near yet below soil saturation), allow better control of these amounts and deliver lower rates (hopefully lower than soil saturated hydraulic conductivity). Drip irrigation also eliminates interception by the canopy. Subsurface drip irrigation drastically reduces soil evaporation (Bonachela et al, 2001). Lastly, increasing the uniformity of the spatial distribution of irrigation also contributes to greater efficiency and water loss reductions, except in specific conditions (noticeable slopes, uneven soil depths or types) where it is better to deliver different doses to different parts of the plots. Therefore, in the general case, localized irrigation systems allow water savings only if satisfactory uniformity is achieved. Here are some commonly adopted averaged values of efficiency at plot scale over a cropping season taking into account direct evaporation, drift, canopy interception, run-off and drainage losses (but not soil evaporation):65% (55-75%) for hose reel machines, 75% (60-85%) for solid sets, 80% (75-90%) for traditional center pivots, 85% (70-95%) for microsprinklers and surface drip systems, and 90% (75-95%) for subsurface drip systems (Howell, 2003). More specifically, in controlled experimental conditions, Carrion et al (2014) estimated efficiency of solid set irrigation to range between 77-79% and 78-82% for sprinklers' spacing of 18mx18m and 15mx15m respectively; higher efficiency is linked to a higher Christiansen's Uniformity Coefficient (CUC) observed with 15mx15m spacings. In the case of subsurface drip irrigation systems under plastic tunnels, Lozano et al (2016) observed that efficiency can reach 81%. Under real field conditions, for surface drip irrigation, Benouniche et al (2014) observed very high variability in field efficiency ranging from 25 to 97%, depending on farmer practices in Morocco. Comparing the efficiency of sprinkler and surface drip systems, Ghinassi (2012) estimated efficiency to range from 63 to 88% for hose reel machines and from 31 to 81% for drip setups. Low drip efficiency values, far below those usually observed, were attributed to inappropriate management. However, when dealing with technology upgrading, it must be kept in mind that localized irrigation systems require investment and maintenance costs that can be dissuasive for farmers, especially for field crops.

Improvements that can be made in irrigation management include irrigation timing (daytime vs nighttime) (Molle et al, 2012; Cavero et al, 2016), regulated deficit irrigation (Geerts and Raes, 2009) and irrigation scheduling. The latter consists in adjusting irrigation frequency and quantities based on an irrigation strategy optimized with models (Evett and Tolk, 2009; Li et al, 2018; Malik et al, 2019, among many others), or on climatic conditions and measured plant or soil water status (Jones, 2004). The most commonly used sensors to monitor soil water status are capacitive probes (Evett et al, 2012) and tensiometric probes (Bianchi et al, 2017). Soil probes are used to schedule irrigation according to actual soil water status, thus avoiding over-irrigation and, in turn, reducing run-off, drainage, and residual soil water after harvest.

Although it is recognized that improvement of irrigation technology and management is likely to generate water savings, in practice, little is known about the extent of water savings that can be really expected at plot scale. The aim of this study was to evaluate irrigation water savings achievable by switching from sprinkler to localized irrigation system or by using soil hydric status probes. For this purpose, we used the French metropolitan (i.e. excluding overseas French territories) context as a case study and compiled all available studies conducted in France. We chose to focus on water savings achieved through the change in the

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irrigation equipment used or the adoption of soil probes for irrigation scheduling. We analysed how these water savings are influenced by factors related to the agro-pedo-climatic context or the irrigation equipment (irrigation or scheduling systems).

2. Materials and methods

2.1. Data collection

We compiled all available studies, conducted on the French metropolitan territory in the past 30 years, which enabled us to compare water consumption either between two different irrigation systems (sprinkler or localized system), or between two different scheduling modes (without and with soil probes), but always within the same context (same year, same soil, same crop). All these studies are based on experimental field trials carried out by chambers of agriculture, technical institutes, research institutes, experimental stations, or regional water management organizations. They were conducted either in experimental stations or by farmers supervised by an irrigation technical advisor. The data reported in these studies are most often produced following protocols written or validated by INRA (National Institute for Agronomical Research) or other public research institutes. The results are most often unpublished or found in grey literature reports because their publication is not among the missions of experimental farms or technical institutes. It can even be against their interest in some cases and publication policies are most of the times difficult to manage within consortium agreements, when the experimental farms are used within the frame of public-private scientific projects. The data originate from 25 different locations, mainly from French regions with the greatest irrigated surface areas (Figure 1), and refer to field crops, fruit and vegetable production. A total of 93 records of irrigation water consumption at plot scale was collected. 70 records detail the comparison of two irrigation systems: a sprinkler system (reel machine, moving lateral, center pivot or solid set) and a localized system (surface drip, subsurface drip or microsprinkler). 23 records compare the water consumption of two scheduling modes: without and with soil probes. Each record is used to assess the water saving achieved between the highest water consuming system and the lowest water consuming one. We selected only data describing water savings achieved without significant yield or quality loss: a yield reduction of up to 10% was tolerated, as it is considered as the maximum yield loss economically acceptable by a farmer.

2.2. Database creation

Each record contains general data concerning the agro-pedo-climatic context, specific data describing both compared situations (two different irrigation systems or two different scheduling modes, i. e. without and with soil sensor), the associated irrigation water amounts and yields, as well as variables calculated from the previous raw data (Table 1). An example of data collected over a 4-year period on an experimental site is presented in annex 1. None of the experiments refers to the use of surface irrigation methods, as they are no longer widely-used in France.

2.2.1. General data

Year, location, soil water holding capacity (WHC), crop type (field crop, vegetable, fruit production), cumulated precipitation (P) and Penman-Monteith reference evapotranspiration (ET_o) during the cropping season. P and ET_o were obtained either from the meteorological station on the experimental site itself, or from the nearest meteorological station of INRA (French National Institute for Agronomic Research) or Meteo France. P and ET_o are cumulated during the cropping season, i.e. from the mean sowing date (or planting or fruit set) to the mean harvest date (see Table 1 for more details).

2.2.2. Specific data allowing the comparison of two irrigation situations

Irrigation systems 1 and 2 are compared (system 1 being the most water consumptive, and system 2 the least consumptive). In all cases, irrigation system 1 is a sprinkler system (hose reel machine, lateral move, center pivot or solid set system) and is called “sprinkler” in the following passages, for simplicity sake. Irrigation system 2 is a localized irrigation system, either based on surface drip (SD), subsurface drip (SSD) or microsprinkler (MS) setups. Two scheduling systems associated with the same irrigation system are compared as well. The first one is based on either traditional farmer practices, weekly irrigation recommendation bulletins, or maximal evapotranspiration (MET) evaluations, and does not use any scheduling device. The second one employs soil sensors (tensiometric or capacitive probes) to adjust the irrigation dose to soil moisture content. For each irrigation or scheduling system, the total amount of irrigation water applied during the cropping season with system 1 (Irr1) and system

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2 (Irr2) are recorded, together with the associated yields (Y1 and Y2). For the comparison of irrigation systems 1 and 2, the mean irrigation dose applied throughout one irrigation event during the cropping season with the sprinkler system (D1) is also given. More information on the methodology used in all 25 experimental sites is given in the supplementary file linked with this article.

2.2.3. Calculated variables

Four calculated variables are used in the analysis, starting with the hydric deficit:

$$HD = ET_o / P \qquad (1)$$

Where HD (unitless) is the hydric deficit of the cropping season, ET_o (mm) the cumulated potential evapotranspiration and P (mm) the cumulated precipitation during the cropping season. HD values above 1 represent situations characterized by effective hydric deficit for crops, and thus requiring irrigation. HD values equal or below 1 would generally not require irrigation and are therefore not considered in this study. HD calculation during the cropping season is based solely on climate factors. It does not include the initial water stock of the soil at the beginning of the season, as this parameter is unknown in almost all cases described in this study. Thus, HD should be considered as an indicator of climatic drought, but not of irrigation requirement. If it took into account the initial water stock of the soil as an input, in addition to precipitations, HD would be lower in years characterized by a very rainy winter (with a high initial stock).

For the comparison of water consumption levels without and with the use of a soil probes, HD was calculated only for open field conditions (excluding plastic tunnel experiments).

Water saving is evaluated as:

$$WS = [(Irr1 – Irr2) / Irr1] * 100 \qquad (2)$$

Where WS (%) is the water saving obtained when using system 2 vs system 1, or when using a soil sensor vs no soil sensor, and Irr1 (mm) and Irr2 (mm) the total amounts of irrigation water applied during the cropping season with system 1 and 2 respectively. We distinguish between the water savings obtained when comparing two irrigation systems (WS-IS) and those obtained when comparing two soil probes (WS-SP).

