Technical note

Design of a pot experiment to study the effect of irrigation with diluted winery wastewater on four differently textured soils

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ABSTRACT

Due to the intensification of environmental legislation, the wine industry is expected to find solutions for the treatment or re-use of winery wastewater. The objective of the study was to design and evaluate a pot experiment for determining the effects of irrigation with diluted winery wastewater on different soils. Four pedogenetically different soils were included in the experiment, i.e., (i) alluvial sand containing 3.3% clay from Rawsonville, (ii) aeolic sand containing 0.4% clay from Lutzville, (iii) shale-derived soil containing 20% clay from Stellenbosch, and (iv) granite-derived soil containing 13% clay from Stellenbosch. The pot experiment was carried out under a rain shelter at ARC Infruitec-Nietvoorbij. Soils were packed in 3.54 dm³ PVC pots to a bulk density of 1 400 kg/m³. The four soils were irrigated using winery wastewater that was diluted to 3 000 mg/L COD. Municipal water was used to irrigate the control treatment of each soil. The relatively simple mixing and irrigation infrastructure enabled irrigation of more than one soil with diluted winery wastewater in one experiment. It was possible to irrigate the soils accurately when approx. 85% of the water had evaporated as no visual drainage occurred. Since the pot experiment could be continued under the rain shelter during winter, results were obtained quicker compared to an open field study. However, weighing the pots every second day was time consuming. Therefore, it is recommended that load cells are to be used to record daily mass losses automatically in future pot experiments.

Keywords: bulk density, irrigation system, rain shelter, simulated season, texture

INTRODUCTION

Increased wine production in South Africa is putting pressure on natural resources such as vegetation, water and soil. This is primarily due to large volumes of wastewater produced during winemaking (Mulidzi et al., 2009). The negative effects of irrigation with winery wastewater on soils are well documented (Bond 1998; Papini, 2000; Mulidzi, 2001; Arienzo et al., 2009; Christen et al., 2010; Laurenson and Houlbrooke, 2011; Laurenson et al., 2012; Mosse et al., 2011; Arienzo et al, 2012). To comply with intensified environmental legislation (Department of Water Affairs, 2013), the wine industry must find solutions for treatment or re-use of winery wastewater (Van Schoor, 2001). Since negative impacts on soils might be less if the winery wastewater is diluted before being re-used for irrigation, such a practice could be more sustainable compared to undiluted wastewater. However, knowledge regarding effects of diluted winery wastewater on different soils in South African grape growing regions is limited.

Determining effects of irrigation with winery wastewater on soils and crops in field experiments requires an elaborate infrastructure, particularly if the wastewater has to be diluted to a predetermined level (Myburgh et al., 2015). Field experiments are usually carried out within one specific soil type. Since different soils respond differently to winery wastewater irrigation (Mulidzi, 2001), it is essential to determine the effects of diluted winery wastewater on soils that differ pedogenically. However, it would be expensive to erect the required infrastructure for a range of soils. A further disadvantage of field experiments is that wineries produce the bulk of their wastewater during the harvest period, i.e., from February to April. Therefore, field experiments can only be carried out annually during harvest. Based on the foregoing, pot experiments seem to be an alternative, since these could include a range of different soils. A further advantage is that winery wastewater can be stored in tanks which will allow experiments to be continued throughout the year if the pots are sheltered from rain. This will reduce the duration of experiments compared to ones carried out in the open field. If pot experiments are carried out correctly, drainage and subsequent leaching of elements can be avoided. The latter can be problematic and difficult to quantify under field conditions.

The objective of the study was to design and evaluate a pot experiment to determine the effects of irrigation with diluted winery wastewater on different soils. Effects of irrigation with diluted winery wastewater on the chemical status of the four soils will be presented in subsequent articles.

MATERIALS AND METHODS

Experiment layout

Four different soils from grape-growing regions in the Western Cape Province, South Africa, were included in the study. A sandy, alluvial soil was collected in a vineyard near Rawsonville in the Breede River valley. This soil belongs to the Longlands form (Soil Classification Work Group, 1991). A sandy, aeolic soil which belongs to the Garies form was collected near Lutzville in the Lower Olifants River valley. A shale-derived soil was collected on the Nietvoorbij Experimental Farm of the Agricultural Research Council (ARC) near Stellenbosch. A granite-derived soil was also collected at Nietvoorbij. The shale and granite soils belong to the Oakleaf and Cartref forms,

respectively. For the purposes of this paper, the soils will be referred to as Rawsonville sand, Lutzville sand, Stellenbosch shale and Stellenbosch granite, respectively.

