

Determination of soil dispersion in response to changes in soil salinity under winery wastewater irrigation

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1. Executive Summary

This trial investigated soil dispersion behaviour in two soils from the Marlborough region that are currently irrigated with winery wastewater. Soils included the Paynter silt loam and the Wairau silt loam, both with textural classes dominated by silt. Soil dispersion is closely associated with the abundance of either sodium (Na^+) or potassium (K^+) on the soil exchange complex relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}). Although guidelines for the application of wastewater to soil provide recommended sodium adsorption ratio (SAR) threshold values for the prevention of sodic conditions in irrigated soils, limited attention is given to the individual and combined effects of K^+ on soil dispersion. This project specifically addressed the relationship between Na^+ and K^+ concentration in winery wastewater and its potential effect on soil structure through adoption of the cation ratio of structural stability (CROSS) equation, recently developed by Rengasamy and Marchuk (2011).

Overall, we found that soil dispersion was extremely low, reflecting the high silt content of these soils. We therefore predict there will be very little risk of soil dispersion where winery wastewater is irrigated to these soil types. Using a number of studies we have, however, developed a conservative upper limit for CROSS values in winery wastewater as a precautionary approach. This better encompasses a range of soils that might be irrigated with winery wastewater in Marlborough yet were not investigated as part of this study; these will primarily be soils with high clay contents.

We suggest wineries continue to annually test wastewater that is applied to land and monitor not only sodium (as SAR) but also potassium by quantifying CROSS values. Given the extremely close relationship between electrical conductivity (EC) and soil dispersion, we recommend this be measured routinely, potentially by using on site portable meters. As a precautionary approach, we suggest that CROSS values of winery wastewater be maintained below 20, given an assumed EC of approximately 1.4 to 2 dS m^{-1} .

2. Introduction

Generation of wastewater is an inevitable component of the wine production process. Typically this wastewater has a high salt concentration due mainly to chemical cleaning products and grape lees. Land application of winery wastewater is increasingly being advocated as a means to mitigate deteriorating surface water quality associated with surface water discharge. As with any land application system, there is an imperative need to maintain soil and plant health in order to enable the on-going attenuation and

assimilation of nutrients, salts and contaminants. A major agricultural concern is the potential for monovalent cations, namely sodium (Na^+) and potassium (K^+), to accumulate in the soil profile and subsequently impact on soil structure. Such effects are likely to differ between soil type (Laurenson *et al.* 2012).

Currently 39 wineries apply winery wastewater to land in the Marlborough District. Few however, take regular soil samples to assess what effect wastewater application may be having on soil properties (Gray 2012). Where available, data indicates a rapid increase in soil exchangeable Na^+ and K^+ following the instigation of winery wastewater irrigation, particularly on poorly drained soils. In a recent AgResearch report submitted to the Marlborough District Council, the need to determine guideline values for Na^+ and K^+ loading to Marlborough soils was identified. Such guidelines for managing winery wastewater are necessary given the high volumes generated in this region and the environmental benefits gained from its disposal to land as opposed to surface waters.

This project specifically addresses the relationship between Na^+ and K^+ concentration in winery wastewater and its potential effect on soil structure in Marlborough soils. Investigations of the physico-chemical processes leading to soil dispersion have been carried out using two key Marlborough soils currently being used for winery wastewater disposal: the Wairau silt loam and a Paynter silt loam. It is intended that this research will help identify threshold wastewater quality parameters that will ensure the protection of soil physical and chemical quality under winery wastewater application.

3. Theory

Winery wastewater has a high concentration of both Na^+ and K^+ which have the potential to reduce soil hydraulic conductivity by causing clays to disperse. Due to the small hydrated ion size, attractive forces between platelets of Ca^{2+} saturated clays are greater than repulsive forces formed by the diffuse double layer (DDL) that operate along the clay's negative surface, thereby limiting expansion of the clay interlayer spacing (Regasamy 1984; Rengasamy 2002). However, when dominated by cations of greater hydrated radius and lower valency, such as monovalent cations (Na^+ and K^+), the repulsive force between platelets is greater. This causes the inter-layer spacing to increase to a point where repulsive forces dominate and the platelet assemblage separates i.e. disperses (Rengasamy 2002).

Soil dispersion is closely associated with the abundance of either Na^+ or K^+ on the soil exchange complex relative to Ca^{2+} and magnesium (Mg^{2+}). Although guidelines for the application of wastewater to soil provide recommended SAR threshold values for the

prevention of sodic conditions in irrigated soils, limited attention is given to the individual and combined effects of K^+ on soil dispersion (ANZECC & ARMCANZ 2000).

The sodium adsorption ratio (SAR; equation 1) and potassium adsorption ratio (PAR; equation 2) are widely used indices that describe the risk of soil dispersion. These equations describe the molar ratio relationship between Na^+ or K^+ and di-valent cations, Mg^{2+} and Ca^{2+} (where concentrations of cations are expressed as $mmol_c L^{-1}$). In wastewaters containing high concentrations of both Na^+ and K^+ , as in the case of winery wastewater, the monovalent cation ratio (MCAR) (equation 3) has also been proposed by Smiles and Smith (2004) to describe the combined effect of both Na^+ and K^+ on clay dispersion. This assumes, however, that the dispersive power of Na^+ and K^+ and the flocculating power of Mg^{2+} and Ca^{2+} are equivalent.