Finally, we need quantities tracking irrigation water productivity:

$$IWP1 = (Y1 / Irr1) * 10 \qquad (3)$$

$$IWP2 = (Y2 / Irr2) * 10 \qquad (4)$$

Where IWP1 (kg.m^{-3}) and IWP2 (kg.m^{-3}) are the irrigation water productivity levels associated with the Y1 (Ton.ha^{-1}) and Y2 (Ton.ha^{-1}) yields and the Irr1 (mm) and Irr2 (mm) total irrigation amounts, applied during the cropping season with systems 1 and 2, respectively.

To assess irrigation water productivity (IWP), we chose the Yield/Irrigation amount indicator (Pereira et al, 2012). Another potential indicator, describing more precisely the supplemental yield obtained thanks to irrigation, could have been used: (Yield of irrigated crop – Yield of non-irrigated crop)/Irrigation amount. However, we do not possess any experimental data on the yield of the non-irrigated crop, as this treatment has not been performed in most experiments. When productivity increases, 1 m^3 irrigation water applied with a localized system gives an equivalent or higher yield than 1 m^3 applied with a sprinkler system.

2.3. Data statistical analysis

To assess the influence of the different factors involved in water saving, several multifactor analyses (ANCOVA) were performed. The dependant variable was water saving (WS-IS or WS-SP). The quantitative factors considered were hydric deficit (HD), soil water holding capacity (WHC); the qualitative factors assessed were crop, irrigation system, soil probe. When a factor was found to have a significant effect on WS, the Fisher test (LSD) at a level of significance of 0.05 was carried out. Mean irrigation dose applied with sprinkler system (D1) was not included as a quantitative factor in the ANCOVA as this data was missing in too many records (48 complete records on a total of 70). All statistical tests were performed using XLStat Software (Addinsoft, 2017).

3. Results and discussion

3.1. Water savings with irrigation systems (WS-IS)

3.1.1. Amounts of irrigation water applied and water savings (WS-IS)

Figure 2 presents raw data that indicate the amounts of irrigation water applied with sprinkler systems (Irr1) and with localized system (Irr2) during the cropping season under the same

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agro-pedo-climatic conditions and the same scheduling mode. For corn, Irr1 ranges from 88 to 331 mm, the reduction obtained with localized systems ranges from 0 to 90 mm. Tobacco has the same range of Irr1 as corn (141 to 338 mm), but the magnitude of reduction with localized systems is higher (83 to 216 mm).

In orchards, Irr1 for apple trees varies between 120 and 396 mm; localized systems allow a reduction ranging between 29 and 185 mm. Peach trees show a higher Irr1 (664 to 733 mm) than apple trees, but the reduction obtained with localized irrigation is lower (5 to 71 mm). Note that sprinkler irrigation above the trees is still in use in France today, although it is progressively replaced by localized systems. Despite the fact that drip irrigation may be the best system to irrigate fruits, growers tend to maintain sprinkler irrigation as it is also used for protection against frost.

For vegetable production, Irr1 ranges from 269 to 458 mm and is lowered only by 0 to 78 mm with localized irrigation.

All points in Figure 2 are located under the 1:1 diagonal: it is thus obvious that localized irrigation systems (microsprinkler, surface and subsurface drip) can, to a greater or lesser extent, help reduce the amount of water applied during the cropping season compared to sprinkler systems (spray gun, center pivot, solid set).

As this article is focused on the reduction of irrigation water amounts resulting from the use of localized irrigation systems, the analysis will most often provide water savings (WS-IS) expressed in % of Irr1 and leave to one side the total irrigation amounts.

Water savings between two irrigations systems (WS-IS) that were observed using surface drip (SD), subsurface drip (SSD) or microsprinkler (MS), compared to a sprinkler irrigation system, ranges from 0% to 77%, which evidences high variability. ANCOVA performed on the WS-IS variable (Table 2a) shows that 65% of the WS-IS variability can be attributed to the following four factors: hydric deficit (HD) ($P<0.001$), scheduling mode ($P<0.001$), localized irrigation system ($P<0.05$), crop type ($P<0.05$). HD appears to be by far the most influential factor, followed by the scheduling mode.

As illustrated in Figure 3, the mean irrigation doses applied at each irrigation event with sprinkler systems vary between 18 and 41 mm for hose reel machine, 15 and 32 mm for center pivot or lateral move, 8 and 50 mm for solid set. Water savings (WS-IS) show an upward trend when sprinkler irrigation dose increases. Values of WS-IS above 40% are observed with sprinkler doses higher than 25 mm (hose reel or solid set).

The water savings between two irrigations systems (WS-IS) are firstly explained by the more efficient application of localized systems that very likely reduce irrigation water losses occurring with sprinkler irrigation resulting from drift in windy conditions, direct evaporation, canopy interception and soil evaporation. Secondly, systems allow the highest water savings when sprinkler systems are used with high application doses. This suggests that, in these cases, sprinkler irrigation doses may not be optimal and losses resulting from run-off or drainage may occur. Localized systems then allow a more accurate matching between the applied dose and the water holding capacity of the soil. Thirdly, the use of rainwater with localized systems is more efficient as irrigation calendar is far less flexible for sprinkler than for localized systems. Considering that the interval between sprinkler irrigations varies between 3 and 10 days (management constraints to share equipment or pumping station between several plots), and that the weather forecast is much less accurate beyond 3-4 days, rainfall can occur between two sprinkler irrigations, thus leading to irrigation water waste. Fourthly, although both irrigation systems compared in this study are used with the same scheduling mode, sprinkler irrigation can be based on a looser management strategy, whereas localized irrigation requires closer monitoring of soil water reserves, so that the scheduling may be more accurate with localized systems. Finally, the results reveal that localized systems may allow effective water savings, which are due to both technology (higher application efficiency) and management (better scheduling accuracy). It is difficult to distinguish these two origins and we will globally consider both in this study.

3.1.2. Influence of hydric deficit on WS-IS

WS-IS (%) tends to decrease when hydric deficit increases (Figure 4). It was fitted with exponential curves in order to evidence trends, but without analyzing statistical significance. Taking all localized systems (SD, SSD or MS) into account, the mean distance from the exponential curve reaches WS-IS of 18%, 14% and 9% for field crops, fruits and vegetables respectively. It appears that, for a hydric deficit value exceeding 4.5, WS-IS always approaches 0%, regardless of the irrigation system or the crop type.

In dry years, the water amounts applied with sprinkler (Irr1) and localized systems (Irr2) are both necessarily higher than in wet years. A decrease in water savings is observed when hydric deficit intensifies. Field operators have also observed this dependence of water savings on hydric deficit. This happens when Irr1 increases less in comparison to Irr2, or when Irr2 increases more than Irr1. In the first case (Irr1 increases less in comparison to Irr2) this phenomenon can be explained by the reduction in drainage occurring during sprinkler irrigation when the latter is not adequately scheduled. In wet years, rainwater can partly fill the soil water reserve, so that a portion of the irrigation amounts applied with sprinkler systems can be lost through deep percolation or by storage in the profile at the end of the growing season, unlike with localized systems where small amounts of water are applied daily. In dry years, all the irrigation water contributes to the soil water reserve replenishment so that no loss occurs and Irr1 can be lowered. In the second case (Irr2 increases more than Irr1), this can be attributed to poor application uniformity, which can occur with localized irrigation, especially drip systems. It can be partially smoothed by rainfall in wet years (Li, 2018). In dry years however, more water (Irr2) has to be applied to compensate soil water content heterogeneity, and the potential water saving is thus reduced (unless different doses can be delivered to different parts of the plot).

From data collected in this study, it would appear that water saving cannot be made when hydric deficit exceeds 4.5. Lamm (2005) also reported that water savings made for a corn crop during a seven-year field experiment were dependent on weather conditions. SSD allowed a 4% water saving compared to LEPA (Low Energy Precision Application) sprinkler irrigation in normal years, but this water saving was not observed in extreme dry years when, on the contrary, water consumption was 4% higher with SSD than with sprinkler irrigation.

It should be kept in mind that the data presented here were obtained from studies conducted under controlled experimental conditions. Under realistic farm conditions, additional factors related to the farmers' irrigation practices would probably reinforce this phenomenon rather than weaken it. In dry conditions, with sprinkler irrigation, even if water should be applied more often to compensate hydric deficit, the farmer may not be able to intensify his water cycles because of the technical configuration of his irrigation scheme, or simply due to issues related to the availability of his irrigation equipment used on several plots. During a dry period, with sprinkler irrigation, farmers often do not apply the entire required water amount, in

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order to conserve water and to safeguard part of the water supply for the end of the cropping season. Both situations could also lead to reduced water saving because Irr1 would increase relatively less than Irr2. Furthermore, in times of drought, farmers using drip irrigation admit that they tend to leave the valves open longer to totally refill the soil water reserve, as they may not be able to refill it again during the next irrigation event. In this case, reductions in water savings would be due to a relatively higher rise in Irr2 compared to Irr1.

