Enhancing water use efficiency in irrigated agriculture through variable rate drip irrigation: the case of a pear orchard in northern Italy

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Abstract

Very few studies applying Variable Rate Irrigation (VRI) by means of drip systems are described in the literature, even if localized irrigation is the most common irrigation strategy for orchards. In the agricultural season 2018, the effectiveness of variable rate drip irrigation was demonstrated in a pear orchard of about one hectare located in Lodi (NUTRIPRECISO project; RDP-EU, measure 1.2.01, Lombardy Region). Through the use of an Electro-Magnetic Induction sensor (EMI) pulled by a quad-bike, soil electrical conductivity field maps were obtained, and two homogeneous zones were identified by applying statistical techniques. A soil profile was opened in each homogeneous zone, soil core samples were collected from each horizon, and soil water content at the field capacity and wilting point were laboratory-measured. Two irrigation Management Zones (MZ) were defined, corresponding to the homogeneous zones; for each MZ, the Total Available Water (TAW) in the rooting zone was computed from the lab measurements and used to obtain the Irrigation Prescription Map (IPM). Based on the IPM, a drip irrigation system characterised by three sectors was designed and realized: two sectors supply water to the two MZs, while the third one illustrates the 'reference irrigation management'. In the first two sectors, drip lines were optimized in terms of spacing between drippers and dripper flow rates according to the soil types. In the third sector, the most common drip lines used in orchards were installed. A wireless sensor network including two soil water content probes for each sector was used to fine-tune the frequency and duration of irrigation events in the first two sectors; in the third sector, irrigation was supplied following the farmer's habit. Drip VRI allowed to reduce the pear orchard water consumption of about 50% compared to the 'reference irrigation management', without losses in yield and product quality.

Keywords: precision agriculture, irrigation prescription map, irrigation system, homogeneous management zone, proximal soil sensing

INTRODUCTION

Globally, around 70% of water consumption is attributable to irrigated agriculture, which produces 40% of total agricultural production (FAO, 2016). The growing problems of water scarcity in many cultivated areas of the planet and the competition among different sectors for its use, combined with issues such as climate change, increase in the world population and growing demand for agricultural products, push agricultural research towards an increasingly sustainable use of water (IPCC, 2014; FAO, 2017).

The spatial heterogeneity of soil-crop system variables (yield, plant status, soil characteristics, etc.), which has always been observed by farmers in the field, has become detectable today with different observation devices (Matese and Di Gennaro, 2015). This convinced operators of the sector and researchers that, on the same field, a uniform management of inputs and crop operations does not always represent the most appropriate agronomic choice. This is the prerequisite for implementing what in literature is referred to as 'site specific crop management' (SSCM) or 'precision agriculture' (PA), i.e. an approach that seeks to match input supply and demand (of N, water, pesticides, etc.) with the aim to increase their use efficiency, taking to environmental and economic advantages (Pringle et al., 2003). According to the American National Research Council (1997) the PA is defined as: 'A strategy that uses information technologies to integrate data from multiple information sources for decision-making purposes aimed at management of agricultural systems'. In other words, the objective is to translate the ever-increasing amounts of data potentially available to farmers into operational decisions (Whelan & McBratney, 2000), moving from a uniform field management to one that is as site-specific as possible.

Although the potential and the advancement of methods and technologies which can be used in PA are often acclaimed, the diffusion of site-specific management techniques in Italy remains very limited compared to other countries. This is probably due to the modest average size of Italian farms, the territorial heterogeneity and the technical and economic difficulties in implementing new high-tech solutions in the field (MIPAAF, 2017).

Viticulture and fruit-growing represent, for the Italian agriculture, productive sectors characterized by a remarkably high profitability. Therefore, although they have a reduced importance in terms of national agricultural area - 365,000 ha of fruit trees and 690,000 ha of vineyards (ISTAT, 2016), representing only about 9% of the national agricultural area - they are crucial in the national agricultural production scenario. Along with their high capacity to produce income, these crops also need high production inputs, in particular they consume important quantities of fertilizers and sometimes of irrigation water. Additionally, it is amply demonstrated by the literature how the production yield and quality for these crops are strongly linked to proper irrigation management. Moreover, areas destined to these crops are often characterized by a high soil vulnerability and by a multiple use of water resources that exacerbates the competition among productive sectors.