$$SAR (mmol/L)^{0.5} = \frac{[Na^+]}{\sqrt{([Ca^{2+}] + [Mg^{2+}])/2}} \quad (1)$$

$$PAR (mmol/L)^{0.5} = \frac{[K^+]}{\sqrt{([Ca^{2+}] + [Mg^{2+}])/2}} \quad (2)$$

$$MCAR (mmol/L)^{0.5} = \frac{[Na^+] + [K^+]}{\sqrt{([Ca^{2+}] + [Mg^{2+}])/2}} \quad (3)$$

However, Rengasamy and Sumner (1998) found the dispersive power of Na^+ and K^+ were not similar in causing clay dispersion. As Chen et al. (1983) reported, the relative contribution of exchangeable cations to soil aggregate stability follows the order $Ca^{2+} > Mg^{2+} > K^+ > Na^+$ and that dispersion of soils with high exchangeable potassium percentage (EPP) tends to be less than soils of equivalent exchangeable sodium percentage (ESP).

As reported by Rengasamy and Sumner (1998), the relative flocculating power for basic cations, as determined from ion valency and ionisation potential, follows the order of $K^+ = 1.8$, $Mg^{2+} = 27$ and $Ca^{2+} = 45$, where $Na^+ = 1$. The estimated dispersive potential of K^+ vs. Na^+ would therefore be 0.56 (i.e. $1/1.8$) and the flocculating effect of Mg^{2+} vs. Ca^{2+} 0.6 (i.e. $27/45$) (Rengasamy 2002).

The 'cations ratio of structural stability' (CROSS) equation (equation 4) has recently been proposed by Rengasamy and Marchuk (2011) as a more appropriate evaluation of waters containing all basic cations including Ca^{2+} , Mg^{2+} , K^+ and Na^+ . This approach has recently been applied by Jayawardane et al. (2011) for assessing the potential impacts of winery wastewater irrigation on soil structure.

$$CROSS (mmol/L)^{0.5} = \frac{[Na^+] + 0.56[K^+]}{\sqrt{\{[Ca^{2+}] + 0.6[Mg^{2+}]\}/2}} \quad (4)$$

Typical concentrations of cations in winery wastewater within the Marlborough region have been determined based on data collected by Marlborough District Council since 1996 and comprises information across 8 sites where winery wastewater was generated and subsequently applied to land (Table 1). Although the electrical conductivity of winery wastewater is not routinely measured in Marlborough, this was estimated from the available data to be approximately 1.4 dS m⁻¹.

Table 1. Chemical composition of winery wastewater from a number of different locations across Marlborough between 1996 and 2009.

Constituent	Average	Range
pH	5.2	(3.8-7.3)
Na ⁺ (mmol _c L ⁻¹)	4.3	(0.3-18.7)
K ⁺ (mmol _c L ⁻¹)	4.6	(0.7-10.5)
Mg ²⁺ (mmol _c L ⁻¹)	0.3	(0.2-0.5)
Ca ²⁺ (mmol _c L ⁻¹)	1.1	(0.6-3.6)
SAR	5.3	(0.3-17.4)
PAR	5.6	(0.9-12.5)
MCAR	10.0	(1.3-25.8)
CROSS	9.2	(2.5-13.3)

4. Experimental set-up

The objective of this experiment was to determine the EC that is required in order to prevent soil dispersion of a Paynter and a Wairau soil equilibrated with solutions of varying CROSS.

4.1 Soil

Soils used in this experiment are classified within the Wairau Soil Unit and included a Wairau silt loam, a Recent soil, and a Paynter silt loam, a Gley soil. The Landcare Research S-Map report (<http://smap.landcareresearch.co.nz>) describes the Paynter soil as having a low infiltration rate and impeded drainage, while the Wairau is moderately to well drained. Soils were collected from the sub-surface layer at a depth of c. 400-600

mm. This sub-surface layer was expected to have greater clay content and therefore greater susceptibility to soil dispersion in response to salt loading relative to the more free draining A horizon soil. Upon collection, soils were air dried in a forced draft oven at 40° C for 48 hours before being sieved through a 2 mm mesh.

4.2 Experimental procedure

Particle size analysis was determined based on Stokes Law using the hydrometer method of Gee and Bauder (1986). Forty grams of soil (< 2 mm) was mechanically whisked with 100 mL of sodium hexametaphosphate (HMP) dispersing solution (50 g HMP L⁻¹) then allowed to stand for 24 hours. The volume of the suspension was made to 1 L by adding deionised water and left to stand for one hour to equilibrate the solution with room temperature. The hydrometer was first calibrated in a reagent blank of 1 L solution without soil (i.e. 1:10 HMP to deionised water) and maintained at room temperature. Measurements were carried out on the reagent blank at similar time intervals as for soil samples. Each soil was replicated four times.

Immediately prior to commencing timing of settling, the soil suspension was thoroughly mixed by manually inverting the cylinder end over end for 30 seconds. The hydrometer value was read from the upper edge of the meniscus surrounding the hydrometer stem after 30 seconds and 8 hours.

The method used to determine clay dispersion follows that described by Rengasamy et al. (1984). Soils were initially equilibrated with a range of prepared solutions that varied in CROSS and total cation concentration (TCC; Table 2). These solutions were made from NaCl, KCl and CaCl₂.2H₂O salts and included total cation concentrations of 1, 5, 10, 15 and 20 mol_c m⁻³.