3.1.3. Influence of scheduling mode on WS-IS

In addition to hydric deficit, WS-IS would also seem to be greatly influenced by the scheduling mode. As shown in Figure 5a, the mean values of WS-IS are 17.6 and 33.7% with scheduling based on water balance alone or on soil probes (plus possibly water balance), respectively.

As described in the Material and Method Section, when both systems are compared, all other factors are equal: same crop, same year, and same soil. As far as possible, we have only compared systems managed with the same scheduling method, either based on water balance (taking into account precipitations, crop evapotranspiration and soil water holding capacity) or on soil water status measurement using capacitive or tensiometric probes (possibly complementary to water balance). However, even within the same scheduling mode, several factors are likely to influence water consumption when the irrigation system changes, such as the run-time for mobile raingun irrigators, probe location and depth in the field, and trigger threshold.

The data collected in this study suggest that localized systems, when compared to sprinkler systems, allow the greatest water savings in situations where irrigation is managed with soil probes. This is probably because soil probes provide information that is closer to the real soil water status than that obtained with water balance. Therefore, soil probes allow a greater reduction in the water amount applied, especially with localized systems.

3.1.4. Influence of crop type and localized irrigation system on WS-IS

The crop type and the localized irrigation system used have a much smaller impact on WS-IS than hydric deficit and the scheduling mode, according to Table 2a. The highest WS-IS values (Figure 5b) are obtained with MS and SD (45.7 and 34.5% respectively, and not significantly different at 5%). The lowest WS-IS is observed with SSD (21.6%).

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Higher WS-IS value with MS than SD and SSD is probably due to specific rooting system development. The volume of soil explored by roots is restricted around drippers (SD and SSD), less limited under MS that makes possible the valorization of a larger volume of soil when HD is low. Lowest WS-IS value with SSD is rather unexpected because SSD, in addition to evaporation and drift, also reduces soil evaporation losses. Results found in the literature most often describe reduced water consumption with SSD when compared with SD (Camp et al, 2000; Evett et al, 2000; Karasahin, 2014). One explanation could be the application heterogeneity associated with SSD, originating from insufficient pressure or emitter clogging. This leads to plot areas with irrigation deficit that cannot be seen directly, but the effect of which can be indirectly observed on the crop. To compensate for this deficit, irrigation duration is sometimes extended, and over-irrigation may occur, thus reducing the water savings potentially achievable with SSD.

Regarding the effect of crop type (Figure 5c), fruit production shows the highest water saving values, followed by field crops and vegetable production (40.0%, 26.1% and 7.9% respectively).

3.1.5. Influence of soil water holding capacity on WS-IS

The influence of WHC on WS-IS is studied in the case of corn, because this crop presents the highest soil WHC variability (50-225 mm) among the collected data. The analysis of variance (Table 2b) indicates that 68% of the WS-IS variability for corn is due to hydric deficit and the soil WHC ($P<0.001$). Figure 6 shows that WS-IS decrease when WHC increases, the highest WS-IS (20 to 70%) are observed in soils with low WHC (less than 100 mm). It should again be noted that, for each WHC value studied, WS-IS is lower in dry years (high HD).

As stated above (section 3.1.1), with sprinkler irrigation, deep percolation mostly occurs in soils with low WHC, when the irrigation dose (D1) is higher than the soil storage capacity. Localized irrigation reduces doses, thus limiting percolation losses, and allows water savings. Localized irrigation is therefore better suited than sprinkler irrigation to soils with low WHC, and this phenomenon is amplified when gun sprinklers are associated to long run-times.

3.1.6. Irrigation water productivity and irrigation systems

IWP scores are presented in Figure 7 on a logarithmic scale in order to spread the points for a more comprehensive view. Only 5 situations out of the 70 situations studied show a reduction

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in productivity between the localized system (IWP2) and the sprinkler system (IWP1). This reduction never exceeds 20% and mainly concerns SSD on field crops. This seemingly atypical result relates to situations where a slight yield reduction (<10%) was observed between sprinkler and localized irrigation. This could be attributed either to water stress induced by insufficient irrigation amounts, or to causes with observed SSD but not directly linked to irrigation, such as bad fertilizer dissolution on soil surface or soil crusting penalizing maize emergence. Some yield decreases with SSD compared to sprinkler irrigation are also found in literature, e. g. for corn (Albasha et al, 2015) or onions (Al-Jamal et al, 2001).

In all other cases, IWP2 is similar or higher than IWP1. This increase in IWP evolves in the same way as WS-IS (Table 3), from SSD to SD and MS (average IWP increase of 33%, 71% and 118% respectively), and from vegetables to field crops and fruits (average IWP increase of 16%, 50% and 81% respectively). Yields obtained with localized systems are equivalent to those obtained with sprinkler systems. In some cases, they are even greater, partly due to the reduction in deep percolation and fertilizer losses, resulting in better fertilizer performance. Therefore, the reduction in irrigation volumes accounts for the increase in productivity observed. Depending on the localized irrigation system or the crop type, this increase in productivity follows the same trend as the related water savings (Figure 5), although differences between drip systems and between crops are not significant (Table 3). In a review compiling numerous American studies, Lamm (2016) established a comparison between SSD and sprinkler systems. For cotton, tomato and corn, he observed enhanced productivity with SSD compared to sprinkler irrigation, which was attributed to reduced water losses as well as increased yield. In Egypt, Abd El-Wahed and Ali (2013) concluded that the use of SD allowed higher corn productivity when compared to sprinkler irrigation. In Europe, a similar IWP increase was also reported for corn with SD (Couto et al, 2013) or SSD (Albasha et al, 2015).

In our results, irrigation water productivity tends to be higher with SD than with SSD although not significantly. In literature, productivity values obtained with SSD are rather greater than with SD, for instance for sugar beet (Hassanli et al, 2010) or corn (Hassanli et al, 2009). However, some decreases in water productivity with SSD compared to SD can be found, e. g. for potatoes (Onder et al, 2005).

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3.2. Water savings with soil probes (WS-SP)

3.2.1. Amounts of irrigation water applied and water savings (WS-SP)

Figure 8 shows the amounts of water for irrigation managed without (Irr1) and with (Irr2) the use of soil probes. For field crops, Irr1 varies between 114 and 294 mm; the reduction when using soil probes varies between 20 and 102 mm. In fruit production, Irr1 is greater (219 to 429 mm) but the reduction observed with soil probes is lower (33 to 66 mm). For vegetable production, Irr1 ranges from 34 to 196 mm and the reduction ranges from 7 to 135 mm. In all cases, water amounts are lower when irrigation is managed with soil probes. Indeed, these devices allow real-time decisions that complement scheduling strategies, where changes to irrigation dates and doses can be made according to the actual soil water status. This results in a reduction in over-irrigation and thus in losses due to run-off, deep percolation and residual soil water after harvesting. Soil probes may also help to optimize rainfall use, as irrigation can be started later in the season and stopped earlier. In sprinkler irrigation, the first, and sometimes also the last irrigation of the season, can be cancelled, which leads to consistent water saving.

As previously stated, we will hereafter focus on water savings resulting from the use of soil probes (WS-SP), expressed in % of irrigation amounts observed without soil probes. Observed values of WS-SP are highly variable according to the situation and range from 7.8 to 75.9%. In the cases where WS-SP values are very high, one may assume that irrigation scheduling without soil probes was incorrect, maybe due to a non-accurate calculation method of irrigation requirement (MET usually obtained from ET_0 and crop coefficient Kc).

3.2.2. Influence of hydric deficit and soil water holding capacity on WS-SP

Data collected to assess WS-SP are from experiments conducted either in open fields or under plastic tunnels. As hydric deficit (HD) takes precipitations into account, only data from open field experiments (i.e. 13 records) were considered to explore the influence of HD on WS-SP. WS-SP varies between 8% and 68% (Figure 9) and shows a slight tendency to increase when HD increases, although this trend is not statistically significant ($P>0.05$, data not shown). It cannot be concluded that hydric deficit has a significant effect on WS-SP. No data for $HD>4.5$ could be collected.