Along with other inputs that can be managed in a site-specific way, even water, if supplied without considering the spatial heterogeneity of irrigation requirements (due to differences in soil properties, micro-topography or crop characteristics) may lead, in the same field, to constantly over-irrigated or under-irrigated areas (Bellvert et al., 2014). The possibility to operate a site-specific management of irrigation input is one of the aspects of PA. The Precision Irrigation (PI) includes the ensemble of technologies and methods aimed at mapping the variability of physical characteristics of soil and crop, at processing the acquired data in order to produce irrigation prescription maps, and at actuating the variable-rate management of the water input. In the fruit production and viticulture sectors, IP is an important strategy not only to increase the irrigation efficiency of agriculture, but also to guarantee, through site-specific management of irrigation interventions, the achievement of certain quantitative and qualitative standards in production (Bellvert et al., 2015; Boshoff, 2010). Although there are several studies in the literature concerning the detection of spatial variability at field scale, studies illustrating strategies and/or devices to manage this heterogeneity through spatially differentiated irrigation application are still really scarce (McClymont et al., 2012). In particular, no study is reported in the literature that investigates the use of drip irrigation systems for variable-rate irrigation of tree crops, despite the fact that this irrigation method is the reference for such productions.

In the above mentioned context, the general objective of this study is to demonstrate, for the 2018 agricultural season, the effectiveness of the variable-rate irrigation method actuated through a drip system in a 1-hectare pear orchard located in the Lombardy Plain (LO). The study includes the detection of soil variability through data collected by an electromagnetic induction (EMI) sensor integrated with those from a traditional soil survey, the field zonation in homogeneous management zones (MZs) based on the collected observational data, and the design, the realization and the management of a variable-rate drip irrigation system (VRDI).

Water volumes and fruit yield and quality obtained applying this approach were finally compared to those obtained in the case of a conventional drip irrigation system.

MATERIALS AND METHODS

Experimental site

The experimental site is a 1-ha pear orchard, located in the Lombardy plain close to the city of Lodi (LO). The orchard is flat, positioned at about 80 m a.s.l., and characterized by a semi-humid climate according to the Koppen classification system. Based on data recorded in the period 1993-2017 at the nearest ARPA (Regional Environmental Protection Agency) agro-meteorological station, located at about 12 km south-east from the experimental site in Cavenago d'Adda (LO), climate is characterized by two rainy periods, respectively in April and September, while highest temperatures occur in July, when rain is minimum (Figure 1).

Soils are classified as 'fine loamy, mixed, superactive, mesic, Ultic Haplustalfs' (USDA, 2014) as reported in the 1:50.000 soil map of the area (ERSAF - Lombardy Regional Agency for Agriculture and Forestry); they are moderately coarse in texture, with a moderate permeability and a moderately good drainage.

The pear orchard is situated in the "Dotti" farm, which is a research facility of the University of Milan. It includes different cultivars in contiguous rows, in particular: *Pyrus communis* 'Williams' (7 rows), 'Conference' (3 rows), 'Abate Fetel' (3 rows), 'Kaiser' (3 rows).

Soil detection and hydrological soil characterization

An EMI sensor dragged by a quad-bike equipped with a GPS receiver was used to measure soil electrical conductivity (EC) throughout the field and produce EC maps at three different depths (0-50 cm, 0-100 cm, 0-180 cm) by point interpolation. All the EC maps were elaborated with statistical techniques, to identify within the orchard homogeneous zones characterised by different types of soils. For each zone, a soil profile was opened and analysed; undisturbed soil samples were collected from the soil horizons and volumetric soil water content at field capacity (FC) and wilting point (WP) were determined in laboratory. From these values, the Total Available Water (TAW; Allen et al., 1998) in the root zone was calculated for each homogeneous zone, as the difference between FC and WP.