Soils were equilibrated with prepared solutions by placing 80 grams of sieved soil with 1 L of solution with known CROSS. The soil-solution was left undisturbed for approximately 48 hours by which time no clay remained in suspension. The solution was then decanted off carefully and soils were dried at 40° C. This procedure was carried out for each of the two soil types and for each combination of CROSS and TCC. In total 240 soil samples were prepared in this way (inclusive of both Paynter and Wairau soils).

Soil dispersion was measured by placing 20 g of 'equilibrated' air-dried soil into a 120 mL transparent jar and adding 100 mL of solution of similar CROSS and TCC to the equilibration solution. Samples were carried out in duplicate. In total 480 samples were prepared in this way (Table 2).

Soil-solutions were left undisturbed for an appropriate sedimentation time before a 10 mL volume of the soil suspension was removed using a pipette from a depth of 50 mm. Clay in suspension was measured gravimetrically with correction made for the weight

contribution from dissolved salts. The quantity of dispersed clay was then determined on an oven-dry soil basis.

Soil EC was determined from a 1:5 soil-water suspension using a calibrated EC electrode (TPS SmartCHEM Conductivity sensor) following the method described in Rayment and Higginson (1992) where a mixed suspension was allowed to settle for 30 minutes prior to EC measurement.

Table 2. Prepared solutions used to equilibrate the Paynter and Wairau soils.

SAR	PAR	CROSS	TCC					Reps
			mmol _c L ⁻¹					
1.0	0	1.0	1	5	10	15	20	2
5.0	0	5.0	1	5	10	15	20	2
10.	0	10.0	1	5	10	15	20	2
15.0	0	15.0	1	5	10	15	20	2
0	1.0	0.5	1	5	10	15	20	2
0	5.0	2.8	1	5	10	15	20	2
0	10.	5.6	1	5	10	15	20	2
0	15.0	8.4	1	5	10	15	20	2
1.0	1.0	1.5	1	5	10	15	20	2
1.0	5.0	3.8	1	5	10	15	20	2
1.0	10.	6.6	1	5	10	15	20	2
1.0	15.0	9.4	1	5	10	15	20	2
5.0	1.0	5.6	1	5	10	15	20	2
5.0	5.0	7.8	1	5	10	15	20	2
5.0	10.	10.6	1	5	10	15	20	2
5.0	15.0	13.4	1	5	10	15	20	2
10.0	1.0	10.6	1	5	10	15	20	2
10.0	5.0	12.6	1	5	10	15	20	2
10.0	10.	15.6	1	5	10	15	20	2
10.0	15.0	18.4	1	5	10	15	20	2
15.0	1.0	15.6	1	5	10	15	20	2
15.0	5.0	17.8	1	5	10	15	20	2
15.0	10.	20.6	1	5	10	15	20	2
15.0	15.0	23.4	1	5	10	15	20	2

5. Results and discussion

5.1 Relationship between total cation concentration and soil electrical conductivity

As expected total cation concentration was strongly correlated with soil EC in both the Paynter and Wairau soils (Figure 1). In all solutions, EC (in dS m^{-1}) was related to total cation concentration by the formula $\text{EC} = \text{TCC} \times 0.1348 + 0.0208$.

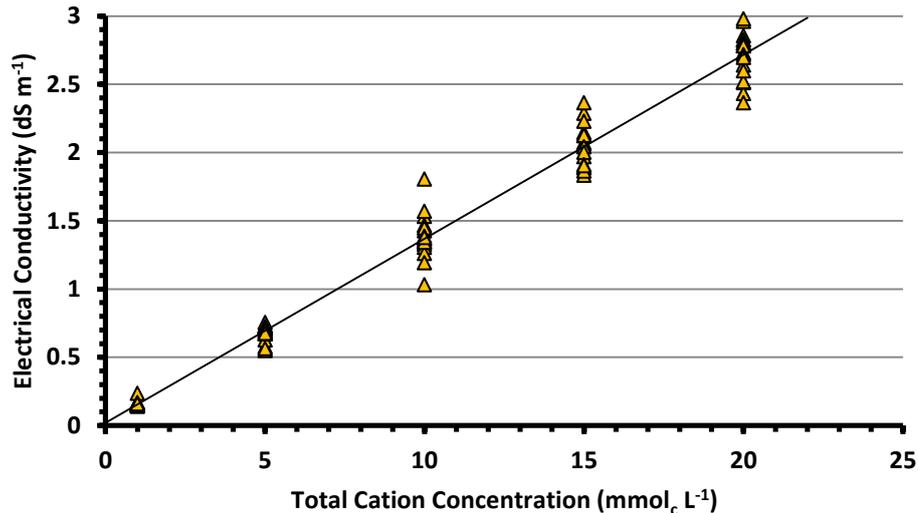


Figure 1. Relationship between total cation concentration of the equilibration solution and EC (dS m^{-1})

5.2 Clay content

Both the Wairau and Paynter soils are alluvial soils that have been deposited by rivers over time, with the Wairau soil being slightly younger than the Paynter soil. The Paynter soil has developed from a clayey alluvium and is poorly drained while the Wairau has developed from a loamy sand alluvium and is relatively well drained. Despite this, clay contents in the Paynter and Wairau soils were broadly similar at 13 and 9%. The percentage of silt was also similar between soils at 66 and 67% for the Paynter and Wairau soils, respectively.

Table 3. Soil particle size and textural class of the Paynter and Wairau soils.