The alluvial sand was collected in a vineyard, whereas the others were from uncultivated land. Composite soil samples were collected from the 0–300 mm layer at each locality and placed in plastic bags for transport and storage. The shale and granite soils were passed through a 6 mm mesh sieve to remove large fragments. Triplicate samples were collected from the composited soils for determining particle size distribution at a commercial laboratory (Bemlab, Strand). Five soil particle size classes were determined using the hydrometer method (Van der Watt, 1966). Soil textural classes were assigned according to standard diagrams of the Soil Classification Working Group (1991).

The pot experiment was carried out under a 20 m x 40 m translucent fibreglass rain shelter at ARC Infruitec-Nietvoorbij near Stellenbosch. Due to logistical constraints, irrigation water for the control treatments, as well as for wastewater dilution, could not be obtained from Lutzville and Robertson. Therefore, the control treatment soils were irrigated with water supplied by the Stellenbosch municipality. For the wastewater treatments, winery wastewater was diluted to a chemical oxygen demand (COD) level of 3 000 mg/L. The undiluted wastewater was collected from the wastewater pit at a winery near Rawsonville, and stored in a 2 500 L plastic stock tank next to the rain shelter. A 500 L plastic tank was filled with municipal water. The COD in the undiluted wastewater and municipal water was measured using a spectrophotometer (Aqualitic COD-reactor, Dortmund) with appropriate test kits (COD, CSB, 0–15 000 mg/L), as described previously (Myburgh et al., 2015). The COD levels were used to calculate the volumes of winery wastewater and municipal water required to obtain the target COD level. The volume (m³) of wastewater required from the stock tank (V_W) to obtain a certain target COD concentration (COD_T) was calculated as follows:

$$V_W = (COD_T - COD_M) \times V_T/(COD_S - COD_m) \qquad (1)$$

where: COD_m and COD_s are the COD concentrations (mg/L) in the municipal water and the stock tank, respectively, and V_T is the tank volume (m³). The volume of wastewater required (V_W) was pumped from the stock tank into another 500 L plastic tank where it was mixed with municipal water. The COD in the diluted wastewater was measured while the irrigations were applied.

Treatments were applied over 4 simulated irrigation seasons. Each season consisted of 6 irrigations, which was estimated as the number of irrigations a vineyard would require during the harvest period, i.e., when the highest volumes of wastewater are produced. Hence, a total of 24 irrigations were applied over the 4 simulated irrigation seasons. Each soil/water treatment combination was replicated 3 times in a complete randomised block design. Following each simulated season, i.e., after 6, 12, 18 and 24 irrigations, the soil chemical status was determined to compare the effect of irrigation with diluted winery wastewater to that of municipal water. Since soil sampling was destructive, a replication 'plot' of each soil/water treatment combination consisted of 4 pots (Fig. 1). At the end of each simulated season, one of the four pots was removed for sampling.

Packing of soils to a predetermined bulk density

The day before the pots were filled, the bulked soils were moistened using municipal water to enhance compaction. Following this, the soils were mixed thoroughly and covered using plastic sheets to minimise water loss. Triplicate soil samples were collected in metal cans to determine the gravimetric water content of the bulked soils. The moist soil samples were weighed and dried in an oven at 105°C for 16 h. Samples were removed from the oven and allowed to cool in a desiccator before they were weighed to obtain their oven-dry mass. Gravimetric soil water content (θ_m) was calculated as follows:

$$\theta_m = (M_w - M_d) \div (M_d - M_c) \qquad (2)$$

where: M_w is the mass of the moist soil plus the can, M_d is the oven-dry mass of the soil plus the can and M_c is the metal can mass. Mass percentage soil water content (SWC_m) was calculated as follows:

$$SWC_m = \theta_m \times 100 \qquad (3)$$

All the soils were packed to a bulk density (ρ_b) of 1 400 kg/m³. The mass of moist soil required to obtain this target ρ_b was calculated as follows:

$$M_p = (\rho_b \times V_s) \times (1 + SWC_m \div 100) \qquad (4)$$

where: M_p is the mass of the moist soil that needs to be packed into the pot (g), ρ_b is the target bulk density (kg/m³), V_s is the soil volume in cm³. Soils were packed into 3.54 dm³ PVC pots which consisted of 200 mm lengths of 150 mm ø PVC pipe with a wall thickness of 4 mm. The base of each pot was machined from a 3 mm thick PVC sheet, and glued onto one of the open ends. A 10 mm ø hole was drilled in the bottom of each pot to allow drainage. A piece of 1.5 mm plastic fly-mesh was placed on the bottom of each pot to prevent the soil from being lost through the drainage hole. All pots were cleaned and weighed before being filled with the soil. A custom-built mechanical press was used to compact the soils to the required ρ_b. The packed soil columns were only 190 mm high, i.e., leaving 10 mm below the upper edge of a pot free. The surface under the rain shelter was first levelled with a gravel layer to promote even distribution of the irrigation water. A layer of coarse building sand was placed on top of the gravel. The pots were placed onto 240 mm ø plastic saucers. The area occupied by the pot experiment was 3.7 m x 7.8 m. For each soil, 4 additional pots were
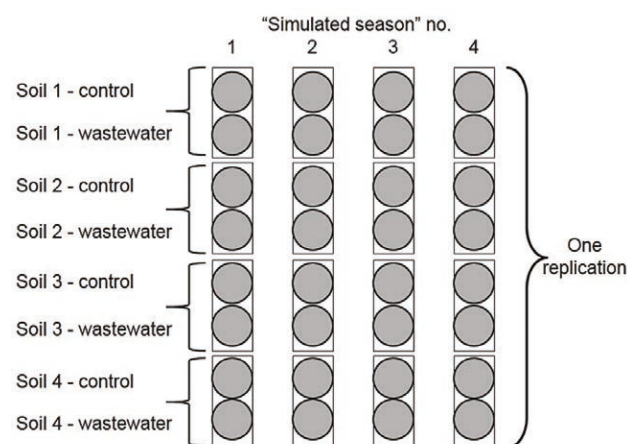
Figure 1
Schematic illustration of the layout of a replication of the treatment pots. In the actual experimental layout, the pots of different treatments were randomised in each replication

21

packed. The soil in these pots was saturated using municipal water. After free drainage had stopped, the pots were weighed to obtain the mean mass for each soil at field capacity. The dry soil mass (M_{od}) in each pot (g) was calculated as follows:
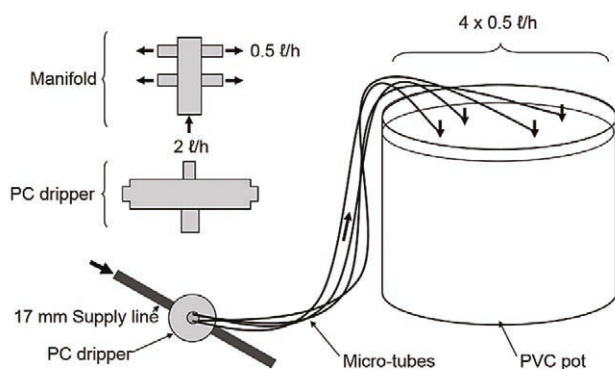
$$M_{od} = V_s \times \rho_b \qquad (5)$$

where: V_s is the volume (dm³) of soil and ρ_b is the target bulk density (kg/m³).

