Assessing the role of rainfall redirection techniques for arresting the land degradation under drip irrigated grapevines

V. Phogat¹,²,³,⁎ T. Pitt³, R.M. Stevens⁴, J.W. Cox³, J. Šimůnek⁵, P.R. Petrie¹,²,⁶

¹ South Australian Research and Development Institute, GPO Box 397, Adelaide SA 5001, Australia
² The University of Adelaide, FMB1, Glen Osmond, SA 5064, Australia
³ CCS Haryana Agricultural University, Hisar 125004, India
⁴ Formerly South Australian Research and Development Institute Staff, Australia
⁵ Department of Environmental Sciences, University of California, Riverside, CA 92521, United States
⁶ The University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Weiping Chen, Associate Editor

Keywords:
Rainfall redirection
Mulching
Leaching
Salinity
Grapevine
HYDRUS-2D

ABSTRACT

Altering the soil surface features can potentially regulate water and solute movement processes in the soils, and reduce the accumulation of salts in the plant root zone. In this study, HYDRUS-2D was used consecutively for three years (2011–2014) to evaluate the potential impact of different rainfall redirection and water harvesting techniques such as no mounding or control (A), mid-row mounding (B), mid-row mounding covered with plastic (C), and plastic buried in the soil in mid-row (D) on water balance, root zone salinity dynamics, and salt balance in the soil in three grapevine producing regions (Loxton, McLaren Vale, and Padthaway) in South Australia. Simulations covered varied soil, climate, irrigation quality (0.3, 1.2, and 2.2 dS/m), and vine management conditions typical of each region. Seasonal transpiration (Tp), evaporation (Es), and drainage (Dr) accounted for 39–49, 26–44, and 17–25%, respectively, of the total drip irrigation applied to the vineyards across the three locations. Relative to the control, mound mid-row soils (B) did not significantly alter the water balance at any site; adding an impermeable plastic layer to that mound (C) reduced Es (48–54%), and increased Dr (by two thirds) and Tp (1–16%). A tremendous ameliorative impact of mid-row mounding with plastic (C) was observed in the spatiotemporal salinity dynamics in the soils at all three locations (salt removal efficiency LEs > 1). An increased leaching fraction under the mid-row mounding with plastic (C) led to considerable (up to 14.6 t/ha) salts leaching from the crop root zone, which was double the other treatments. Buried plastic (D) showed slightly better outcomes than the control or mid-row mounding, particularly for seasonal salt leaching in heavy textured soils. Salt removal efficiency (LEs) > 1 in light- and medium-textured soils as compared to heavy-textured soils indicates better salt removal in the former soils. The results demonstrated that the mid-row mounding with plastic is an effective technique to reduce root zone salinity in the drip-irrigated horticultural crops.

1. Introduction

Irrigation induced soil salinization is a worldwide phenomenon, especially in arid and semiarid regions where poor quality water is used for crop production. It is not only impacting soil quality and reducing crop productivity but also curtailing the cultivated area and rendering the soil unfit for sustainable crop production (e.g., Cao et al., 2018). Poor quality water includes untreated or recycled municipal sewage water, partially treated or untreated effluents/spent wash from industries, groundwater and drainage water, which are often used for irrigating the crops as a supplement to the rainfall or a good quality source. Food and Agriculture Organization (FAO, 2016) reported that > 19 percent of the total irrigated land (about 62 m ha) in the world suffers from salinization. Every day for > 20 years, an average of 2,000 ha of irrigated land in arid and semi-arid areas across 75 countries have been degraded by salt-related degradation (Qadir et al., 2014). It is anticipated that increased temperature and reduced rainfall projections by IPCC (2014) may intensify the risks of soil salinization and endanger sustainable crop production, including high-value horticultural crops such as grapevine.

Irrigated grapevines are grown across every continent and are highly managed growing systems where water availability and its quality are often the most limiting factors (Flexas, 2016; da Silva et al., 2018). In Australia, > 90% of grapevines are grown under highly...
efficient micro-irrigation systems (ABS, 2015). South Australia is a major grape and wine-producing region in Australia, contributing 48% of the total wine grape crush, and 93% of vineyards use supplementary drip irrigation (ABS, 2015). But, the quality of irrigation water used for grapevine cultivation is highly variable across different vine-growing regions. For example, in McLaren Vale, recycled water ($EC_w = 1.0–1.7$ dS/m) is commonly used to supplement rainfall. In contrast, in the South East region, groundwater ($EC_w = 1.9–2.4$ dS/m) is the dominant source for irrigating grapevines (Stevens et al., 2012; Pitt et al., 2015). Increased use of these waters (recycled and groundwater) for irrigation, frequent droughts, and climate change projections of diminishing precipitation are putting enormous pressure on growers to maintain and sustain viticulture production around the world (e.g., DeGaris et al., 2015; van Leeuwen and Darriet, 2016). Besides, increased use of saline water for irrigating grapevines is posing a potential danger of soil salinization, inflicting a serious impact on the long-term sustainability of these vineyards (Stevens et al., 2012).

Irrigated agriculture has managed the use of saline waters by leaching of salts from the rootzone depending on crop salt tolerance (Ayers and Westcot, 1985). The traditional irrigation management strategy under conditions where the supply of water is not limited is to provide extra water such that the ratio of the actual depth of drainage to the depth of irrigation, i.e., the leaching fraction (LF), satisfies the leaching requirement (LR) (FAO, 1994). Due to the complexities of interactions between water, soil, and plant uptake, matching of LF with LR is not straightforward (Dudley et al., 2008). In addition, the unavailability of good quality water and the complexity of implementation of LR for salinity control under drip irrigation systems may lead to enormous amounts of salt deposition laterally in the soils (e.g., Hanson et al., 2008). Complex soil heterogeneity and widespread stratification in Australian grapevine growing areas and poor drainage conditions may also confound efforts to tackle soil salinization (Singh, 2019; Wichelns and Qadir, 2015).

Under such situations, on-farm water harvesting techniques such as mulching and rainfall redirection play a key role in regulating water and solute movement processes in the soil (Wang et al., 2009). For example, drip irrigation coupled with plastic mulch has been introduced over a large area in China to reduce evaporation and to optimize the efficiency of available water resources (Liu et al., 2013). Several studies have reported benefits of mulching in term of water use efficiency (Adhikari et al., 2016; Zhao et al., 2014; Yu et al., 2018), seed emergence (e.g., Dong et al., 2010), crop yield (Qin et al., 2014; Yu et al., 2018), salinity control (Bezborodov et al., 2010; Abd El-Mageed et al., 2016), soil temperature management (e.g., Li et al., 2017; Zhang et al., 2018), and weed control (e.g., Ramakrishna et al., 2006). Field experiments on rainfall redirection techniques (removing under vine mound and mulching in mid-row with rainfall harvesting) have established a reduction of the soil salinity and Na⁺ and Cl⁻ content in wine grapes (Stevens et al., 2013; Pitt et al., 2015). However, it is not clear whether these techniques apply beyond the particular combinations of water quality, climate, and soils at the experimental sites. Indeed, it is worth examining the impact of these techniques on water balance, root zone salinity dynamics, and salt leaching in soils.