	Sand (%)	Silt (%)	Clay (%)	Textural class
Paynter	22 ± 2	66 ± 1	13 ± 1	Silt loam
Wairau	24 ± 3	66 ± 1	9 ± 1	Silt loam

5.3 Dispersion of the Paynter Soil

Here we describe the dispersion results following equilibration of soils with SAR and PAR, these being either a binary Na-Ca or K-Ca system. Therefore no combined influence of Na⁺ and K⁺, as in the case of CROSS, is present.

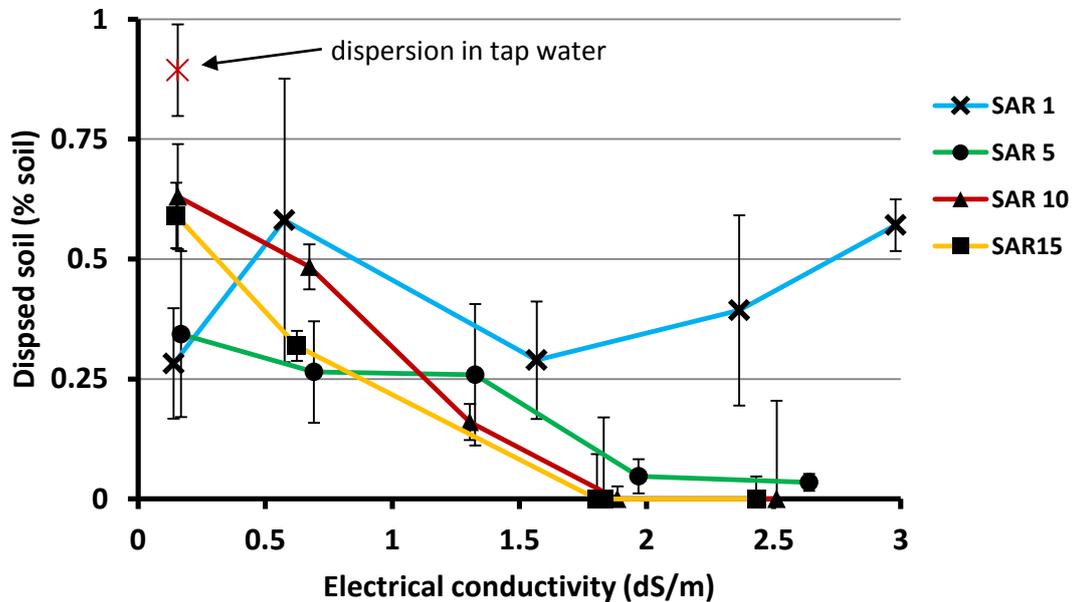


Figure 2. Soil dispersion (% of total soil) in the Paynter soil in response to varying SAR and increasing EC (dS m⁻¹). Error bars indicate the standard deviation between samples.

Dispersion in the Paynter soil varied considerably in response to SAR treatments. Although soil dispersion for a given value of SAR tended to increase with decreasing EC, this was not apparent for the SAR 1 treatment. Despite this trend, no significant difference was evident between the various salt solutions. At SAR 1, soil dispersion generally increased with increasing EC and we suspect that at this very low concentration much of the cations in solution precipitated, thereby limiting the treatment effect.

Importantly, dispersion in response to the Na⁺ salt solutions was not significantly different to those equilibrated with tap water, where EC of the 1:5 solution was 0.155 dS m⁻¹. It is therefore apparent in Figure 2 that soil dispersion was low in all treatments.

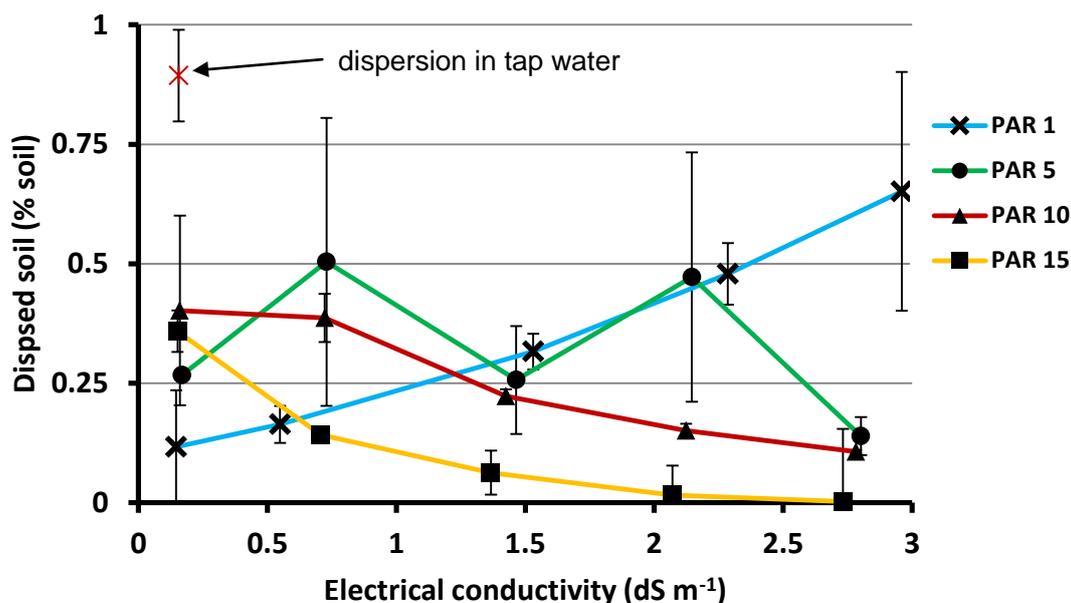


Figure 3. Soil dispersion (% of total soil) in the Paynter soil in response to varying PAR. Error bars indicate the standard deviation between samples.

