

Vineyard irrigation: comparison of drip irrigation and deep sub-irrigation systems(deep root irrigation) for sustainable consumption of the water resource

Sergio Puccioni¹, Marco Ammoniaci^{1*}, Simone Garavelloni¹, Marco Pierucci¹, Paolo Valentini¹, Giovanni Pierucci¹, Chiara Biselli², and Mauro E.M. D'arcangelo¹

¹CREA, Centro di Ricerca Viticoltura ed Enologia, Viale Santa Margherita, 80 Arezzo, Italia

²CREA, Centro di Ricerca Foreste e Legno, Viale Santa Margherita, 80 Arezzo, Italia

Abstract. Increasingly frequent adverse weather events, such as reduced rainfalls and high temperatures, are challenging viticulture, with consequences on grape production and quality. The objective of this three-years study conducted in Arezzo was to compare two treatments, Drip Irrigation System (DIS) and Deep Root irrigation (DRI), in vineyard to evaluate their impacts on grape and pruning wood productions. The research assessed various measures, including soil humidity, plant water status, canopy thermal imaging, production and grape quality, as well as the effectiveness of a new sub-irrigation technique. The results do not definitively indicate which method is superior, as both systems produce comparable outcomes in several key aspects, even if DRI consumes less water compared to DIS. The study highlights the need for advanced irrigation practices and innovative technologies to improve vineyard productivity and sustainability to face changing climate conditions.

1. Introduction

In recent years, the frequency of adverse weather events, characterized by limited rainfalls and elevated temperatures during the growing season, has increased, leading to significant challenges in viticulture. These climatic changes can negatively affect the quantity and quality of grape production, particularly in vineyards located on hilly terrains. Such areas are especially vulnerable due to their susceptibility to erosion, low organic matter content, and exposure to wind and direct solar radiation [1]. To mitigate the impacts of these adverse weather conditions, adopting effective irrigation practices is crucial. The goal is not only on ensuring the survival of grapevines but also in optimizing the use of scarce water resources while maintaining high-quality production. A promising approach is subsurface irrigation, which delivers water directly to the root zone, thereby enhancing crop development while increasing water use efficiency by reducing evaporation losses and surface runoff. Furthermore, it mitigates the proliferation of fungal pathogens and weed growth. As the system is installed underground, it minimizes the risk of damage from agricultural machinery and farm operations, leading to more efficient farm operations [2,3]. Traditional sub-irrigation systems, however, have limitations as they require installation during the initial planting phase, involving burial of subterranean pipes. Additionally, these systems face challenges in monitoring water application and system operation, which can result in under-irrigation or over-irrigation. Ongoing maintenance is crucial to resolve issues like leaks, root intrusion, and soil compression, which can reduce water flow and system efficiency [4]. Recent advancements have introduced a novel device that can retrofit existing self-compensating drip irrigation

systems, enabling subsurface irrigation even after the vines are already established, while maintaining the benefits of sub-irrigation. This innovation offers a practical solution for adapting to changing climatic conditions and improving water management in vineyards. Overall, the integration of such advanced irrigation technologies represents a significant step towards the maintenance of vineyard productivity and quality in the face of increasingly challenging environmental conditions. The present work evaluated the effectiveness of innovative devices that can achieve sub-irrigation adapting pre-existing traditional drip irrigation systems, through Deep Root Irrigation (DRI).

2. Material and method

2.1 Study area

The experimental trial was conducted from 2021 to 2023 at *Villa la Ripa Estate* in Poggio del Gallo (province Arezzo, Lat. 43.505 N, Lon. 11.910 E, 380 m a.s.l.). To characterize the seasonal climatic trends, meteorological data were obtained from San Fabiano (AR) weather station (distance 4.1 km). In addition, the growing degree days (GDD) were calculated from the climatic data [5]. The vineyard, equipped with a drip irrigation system, was planted in 2017 with Cabernet Sauvignon variety grafted on 110R, with a row spacing of 2.4 m and a vine spacing of 0.80 m. The experimental plot was divided into two areas: the Drip Irrigation System (DIS) and the Deep Root Irrigation system (DRI). Measurements were conducted for each irrigation system on three replicates of six plants each, which were evenly distributed along the row. The DRI plot was created by adding the new technology, Deep Root Irrigation, to the