Conducting long-term experiments involving numerous variables under varied soil, water, and climate conditions are costly, and labor- and time-intensive. On the other hand, numerical models are excellent cost-effective tools to study the impact of climate, soil, water, and crop variables on water and solute transport in the soil (Phogat et al., 2018a). Among the available agro-hydrological models, HYDRUS (2D/3D) (Šimůnek et al., 2016) has been widely used to simulate water movement and salinity dynamics under drip irrigation (Ramos et al., 2012; Selim et al., 2013; Chen et al., 2015; Phogat et al., 2014, 2019) because of its flexibility to accommodate different types of complex boundary conditions, to consider root water and nutrients uptake, and its ease of use due to a user-friendly graphical interface. However, few modelling studies have included a mulched boundary for drip irrigation (e.g., Liu et al., 2013; Wang et al., 2014; Li et al., 2015; Zhao et al., 2018). These studies were only confined to evaluating the dynamics of water distribution in soils, and the reduction of evaporation due to mulched conditions on the flat surface by considering a no-flow boundary over the mulched surface. Simulations of water and salinity dynamics under different mid-row rainwater harvesting techniques (e.g., mounding with and without plastic, and sub-surface plastic) coupled with drip irrigation of grapevines could potentially serve as a new concept for implementing the surface boundary in modelling studies. Furthermore, to our knowledge, no modelling study has been focused on evaluating the ameliorative effect of rainfall directed from the mid-row of horticultural crops.

Therefore, in this investigation, HYDRUS-2D was used to evaluate the impact of different rainfall redirection and water harvesting techniques (A - no mounding or control, B - mid-row mounding, C - mid-row mounding covered with plastic, and D - plastic buried in the soil in mid-row) on water balance, root zone salinity dynamics, and salt balance in different grapevine growing regions (Loxton, McLaren Vale, and Padthaway) over multiple seasons (2011–2014) involving varied soil, climate, irrigation quantity and quality, and crop conditions. The outcome of this investigation would be helpful in evaluating these innovative practices for controlling soil salinization and salt leaching for sustainable grape production.

2. Materials and methods

2.1. Description of the study sites

The present investigation was carried out in three grapevine growing regions in South Australia (SA), i.e., McLaren Vale (McLaren Vale region), Padthaway (South East), and Loxton (Riverland) (Fig. 1). These sites have different climate, soil, irrigation water quality, and growing practices, representing diverse and varied conditions for grapevine cultivation. The water and salt balance modeling study was conducted for three consecutive seasons (2011–12 to 2013–14) at the three locations. All experimental details including soil characterization, irrigation scheduling, water quality, crop performance and yield for these trials can be found in Pitt et al. (2015), Stevens et al. (2012, 2013), and Phogat et al. (2017, 2018b) for the McLaren Vale (McLc), Padthaway (Pad), and Loxton (Lox) sites, respectively. However, brief site-specific information about data acquisition relevant to the current study is given below.

2.1.1. McLaren Vale

McLaren Vale (McL) is a premium wine grape region in South Adelaide, which is characteristic by a Mediterranean climate. The climate data for the study site were obtained by running a data drill for the study site (Jeffrey et al., 2001). The average maximum temperature, potential evapotranspiration, and rainfall for the last 100 years at the experimental site were 20.9 °C, 1568.5 mm, and 555 mm, respectively. Other data for simulations were obtained from an experimental study conducted at a commercial Cabernet Sauvignon vineyard (35°14’S and 138°31’E) located within the region (Pitt et al., 2015). The vineyard was planted in 1998 with a vine spacing of 2.75 m by 1.8 m. The vines were irrigated with a drip system with 1.2 L/h drippers spaced at 0.6 m and aligned along the length of vine rows. Treated wastewater for irrigation was obtained from the Christies Beach Wastewater Treatment Plant and distributed through a pipeline scheme managed by Willunga Basin Water (WBW). Water samples were collected from irrigation emitters throughout the growing season and assessed for salinity (Pitt et al., 2015). The average irrigation water salinity ($EC_w$) during the study period (2011–14) was 1.2 dS/m (range 1.0–1.3 dS/m). The amounts of seasonal supplementary irrigation applied to grapevine at McLaren Vale ranged from 86.6 to 135.3 mm during 2011–14 (Table 1).

A comprehensive soil testing program was carried out at the McLaren Vale study site due to the existence of a complex
heterogeneous soil formation in this region (Pitt et al., 2015). Undisturbed core samples were collected from 0 to 15, 30–60, and 60–100 cm soil depths under vine (UV), under the track (UT), and in mid-row (MR) regions to examine the variability in soil characteristics (Pitt et al., 2015). The soil hydraulic parameters (Table 2) were estimated following van Genuchten-Mualem constitutive relationship (van Genuchten, 1980), utilizing measured soil water retention data on undisturbed soil cores collected from UV, UT, and MR regions. The saturated hydraulic conductivity ($K_s$) and the bulk density ($D_b$) were also measured on undisturbed soil cores following standard procedures (Klute, 1986). Hence, input parameters represent a complex variability existing at different soil depths and laterally across the vine rows.

### 2.1.2. Padthaway

Padthaway (36°37’S and 140°32’E), in the South East of South Australia, is characterized by the presence of medium-textured soils underlain with limestone rocks, popularly known as *Terra rossa*. Padthaway (Pad) has a warm Mediterranean climate with good rainfall. The average rainfall and potential evapotranspiration over the last 100 years amount to 523.3 and 1553.4 mm, respectively. Climate parameters for modelling were taken from a nearby Bureau of Meteorology observatory.

Relevant crop data for modelling was obtained from a field experiment in a commercial own-rooted Chardonnay vineyard, located approximately 12 km south of Padthaway (Stevens et al., 2012, 2013). The vineyard was planted in 1996 with Chardonnay clone I10V1. Salinity trends in the shallow unconfined aquifer on the Padthaway Flat are quite variable and are influenced by rainfall patterns and the types of irrigation practices. Surface drippers spaced at 60 cm were used to apply supplementary groundwater irrigation to vines with a salinity varied from 1.9 to 2.3 dS/m. The average salinity of irrigation water ($EC_{iw}$) over the three seasons (2011–14) was 2.2 dS/m. The pressure compensated drippers had a discharge of 2.1 L/h. In the absence of good quality surface water resources at Padthaway, irrigated vines were solely dependent on groundwater for supplemental irrigation. Seasonal water applications during the simulation period amount to 242.5 mm (Table 1).