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The analysis of variance (Table 2c) encompasses all collected data (open field and plastic tunnel experiment). Hydric deficit, due to its observed non-significant effect, was not included as a factor and 62% of the variability of WS-SP can be attributed to: WHC, probe type, irrigation system and crop type. However, only the irrigation system and the crop type contribute significantly ($P<0.05$) to the WS-SP values.

Contrary to WS-IS, WS-SP is not dependent on pedo-climatic conditions (HD and WHC) as HD and WHC have no significant effect on WS-SP. As scheduling with soil probes is based not on the total precipitation amounts since the beginning of the cropping season, but on their real effect on soil water status (water tension or moisture content), it is understandable that WS-SP do not depend on the hydric deficit of the year. However, more data would be necessary to confirm this trend and further experiments are needed to check if soil probes are likely to allow WS in extreme dry years (HD>4.5). Likewise, the information provided by soil probes is basically independent from WHC. It can be possibly computed *ex post* with WHC to calculate the irrigation amount to be applied. Therefore WS-SP does not depend on WHC either.

3.2.3. Influence of soil probe type on WS-SP

As shown in the analysis of variance (Table 2c), there is no significant difference between water savings originating from the use of tensiometric probes and those obtained with capacitive probes (31.0 and 36.6% respectively) (Figure 10a). Therefore, it appears that to achieve water savings the key factor is to schedule irrigation, regardless of the type of probe. However, it should be noted that both kinds of probes cannot be used indifferently in all types of soils. For example, tensiometers are not suitable in very stony or crack-prone soils and the use of capacitive probes may be problematic in heavy clay soils.

3.2.4. Influence of crop type and irrigation system on WS-SP

The average water saving is 25.5% when using soil probes in a SSD or a sprinkler system. It is significantly higher (41.5%) in a SD system (Figure 10b). Water savings decrease from vegetable production (41.5%) to field crops (29.3%) and fruit production (20.9%) (Figure 10c). The data presented in this study are in agreement with those found in the literature. On corn irrigated with SD in Italy, Ghinassi et al (2003) show that scheduling with tensiometers resulted in water saving of 30% compared to scheduling based on advisory services. In Greece,

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irrigation amounts can be reduced by 12.5% on sorghum with scheduling when using capacitive probes (Papanikolaou and Sakellariou-Makrantonaki, 2013).

3.2.5. Irrigation water productivity and scheduling with soil probes

IWP is logically always higher for irrigation scheduling using soil probes than for irrigation scheduling without soil probes (Figure 11). The greatest increases in productivity (up to 80%) are observed in SD systems for vegetable production. Again, this gain in productivity is directly linked to water saving observed with the use of soil probes. Reported increases in productivity are 39% with tensiometers on corn (Ghinassi et al, 2003) and 10% with capacitive probes on sorghum (Papanikolaou and Sakellariou-Makrantonaki, 2013).

4. Conclusion

This study compiled all available field studies conducted on the French metropolitan territory over the past 30 years, concerning water savings achieved with localized systems (surface drip, subsurface drip or microsprinkler) compared with sprinkler systems (reel machine, lateral move, center pivot or solid set system), as well as with scheduling based on soil probes compared with traditional water balance management. Our work shows that localized irrigation systems, as well as soil probes, are very effective solutions that can be used to save water at plot scale and thus increase irrigation water productivity. However, it is not reasonable to generalize values on water savings, as they are highly variable and may depend on several factors (hydric deficit of the cropping season, soil water holding capacity, scheduling mode and other factors not taken into account in the present work).

The main conclusions of this study are the following. (1) Water savings obtained with localized systems (WS-IS) severely decrease when hydric deficit increases and when soil water holding capacity rises. They tend to be higher when the localized system and the sprinkler system in question are managed with soil probes. (2) Water savings obtained with the use of soil probes (WS-SP) seem, on the contrary, independent of hydric deficit and soil water holding capacity. The type of soil probe (tensiometric or capacitive) has no influence on the obtained water savings. (3) Water savings achieved with either localized systems or soil probes result in increased irrigation water productivity and are very marginally influenced by the crop type.

This study deals with observed values of obtained water savings. They may help to evaluate water savings potentially attainable when changing the irrigation system (e.g. from sprinkler to localized irrigation) or adopting soil probes for irrigation scheduling. They may also help public authorities to assess potential reduction of water withdrawal for irrigation at the regional or basin scale. Moreover, they may provide basic guidelines to funding institutions and regulatory bodies, to direct subsidies towards the most relevant equipment in terms of water saving potential.

A crucial observation is that water savings obtained with localized irrigation systems are highly dependent on pedo-climatic conditions (most significant in moderate hydric deficit conditions) whereas those obtained with soil probes are not. To promote water savings, it seems advisable (along with investments in water saving equipment) to encourage the use of irrigation-scheduling tools that rely on soil water data obtained from soil probes.

Finally, it is important to remember that water savings at plot level do not necessarily imply long-term water savings at the territory scale (Grafton et al, 2018). The adoption of more efficient irrigation equipment often leads to increased water withdrawal due to changes in crop choices and crop rotation patterns, or to the extension of irrigated area. This is the so-called “rebound effect” (Pfeifer and Lin, 2014; Berbel et al, 2015). To achieve reductions in water extractions, improvements in irrigation efficiency has to be simultaneously linked with measures that decrease the quantity of water that farmers are allowed to extract.

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Table 1. Categories of data and variables contained in the database.

	Records comparing the water consumption of a sprinkler system and a localized system				**Records comparing the water consumption of an irrigation system scheduled without and with the use of a soil probes**			
	Data and variables	**Unit**		**Details or calculation method**	**Data and variables**	**Unit**		**Details or calculation method**
General data	Year			From 1990 to 2017	Year			From 2000 to 2015
	Location			Name of the municipality	Location			Name of the municipality
	Soil water holding capacity (WHC)	mm			Soil water holding capacity (WHC)	mm		
Specific data	Crop type			Field crops : corn, wheat, soya bean, pea, tobacco Fruits : apple, peach, chestnut Vegetables : onion, melon	Crop type			Field crops : corn, potato Fruits : apple, walnut Vegetables : zucchini, strawberry (under plastic tunnel)
	Cumulative Precipitation (P)	mm	P	Cumulated during the cropping season: Corn, soya bean : from 20/04 to 15/09 Wheat : from 15/03 to 25/07 Pea : from 15/03 to 25/07 Tobacco : from 01/05 to 30/09 Apple, chestnut : from 01/06 to 30/09 Peach : from 01/04 to 30/09 Onion : from 20/05 to 30/08 Melon : from 15/03 to 30/08	Cumulative Precipitation (P), only for open field experiments	mm	P	Cumulated during the cropping season: Corn: from 20/04 to 15/09 Potato: from 01/06 to 15/09 Apple, walnut: from 01/06 to 30/09 Zucchini: from to 20/03 to 05/06
	Cumulative reference evapotranspiration (ET_o)	mm	ET_o		Cumulative reference evapotranspiration (ET_o), only for open field experiments	mm	ET_o	
	Irrigation system 1			The more consumptive system (sprinkler irrigation) : spray gun, central pivot, solid-set	No probe			Irrigation support service or traditional management
	Irrigation system 2			The less consumptive system (localized irrigation) :	Soil probe type			Tensiometric probe Capacitive probe

				surface drip (SD), subsurface drip (SSD), microsprinkler (MS)				
	Scheduling mode			Water balance or scheduling with soil probes (tensiometric or capacitive)	Irrigation system			Sprinkler, surface drip (SD), subsurface drip (SSD)
	Total amount of irrigation water applied during the cropping season with system 1	mm	Irr1		Total amount of irrigation water applied during the cropping season without soil sensor	mm	Irr1	
	Total amount of irrigation water applied during the cropping season with system 2	mm	Irr2		Total amount of irrigation water applied during the cropping season with soil sensor	mm	Irr2	
	Mean dose applied during the cropping season with system 1	mm	D1					
	Yield with system 1	Ton.ha^{-1}	Y1		Yield without soil sensor	Ton.ha^{-1}	Y1	
	Yield with system 2	Ton.ha^{-1}	Y2		Yield with soil sensor	Ton.ha^{-1}	Y2	
Calculated variables	Hydric deficit indicator	-	HD	$HD = ET_o /P$	Hydric deficit indicator (only for open field experiments)	-	HD	$HD = ET_o /P$
	Water saving when using system 2 vs system 1	%	WS-IS	WS-IS = [(Irr1-Irr2)/Irr1] x 100	Water saving when scheduling irrigation with soil probe	%	WS-SP	WS-SP = [(Irr1-Irr2)/Irr1] x 100