*Corresponding author: marco.ammoniaci@crea.gov.it

drip irrigation system. DRI is manufactured by DeepRoot REVOLUTION LLC (Calistoga, CA) and consists of devices made of spongy plastic material specifically designed for irrigation systems[6]. The 6.4 mm diameter polyethylene tube links the dripper to the bulb and the terminal caps at both ends are made of thermoplastic resin. A laminated copper element inside the upper cap prevents fungi, bacteria, algae, and root intrusion. DIS delivers water to the soil through a system of tubing and drippers. The devices are connected to dripper of an existing system and the irrigation flow rate characteristics are preserved. The model DRI-12 bulbs, with a length of 30.5 cm, were buried near the roots, in this way, the drip system is converted into a subsurface irrigation system. (Fig. 1).

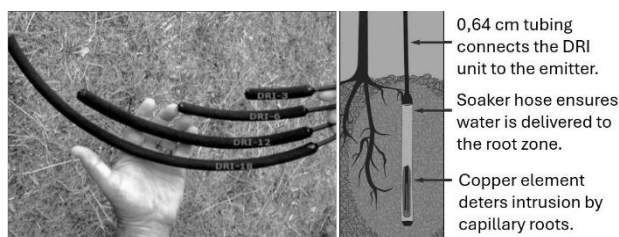


Fig. 1. Structure of the different DRI bulbs size, made by Deep Root REVOLUTION LLC [6].

The irrigation schedule was differentiated between the two systems by reducing the active irrigation time for the DRI treatment to 5 hours per cycle, compared to 8 hours for the DIS treatment. Field trials conducted to assess the actual water delivery rate of each device showed that the DRI system delivers a lower flow rate (3.8L/h) compared to the DIS system (4.0 L/h). Consequently, the total water supplied per irrigation cycle amounted to 19 L per plant for the DRI treatment and 32 L per plant for the DIS treatment, resulting in a 40% reduction in water application per plant. The irrigation dates were managed and conducted by the winery in the following dates: in 2021 on 29 June, 06, 10, 20, 27 July, 05, 13, 19, 25 August; in 2022 on 24 June, 1, 11, 18, 25 July, 05, 11 August; in 2023 on 30 June, 13, 20 July, 02, 20 August.

Tab. 1. Amount of water delivered per plant per treatment and per hectare per year (5200 vines/ha - 2.4 meters space rows and 0.8 metres vine spacing)

Year	Total litres for year DRI per plant	Total litres for year DIS per plant	Total m ³ for year DRI per hectare	Total m ³ for year DIS per hectare
2021	171	288	889	1498
2022	133	224	691	1165
2023	95	160	494	832

2.2. Soil Moisture Measurement

In 2021, soil moisture at 50 cm depth was measured before and after irrigation, to evaluate changes in humidity within the root zone. Soil samples were collected beneath the rows, corresponding to the vertical

position of the irrigation devices. Each soil sample was sieved to remove particles larger than 2 mm and then dried at 110°C for 24 hours. The water content was calculated from the weight difference before and after drying, expressed as a percentage of the initial sample weight.

2.3 Plant Water Status and Thermal Imaging

The stem water potential was assessed using a Scholander pressure chamber (SKPM 1400 Series Plant Moisture System). Leaves were covered with aluminium foil 45 minutes before the measurement to prevent transpiration and let the leaf to equilibrate with the rest of the plant [7]. The canopy surface temperature was measured using a FLIR T540 thermal camera, which is inversely correlated with the amount of transpired water[8]. To monitor the vines condition over time, the Crop Water Stress Index (CWSI) was calculated from canopy temperature values, using extreme temperature references (wet temperature and dry temperature) [9]. A CWSI value close to 1 indicates that the plant is subjected to severe water stress. The CWSI and stem water potential measure were taken on three different dates: before irrigation, three days after irrigation, and seven days after irrigation. The surveys were conducted between 12:00 PM and 1:00 PM.