The soils at the Padthaway study site varied from sandy clay loam at the surface to clay at lower depth (Stevens et al., 2012). The soil hydraulic parameters (Table 2) used in the modelling study were estimated from measured values of the water content-pressure head relationship in undisturbed cores taken from 0 to 30 and 30–100 cm. Other soil parameters (the saturated hydraulic conductivity and bulk density) for both layers were also measured on undisturbed soil cores. Similar hydraulic parameters were assumed at different locations across the vine lines (UV, UT, and MR). While measured initial soil salinity ($EC_e$) at UV down to the 80 cm depth varied from 4 to 4.5 dS/m at the start of the simulation, the $EC_e$ at MR and UT (1.2 to 2.0 dS/m, respectively) were less than half of that (Stevens et al., 2012).

### 2.1.3. Loxton

Loxton (34°27’S and 140°34’E) is a part of the Riverland vineyard region, which is located along the River Murray corridor and utilizes the good quality river water for grapevine irrigation. It has a warmer Mediterranean climate and receives less rainfall compared to the other two regions. The average maximum temperature, potential evapotranspiration, and rainfall for the last 100 years were 23.8°C, 1823 mm, and 265 mm, respectively (Phogat et al., 2017).

The Chardonnay vineyard at Loxton (Lox) was irrigated with a surface drip system. The water was applied through pressure compensated drippers with a discharge of 1.6 L/h. The plant spacing is similar to the vineyards at the other two locations. The vineyard was irrigated with water from the River Murray, which has salinity varying from 0.2 to 0.4 dS/m, with a mean value of 0.3 dS/m during the study period (Phogat et al., 2018b). Seasonal irrigation applications were much

---

**Table 1**

<table>
<thead>
<tr>
<th>Location</th>
<th>2011–12 P (mm)</th>
<th>2012–13 I (mm)</th>
<th>2013–14 P (mm)</th>
<th>Average P (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McLaren Vale</td>
<td>614.3</td>
<td>86.6</td>
<td>437.1</td>
<td>524.0</td>
</tr>
<tr>
<td>Padthaway</td>
<td>466.4</td>
<td>242.5</td>
<td>446.4</td>
<td>496.6</td>
</tr>
<tr>
<td>Loxton</td>
<td>298.2</td>
<td>322.5</td>
<td>198.7</td>
<td>281.7</td>
</tr>
</tbody>
</table>

---

Fig. 1. Locations of study sites (Loxton, McLaren Vale and Padthaway) in different grapevine regions in South Australia.
higher at Loxton as compared to the other two locations due to less rainfall and low water retention capacity of light-textured soils. The average seasonal irrigation over the three seasons at Loxton was 378 mm (Table 1).

The soils at the Loxton site are predominately sandy in texture. The soil hydraulic parameters for this modelling study were taken from Phogat et al. (2017) and are shown in Table 2. The saturated hydraulic conductivity \( K_s \) and the bulk density \( D_b \) were measured on undisturbed core samples using standard procedures. Similar soil hydraulic parameters were assumed at different locations across the vine lines [under vine (UV), under the track (UT) and in the mid-row (MR) regions]. Furthermore, HYDRUS-2D was calibrated and validated for spatial and temporal distributions of the soil water content over multiple seasons (Phogat et al., 2017).

### 2.2. Modelling domain and boundary conditions for different treatments

Field experiments at Padthaway and McLaren Vale consisted of four rainfall harvesting and redirection treatments, i.e., control (A), a mid-row mound (B), a mid-row mound covered with plastic (C), and buried plastic in the mid-row region (D). The establishment of these treatments at field sites is discussed in Stevens et al. (2012) and Pitt et al. (2015), respectively, and is shown in Fig. 2 for the McLaren Vale site. Similar modelling scenarios were conducted at Loxton to match the treatments at the other two sites. In the control treatment, actual mid-row conditions show depressions in the wheel ruts due to heavy traffic associated with mechanical pruning (or pre-pruning), fungicide/herbicide spray program, and mechanical harvest operations. In the other treatments (B, C, and D), a shallow ripping operation and/or removing the under vine mound soil facilitated the mid-row mound operations. These modifications on the soil surface are also illustrated in the modelling domains (Fig. 3).

The modelling domains for different treatments were constructed in HYDRUS-2D (Šimůnek et al., 2016) based on the vine spacing, drip design parameters, and mid-row treatments (Fig. 3). The vine row is present in the centre of the domain, which was extended equally on both sides across the vine row. The vertical depth was equal to 100 cm, which relates to the rooting depth of grapevines in the field experiments (Stevens et al., 2012; Pitt et al., 2015; Phogat et al., 2017). A time-variable flux boundary condition was applied to a 20 cm long boundary directly below the dripper, centred on 137.5 cm from the top left corner of the soil domain (Fig. 3). The length of this boundary was selected to ensure that all irrigation water could infiltrate into the soil without producing positive surface pressure heads, because positive pressure heads at the flux boundary could make the numerical code unstable (Šimůnek et al., 2016). During irrigation, the drip line boundary was held at a constant water flux, \( q \), equal to the dripper discharge rates at different locations. The atmospheric boundary condition was assumed for the remainder of the soil surface. A no-flow boundary condition was specified on the left and right edges of the soil profile to account for flow and transport symmetry. A free drainage boundary condition was assumed at the bottom of the soil profile.

To implement a plastic cover over the mound (treatment C), arcs were constructed 3–5 cm below the surface boundary, and a no-flow boundary condition was imposed in the domain over the plastic sheet on both sides at the desired locations (see Fig. 3). The extent of evaporation from the soil over the no flow mulched surface was assumed equal to the losses due to wear and tear of the mulch. Liu et al. (2013) reported that plastic mulch reduced the soil evaporation by 90% under optimum conditions. However, year-old mulch can deteriorate and be torn apart at some places, leading to significant evaporation losses. Essentially, placing the plastic mulch below a thin soil layer helped to protect it from the hot weather and other mid-row operations (Pitt et al., 2015). Another advantage of adopting this approach was to facilitate rainwater movement along the ridge/mound to the lower reaches of the furrow/soil. This approach, further, allowed simulating the variable impact of dynamic pressure heads due to rainfall on flow conditions in the soils. Similarly, for treatment D, a no-flow boundary was embedded into the domain at the location (10 cm below the soil surface) where the plastic sheet was placed in the field studies. Fine mesh size was adapted below the time-variable flux boundary (below the dripper) in all treatments to facilitate dynamic flow conditions in response to frequent irrigations. All specified boundary conditions are illustrated in Fig. 3. Simulations were conducted separately for each treatment for three years (July 1, 2011–June 30, 2014) using daily time steps for boundary conditions.