	Productivity of irrigation water with system 1	$Kg.m^{-3}$	IWP1	IWP1 = Y1/Irr1	Productivity of irrigation water without soil probe	$Kg.m^{-3}$	IWP1	IWP1 = Y1/Irr1
	Productivity of irrigation water with system 2	$Kg.m^{-3}$	IWP2	IWP2 = Y2/Irr2	Productivity of irrigation water with soil probe	$Kg.m^{-3}$	IWP2	IWP2 = Y2/Irr2

Table 2. Analysis of variance for variable WS-IS (water saving with localized irrigation system) and variable WS-SP (water saving with soil probes)

a. Analysis of variance for variable WS-IS						
Source of variability	Df[a]	Sum of squares	Mean square	F[b]	P-value	Significance
Hydric deficit (HD)	1	9524.11	9524.11	57.8	< 0,0001	***
Localized system	2	1313.26	656.3	3.9	0.024	*
Crop type	2	1463.63	731.81	4.4	0.016	*
Scheduling mode	1	2586.29	2586.29	15.7	0.0002	***
Model $R^2 = 0.648$ (***)						
b. Analysis of variance for variable WS-IS for corn						
Source of variability	Df[a]	Sum of squares	Mean square	F[b]	P-value	Significance
WHC	1	1369.359	1369.359	13.505	0.0009	***
Hydric deficit (HD)	1	3500.449	3500.449	34.522	< 0,0001	***
Model $R^2 = 0.677$ (***)						
c. Analysis of variance for variable WS-SP (including data from experiments under plastic tunnels)						
Source of variability	Df[a]	Sum of squares	Mean square	F[b]	P-value	Significance
Water holding capacity (WHC)	1	3.843	3.843	0.022	0.883	NS
Probe type	1	129.503	129.503	0.756	0.397	NS
Irrigation system	2	1813.631	906.815	5.294	0.017	*
Crop type	2	1971.659	985.829	5.755	0.013	*
Model $R^2 = 0.619$ (**)						

[a] Df: Degree of freedom.

[b] F: Fisher statistic.

Table 3. Effect of localized irrigation system and crop type on irrigation water productivity (IWP) increase (%). In the same column, values with the same letter are not significantly different by LSD test at P < 0.05.

Irrigation water productivity (IWP) increase (means in %)			
Localized system		Crop type	
SD[a]	70.9 ab	Field crop	50.2 a
SSD[b]	32.8 b	Vegetable	16.3 a
MS[c]	117.7 a	Fruit	81.3 a

[a] SD: surface drip

[b] SSD: subsurface drip

[c] MS: microsprinkler

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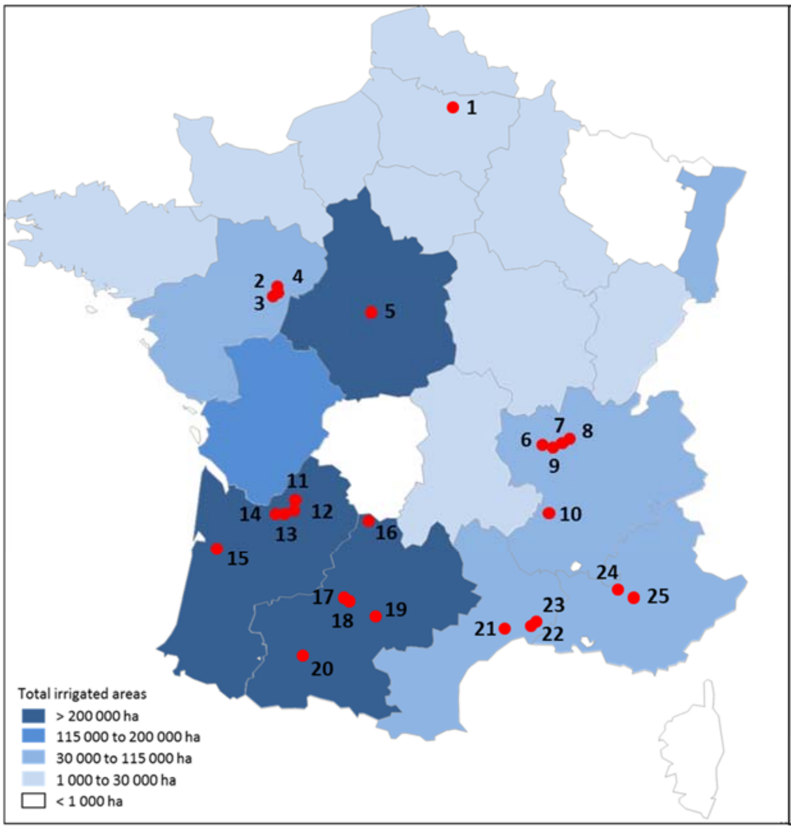
Figure 1. Irrigated areas in France (2010) and location of the 25 experimental sites where data were collected



Localities

1	Villers-St-Christophe (02)
2	Le Lude (72)
3	Le Lude 2 (72)
4	Vaas (72)
5	Tour en Sologne (41)
6	Brindas (69)
7	Pusignan (69)
8	Saint-Maurice de Gourdans (01)
9	Genas (69)
10	Vernoux en Vivarais (07)
11	Douville (24)
12	Bergerac (24)
13	Lanxade (24)
14	Prigonrieux (24)
15	Villeneuve-de-Marsan (40)
16	Martel (46)
17	Montauban 1 (82)
18	Montauban 2 (82)
19	Parisot (81)
20	Masseube (32)
21	Montpellier (34)
22	Saint-Gilles (30)
23	Bellegarde (30)
24	Reillanne (04)
25	Roumoules (04)

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Figure 2. Comparison between the amounts of irrigation water applied during the cropping season with sprinkler systems (Irr1) or localized systems (Irr2)

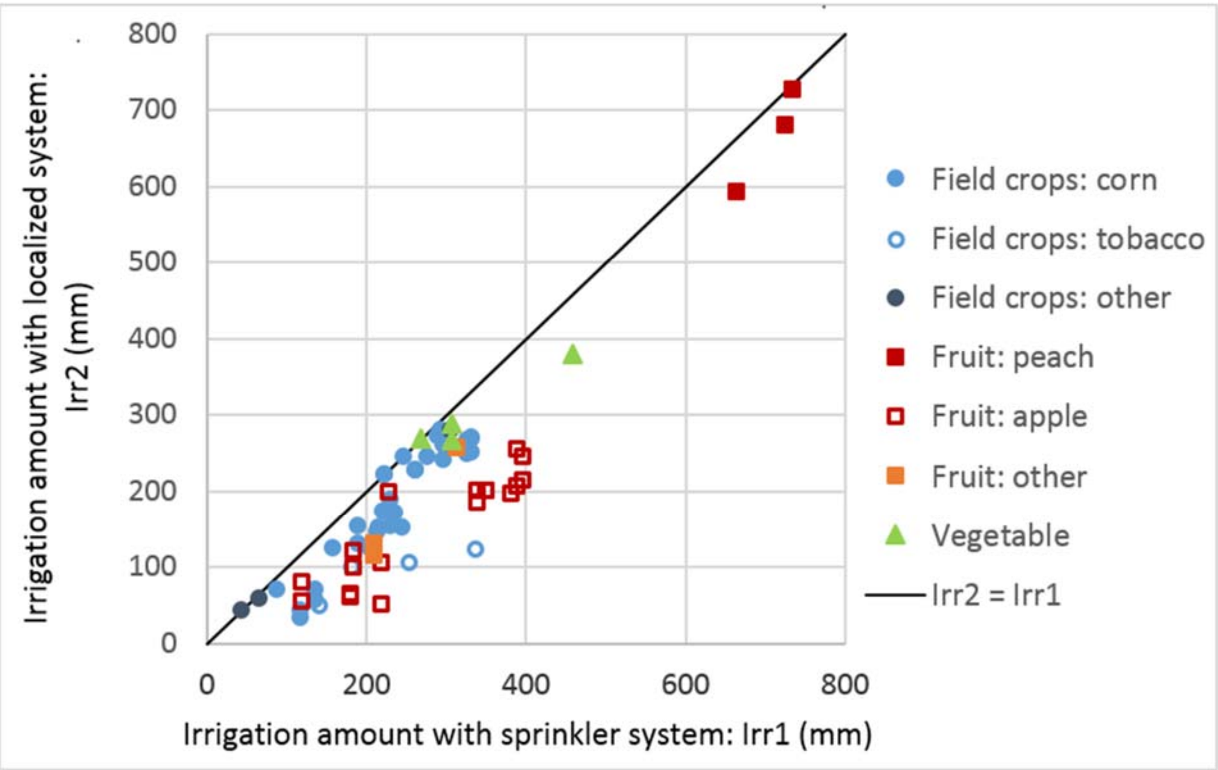

Figure 3. Water saving (WS-IS) observed between a sprinkler system and a localized irrigation system, according to the mean sprinkler irrigation dose (D1)