Clay dispersion response to varying PAR showed similar variation between treatments to that observed for SAR. In general, the amount of dispersed soil for a given PAR value was lower than the corresponding SAR value, indicating a greater effect of Na⁺ relative to K⁺ on soil dispersion. However, the amount of dispersed soil was low and few differences were detectable between treatments.

5.4 Dispersion of the Wairau Soil

In general dispersion of the Wairau soil tended to be higher at the lower EC values with exception of the SAR 1 and 5 equilibrated soils. Interestingly, at SAR 10 and 15 dispersion of the Wairau soil was greater than that measured in the Paynter soil. However this difference was not significant given the high variation between replicated samples. Soil dispersion in response to the salt solutions was marginally higher than that measured under tap water, however this was not a significant difference.

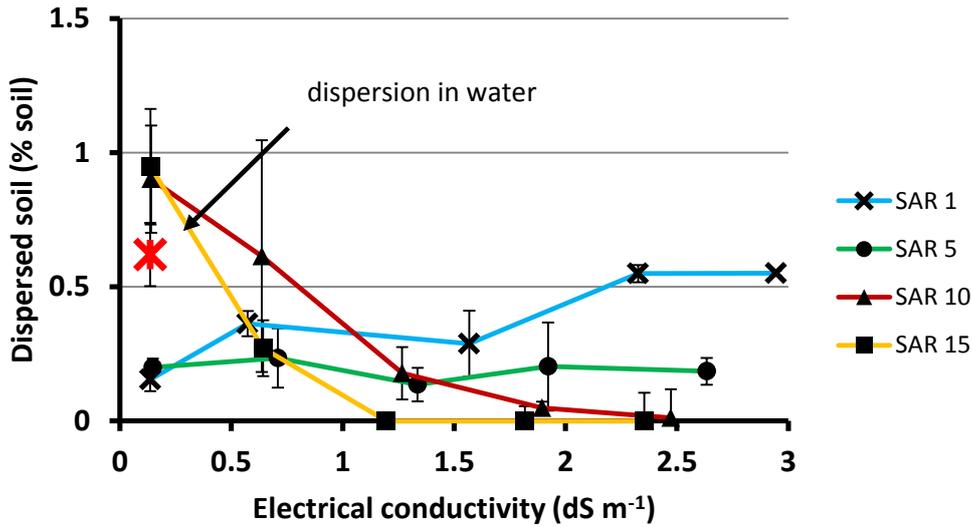


Figure 4. Soil dispersion (% total soil) in the Wairau soil in response to varying SAR and increasing EC (dS m⁻¹). Error bars indicate the standard deviation between samples.

Soil dispersion in response to PAR was similar to that measured for SAR, and was marginally higher than that measured in the Paynter soil. Once again, this difference was not significant. In both PAR 1 and SAR 1 treatments, soil dispersion appears to increase with increasing EC and as mentioned previously this was likely a reflection of the cations in solution precipitating out at such low concentrations. Importantly, there was no significant difference in soil dispersion in response to salt solution and tap water. Furthermore, in both cases (PAR and SAR) dispersion was extremely low.

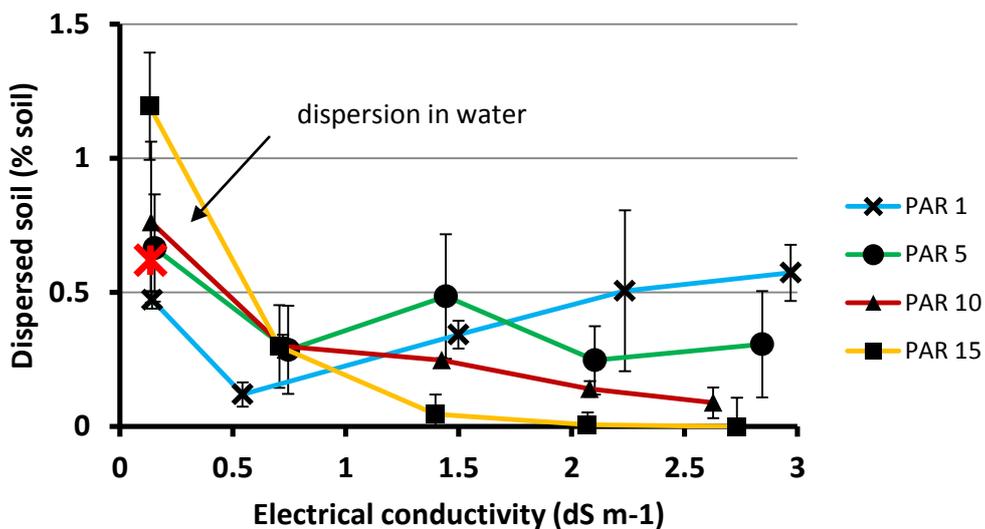


Figure 5. Soil dispersion (% total soil) in the Wairau soil in response to varying PAR. Error bars indicate the standard deviation between samples.

5.5 Soil dispersion in response to CROSS

Here we present the results of all solutions with varying CROSS in a ternary Na-K-Ca system (as listed in Table 2).