### 2.3. Estimation of potential transpiration \( (T_p) \) and potential evaporation \( (E_p) \)

HYDRUS-2D requires daily values of potential \( T_p \) and \( E_p \) under the field conditions as inputs and then calculates modelled values depending on soil moisture dynamics. In this study, the FAO-56 dual-crop coefficient approach was employed to estimate the daily values of potential \( T_p \) and \( E_p \) for grapevine at three locations (Allen et al., 1998). This method has been used previously in many studies for input data generation (e.g., Phogat et al., 2014, 2017). It combines two coefficients, i.e., a basal crop coefficient \( (K_{cb}) \) responsible for transpiration

---

**Table 2**

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Soil depth (cm)</th>
<th>( \theta_s ) (cm³ cm⁻³)</th>
<th>( \theta_r ) (cm³ cm⁻³)</th>
<th>( a ) (cm⁻¹)</th>
<th>( n )</th>
<th>( K_s ) (cm d⁻¹)</th>
<th>( l )</th>
<th>( D_b ) (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McLaren Vale</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy clay loam (UV)</td>
<td>0–30</td>
<td>0.23</td>
<td>0.50</td>
<td>0.014</td>
<td>1.5</td>
<td>137.8</td>
<td>0.5</td>
<td>1.50</td>
</tr>
<tr>
<td>Sandy clay loam (UT)</td>
<td>0–30</td>
<td>0.23</td>
<td>0.46</td>
<td>0.013</td>
<td>1.5</td>
<td>57.4</td>
<td>0.5</td>
<td>1.55</td>
</tr>
<tr>
<td>Sandy clay loam (MR)</td>
<td>0–30</td>
<td>0.19</td>
<td>0.47</td>
<td>0.011</td>
<td>1.4</td>
<td>153.9</td>
<td>0.5</td>
<td>1.44</td>
</tr>
<tr>
<td>Clay (UV)</td>
<td>30–65</td>
<td>0.26</td>
<td>0.49</td>
<td>0.014</td>
<td>1.4</td>
<td>20.7</td>
<td>0.5</td>
<td>1.55</td>
</tr>
<tr>
<td>Clay (UT)</td>
<td>30–65</td>
<td>0.31</td>
<td>0.49</td>
<td>0.03</td>
<td>1.4</td>
<td>33.2</td>
<td>0.5</td>
<td>1.55</td>
</tr>
<tr>
<td>Clay (MR)</td>
<td>30–65</td>
<td>0.27</td>
<td>0.50</td>
<td>0.01</td>
<td>1.4</td>
<td>87.7</td>
<td>0.5</td>
<td>1.40</td>
</tr>
<tr>
<td>Clay (UV)</td>
<td>65–100</td>
<td>0.26</td>
<td>0.49</td>
<td>0.114</td>
<td>1.2</td>
<td>58.7</td>
<td>0.5</td>
<td>1.49</td>
</tr>
<tr>
<td>Clay (UT)</td>
<td>65–100</td>
<td>0.27</td>
<td>0.46</td>
<td>0.12</td>
<td>1.2</td>
<td>13.8</td>
<td>0.5</td>
<td>1.49</td>
</tr>
<tr>
<td>Clay (MR)</td>
<td>65–100</td>
<td>0.25</td>
<td>0.43</td>
<td>0.014</td>
<td>1.4</td>
<td>35.1</td>
<td>0.5</td>
<td>1.32</td>
</tr>
<tr>
<td>Padthaway</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>0–30</td>
<td>0.07</td>
<td>0.48</td>
<td>0.02</td>
<td>1.25</td>
<td>26.0</td>
<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Clay loam</td>
<td>30–100</td>
<td>0.17</td>
<td>0.44</td>
<td>0.058</td>
<td>1.3</td>
<td>11.0</td>
<td>0.5</td>
<td>1.44</td>
</tr>
<tr>
<td>Loxton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0–30</td>
<td>0.04</td>
<td>0.4</td>
<td>0.027</td>
<td>2.2</td>
<td>388.8</td>
<td>0.5</td>
<td>1.53</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>30–60</td>
<td>0.05</td>
<td>0.38</td>
<td>0.04</td>
<td>1.7</td>
<td>259.2</td>
<td>0.5</td>
<td>1.41</td>
</tr>
<tr>
<td>Loam</td>
<td>60–100</td>
<td>0.05</td>
<td>0.37</td>
<td>0.04</td>
<td>1.62</td>
<td>172.8</td>
<td>0.5</td>
<td>1.44</td>
</tr>
</tbody>
</table>

\( \theta_s \) is the residual water content, \( \theta_r \) is the saturated water content, \( K_s \) is the saturated hydraulic conductivity, \( D_b \) is the bulk density, and \( a, n, l \) are the van Genuchten shape parameters.
and a soil evaporation coefficient \((K_e)\) (i.e., \(K_e = K_{cb} + K_c\)), with daily reference crop evapotranspiration \((ET_0)\) to estimate daily crop evapotranspiration \((ETC)\) as follows:

\[
ETC = (K_{cb} + K_c) \cdot ET_0
\]

Standard \(K_{cb}\) values for grapevine were adjusted for the local climate, taking into consideration crop height, wind speed, and minimum relative humidity averages for the period under consideration (2011–2014) at all locations (Allen et al., 1998). Location-specific parameters used to estimate daily \(E_s\) and \(T_p\) for grapevine following the FAO-56 dual-crop coefficient approach for three locations are given in Table 3. Values of daily potential transpiration \((T_p)\) and soil evaporation \((E_s)\) obtained in this way were used as time-variable boundary conditions (see Fig. 3) in the HYDRUS-2D model, along with precipitation received at the site during the study period. More details about the FAO-56 dual-crop coefficient can be found in Allen et al. (1998) and Allen and Pereira (2009).

2.4. Solute parameters for salinity dynamics in the soil

Soil solution salinity \((EC_{sw})\) distribution was modelled as a non-reactive solute (e.g., Ramos et al., 2011; Wang et al., 2014; Phogat et al., 2014, 2019). These studies demonstrated that this approach could be successfully used in environments under intensive irrigation and fertigation management. The longitudinal dispersivity was assumed as one/tenth of the modelling domain (with the transverse dispersivity being one-tenth of the longitudinal dispersivity) (Beven et al., 1993; Cote et al., 2003) and the molecular diffusion coefficient of salts in water was considered as 1.656 cm²/day (Phogat et al., 2017). The data for EC of irrigation water \((EC_{iw})\) was based on the water quality analysis. However, average values of \(EC_{iw}\) were considered for modelling for all locations (McLaren Vale = 1.2, Padthaway = 2.2, and Loxton = 0.3 dS/m) as there was only a small variation in the irrigation water quality over the study period. The rainfall chemistry analyzed by Cresswell et al. (2010) in the Adelaide region estimated the salinity \((EC_{rw})\) of 0.12 dS/m, and this value was used in simulations as a common value for all locations. To facilitate the prediction of the leaching of salts from the soil profile, all input \(EC_{iw}\) and \(EC_{rw}\) values were converted into mass units using a common approximation \((1 \text{ EC (dS/m)} = 640 \text{ mg salts/L})\). The salt leaching efficiency was estimated to compare the effectiveness of various rainfall redirection techniques. It was estimated for all locations annually as the amount of salts leached below a 1 m depth per volume of water drained.