Agro-meteorological data and estimation of crop water requirement

In order to calculate the crop water requirement, which represents the upper limit of the crop irrigation requirement, evapotranspiration of the orchard in well-watered soil conditions (*ETc*) was estimated following the Paper FAO-56 (Allen et al., 1998) 'single crop coefficient' approach. According to this method, *ETc* is computed by multiplying the evapotranspiration of a well-watered reference grass surface (*ETo*) by Kc, a coefficient incorporating the crop characteristics and expressing the difference in evapotranspiration between the cropped and reference grass surfaces. *ETo* values were estimated at a daily time step using the agrometeorological data registered at the ARPA weather station of Cavenago d'Adda for the period 1993-2017 (Figure 1a). In particular, daily series of air temperature, relative humidity, solar radiation and wind velocity were used to calculate daily average *ETo* values for the period March – September (Figure 1b). To be precautionary, the pear irrigation requirement in each phenological stage was considered equal to its average water requirement, neglecting the possible contribution of rains.

Crop coefficient and crop development stage

Girona et al. (2010) highlight that *Kc* series for tree crops are influenced by many site-specific factors: type of cultivar, row orientation, canopy shape and structure, training system, planting distance, ground management on the row and between rows. Hence, uncertainty exists to some extent when series of tabulated Kc are transferred to different crop systems (Allen et al., 2009); for this reason, when possible, Kc series and phenological stage lengths should be measured locally (Steduto et al., 2012) and used for the ETc estimation. To build the Kc pattern, the values of 0.5, 1.05 and 0.85 reported in *Allen and Pereira* (2009) for the pear orchard were used respectively for Kc_{ini}, Kc_{mid} and Kc_{end}. As suggested by Paper FAO-56, Kc_{mid} and Kc_{end} values were corrected on the basis of measured values of minimum relative air humidity and wind velocity, and values of 1.04 and 0.83 were finally obtained. Lengths of the four phenological stages (Δ_{ini}, Δ_{dev}, Δ_{mid} e Δ_{end}), equal to 30, 65, 60 and 30 days respectively, were obtained considering the values reported in FAO-56, FAO-66 and the phenology typically observed for pear orchards in Padana Plain.

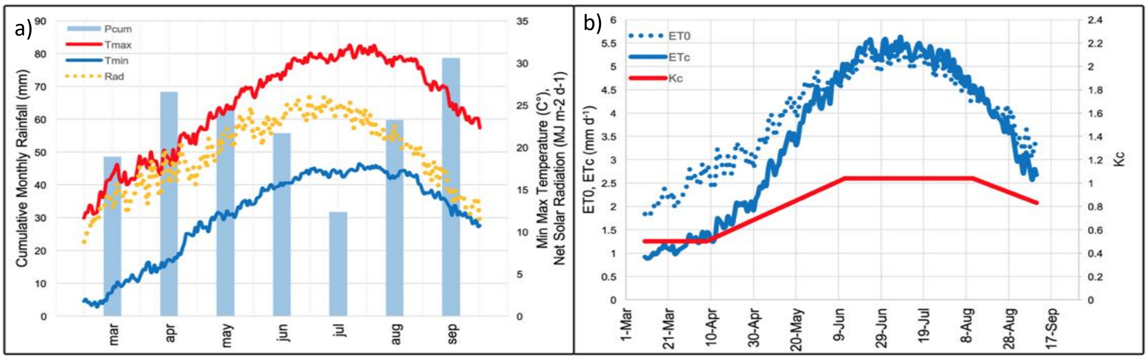

Figure 1. a) Average daily values of minimum and maximum air temperatures, solar radiation and monthly rainfall registered at the Cavenago d'Adda meteo station in the period 1993-2017; b) average daily values of ETo, ETc and Kc estimated for the period March-September.

VRDI system design, preliminary irrigation scheduling and irrigation management

In order to design the Variable Rate Drip Irrigation (VRDI) system for the orchard, different Management Zones (MZ) were defined, corresponding to the homogeneous zones identified from the EC maps. An irrigation prescription map (IPM) was obtained on the basis of the TAW value computed for each homogeneous zone.