Irrigation system

Two 0.74 kW, 3 m³/h pumps (Foras, Berg River Irrigation, Paarl) were used to apply the municipal and diluted winery wastewater to the respective soil/water treatment combinations. The municipal and diluted winery wastewater passed through two 130 μm ring filters (Arkal, Netafim, Kraaifontein) installed downstream of each pump. An 8-way manifold with a ball valve at each outlet allowed individual irrigation of 8 soil/water treatment combinations. Water was distributed through a network consisting of 17 mm ø laterals, and applied to each pot by means of a 2 L/h pressure compensating button dripper with a 4-way manifold attached to it (Netafim, Kraaifontein). Four 700 mm long, 3 mm inner ø micro-tubes were attached to each dripper manifold (Fig. 2). In order to obtain equal flow through the four micro-tubes, an inline labyrinth-type dripper (Arrow, Netafim, Kraaifontein) was inserted in the open end of each micro-tube to create some back pressure. To distribute the irrigation water uniformly over the soil surface, the four micro-tubes were supported by a brace placed onto each pot (Fig. 3). The brace, in the form of a cross, was made from two 1.8 mm x 7 mm x 205 mm galvanised metal strips. On each side of the metal strips, the last 20 mm was bent at a rectangle so that the brace fitted firmly onto a pot. The four micro-tubes were pushed through 5 mm ø holes drilled in the brace. The flow rate through each of the four micro-tubes was 0.5 L/h. The total flow rate through the four micro-tubes (Q_{drip}) was 34 mL/min.

Irrigation volumes

The volume of water applied to each soil was recorded using water meters. The mass of water in each soil at field capacity (WM_{fc}) was calculated as follows:

$$WM_{fc} = M_{fc} - M_{od} \qquad (6)$$

where: M_{fc} is the mean pot plus soil mass at field capacity (g) and M_{od} is the pot plus oven-dry soil mass (g). To irrigate when WM_{fc} had evaporated to a specific depletion percentage (P), the pot plus soil mass at that depletion percentage (M_{depl}) was calculated as follows:

$$M_{depl} = M_{od} + (WM_{fc} \times P \div 100) \qquad (7)$$

Since weighing 96 pots was too laborious, only 4 representative pots per soil/water treatment, i.e., 32 in total, were weighed. Before weighing these pots, the braces bearing the micro-tubes were removed. An electronic balance was used to weigh the pots every second day until the mass reached M_{depl}. Assuming that the water density is 1 g/cm³, the irrigation volume required per pot was calculated as follows:
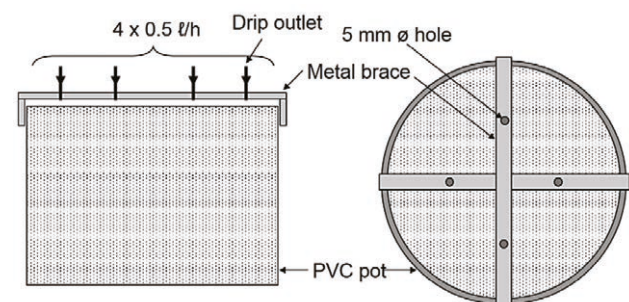
$$V_{irr} = WM_{fc} - M_{act} \qquad (8)$$

where V_{irr} is the volume of water required per pot (mL) and M_{act} is the actual pot plus soil mass before irrigation (g). The time required to apply V_p was calculated as follows:

$$t = V_{irr} \div Q_{drip} \qquad (9)$$

where t is the time (min) and Q_{drip} is the total flow rate through the four micro-tubes (mL/min). The soils were irrigated when their P reached approx. 85%. This high level of depletion was to ensure adequate soil aeration between irrigations. When pots were removed for soil chemical analyses, their irrigation water was collected in 500 mL glass beakers and discarded. This was to maintain the same irrigation system flow rate throughout the experiment.

RESULTS AND DISCUSSION

Since only topsoil was used in the study, characteristics of the deeper horizons were considered to be irrelevant. With the exception of the Stellenbosch granite soil, which had a high coarse sand fraction, fine sand dominated the sand fraction (Table 1). According to Van Huyssteen (1989), this particular soil contains approx. 47% gravel, i.e., 2–6 mm ø, in its natural state. All soils compacted with relative ease to a ρ_b of 1 400 kg/m³. When the soils were packed into the pots, mean water contents were 14.9%, 11.7%, 12.1% and 14.5%, respectively, for the Rawsonville sand, Lutzville sand, Stellenbosch shale soil and Stellenbosch granite soil. Irrigation amounts applied to

Figure 2
Schematic illustration of the configuration of the pressure-compensating (PC) dripper, manifold and micro-tubes to distribute water evenly in the pots

Figure 3
Schematic illustration of a PVC pot with galvanized metal braces supporting the four micro-tubes

the Rawsonville sand, Lutzville sand, and Stellenbosch shale soil over the four simulated seasons were comparable, but the Stellenbosch granitic soil received substantially less water (Table 2). As expected, the COD in the municipal water was substantially lower compared to the diluted winery wastewater (Table 3). The COD in the diluted winery wastewater was reasonably close to the target level of 3 000 mg/L. Since the COD was comparable between the four simulated seasons (Table 3), it indicated that the chemical status of the water in the tanks remained stable.