The initial water content distribution was set to either measured values (McLaren Vale and Padthaway) or to field capacity (Loxton). Measured values of \(EC_e\) in the soil were converted to salinity at actual soil water content following a linear relationship by Pitt et al. (2015) and to salt mass as per the approximation \(1 \text{ EC (dS/m)} = 640 \text{ mg salts/L}\).
3. Results and discussion

### 3.1. Seasonal water balance

Seasonal water balance components for grapevine under different rainfall redirection treatments at the McLaren Vale site are shown in Table 4. The average water balance, irrespective of seasons and treatments, divided the transpiration ($T_p$), evaporation ($E_s$), and drainage ($D_r$) as 39, 44, and 17% of the total water application, respectively. Among the treatments, the results were similar for the mid-row mound treatment (B) and the control (A), while $T_p$ increased slightly for buried plastic (D) relative to the control. The mid-row mound + plastic (C) maximised vine water uptake followed by the buried plastic treatment. The average increase in grapevine $T_p$ in the mid-row mound + plastic treatment was 16% higher than the control. Normally, transpiration/root water uptake are expected to increase for sites with plastic mulch as compared to no mulch sites (Allen et al., 1998), because temperatures are higher under mulch, and root growth is promoted (Gao et al., 2014; Saglam et al., 2017). At the same time, there was a drastic reduction (54%) in $E_s$ in the mid-row mound + plastic treatment, which may have produced higher $D_r$, especially during the 2012–13 and 2013–14 seasons. Therefore, the average seasonal $D_r$ in mid-row mound + plastic treatment increased three times compared to the other treatments. Moreover, the average soil water storage ($ΔS$) also increased about four times under mid-row mound + plastic as compared to the control. The water conservation effect of plastic mulch has been documented in many previous studies for drip irrigation (e.g., Saglam et al., 2017).

The average water balance components at Padthaway were comparable to the McLaren Vale site. Nonetheless, the average soil water storage ($ΔS$) at the end of the grapevine season was 5% higher, and the average $E_s$ component was 7% lower than at the McLaren Vale site (Table S-1, supplementary material). Similarly, $T_p$ and $D_r$ also increased by 7.5% and 19% (almost three times), respectively, when the control treatments were compared. On the other hand, at Loxton, rainfall re-direction techniques had a little impact on vine water uptake as $T_p$ remained similar in all treatments (Table S-2, supplementary material). However, average $T_p$ accounted for 49% of the applied water, while 26% of irrigation and rainfall contributed towards $E_s$, with the remaining 25% of water draining out of the soil profile (1 m). Drainage ($D_r$) almost doubled in the mid-row mound + plastic treatment (C) compared to the control (A), showing the impact of surface mulching on direct water loss from the soil surface.

Leaching fractions (LF) estimated for the range of treatments at the three locations are shown in Fig. 4. The average LF for the mound only (B) and buried plastic (D) treatments were similar to the control (A). However, annual LFs were influenced by the site-specific soil texture and climate conditions (rainfall), being higher at Loxton (0.15–0.25). Notably, LFs were considerably lower at Padthaway during 2011–12 due to a relatively dry soil profile at the start of the simulation compared to the other sites. Later on, the LF at Padthaway matched corresponding values at McLaren Vale. On the other hand, the LF in the mid-row mound + plastic (C) treatment increased on average three times at McLaren Vale (0.26–0.39) and Padthaway (0.16–0.4) and two times at Loxton (0.31–0.4) compared to the corresponding average values for other treatments. Hanson et al. (2008) reported similar leaching fractions (0.07–0.31) under drip irrigation, which encourages rapid localized leaching, especially in light-textured soils.

Indeed, treatment mid-row mound + plastic has emerged as the
The most favourable treatment with increased plant water uptake, a higher fraction of the evaporative flux diverted towards leaching, a substantial increase in the LF, which altogether can help in maintaining a favourable environment by transporting salts out of the root zone. These results further confirm that plastic mulching, compared to the mid-row mounding, was an effective on-farm water management strategy that can improve the rhizosphere environment for a long-term sustainable grapevine production.

### 3.2. Soil salinity dynamics

#### 3.2.1. Spatiotemporal salinity distribution in the soil

The impact of the rainfall redirection techniques on spatial salinity \((EC_e)\) dynamics in the soil at the end of 2011–12, 2012–13, and 2013–14 growing seasons at the three locations is shown in Fig. 5. Generally, the \(EC_e\) distribution at the McLaren Vale and Padthaway sites in the under-vine (UV) was higher than in the mid-row irrespective of the treatment because drip irrigation applies water close to the vines. Rapid water...
extraction due to the high root density in this region results in the deposition of salts. On the other hand, in the mid-row, reduced water uptake and little salt addition via irrigation coupled with adequate rainfall-induced salt flushing produced lower \( EC_{w} \). However, at McLaren Vale, a trend towards increasing \( EC_{w} \) occurred, especially in the under-vine at the end of successive seasons, which is correlated with proportionally higher additions of salts through irrigation coupled with less localized leaching. Among the treatments, the bigger \( EC_{w} \) “bulge” was present in the under-vine in the control (A) and the mid-row mound (B) treatments as compared to the mid-row mound + plastic (C). At the end of the 2013–14 season, the maximum \( EC_{w} \) in the under vine region was 4.2, 3.5, 3.0, and 3.5 dS/m, respectively, in the control (A), a mid-row mound (B), a mid-row mound + plastic (C), and buried plastic (D) treatments at McLaren Vale. However, salinity remained below 0.5 dS/m in a mid-row mound + plastic (C), whereas it was < 0.9 dS/m in the control (A) and mid-row mound (B) treatments and much higher in the buried plastic (D) (0.9–1.5 dS/m). The results showed that at McLaren Vale, the predominance of heavy-textured heterogeneous soils and high irrigation water salinity encouraged salt deposition in the vicinity of the vine. This situation is similar to the poorly drained soils, which potentially encourage salinization and waterlogging problems in irrigated agro-systems (Vichelins and Qadir, 2015; Singh, 2019).

At Padthaway, the extent of \( EC_{w} \) distribution in the soil was much greater than at McLaren Vale, irrespective of regions and treatments, because the initial salinity in the under-vine (4–4.5 dS/m) and mid-row (1.2–1.8 dS/m) regions was very high compared to the other two sites. Apparently, the high \( EC_{iw} \) of the irrigation water (2.0–2.35 dS/m), coupled with medium to heavy-textured soils with low hydraulic conductivity (11–26 cm/day), is conducive to salt deposition within the soil profile in the immediate vicinity of the vine (under-vine region), where irrigation is applied through drippers. Therefore, pockets of high \( EC_{z} \) (5.5–7.0 dS/m) at Padthaway still existed under the vine below the 50 cm depth in all treatments except mid-row mound + plastic at the end of the 2011–12 vine growing season (Fig. 5iii). The maximum salinity zone had an average \( EC_{z} \) from 3.5 to 4.0 dS/m at the end of 2013–14. However, this zone spreads over a large area in the control (A) and mid-row mound (B) treatments as compared to buried plastic (D), where it was restricted within a small region, mostly in the deeper zone of the profile. In mid-row mound + plastic (C), a significant volume of water passed through the zone of high salinity, pushing the salts out of the profile. Consequently, salinity was greatly reduced during the first season. During the following seasons (2012–13; 2013–14), the soil profile salinity was reduced below threshold (2.2 dS/m) in almost the entire mid-row, whereas pockets of higher salinity existed in the under-vine below 30 cm. Hence, treatment mid-row mound + plastic (C) continued to be by far the most effective at salt removal compared to the other treatments.