2.4 Production, Grape quality and Winter Pruning Data Collection

At harvest (21 September 2021, 21 September 2022 and 27 September 2023), field measurements included average yield per plant from 15 vines per trial. Average cluster weight and average berry weight were collected. In 2022 and 2023, at harvest, three samples of 200 berries each were collected for each trial and mean berry weight was recorded. Technological maturity (sugar content, total acidity, and pH) following official OIV methods, as well as organic acids (malic, tartaric, and citric acids) using HPLC-DAD were analyzed [10]. The second portion was used to determine the phenolic maturity index[11].

During winter (27 January 2022, 03 March 2023 and 19 February 2024), the weight of pruning wood was measured from plants evenly distributed along the rows in each treatment.

2.5 Statistical Analysis

The normality of the data was assessed using the Shapiro-Wilk test, and homogeneity of variances was evaluated with Levene's test. After confirming these assumptions, a one-way analysis of variance (ANOVA) was applied each year separately to identify significant differences between the two treatments.

3. Results and Discussion

3.1 Weather Data and Irrigation Date

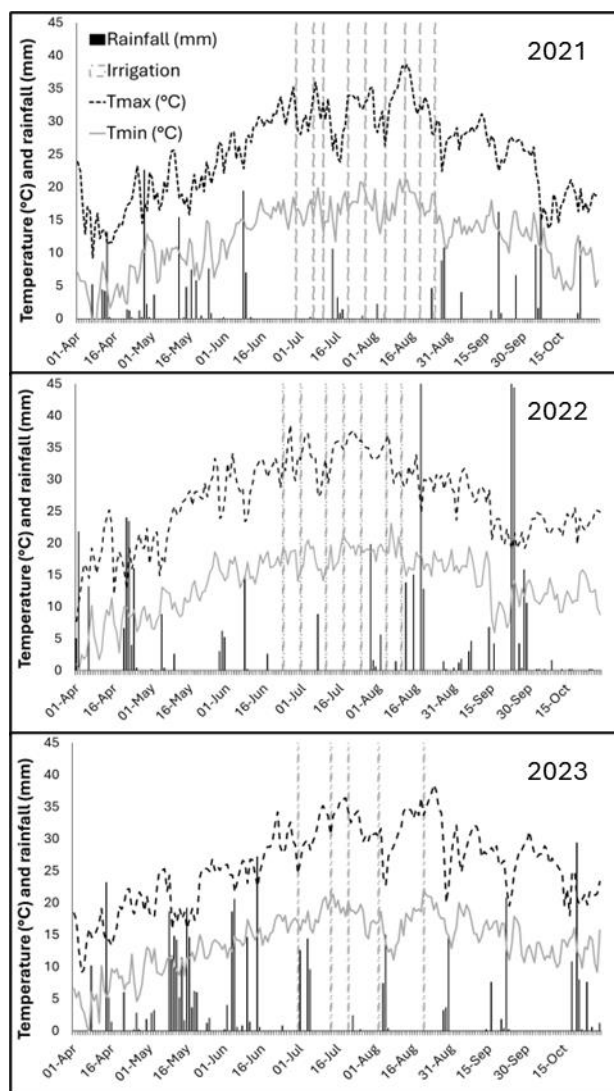


Fig 2. Temperature (°C) and rainfall (mm) patterns over three consecutive years, 2021, 2022, and 2023. For each year the graphs for each year display daily maximum (Tmax) and minimum (Tmin), rainfalls and irrigations.

The 2021 season, which accumulated 1873 GDD, was marked by unusual climatic conditions, including a prolonged winter followed by temperature drops in spring, which led to delayed frosts on April 7 and 8. These frosts significantly damaged post-bud break stages and affected vine development and productivity. A dry spring and hot summer further stressed the vines, although heavy rainfall on August 28 and 29 provided sufficient water, allowing irrigation to be suspended. The early months of 2022, (2156 GDD, where characterized by reduced winter precipitation and short periods of temperatures above 0°C. From April onwards, temperatures rose steadily, peaking over 37°C in July. Irregular rainfall, with a dry period from late April to mid-August, caused severe stress to vines, but a raining end of season followed. Heavy rains on August 19 led to the suspension of irrigation for the rest of the season.