At all levels of CROSS the quantity of dispersed clay in both the Paynter and Wairau soils was less than 1.2% dispersed clay on soil gravimetric basis (Figure 6). This is likely to reflect the high silt content of these soils and correspondingly low clay contents (Table 3). Silt particles have very low surface charge and therefore do not disperse to the same extent as clay particles. Clays consists of negatively charged assemblages of platelets called domains (Oster *et al.* 1980). These are contained within micro-aggregate structures bound together with organic matter (White 2006). Stability of the clay domain relies on a balance being maintained between opposing forces of repulsion and attraction within the layering of the clay sheeting (a phenomenon not apparent in silts). When repulsion forces dominate within the clay domain, platelets are forced apart (i.e. deflocculated); when attraction forces dominate the clay is flocculated.

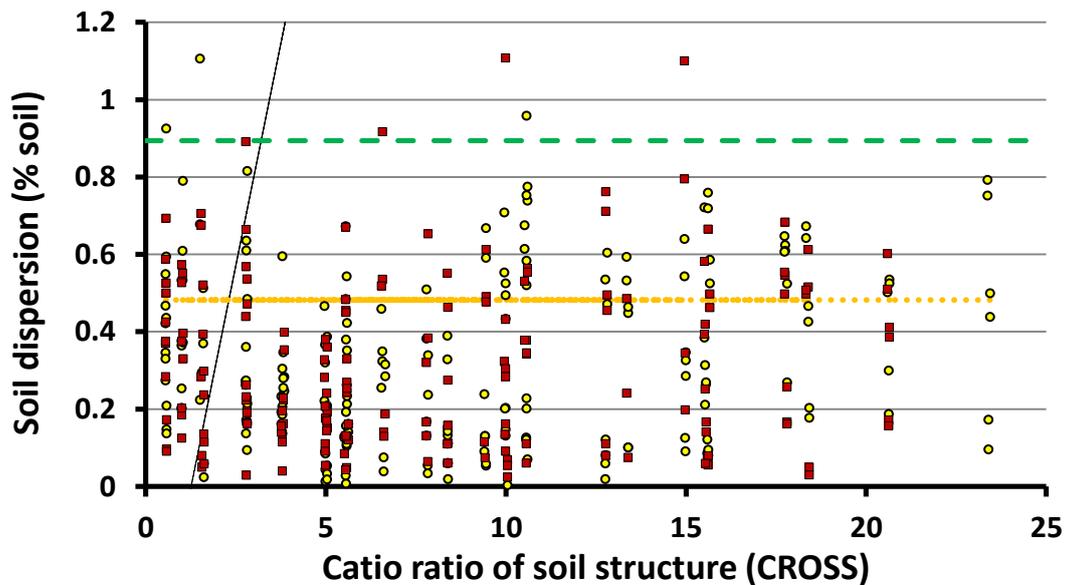


Figure 6. Percentage of dispersed soil (% on an oven dry soil basis) in the Paynter (■) and Wairau (●) Soil equilibrated with waters of varying CROSS and EC. Soil dispersion predicted by Rengasamy and Marchuk (2011) is shown (—) and the dispersion of the Paynter (---) and Wairau (----) soil in response to equilibration with tap water (EC 0.156 dS m⁻¹).

In an experiment reported by Rengasamy and Marchuk (2011), the percentage of soil dispersed from a number of soils that varied in texture, CROSS and TCC was measured. Textural classes included a sandy loam (10% clay content), clay loam (24% clay content) and clay (40% clay content). Across all soil textural classes, dispersed soil reported by Rengasamy and Marchuk (2011) accounted for 0.4 to 4.2 % (on a soil gravimetric basis). However the percentage of clay in the soil was highly influential on the resulting dispersion measured. In the sandy loam soils for instance, dispersed soil

was less than 1.1 % when CROSS was approximately 3. This is similar to that measured in the Wairau and Paynter soils that had similar clay contents (i.e. c. 10%). The Paynter soil had slightly higher clay content than the Wairau soil and the dispersion measured tended to be marginally higher than that measured for the Wairau soil; however this difference was not significant and tended not to be related to CROSS (Figure 6).

As put forth by Curtin et al. (1994), minor incidences of dispersion are unlikely to cause a significant deterioration of soil structure. In order to define a threshold above which dispersed soil could be attributed to the specific influence of the CROSS and EC value, we have quantified the amount of soil dispersed in response to tap water. This water has similar EC to river water used for irrigation throughout the Marlborough region. Soil dispersion in response to tap water was equivalent to 0.9 % of the total soil for the Paynter soil and 0.5 % of total soil in the Wairau soil. This was not significantly different to dispersed soil measured from the series of salt solutions with varying CROSS i.e. less than 1.2 % dispersed soil in all cases. This further indicates that dispersion in the Wairau and Paynter soils is generally low.

5.6 Predicted threshold cation concentration

In an Australian soil with 50 % clay content, Jayawardane et al. (2011) developed a relationship between threshold cation concentration and solution CROSS. Based on the relationship between total cation concentration and EC (Figure 1) we have presented the relationship as EC and solution CROSS in Figure 7. Values to the left of the line will be expected to remain stable while those to the right are expected to disperse. For instance, where CROSS equals 10, solution EC for the two Marlborough soils must be maintained above approximately 0.7 dS m^{-1} to prevent dispersion.

Although EC is not routinely measured in winery wastewater, based on limited data we have we estimate this to be approximately 1.4 dS m^{-1} . Therefore, based on the curve in Figure 7 it would be predicted that winery waster with a CROSS above 16 will lead to dispersion at an EC of 1.4 dS m^{-1} .

