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Water table management to save water and reduce nutrient losses from agricultural fields: 6 years of experience in North-Eastern Italy

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ABSTRACT

To evaluate the performances of a controlled drainage system in optimizing water use and reducing nutrient losses from agricultural fields, an experimental facility was set up in north-eastern Italy in 1996. Water table management was tested in combination with surface (open ditches) and subsurface (pipe) drainage systems. Data were collected from 2007 to 2013 on: water table depth, drained volumes, nitrogen and phosphorus concentrations in groundwater and in drainage water.

Nitrogen in groundwater showed higher concentrations when controlled drainage was combined with open ditches system, with a median of 13.43 mg L^{-1} for NO_3-N and 18.68 mg L^{-1} for total N. Drainage water showed an opposite trend: subsurface pipes with free drainage provided highest concentrations due to extensive leaching (a median of 20.7 mg L^{-1} for NO_3-N and 24.0 mg L^{-1} for total N). Phosphorus concentrations showed notable differences in drainage water, with higher values in the controlled drainage – open ditches system due to surface runoff (a median of 0.190 mg L^{-1} for PO_4-P and 0.536 mg L^{-1} for total P).

In general, the most hazardous period for surface water pollution was autumn-winter, due to rainy weather and fertilizer application on bare soil.

Overall, water table management reduced total water discharge by 81% compared to free drainage. On average, with controlled drainage annual nitrogen losses were lowered by 92% (from 29 to 2 kg NO_3-N ha^{-1}) and annual phosphorus losses by 65% (from 0.14 to 0.05 kg PO-$_4$P ha^{-1}). Free drainage with subsurface pipe was the worst combination from the environmental point of view: annual nitrogen and phosphorus losses were 46 kg NO_3-N ha^{-1} and 0.10 kg PO_4-P ha^{-1} respectively.

Water table management clearly proved to be a reliable tool to improve both water usage and quality.

1. Introduction

Saving water is a key issue in modern agriculture. In this context, managing water outflows may help in optimizing water use and avoiding drought stress. In addition, there are environmental concerns about nutrient losses via drainage water, especially as regards nitrogen and phosphorus pollution and the related eutrophication processes (Boesch and Brinsfield, 2000; Dodds and Smith, 2016; Skaggs et al., 2012; Withers and Haygarth, 2007).

Controlled drainage is a precipitation harvesting method with the aim of retaining water in the soil. According to Evans et al. (1995), it proved to be capable of both saving water (about 30% less outflow volumes than conventional drainage) and reducing nutrient losses (30–50% nutrient losses reduction).

In areas with shallow groundwater, controlled drainage allows the water table level to be set at the desired height by retaining an appropriate amount of drainage water in collecting ditches. During the coldest and rainiest period, when rainfall exceeds evapotranspiration rate (autumn and winter in northern Italy), controlled drainage can be used to avoid complete water outflow and reduce nutrient losses to surface waters. However, at the same time, particular attention must be paid to prevent waterlogging (Gilliam and Skaggs, 1986). During the driest period (spring and summer), especially close to the sowing date of summer crops, water table management is crucial to retain as much water as possible in order to avoid drought stress. In general, to optimize water use, proper timing and accuracy are required in regulating water table level (Ale et al., 2009).

Environmental benefits of controlled drainage have been verified worldwide (Bonaiti and Borin, 2010; Drury et al., 2014; Luo et al., 2008; Sunohara et al., 2015; Wesström et al., 2001,2014; Xiao et al., 2015), and crop biomass or production can also be improved, with results depending on the weather conditions of each year (Ghane et al., 2012; Kross et al., 2015; Madramootoo et al., 1993; Poole, 2015). In addition, to minimize uncertainty in water table management,

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simulation models have been applied in many shallow groundwater systems, with the aim of predicting the effects of different drainage and water management schemes on water table depth, soil moisture and nutrient losses (Borin et al., 2000; Fang et al., 2012; Negm et al., 2016).

Different drainage management strategies and devices are now available to increase water retention and regulate water table level, so that controlled drainage is also effectively applied at watershed scale with positive results (Kröger et al., 2015).

As reported by Skaggs et al. (2012), controlled drainage has been widely studied in the United States, as well as on glacial-derived soils in colder regions (Canada and Sweden). However, no experiences are reported for the Mediterranean area. In this context, the lower part of the drainage basin of Venice lagoon, in north-eastern Italy, shows appropriate attributes for the application of controlled drainage, as characterized by flat lands and by the presence of a shallow phreatic groundwater. At the same time, though, great fluctuation in water table level during different seasons, low organic matter content in these soils, and the different climatic conditions may constitute peculiar traits that influence the effects of water table management. Considered all of this, and since Venice lagoon is also sensitive to water pollution (Sfriso, 1987), a field experiment was set up in this area in 1996, in order to study the efficacy of controlled drainage in limiting water and nutrient losses from agricultural fields, using a combination of two different outflow management strategies (free and controlled drainage) and two land drainage systems (subsurface pipe and open ditches). This paper, focusing on data collected during the monitoring period 2007–2013, updates the results presented previously on water discharge and N balance (Borin et al., 2002; Bonaiti and Borin, 2010), and adds information on P losses.