The 2023 season reached 2096 GDD with abundant and frequent rainfall in May and June, with consistently high temperatures exceeding 38°C from mid-July, interspersed with rainfalls that prevented plant stress.

3.2 Soil Moisture Data

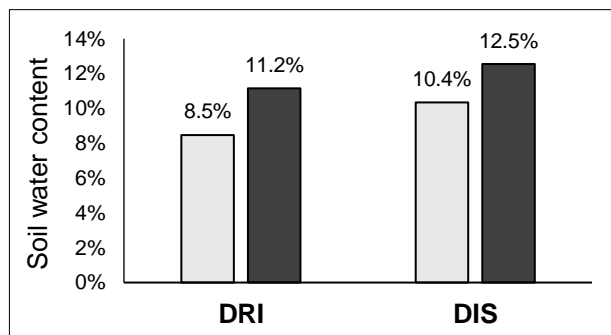


Fig. 3. Percentage of water in the soil, expressed as w/w. Soil moisture before (light columns) and three days after irrigation (dark columns) in the areas subjected to DRI and DIS treatment.

Both treatments showed an increase in soil moisture, with the DRI rising by +2.68% and the DSI treatment by +2.18% three days after irrigation. Despite the lower water input in the DRI treatment, both systems retained moisture similarly, with no significant statistical differences observed. The DRI system may enhance water use efficiency by delivering water below the surface, minimizing evaporation and runoff losses. In contrast, the DSI system, applying water at the surface, is more vulnerable to these losses, resulting in lower overall water retention.

3.3 Canopy Thermal Imaging and Plant Water Status data

In the three years of observation, no significant differences were found in the leaf water potential associated with the different irrigation methods. For example, looking at the data from a monitoring conducted in the third decade of August 2021 (Fig. 4), it is also noticeable that the irrigations, as established, did not alter the water potential but kept it stable, preventing further deterioration. However, the supportive effect of irrigation was highlighted by a decrease in the CWSI index, indicating a slight increase in water availability. Three days after irrigation, the DRI method also showed a significantly lower CWSI value. However, this difference was minimal and was not observed in the measurement seven days later. A similar trend was observed in the other years, although it was not statistically significant.

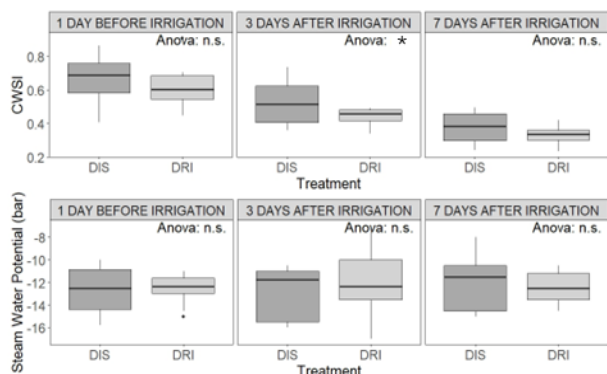


Fig. 4. CWSI index and stem water potential under the two different treatments (DRI and DIS). At three different time points: 1 day before irrigation, 3 days after irrigation, and 7 days after irrigation. For each parameter, significant differences are indicated with the level of statistical significance (* = $P<0.05$; ** = $P<0.01$; *** = $P<0.001$, n.s. = not significant).

3.4 Harvest and Winter Pruning Data

Tab. 2. Mean values and analysis of variance of grape production weights and pruning wood weights. For each parameter, significant differences are indicated with the level of statistical significance (* = $P<0.05$; ** = $P<0.01$; *** = $P<0.001$, n.s. = not significant).