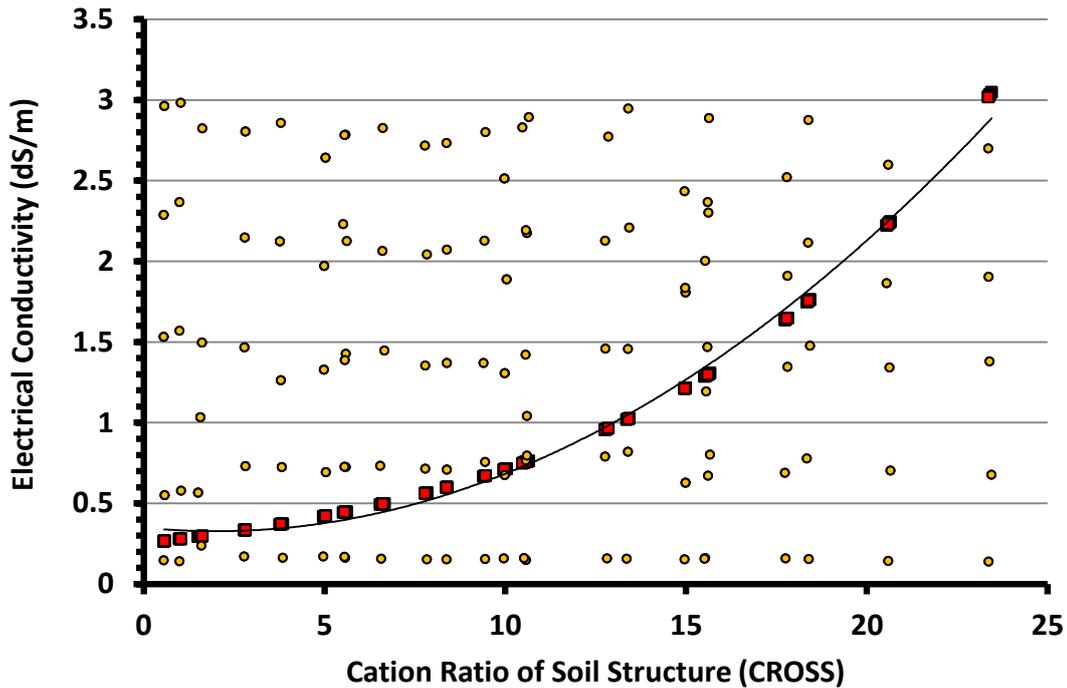


Figure 7. Predicted threshold cation concentration (■) required to prevent soil dispersion, as developed by Jayawardane et al. (2011). The CROSS and TCC of solutions used to equilibrate the Wairau and Paynter soils is also shown (●).

However, as previously discussed, dispersion of the soils used in our study was low at all values of CROSS, including those above 16. The predicted threshold cation concentration developed for Australian soils by Jayawardane et al. (2011) is therefore likely to over-estimate the risk of soil dispersion in the Wairau and Paynter soils. We believe this is due to the highly contrasting texture of the Marlborough soils, in particular the high silt content (i.e. 66-67%) relative to those soils investigated by Jayawardane et al. (2011), where silt content was only 16%.

Based on the data obtained from this study we believe that winery wastewater with a CROSS of c. 23 can be applied to the Paynter and Wairau silt loam soils without adversely affecting soil structure significantly more than expected under irrigation by river water. It should be noted that this assessment is based on the two soils included in this study only and does not extend to all soils in the Marlborough region. However, effort was taken in the experimental methodology to include a soil that we believed had a high potential to disperse (i.e. a subsoil was chosen over A horizon soils; a high clay content was also selected relative to most soils in the region; and evidence of impeded drainage). We note from S-map data that although the Paynter soil profile is dominated by silt in the upper horizons, this overlies (at depth) coarse clay that may be more affected by salinity than the soils used in this investigation.

Therefore as a precautionary approach we recommend an upper threshold limit for winery wastewater CROSS that we believe is suitable for soils of the Marlborough region. This recommended limit is applicable to soils with higher clay contents than those described in this study. This threshold limit has been derived based on data presented in this report, from Laurenson (2011), Jayawardane et al. (2011) and SAR vs EC values reported in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000).

The relationship between the threshold EC required for flocculation and CROSS of winery wastewater is shown in Figure 8. Information from Laurenson et al. (2012) suggested that an EC of 1.4 dS m^{-1} was required to flocculate an Australian clay soil with a CROSS of 18. This is similar to that predicted by Jayawardane et al. (2011) and the ANZECC Guidelines (2000). Between the three models, there is some variation in the predicted threshold EC values above and below this point. However, the ANZECC Guidelines do provide a conservative compromise between models. Therefore we suggest these values be used to define the upper limit for CROSS and EC of winery wastewater when applied to soils in the Marlborough region.