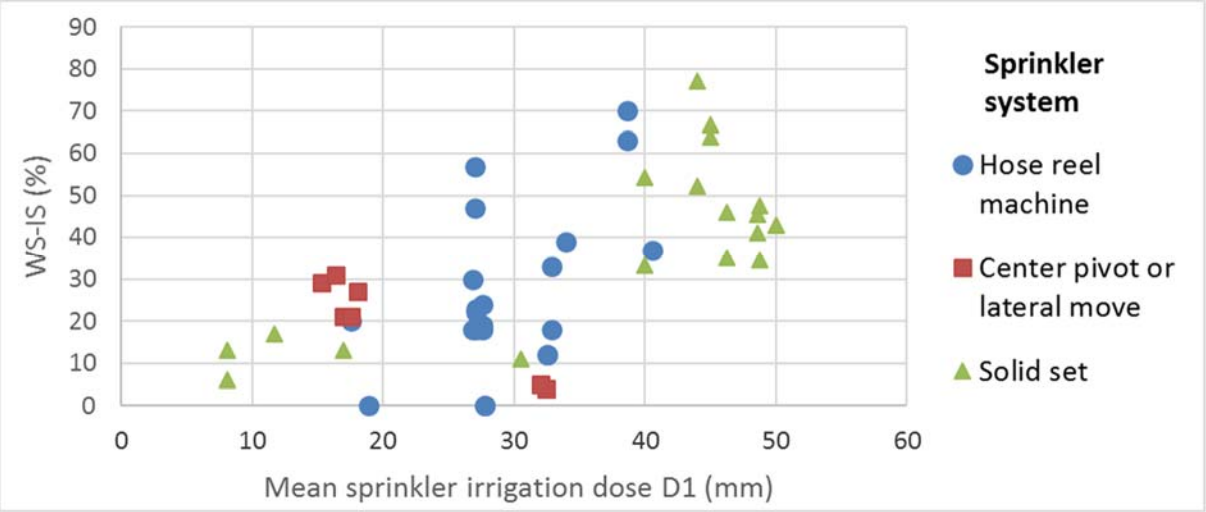

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Figure 4. Water saving (WS-IS) observed between a sprinkler system and a localized irrigation system, according to the hydric deficit of the cropping season. Exponential curves for each crop type. SD: surface drip, SSD: subsurface drip, MS: microsprinkler

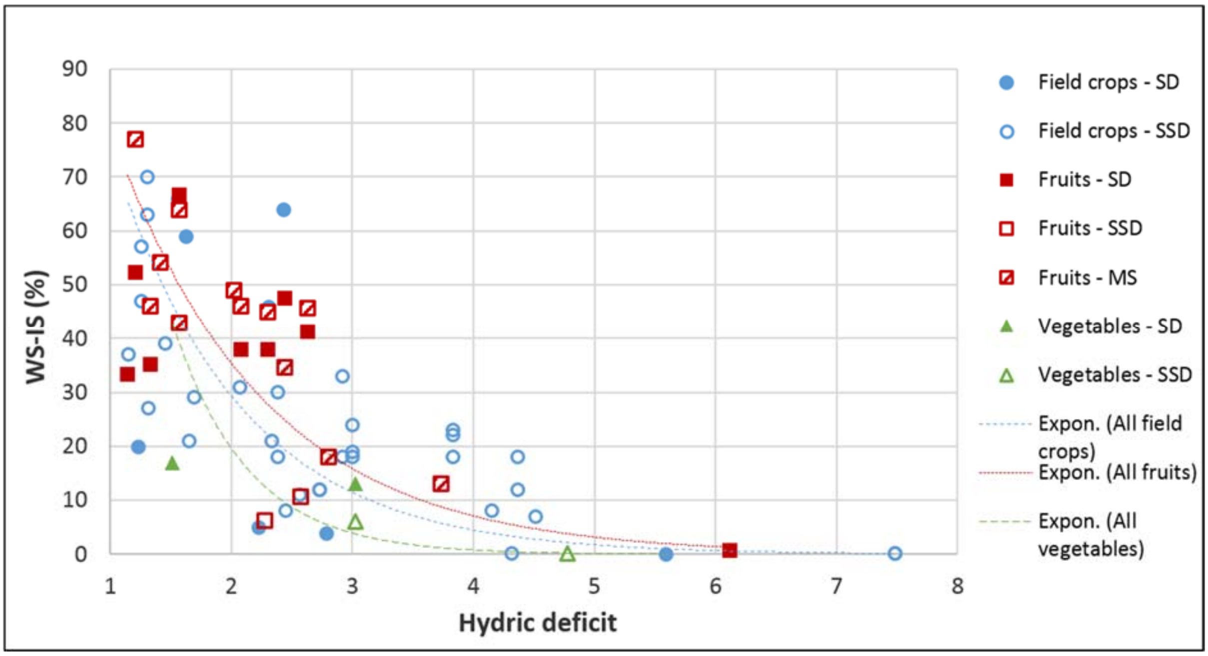

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Figure 5. Effect of scheduling mode (a), localized irrigation system (b) and crop type (c) on water saving achieved by changing irrigation system (WS-IS). Red crosses denote mean values. On the same graph, values with the same capital letter (between parentheses) are not significantly different (LSD test at 5% level). SD: surface drip, SSD: subsurface drip, MS: microsprinkler

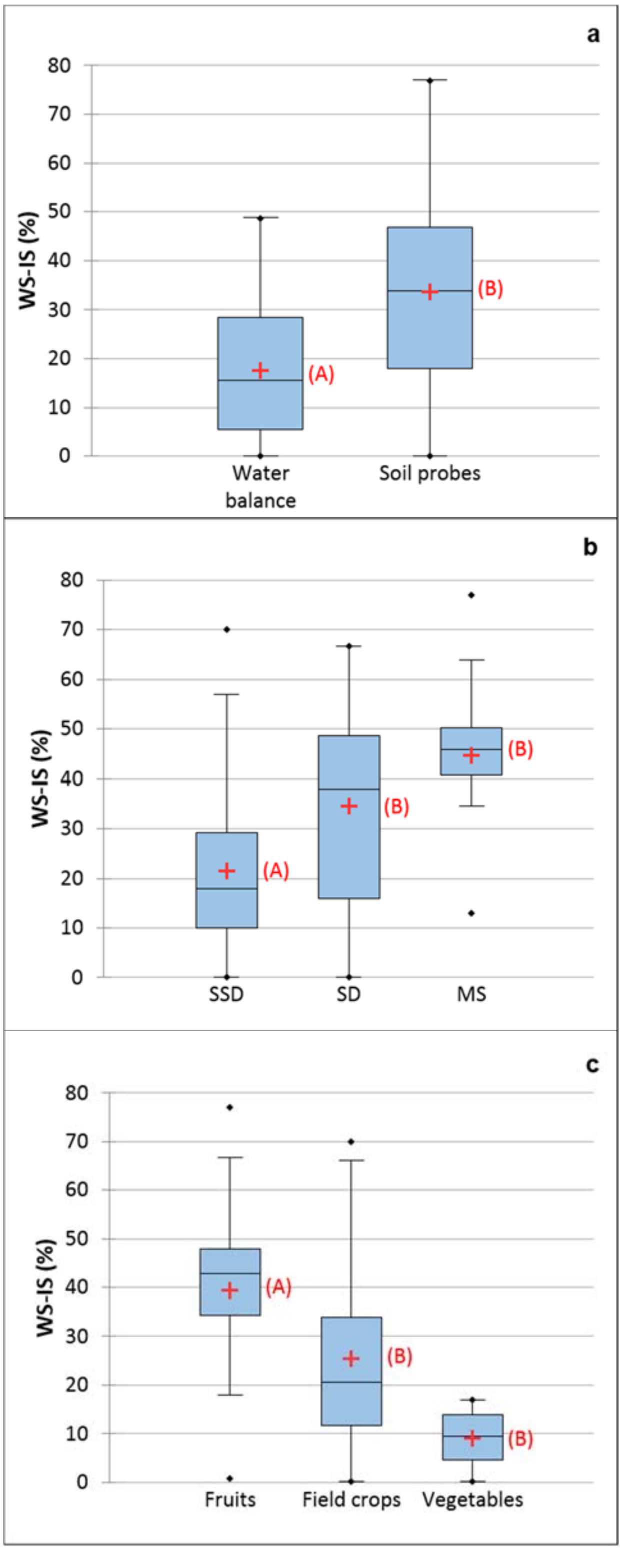

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Figure 6. Water saving (WS-IS) in corn crops according to the water holding capacity (WHC) of the soil. HD: hydric deficit (unitless)