On the basis of the IPM, a VRDI system characterized by as many sectors as the MZs, each one controlled by an independent electrovalve, was designed and realized. Drip lines selected for the sectors were different in terms of spacing between drippers and dripper flow rates, based on the type of soil. An additional sector, designed to include as much as possible the soil variability within the orchard as well as the presence of different cultivars, was established as the 'reference sector'; the most common drip lines used for drip irrigation in orchards were installed in this sector.

A preliminary irrigation schedule for each crop phenological stage and each sector was obtained on the basis of TAW values and crop water requirements. This irrigation schedule was initially used to manage irrigation turn periods, duration and depths within sectors.

The gross maximum water depth which can be provided by irrigation, $h_{al\,max}$ (mm), was calculated as a function of: TAW (-); p (-), the fractional depletion of TAW, set to 0.5 for pear, as suggested in Allen et al. (1998); Z_r (mm), the rooting depth, set to 1000 mm for pear); S_b (-), the wetted surface,set to 20%; E_{adac} (-), the efficiency of the irrigation method, set to 95% for drip irrigation. The equation for $h_{al\,max}$ is as follows:

$$h_{al\,max} = Z_r \cdot p \cdot TAW \cdot \frac{S_b}{E_{adac}} \quad (1)$$

The irrigation turn period, T_g (days) was calculated for each growth stage, dividing $h_{al\,max}$ by the daily average value of the irrigation requirement, F_{il} (mm d^{-1}), calculated for that period:

$$T_g = \frac{h_{al\,max}}{F_{il}} = \frac{h_{al\,max}}{(ET_c/E_{adac})} \quad (2)$$

The value of T_g calculated according to the equation (2), was rounded to the nearest lower integer T_{gi}, so that the actual gross water depth h_{al} (mm) was calculated as follows:

$$h_{al} = T_{gi} \cdot F_{il} \quad (3)$$

Finally, the duration of irrigation event for each growth stage, d_a (hour), was calculated as:

$$d_a = h_{a\,l}/\,I_a \quad (4)$$

where I_a (mm h^{-1}) is the irrigation intensity within each sector, depending on the characteristics of the VRDI system (dripper flow rate, dripper distance and plant row distance in the orchard, as reported in Table 1).

The preliminary irrigation scheduling defined using equations from (1) to (4), was modified taking into account the actual soil moisture dynamics, measured by means of a wireless soil water content sensor network (WSN) installed within the orchard. In particular, the soil water content sensors were installed at two depths (35 and 70 cm) in one point for each irrigation sector. An additional point of the WSN was located within the 'reference sector', even if the irrigation in this sector was provided according to farmer's decisions and soil water content sensors were used uniquely to monitor the resulting soil moisture patterns.

Product quantity and quality

Pears were harvested in the middle of September 2018, and the yield was registered for each sector. Moreover, six biological repetitions were collected for each sector to determine fruit quality parameters. The firmness of the collected pears was analyzed by using the penetrometer FT 327 (Effegi, Italy), then the pears were grinded to obtain the pear juice. Sugar content (°Brix) of must and pear juice was determined by using the refractometer RBO (Optech, Germany). Titratable acidity (g L^{-1}) and pH were determined by using the titrator CRISON Compact. Significant differences of the analyzed parameters were detected by using the one-way ANOVA test ($p \leq 0.05$). Duncan test ($p \leq 0.05$) was used for post-hoc comparisons.

RESULTS AND DISCUSSION

Design and implementation of the VRI system

Starting from the EC maps obtained by the EMI survey (Figure 2a), two homogeneous zones with similar soil properties were identified (Figure 2b; yellow and green areas); the two homogeneous zones are characterised by TAW values over the rooting depth of 8.1% and 11.4%, respectively. Two MZs were defined, one for each homogeneous zone. A VRDI system was realized, characterized by independent sectors (Figure 2c) designed on the basis of the IPM obtained from the TAW values assessed for the two MZs. Sectors 1-2-1 and 1-2-2 corresponded to the MZs with TAW values of 8.1% and 11.4%, respectively; Sector 1-1 was the 'reference sector' realized in a portion of the orchard including all the pear cultivars. Details of the irrigation system are reported in Table 1.