Interestingly, at Loxton, \( EC_{z} \) remained lower in the UV region as compared to MR, irrespective of the rainfall redirection treatments (Fig. 5iii). At the end of the 3rd season (2013–14), a low \( EC_{z} \) zone (< 0.5 dS/m) increased laterally in all treatments. The presence of sandy soils and a three times higher amount of irrigation water of \( EC_{iw} \) of 0.3 dS/m applied within a localized region facilitated rapid leaching of the salts. In contrast, \( EC_{iw} \) at McLaren Vale and Padthaway was 4 and 7 times higher, respectively, than at Loxton, which potentially added an enormous quantity of salts in the soil in the under-vine area in these drip-irrigated vineyards. \( EC_{z} \) in the soil profile always remained below the grapevine threshold (2.2 dS/m) in all treatments. The buried plastic treatment allowed a small amount of salt deposition just below the plastic; this is due to the plastic membrane blocking vertical drainage of water and promoting lateral salt migration to the area underneath the plastic. In mid-row mound + plastic (C), the low salinity zone (< 0.5 dS/m) extended further under the vine compared to the other treatments. It is also evident that most of the irrigation-induced salts were leached out of the 1 m soil profile. Hence, the current irrigation amount and quality of water did not pose any salinity threat in the root zone of the vine, irrespective of treatments. Christen et al. (2007) showed a similar impact on the salinity distribution when using good quality irrigation water in a loamy soil.

Daily profile-averaged \( EC_{z} \) in the under-vine and mid-row regions at the McLaren Vale and Padthaway sites are shown in Fig. 6. Data for the Loxton site is not shown as the salinity levels were much lower than the grapevine threshold \( EC_{z} \) of 2.2 dS/m (Zhang et al., 2002). A progressive increase in \( EC_{z} \) was found at McLaren Vale in all treatments over the three seasons except in mid-row mound + plastic (C) where \( EC_{z} \) remained almost constant (< 0.5 dS/m). \( EC_{z} \) (0.9 dS/m) in buried plastic (D) was maximum in the mid-row region at the end of the simulation. Despite increasing trends, \( EC_{z} \) remained below the crop threshold in the mid-row region in all treatments. On the other hand, it increased above the threshold in the under-vine during the latter half of 2013–14, irrespective of treatments. It seems that heavy-textured soils with enormous profile heterogeneity and anisotropic flow conditions (Pitt et al., 2015) have played a crucial role in nullifying the treatment impact at McLaren Vale compared to the other Padthaway.

At the Padthaway site, the average \( EC_{z} \) in the MR region remained below the threshold in all treatments except buried plastic (D). Interestingly, in this treatment, \( EC_{z} \) under the mid-row increased above the threshold during the 2013–14 growing season. Buried plastic possibly harboured more salts directly below the plastic layer due to the
blockage of vertical drainage, as was also seen at Loxton also (Fig. 5). Although the average $E_{cv}$ in the under-vine reduced drastically in all treatments after an initial increase during the 2011–12 summers. Although it remained higher than the grapevine threshold (2.2 dS/m), the impact of the rainfall redirection was very dramatic in the mid-row mound + plastic (C) treatment where $E_{cv}$ fell below the threshold during the post-winter season of 2013–14. The mean $E_{cv}$ in the buried plastic (D) treatment falls between values obtained in the control (A) and mid-row mound + plastic (C) treatments in the under-vine area. In other studies also mulching has been found to be a better field-management option to reduce the upward movement of salts and evaporative water losses (Zhao et al., 2014; Chen et al., 2016) and that mulching with different materials is a promising technique for salinity control in agriculture (Bezborodov et al., 2010; Abd El-Mageed et al., 2016).

The mid-row mound + plastic treatment (C) maintained relatively lower salinity within the vine root zone as compared to the other treatments, especially for recycled water and groundwater irrigated grapevines with heavier-textured soils, providing a better growing environment for vine and a superior salt leaching approach as compared to other techniques. The results of the modelling suggest that the treatments behaved differently at different locations, and the impact on the $E_{cv}$ distribution under grapevine due to rainfall redirection techniques depends on combined effects of the soil type, water quality, and weather conditions.

### 3.3. Seasonal salt balance

Salt balance dynamics in the soil under different rainfall redirection techniques is shown in Table 5. There were different initial amounts of salts in the soils at different sites due to textural differences, and the quantity and quality of water used for grape production. At Padthaway, initial salt contents (8298 kg/ha) in the soil profile were 3.5 and 5 times higher than at McLaren Vale and Loxton, respectively. The annual amount of salts added through irrigation ($I_S$) during the simulation period (2011 to 2014) varied from 631 to 1038 and from 900 to 1200 kg/ha at the McLaren Vale and Loxton sites, respectively. However, almost similar amounts of $I_S$ (3352.8 kg/ha) were added annually at Padthaway during different years due to less variation in the seasonal irrigation volumes. Additionally, the amount of salts added through the rain ($P_S$) at McLaren Vale (302–434 kg/ha), Padthaway (308–408 kg/ha), and Loxton (136 to 247 kg/ha) were much lower as compared to salts added through irrigation during the same period.

Although salt additions in the soil in different treatments were similar, salt storage ($\Delta S_S$) and leaching ($Dr_S$) altered due to different rainfall redirection techniques (Table 5). Interestingly, all treatments showed an increased amount of salt remaining in the profile at McLaren Vale and Padthaway (except mid-row mound + plastic) during all seasons where recycled water and groundwater were used for irrigation, respectively. On the other hand, at Loxton, salt leaching was very rapid, and a high amount of leaching occurred compared to the amount added through irrigation and rainfall (Table 5). Therefore, there was a net depletion of salts from the soil at the end of the 2013–14 season in all treatments. Similarly, the average salts storage at Padthaway in the mid-row mound + plastic (C) treatment was reduced by half as compared to the other treatments due to a rapid increase in the drainage flux, which, however, was not sufficient to flush all salts out of the soil profile. This suggests that soil texture and heterogeneity play an important role in the transient salt storage in the soil.