The soil water contents at field capacity of the soils were comparable, except for the Stellenbosch granite soil (Fig. 4). This indicated that this particular soil had a lower water-holding capacity compared to the other soils. The lower water-holding capacity of the Stellenbosch granite soil was probably due to the high coarse sand content (Table 1). Initially, the soil water content was restored to field capacity following irrigation in all soils. However, in the case of the Stellenbosch granite, field capacity was only restored following the first two irrigations (Fig. 4D). From the third irrigation onwards, visual observation revealed that the irrigation water ponded on the soil surface due to poor water infiltration. Consequently, the target soil water depletion level was reached following irrigation, but field capacity could not be restored (Fig. 4D). Although actual soil water content was not measured in the pots, it can be assumed that only the upper section of the profile in the Stellenbosch granite soil was wetted.

Although the level of COD differed substantially between the municipal and winery wastewater (Table 3), water infiltration problems occurred where municipal water, as well as winery wastewater, was applied to the granite soil. The sodium adsorption ratios in the municipal and winery wastewater were 0.8±0.1 and 4.6±0.6, respectively (Mulidzi and Myburgh, 2014). This confirmed that poor water quality did not cause the problem. Since the soil was not saline, irrigation with low salinity water could not have caused the problem in the case of the clean water treatments. When irrigated with clean river water and a range of diluted winery wastewaters, the near-saturation hydraulic conductivity of this particular soil was considerably lower compared to the other soils, irrespective of the level of water quality (Howell and Myburgh, 2014).

With the exception of the Stellenbosch granite soil, the soil water content was managed between field capacity and the refill point (Fig. 4). This indicated that the soils were well-aerated between irrigations. Since the lower part of the Stellenbosch granite must have remained dry, it implied that this soil was also well-aerated between irrigations. Visual observation revealed that no drainage occurred after irrigations had been applied. Therefore, it can be assumed that no leaching occurred of elements applied via the municipal or diluted winery wastewater. The foregoing indicated that the lysimetric approach provided an accurate measure of the irrigation volumes required. It is important to note that the pot experiment was completed in approximately 2.5 years, whereas it would have taken 4 years to do the wastewater irrigations in a field experiment.

TABLE 1
Locality, soil form, particle size distribution (≤ 2 mm) and textural class for the 4 soils included in the study

	Rawsonville sand	Lutzville sand	Stellenbosch shale	Stellenbosch granite
Latitude	−33.693698°	−31.558906°	−33.911717°	−33.917296°
Longitude	19.322569°	18.353115°	18.871152°	18.864484°
Clay (<0.002 mm)	3.3	0.4	20	13
Silt (0.002–0.02 mm)	1	1	13	17
Fine sand (0.02–0.2 mm)	60	69	50	33
Medium sand (0.2–0.5 mm)	29	26	5	3
Coarse sand (0.5–2 mm)	8	2	12	35
Soil textural class	Fine sand	Fine sand	Fine sandy clay loam	Coarse sandy loam

TABLE 2
Total irrigation amounts applied to 4 different soils during 4 simulated seasons

Soil	Irrigation applied (mm/season)				Total
	Season 1	Season 2	Season 3	Season 4	
Rawsonville sand	291	289	287	289	1 156
Lutzville sand	281	282	282	281	1 126
Stellenbosch shale	246	250	246	245	987
Stellenbosch granite	181	180	184	183	728

TABLE 3
Variation in chemical oxygen demand (mg/L) in the water used for the pot experiment