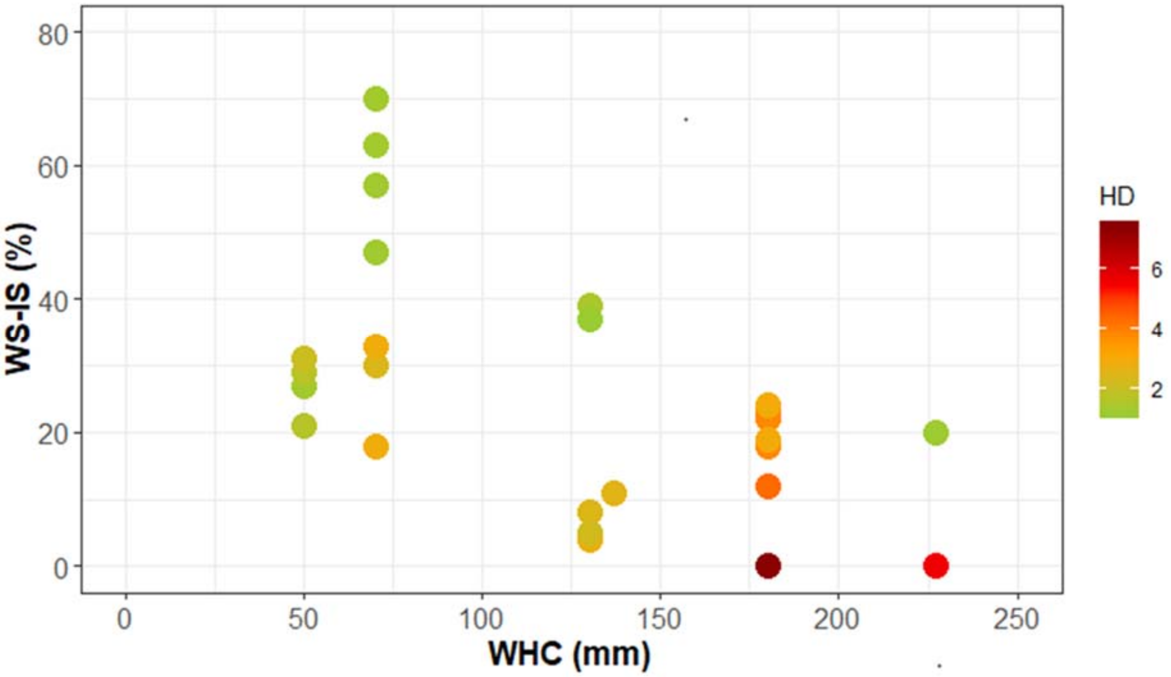

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Figure 7. Irrigation water productivity of the localized irrigation system (IWP2) compared to the sprinkler system (IWP1) for field crops, fruits and vegetables. SD: surface drip, SSD: subsurface drip, MS: microsprinkler.

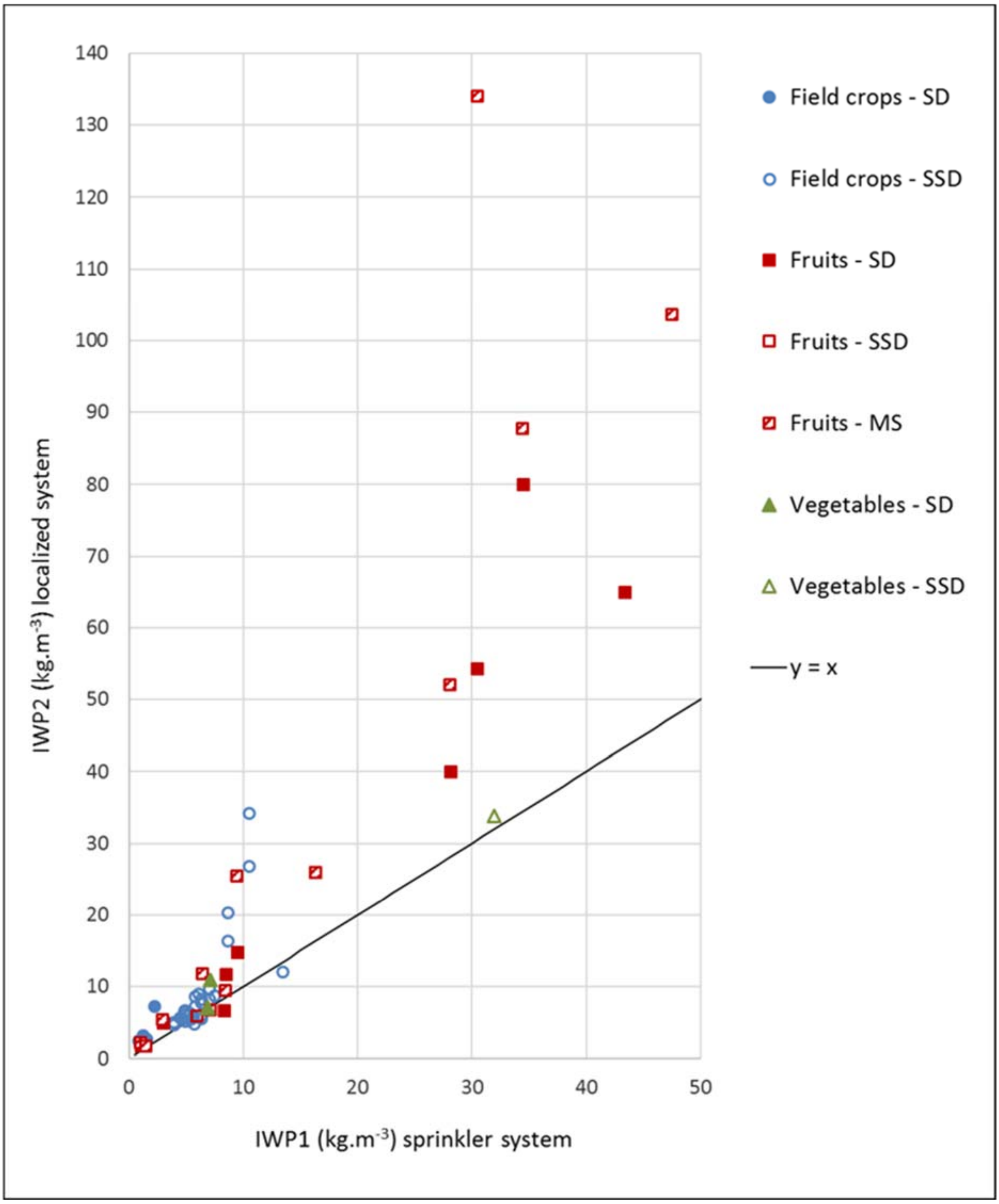

Figure 8. Comparison between the amounts of irrigation water applied during the cropping season without the use of soil probes (Irr1) and with the use of soil probes (Irr2)