The average annual amount of salts leaching ($Dr_S$) in the control treatment (A) at each of the study sites remained almost similar to other mid-row mound ($B$) over the three seasons (Table 5). Similarly, the dynamics of daily salts leaching in these treatments (A and B) almost overlapped over the entire simulation period (2011–2014) at all locations except for slight deviations at Loxton (Fig. 6). This suggests that mid-row mounding (B) had a small impact on salts leaching from the root zone, irrespective of soil, water, and climate conditions. However, the mid-row mound + plastic (C) treatment resulted in more than twice the average salt mass removed (884 kg/ha) as compared to the control (406 kg/ha) at McLaren Vale. Similarly, the buried plastic (D) treatment also showed higher average salts leaching (563 kg/ha) than the control (A) at Loxton. Although the average amount (4860 kg/ha) of salts leached ($Dr_S$) at Padthaway in the mid-row mound + plastic treatment (C) was more than one and half times of the control (A), it was about five times the corresponding amount at McLaren Vale. It is estimated that about 14.6 t/ha salts were leached during 2011–14 at Padthaway in the mid-row mound + plastic treatment (C), which was 57% higher than for the control. Total salt leaching in other treatments ranged from 9.3 to 9.7 t/ha. The drastic increase in the salt leaching in the mid-row mound + plastic (C) treatment occurred due to the twofold strategy of the redirection of rainfall and the reduction of evaporation losses due to the surface cover. It can be seen that the

### Table 5

Seasonal salt additions by irrigation ($I_S$), precipitation ($P_S$), salt leaching ($Dr_S$), and soil storage/ depletion ($\Delta S_S$) in the soils (kg/ha) for grapevine at different locations under different treatments during 2011–2014.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Year</th>
<th>McLaren Vale</th>
<th>Padthaway</th>
<th>Loxton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_S$</td>
<td>$P_S$</td>
<td>$Dr_S$</td>
<td>$\Delta S_S$</td>
</tr>
<tr>
<td>A Initial salts</td>
<td>2394.4</td>
<td>8297.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011–12</td>
<td>631.0</td>
<td>433.9</td>
<td>292.7</td>
<td>3166.6</td>
</tr>
<tr>
<td>2012–13</td>
<td>994.1</td>
<td>302.3</td>
<td>377.6</td>
<td>4085.3</td>
</tr>
<tr>
<td>2013–14</td>
<td>1038.4</td>
<td>373.7</td>
<td>548.0</td>
<td>4949.4</td>
</tr>
<tr>
<td>Average</td>
<td>887.8</td>
<td>370.0</td>
<td>406.1</td>
<td>4067.1</td>
</tr>
<tr>
<td>B Initial salts</td>
<td>2454.1</td>
<td>8702.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011–12</td>
<td>631.0</td>
<td>433.9</td>
<td>287.0</td>
<td>3211.1</td>
</tr>
<tr>
<td>2012–13</td>
<td>994.1</td>
<td>302.3</td>
<td>408.9</td>
<td>4118.5</td>
</tr>
<tr>
<td>2013–14</td>
<td>1038.4</td>
<td>373.7</td>
<td>591.1</td>
<td>4939.5</td>
</tr>
<tr>
<td>Average</td>
<td>887.8</td>
<td>370.0</td>
<td>429.3</td>
<td>4096.4</td>
</tr>
<tr>
<td>C Initial salts</td>
<td>2440.9</td>
<td>8816.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011–12</td>
<td>631.0</td>
<td>433.9</td>
<td>840.2</td>
<td>2665.6</td>
</tr>
<tr>
<td>2012–13</td>
<td>994.1</td>
<td>302.3</td>
<td>839.7</td>
<td>3122.3</td>
</tr>
<tr>
<td>2013–14</td>
<td>1038.4</td>
<td>373.7</td>
<td>971.6</td>
<td>3526.2</td>
</tr>
<tr>
<td>Average</td>
<td>887.0</td>
<td>370.0</td>
<td>883.8</td>
<td>3116.9</td>
</tr>
<tr>
<td>D Initial salts</td>
<td>2375.1</td>
<td>8122.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011–12</td>
<td>631.0</td>
<td>433.9</td>
<td>246.6</td>
<td>3193.4</td>
</tr>
<tr>
<td>2012–13</td>
<td>994.1</td>
<td>302.3</td>
<td>495.1</td>
<td>3994.7</td>
</tr>
<tr>
<td>2013–14</td>
<td>1038.4</td>
<td>373.7</td>
<td>948.1</td>
<td>4458.7</td>
</tr>
<tr>
<td>Average</td>
<td>887.0</td>
<td>370.0</td>
<td>563.2</td>
<td>3882.3</td>
</tr>
</tbody>
</table>

A is control, B is mid-row mound, C is mid-row mound + plastic, D is buried plastic.
drainage flux (6.7 ML/ha) in this treatment was more than double as compared to the other treatments (2.6–2.7 ML/ha) (Table 4). Differences in daily salt leaching in different treatments and at different locations are also distinctly visible during the entire simulation period (Fig. 6). High episodic salts leaching peaks occurred especially at the McLaren Vale and Padthaway sites, whereas leaching was a continuous process in the sandy soil at Loxton. Typically, large peaks at all locations were preceded by high rainfall events and were also influenced by the amount of salts present in the soil. Notably, at Padthaway, huge amounts of salts (2.35 kg/ha/yr) are added in the soils (see Table 5) through high salinity (2.2–2.35 dS/m) groundwater irrigation, which are deposited in the soil and ready to be transported following large rainfall events generating large leaching fractions.

Indeed, the huge amount of salt leaching at Padthaway, irrespective of treatments, may raise salinity concerns for shallow groundwater aquifers. A groundwater monitoring study observed an increase in the salt content by about 600 mg/L in shallow aquifers from around 800 mg/L to 1400 mg/L in parts of Padthaway during the last 25 years (Cleugh, 2006). Apparently, excessive transport of irrigation-induced root zone salts under grapevine may pose a potential danger for the groundwater quality. Hence, a trade-off exists between the extent of leaching and the imminent threat of groundwater degradation and, judicious decisions are required for sustainable salinity management and controlling the pollution of groundwater.

3.4. Leaching efficiency and leaching requirement

Salt removal (leaching) efficiency (LEs) is defined as the ratio of the amount of salts leached from the soil profile and the corresponding amount added during a given time (e.g., an annual or crop cycle), which offers a more quantitative measure of the salt balance to compare different treatments (Lu et al., 2019). At McLaren Vale, the LEs remained less than one irrespective of treatments and seasons, indicating an overall tendency of salt deposition in the root zone (Fig. 7). However, LEs increased almost two-fold in the mid-row mound + plastic (C) treatment compared to the control and mid-row mound, and varied from 0.63 to 0.77 kg salts leached/kg added. Interestingly, at Padthaway, during 2011–12, LEs was very low (average 0.12–0.13 kg leached/kg salts added) in all of the treatments besides mid-row mound + plastic (1.04 kg leached/kg added). In the later years of the simulation, it reached a value larger than one (1.01) only under the mid-row mound during 2013–14 and the buried plastic (1.37) during 2012–13. However, LEs remained above one in mid-row mound + plastic (C) during all seasons and reached a maximum value of 1.81 kg salts leached/kg added during 2012–13. Therefore, only the mid-row mound + plastic (C) treatment showed continuous depletion of salts from the soil at Padthaway.