Table 1. Main properties characterising the three sectors of the VRDI system.

Irrigation Sector	Dripper spacing (m)	Dripper flow rate (l h^{-1})	Irrigation intensity (mm h^{-1})	TAW (%)
Sector 1-1 (reference)	0.6	1.6	0.67	-
Sector 1-2-1	0.4	1.6	1.0	8.1
Sector 1-2-2	0.6	2.3	0.96	11.4

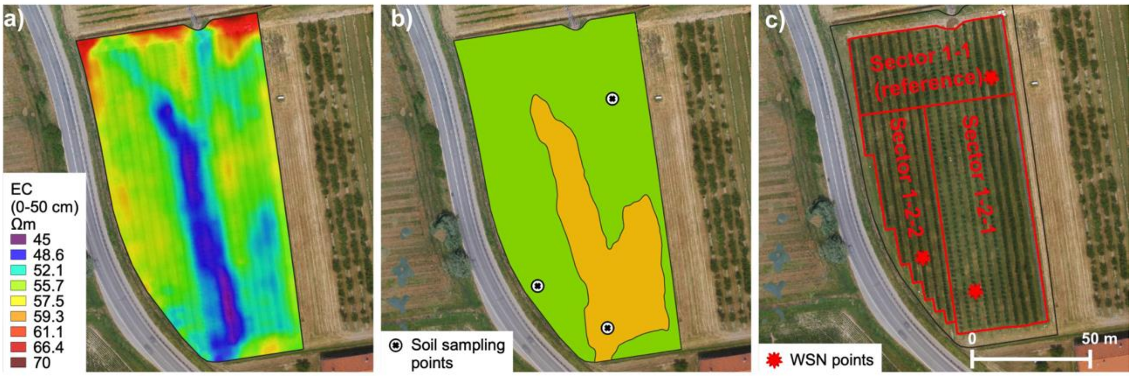

Figure 2. a) EC map for the 0-50 cm depth; b) homogeneous zones identified by statistical analysis of EC maps (green and yellow areas) and position of soil profiles; c) irrigation sectors and position of soil water content probes.

Irrigation scheduling and management

At the beginning of the irrigation season, the irrigation management for sectors 1-2-1 and 1-2-2 was scheduled for each phenological stage as reported in Table 2. This initial schedule was modified during the season by taking into account the soil water content measured by the WSN. In particular, irrigation in Sectors 1-2-1 and 1-2-2 was managed in order to avoid that the average soil water content (average of values measured at 35 and 70 cm of depth) could drop under a fixed threshold, which was set as the 50% of the TAW value along all phenological stages, according to the recommendations of Allen et al. (1998) for pear orchards. In the reference Sector 1-1, irrigation was provided according to farmer's decisions.

Table 2. Irrigation schedule for Sectors 1-2-1 and 1-2-2, for each phenological stage.

Irrigation Scheduling	Sector	Phenological stage				
		Budburst - flowering	Fruit growth by cell division	Rapid shoot growth	Fruit fill - harvest	Harvest
F_{il} (mm d^{-1})	1-2-1	1.2	3.0	5.5	5.3	3.7
	1-2-2	1.2	3.0	5.5	5.3	3.7
T_g (d)	1-2-1	7	3	1	1	2
	1-2-2	10	4	2	2	3
d_g (h)	1-2-1	8.3	9.0	5.5	5.3	7.5
	1-2-2	12.5	12.5	11.5	11.0	11.5
h_{al} (mm)	1-2-1	8.3	9.0	5.5	5.3	7.5
	1-2-2	12.0	12.0	11.0	10.5	11.0

Water use efficiency and crop yield and quality

Volumes of water supplied to each sector were measured through a flow discharge counter; they are reported in Table 3. In Sectors 1-2-1 and 1-2-2 water volumes were, respectively, 839 and 1 083 m^{3}ha^{-1}, resulting in a water saving of 52% and 38% if compared to the water applied in the reference sector (1 757 m^{3}ha^{-1}). Globally, considering both sectors, the volume of water saved compared to the reference sector was 48%.