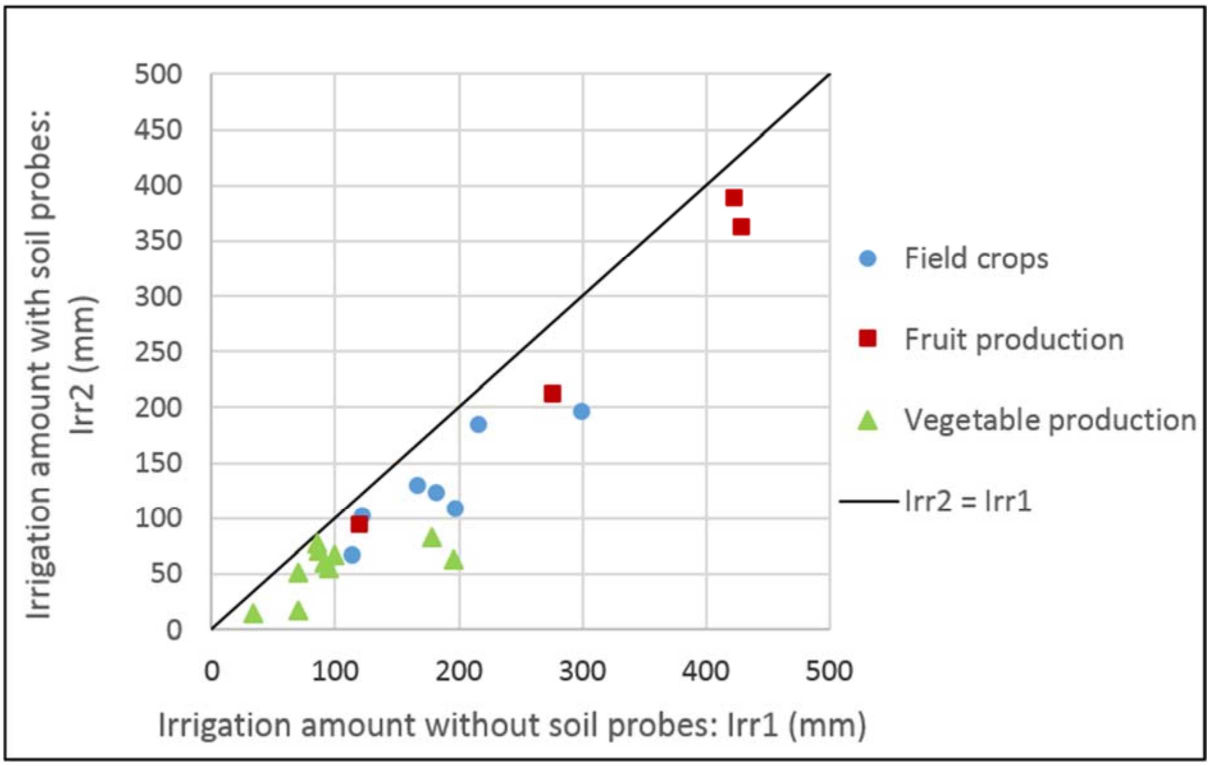

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Figure 9. Water saving realized by using soil probes (WS-SP) to schedule irrigation in open field conditions (data from experiments under plastic tunnels were excluded), according to the hydric deficit of the cropping season. Spr: Sprinkler irrigation, SD: surface drip.

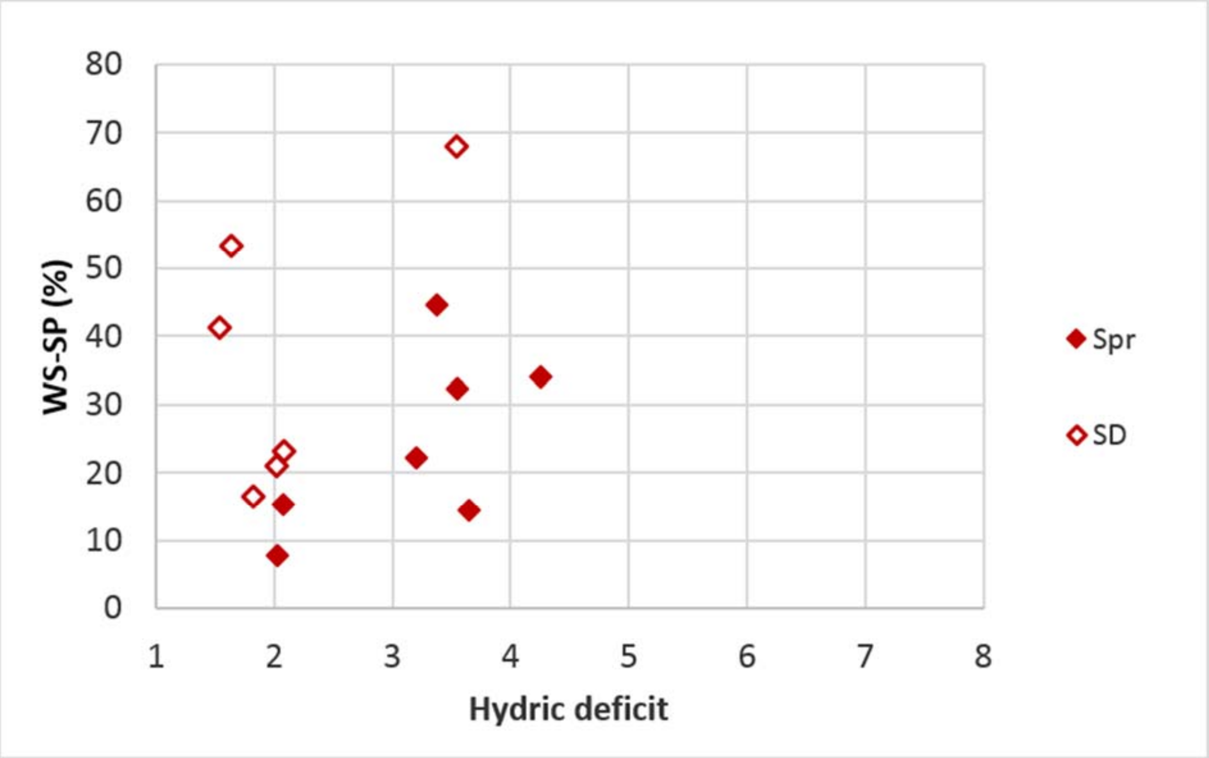

Figure 10. Effect of probe type (a), irrigation system (b) and crop type (c) on water saving achieved by using soil probes (WS-SP). Red crosses denote mean values. On the same graph, values with the same capital letter (between parentheses) are not significantly different (LSD test at 5% level). SD: surface drip, SSD: subsurface drip.

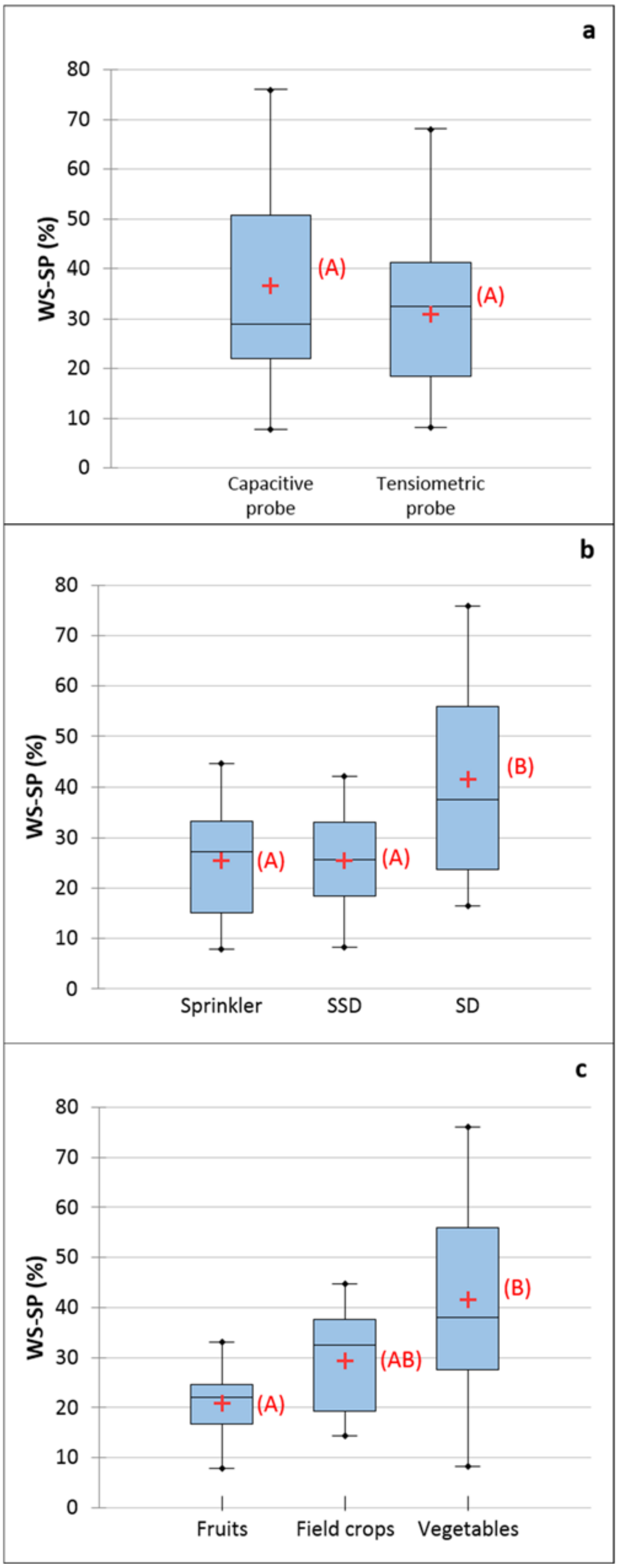

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Figure 11. Irrigation water productivity with (IWP2) and without (IWP1) using soil probes. Spr: Sprinkler irrigation, SD: surface drip, SSD: subsurface drip.