The LEs remained larger than one at Loxton irrespective of treatments and seasons, indicating a strong depletion pattern. However, the mid-row mound + plastic (C) treatment had a maximum LEs value of 1.74 kg salts/kg salts applied during 2011–12. Hence, the occurrence of LEs larger than one at Loxton is attributed to the prevalence of highly permeable sandy soils, low salinity of irrigation water (0.3 dS/m), and almost double amount of irrigation application than at the other sites, which facilitated the rapid flushing of salts from the root zone.

In drip-irrigated systems, it is hard to determine the leaching requirement (LR) due to spatially-variable soil wetting patterns that lead to localized leaching below the drip line (Hanson et al., 2008). Historically, LR is the LF, which when passed through the root zone, reduces the root zone salts below the crop threshold. Hence, in drip irrigation systems, a LF that corresponds to LEs > 1 can potentially leach annually added salts from the root zone. It can serve as a good estimate for leaching of irrigation induced salts from the root zone. Hence, a site-specific relationship was developed between a seasonal LF and corresponding LEs at different locations, irrespective of treatments (Fig. 8). At Lox (sandy soils), a very low LF (0.1) was found to rapidly attain LEs > 1, while at Padthaway (medium-textured soils), the threshold LF was 0.18. The threshold LF for the McLaren Vale site (heavy textured, heterogeneous soils) was exceptionally high (0.74), which seems impractical. However, in the mid-row mound + plastic treatment (C), an average LF of 0.33 was able to flush 70% of added salts at McLaren Vale, thus showing promising results. On the other hand, this soil has restricted drainage conditions (Singh, 2019), especially in the subsoils, which may require different management options for salinity control. Overall the mid-row mound covered with plastic (C) was the most efficient technique for leaching salt from the root zone and attaining LEs > 1, especially at Padthaway. Salt leaching results were extremely variable as influenced by soil texture and heterogeneity. These techniques should be adopted cautiously depending on the soil, climate, and irrigation water quality at a particular location.

The main drawback of the plastic mulch is its cost, its labour-intensive application, and environmental risk of plastic residues in the soil (Silin and Xujian, 2008; Changrong et al., 2014). These issues need due consideration before implementing the mounding with plastic strategy although biodegradable plastic mulching (Adhikari et al., 2016; Saglam et al., 2017; Chen et al., 2019, 2020) or sprayable biodegradable polymer membrane (Filipović et al., 2020) are viable options for addressing the environmental issues. Other options of environmentally friendly mulching, such as compost, wood chips, and plant residues, are also available. The application of organic mulches is equally labour intensive, but they have numerous other beneficial impacts such as increasing soil water retention (Granatstein and Mullinix, 2008; Yu et al., 2018), and enhancing soil organic matter, nutrient cycling, and N availability (Neilsen et al., 2003; Sanchez et al., 2003; Hoagland et al., 2008; TerAvest et al., 2010). On the other hand, they also have adverse impacts, such as causing tree root diseases, rodent infestation (Merwin and Styles, 1994), and weed seed distribution

Fig. 7. Average salt leaching efficiency in terms of percent of annual salts leached from the total added (kg/kg salts added) and percent of salts leached per m³ of drainage (Dr) (kg/m³ of drainage) at McLaren Vale (McL), Padthaway (Pad), and Loxton (Lox) under different treatments (A - control, B - Mid-row (MR) mound, C - MR mound + plastic, D - Buried plastic).

Fig. 8. Relationship between the salt leaching efficiency (LEs) (kg salts leached/kg salts added) and a leaching fraction (LF) in different soils at McLaren Vale (McL), Padthaway (Pad), and Loxton (Lox).
(Rowley et al., 2011). Moreover, their role in redirecting rainfall, salts dynamics, and leaching seems limited and not yet fully explored. Therefore, the use of plastic mulches still seems to be a relatively better alternative if the overall goal is to reduce the soil salinization and leaching of soluble salts from the crop root zone.

4. Conclusions

Leaching of soluble salts from an irrigated soil root zone is necessary for sustainable crop production since all water additions, and subsequent evaporation and transpiration, will increase salt concentrations. This investigation was carried out to understand the impact of different mid-row management techniques such as mounding and plastic mulching for directing rainfall for reducing salt accumulation in the root zone of drip-irrigated grapevines. Four different treatments [no mounding or control (A), mid-row mounding (B), mid-row mounding covered with plastic (C), and plastic buried in the soil in the mid-row (D)] were evaluated using a numerical model (HYDRUS-2D) for simulating the water balance, root zone salinity dynamics ($E_{Root}$), and salt dynamics in the soil for multiple seasons (2011–2014) in three grape growing regions. These vines had been irrigated with varied water qualities, ranging from river water (0.2–0.5 dS/m) at Loxton, recycled water (1.0–1.3 dS/m) at McLaren Vale, and groundwater (1.9–2.3 dS/m) at Padthaway.

Results demonstrated that mid-row mounding with plastic mulching (C) was effective at controlling salinity under drip-irrigated grapevines. It showed a threefold increase in drainage flux ($D_{D}$), a drastic reduction in evaporation ($E_{E}$) (48–54%), and an increase in transpiration ($T_{P}$) of grapevine (1–16%), as compared to the control (A). Despite such remarkable impacts of mid-row mounding coupled with plastic mulch, soil texture, and the quantity and quality of irrigation water have played an important role in controlling salt transport in the soil. Modelling simulations confirmed that in heavy textured highly heterogeneous soils (McLaren Vale site) in vineyards irrigated with recycled water ($E_{Root} = 1.2$dS/m), this treatment, in spite of one and half times higher salts leaching than in the other treatments, could not maintain a salt removal efficiency ($LE_{S} > 1$) over the simulation period. Therefore, the final average profile $E_{Root}$ in the under-vine (UV) region increased from 1.1 to 2.4 dS/m, which is more than the salinity tolerance threshold (2.2 dS/m) for grapevines. Groundwater-irrigated ($E_{Root} = 2.2–2.35$dS/m) grapevines on medium-textured soils (Padthaway site) with double the irrigation amount compared to McLaren Vale, and a similar annual rainfall maintained $LE_{S} > 1$ during all three seasons, reduced the average $E_{Root}$ in the UV region from 5.2 to 3.2 dS/m. A leaching fraction of 0.18 was found to leach all annually added salts out of the root zone in the latter soils. These results suggest that rainfall redirection techniques have the potential to play an important role in reducing root zone salts. Still, the extent of the reduction will vary depending on the soil and agro-climatic zone. The requirement for salt removal from the soil is influenced by soil texture, soil heterogeneity, irrigation quantity and quality, rainfall volume, distribution and intensity, and the salinity tolerance threshold of the cropland, thus requires site-specific modelling and management.

CRediT authorship contribution statement


Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are thankful to the Australian Water Recycling Centre of Excellence (Grant ID: AWRCOE 3145) and the Goyder Institute for Water Research (Grant ID: 1.1.3) for funding assistance.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2020.125000.

References