Date	Data	Treatment	Mean	Anova
2021	Grape yield per plant (kg)	DIS	1.19	n.s.
		DRI	1.00	
2021	Wood weight (kg)	DIS	0.34	n.s.
		DRI	0.23	
2022	Grape yield per plant (kg)	DIS	1.41	n.s.
		DRI	1.10	
2022	Wood weight (kg)	DIS	0.33	*
		DRI	0.24	
2023	Grape yield per plant (kg)	DIS	2.17	n.s.
		DRI	2.07	
2023	Wood weight (kg)	DIS	0.40	n.s.
		DRI	0.33	

For grape production, DIS consistently showed slightly higher values. For instance, on 2021, DIS recorded a grape weight of 1.19 kg per plant, while DRI yielded 1.00 kg. This trend persisted over the years, with DIS achieving 1.41 kg on 2022 compared to 1.10 and 2.17 kg on 2023, compared to 2.07 kg for DRI. Despite these higher yields, the differences in grape weights between DIS and DRI were not statistically significant. In contrast, pruning wood weights revealed a more pronounced difference. A significant difference was recorded on 2022, with DIS showing a higher pruning wood weight of 0.33 kg compared to 0.24 kg for DRI. Although earlier measurements (2021), showed a similar trend (0.34 kg for DIS compared to 0.23 kg for DRI) and they were not statistically significant.

3.5 Grape quality and phenolics content

Tab. 3. Berry weight, pH, titratable acidity, sugar content, organic acids, citric acid, total and extractable anthocyanins, total phenolic index, extractability percentage, and seed maturity, for DRI and DIS treatments on 21 September (2022), and 27 September (2023). For each parameter, significant differences between the averages are indicated with the level of statistical significance (* = $P<0.05$; ** = $P<0.01$; *** = $P<0.001$, n.s. = not significant).

Date	Treatment	Berry weight (g)	pH	Tit. acidity (g/L)	Sugars (°Brix)	Malic acid (g/L)	Tart. acid (g/L)
2022/09/21	DRI	0.98	3.55	3.72	24.9	0.75	5.97
	DIS	1.02	3.49	4.16	23.8	0.85	6.40
	Anova	n.s.	n.s.	**	*	n.s.	**
2023/09/27	DRI	1.04	3.35	7.47	20.4	1.34	9.21
	DIS	1.17	3.45	7.45	21.4	1.56	8.61
	Anova	n.s.	*	n.s.	n.s.	n.s.	n.s.

Date	Treatment	Citric acid (g/L)	Total Anth. (mg/kg)	Extr. Anth. (mg/kg)	TPI (DO 280 nm)	Extract ab. %	Seed mat. %
2022/09/21	DRI	0.16	2137	859	81.1	59.6	57.6
	DIS	0.17	2032	813	71.5	59.9	53.8
	Anova	n.s.	n.s.	n.s.	*	n.s.	n.s.
2023/09/27	DRI	0.28	1578	727	35.0	53.7	16
	DIS	0.26	1500	653	34.8	55.9	24
	Anova	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

In 2022, DIS and DRI grapes exhibited overall similar characteristics in terms of berry weight, pH, and most compositional parameters. The main differences were the significantly higher titratable acidity and tartaric acid in DIS, while citric acid and extractability percentage were slightly higher but not statistically significant. The only other notable distinction was the higher total phenolic index (TPI) in DRI. The lower total acidity and tartaric acid in DRI may suggest slight water stress, further supported by the reduced canopy development, as indicated by the lower wood weight.

In 2023, DIS had a slightly higher berry weight and pH compared to DRI, with no other significant differences observed between treatments. There were no significant differences in citric acid, total anthocyanins, extractable anthocyanins, TPI, or seed maturity.

Overall, the differences year to year in berry weight and other metrics were generally minimal, with the general differences between DRI and DIS are modest.

4. Conclusion

The challenges posed by climate change significantly impact agricultural production and need to be properly addressed. In viticulture, the rising temperatures and irregular precipitation patterns are threatening productivity, particularly in regions such as central Italy, where vines are traditionally non-irrigated. On the other hand, the introduction of irrigation practices could lead to a significant increase in water usage for grape production in a context of water scarcity, where resources must also be allocated to other essential sectors beyond agriculture. Therefore, adopting proper and efficient vineyard management techniques to minimize water consumption while ensuring economically sustainable yields is becoming a decisive factor in maintaining viticultural productivity.