2. Materials and methods

2.1. Site description

The field trial was set up in 1996 on the experimental farm of Padova University at Legnaro (45° 20′ 53″ N; 11° 57′ 11″ E, 6 m above sea level), in north-eastern Italy. The area is part of the Padano-Veneta plain, and belongs to the drainage basin that delivers water to the Venice lagoon.

Weather data were collected from the meteorological station of the regional agency for environmental protection (ARPAV), located near the experimental fields. Long-term (1995–2014) average rainfall and air temperature were measured, and reference evapotranspiration (ET0) was calculated with Hargreaves formula calibrated locally (Berti et al., 2014).

Long-term median annual rainfall is 915 mm y^{-1}, ranging from a minimum of 601 mm y^{-1} to a maximum of 1311 mm y^{-1}. Autumn is the rainiest season: September, October and November have a median of 78, 88 and 96 mm of precipitation, respectively.

The median annual ET0 is 989 mm y^{-1}, with an interquartile range of 77 mm y^{-1}. The season with the highest median monthly reference evapotranspiration rates is summer: 154 mm in June, 167 mm in July and 145 mm in August. The average annual water balance therefore shows an excess during autumn-winter, while water shortage occurs in summer. Fig. 1 provides the monthly rainfall and reference evapotranspiration values for the 1995–2014 period.

Annual mean temperature is 13.5 °C, annual average minimum temperature is 8.7 °C and annual average maximum is 18.6 °C. The month with the lowest average minimum temperature is January (−0.15 °C), while the month with the highest average maximum is July (29.5 °C).

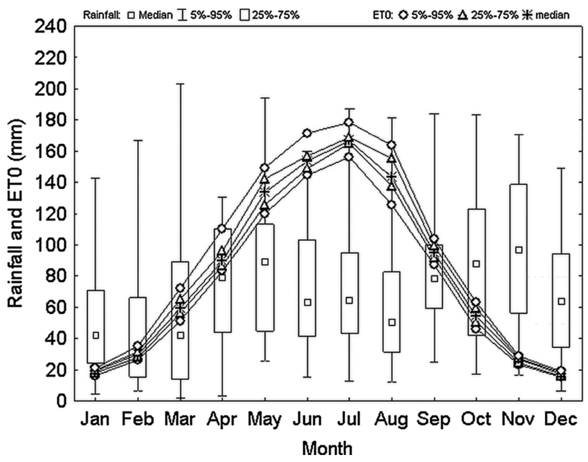

Fig. 1. Long-term (1995–2014) monthly distributions of rainfall (boxplots) and potential evapotranspiration (lines with markers). 5th-25th-50th-75th-95th percentiles are reported.

Soil in the experimental field is heterogeneous, with the following soil texture: silt (30–48%), sand (15–47%), clay (24–45%). In general, soil of the superficial layers is loam, but silt content increases with depth. From layer 90–120 cm down, soil becomes generally silty-loam. At 3 m depth, an impermeable layer allows the formation of a shallow phreatic groundwater. Overall, there is also a gradient of increasing sand content from west to east. Our experimental design provides replicates of our theses in different parts of the field, thus mitigating eventual effects of soil variability on water fluxes and water quality. Organic matter content is on average 1.61% in the first layer (0–30 cm), and decreases with depth. Carbonate content is high (total limestone is 32%, the active fraction 12%). pH is sub-basic (7.6–8.1). Field capacity (at 0.01 MPa) corresponds to 21.5–27% of the dry weight, wilting point (at 1.5 MPa) to 5–6.5%. Bulk density is 1.3 t m^{-3}; surface infiltration rate varies from a minimum of 0.025 m d^{-1} where soil is firm and particularly silty, to a maximum of 2.4 m d^{-1}. Permeability coefficient is about 1 m d^{-1}.

2.2. Experimental layout

The experimental area, covering a surface of 5.5 ha, is organized in 12 plots (0.3–0.5 ha each), with a split-plot design consisting of a combination of 2 factors (with 3 replicates for each thesis): water table management (controlled drainage CD, or free drainage FD) and land drainage system (open ditches O, or subsurface pipe drainage P).

Fig. 2 provides an overall view of the experimental facility.

Controlled drainage plots are located in the northern part of the field, separated from free drainage (in the southern part) by a PVC film buried up to a depth of 1.5 m, in order to limit lateral seepage.

Downstream of each plot, a 1.2 m delivery ditch collects all the drainage and runoff water: in controlled drainage plots a PVC riser is inserted at the end of the ditch to avoid complete outflow. The riser is composed of modular pieces, which can be assembled in many ways in order to set the maximum level the water in the collecting ditch can reach, and consequently influence the water table level inside the plot. At the outlet of each delivery ditch a buried pipe takes water into a sump, where a turbine flow meter is installed to measure outflow waters (composed of a mixture of drainage and runoff water). There are 4 sumps in the field: each of them collects water from 3 plots and delivers it via a 300 mm-diameter PVC buried pipe to the pump of the wetland system. The water is then pumped into the constructed flow wetland where it receives further treatment for pollutant removal.

At the center of each plot, a phreatimeter is inserted into the soil up to the depth of 3 m. The phreatimeter is made of a perforated PVC pipe, so that the water inside the phreatimeter is in equilibrium with the groundwater. The 12 phreatimeters are used for water table level measurements and for groundwater samples collection.

The complete path followed by water from the plots towards the wetland is represented in Fig. 3.

The ARPAV meteorological station is located in the southern part of