Water source	Season				Mean
	1	2	3	4	
Municipal water	35	25	26	26	28±4
Diluted winery wastewater	3 149	3 257	3 243	3 190	3 210±43
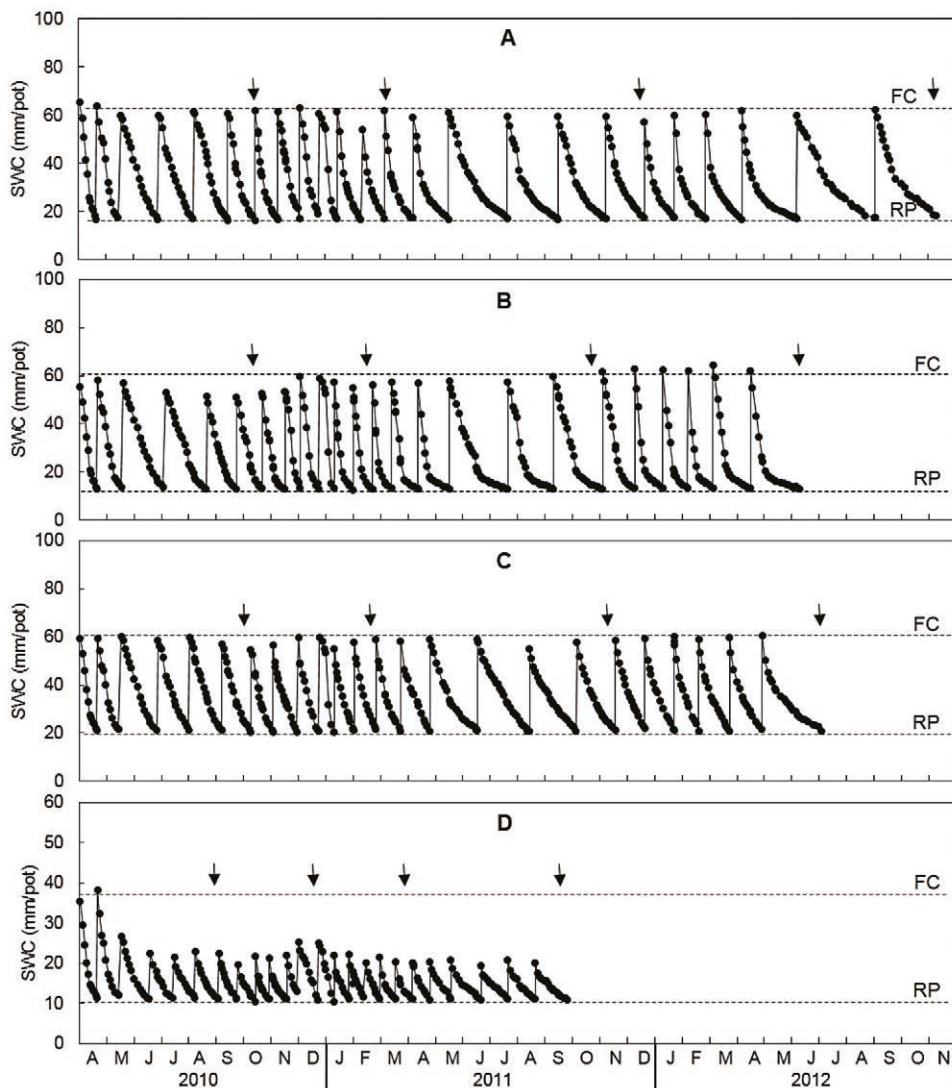
Figure 4
Temporal variation in soil water content (SWC) in (A) Rawsonville sand, (B) Lutzville sand, (C) Stellenbosch shale and (D) Stellenbosch granite soils measured in a pot experiment. Arrows indicate when soil chemical status was determined after each of the simulated seasons. 'FC' and 'RP' indicate field capacity and refill point, respectively.

CONCLUSIONS

It was possible to subject more than one soil to irrigation with diluted winery wastewater by using a single mix and irrigation infrastructure. Since the pot experiment could be continued under the rain shelter during winter, results were obtained quicker compared to an open field study. Although only representative pots were weighed, the procedure was still time consuming. Therefore, it is recommended that load cells are used to record daily mass losses automatically. Automatic recording will also be useful for determining mass losses if experiments are carried out with potted plants.

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