This study examined advancements in irrigation techniques through the introduction of a rational water dispersion system in vineyards. The adopted protocols enabled the vineyard to overcome the most critical periods of the seasons, achieving approximately 40% water savings compared to a traditional drip irrigation system. The study suggests that leaf water potential measurements did not show significant differences over the experimental years, despite the reduced water usage. Nevertheless, over the years, the DRI consistently resulted in lower values for both grape yield and pruning wood weight, leading to an overall lower productivity. This suggests that the 40% water savings may have been excessive in this case. For this reason a calibration period is necessary to optimize results and avoid evaluation mistakes. The study also highlighted the need for an environmental monitoring system to precisely determine soil moisture and establish objective criteria for the farm soil tillage and irrigation scheduling. Effective irrigation must be guided by continuous data flow linking grape quality indices with soil water content.

This approach is particularly promising as it offers an opportunity for a relatively simple and potentially effective transition, representing an innovative irrigation system in contrast to traditional drip irrigation methods. However preliminary analyses indicate that the predominant limitation is economic. The cost per device, including installation and materials, is approximately €4.00, which, for a vineyard, such as the one under study, with a density of 5,000 vines per hectare, this represents a significant investment, which should be compared with the installation cost of a subsurface irrigation system. If the implementation of these devices leads to an estimated 40% reduction in water usage, considering the current economic conditions, this technology seems advantageous only in regions where the cost of water is high or where scarcity requires strict conservation measures. However, the cost benefit balance remains complex, as it is influenced by various local factors and requires analyses such as life cycle cost and feasibility studies to fully evaluate the long term viability and overall benefits of this technology.

References

1. G.V. Jones, et al., Climate change and its consequences for viticulture. *Managing wine quality*, 727–778 (2022).
2. J. E. Ayars, A. Fulton, B. Taylor, Subsurface drip irrigation in California - Here to stay? *Agric. Water Manag.* **157** (2015): 39-47.
3. A. Pisciotta, et al., Response of grapevine (Cabernet Sauvignon cv) to above ground and subsurface drip irrigation under arid conditions *Agric. Water Manag.* **197** (2018): 122-131.
4. L.R. Sinobas, M.G. Rodríguez, A review of subsurface drip irrigation and its management. *Water Quality, Soil and Managing Irrigation of Crops* (2012): 171-194.
5. A.J. Winkler, J.A. Cook, W.M. Kliewer, L.A. Lider. 1974. *General Viticulture: Second Revised Edition*. University of California Press: Berkeley, CA. ISBN: 9780520025912, 0520025911.
6. Y. Dilruba, D. Zoldoske, T. Jacobsen, Deep Root Irrigation. PG&E's Emerging Technologies Program, Project number ET15PGE1921 (2019).
7. L. E. Williams, F. J. Araujo, Correlations among predawn leaf, midday leaf, and midday stem water potential and their correlations with other measures of soil and plant water status in *Vitis vinifera*. *J. Am. Soc. Hortic. Sci.* **127.3**: 448-454 (2002).
8. M.K. Nanda, U. Giri, N. Bera, Canopy Temperature-Based Water Stress Indices: Potential and Limitations. In: Bal, S., Mukherjee, J., Choudhury, B., Dhawan, A. (eds) *Advances in Crop Environment Interaction*. Springer, Singapore (2018).
9. N. Belfiore, et al., Infrared thermography to estimate vine water status: Optimizing canopy measurements and thermal indices for the varieties Merlot and Moscato in northern Italy. *Agronomy* **9.12** (2019): 821.
10. V. Ivanova-Petropulos, D. Petruševa, S. Mitrev, Rapid and Simple Method for Determination of Target Organic Acids in Wine Using HPLC-DAD. *Analysis. Food Anal. Methods.* **13**, 1078–1087 (2020).
11. N. Saint-Cricq de Gaulejac, N. Vivas, Y. Glories, Phenolic maturity: definition and control. *Rev. Fr. Oenol.* **173**, 22-25 (1998)