Table 3. Water volumes supplied to each irrigation sector of the field.

Irrigation Sector	Sector surface (ha)	Water volume (m^3)	Unit water volume (m^3ha^{-1})	Difference to Sector 1-1 (%)
Sector 1-2-1	0.38	315.3	838.6	-52%
Sector 1-2-2	0.18	199.3	1083.2	-38%
Sectors 1-2-1 and 1-2-2	0.56	514.6	918.9	-48%
Sector 1-1 (reference)	0.22	383.0	1756.9	-
Total	0.78	896.7	1152.6	-

As illustrated in Table 4, despite the important reduction in water volumes provided by irrigation in Sectors 1-2-1 and 1-2-2, with respect to the reference sector, no yield losses occurred, except for the *Pyrus communis* 'Conference', for which the production per tree decreased. In this case, however, the decrease of production was counterbalanced by an increase of fruit average weight. For what concerns fruit quality, analysis conducted on the fruits showed no relevant variations of quality parameters between the reference and other sectors (Table 4).

Table 4. Yield and quality parameters measured for each pear cultivar (except for *Pyrus communis* 'Williams') in sectors with variable rate irrigation (only Sector 1-2-1 was considered because Sector 1-2-2 was entirely cropped with *Pyrus communis* 'Williams'). The values were compared with ones measured in the reference Sector 1-1.

Yield and quality parameter	Conference		Abate Fetel		Kaiser	
	S. 1-1	S. 1-2-1	S. 1-1	S. 1-2-1	S. 1-1	S. 1-2-1
Production (kg)	29.2 ± 4.3	16.8 ± 3.1	20.7 ± 1.8	23.3 ± 3.7	9.4 ± 1.9	12.9 ± 3.4
Number of fruits	235.7 ± 26.6	116.7 ± 19.1	92.7 ± 7.8	102.7 ± 16.7	49.3 ± 8.1	68.0 ± 16.6
Average fruit weight (g)	124.0 ± 14.4	143.9 ± 5.8	223.4 ± 2.1	227.2 ± 8.3	189.0 ± 8.3	189.4 ± 16.7
Firmness (kg cm^{-2})	2.7 ± 1.0	4.0 ± 0.3	3.1 ± 0.8	4.7 ± 0.1	5.0 ± 1.6	6.4 ± 0.9
Sugars (°brix)	14.0 ± 1.0	15.8 ± 1.1	14.3 ± 0.7	14.7 ± 0.6	15.5 ± 1.6	15.7 ± 1.4
pH	4.8 ± 0.1	4.6 ± 0.1	4.1 ± 0.1	4.1 ± 0.1	4.4 ± 0.1	4.2 ± 0.1
Total acids (g l^{-1})	3.1 ± 0.6	3.7 ± 0.3	2.1 ± 0.3	2.3 ± 0.4	2.2 ± 0.9	2.9 ± 0.9

CONCLUSIONS

This work focused on the investigation of the effectiveness of a VRDI system in a 1-ha pear orchard located in the Padana plain (Northern Italy) during the irrigation season 2018. Procedures and tools proposed by the Precision Agriculture were implemented, starting from a preliminary detection phase, in which soil properties of the field were investigated through proximal sensing and traditional soil sampling. According to the soil hydrological characterization, two different MZs were defined and a VRDI system consisting of two sectors (plus a 'reference sector', managed by the farmer) was designed and realized. A soil water content WSN was installed, with sensors at two depths in one point within each sector. The preliminary irrigation scheduling, defined taking into account soil properties and pear irrigation requirements in each phenological stages, was dynamically modified during the growth season, based on the soil moisture measurements. In particular, irrigation was supplied in the two sectors in order to maintain the soil water content in the root zone above a fixed threshold, beyond which the crop would start suffering for water shortage. Despite the small orchard size, results of the study are very encouraging: water supplied to the two sectors was, globally, 48% less than the water used in the reference sector. A slight reduction of yield occurred in the case of *Pyrus communis* 'Conference', but this was balanced by an increase in fruit weight. In terms of fruit quality, no statistically relevant differences between the two sectors and the reference one were found.

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