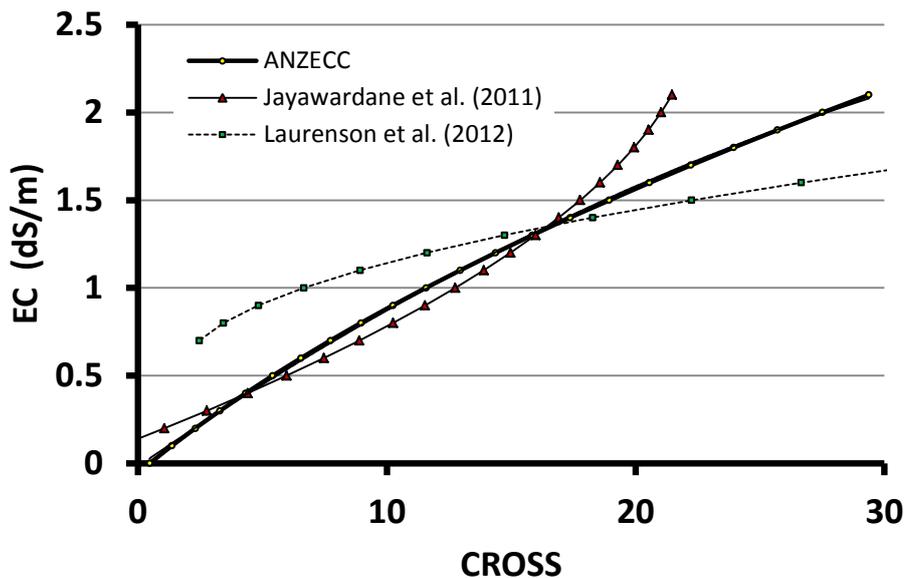


Figure 8. Reported threshold EC (dS m^{-1}) values required to maintain soil flocculation as predicted by Laurenson et al. (2011), Jayawardane et al. (2011) and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000).

Based on information obtained from Marlborough District Council, we predict that winery wastewater will typically have an EC less than 1.5 dS m^{-1} and therefore the upper CROSS should be maintained below 20, as predicted by the ANZECC model in Figure 8. We accept this is a conservative estimate of the potential dispersion risk in

Marlborough soils irrigated with winery wastewater. However we feel this precautionary approach better encompasses soils that might have higher clay contents and therefore disperse to a greater extent with increasing CROSS.

6. Relationship between solution CROSS and soil cations

Measurement of SAR as an indicator of sodicity has often been used as a surrogate to measuring exchangeable sodium percentage (ESP) which is a considerably more expensive and time consuming measure. Measuring CROSS and EC in a soil:water suspension of 1:5 will enable direct comparison to the recommended threshold values in Figure 8. In general the SAR of the water is approximately equal to the ESP of the soil to which it is applied; however in the case of CROSS this relationship may differ and research on this is currently limited. We suggest the CROSS of the soil-water extract be maintained less than 20.

As noted by Laurenson et al. (2012), clay in soils tends to disperse when the soil ESP increases above 6 to 7, however this will vary considerably between soil types. For instance, a sandy soil irrigated with municipal wastewater in Rotorua had an ESP of 30 yet no apparent structural damage (Hopkins 1997). Given the comparative dispersive effect of K^+ relative to Na^+ is 0.56 (Rengasamy and Marchuk 2011), it would seem apparent that an EPP of 11 to 13 could be maintained without adversely affecting soil structure. Based on this approach the sum of exchangeable Na^+ + $[0.56 \times (\text{exchangeable } K^+)]$ should ideally be maintained less than 7% of the cation exchange capacity. However, as noted, this variation in critical ESP and EPP ratios is highly dependent on soil type and will vary during the season, particularly with repeated applications of winery wastewater.

7. Seasonal salt accumulation in the soil profile

In Marlborough, both Pallic and Recent soils are widely used for grape growing with a smaller region of Organic soils on the river escarpments of the lower Awatere Valley. Recent soils drain freely and monovalent cations will percolate more readily with annual rainfall and irrigation cycles due primarily to these soils' bulk densities and clay contents. It is likely, therefore, that accumulation of Na^+ and K^+ associated with winery wastewater irrigation will be less pronounced than in the heavier Pallic soils that have slower drainage.

A recent survey of 27 sites carried out by the Marlborough District Council (Gray 2012) indicates that ESP was on average six times greater (ESP 9.9) where winery wastewater was irrigated relative to control sites (ESP 1.7). Exchangeable potassium

percentage (EPP) was on average 2.5 times higher (EPP 13) under winery wastewater relative to control soils (EPP 5.3). There was, however, considerable variation in both ESP and EPP.

Based on the report by Gray (2012), there appears to be limited evidence that ESP or EPP are at concerning levels despite the large variation in soil drainage properties across the sites sampled. Therefore we suggest that if the CROSS of winery wastewater, with an EC of 1.5 dS m^{-1} , is kept below 20, no adverse soil structural changes will develop. This recommendation will need to be revised for winery wastewater with lower EC according to Figure 8.

8. Conclusions

This trial aimed to determine a level of CROSS and EC that would cause a Paynter and a Wairau soil to disperse. This was done with the intention of developing guidelines for winery wastewater irrigation in Marlborough. The range of CROSS and EC values used closely resemble those found in winery wastewater in this region. Overall we found that soil dispersion was extremely low relative to reported values for Australian soils. We believe the low level of dispersion observed reflects the high silt content of these soils and therefore predict there will be very little risk of soil dispersion where winery wastewater is irrigated to these soil types. A precautionary approach has, however, been taken and a conservative upper limit for CROSS in winery wastewater has been determined. This has been based on a number of studies and therefore better encompasses a range of soils that might be irrigated with winery wastewater in Marlborough.

9. Recommendations

- We suggest wineries continue to routinely test wastewater that is applied to land and monitor not only sodium (as SAR) but also potassium contents. The most appropriate means to do this is through calculation of the CROSS value using equation 4:

$$CROSS (mmol/L)^{0.5} = \frac{[Na^+] + 0.56[K^+]}{\sqrt{\{[Ca^{2+}] + 0.6[Mg^{2+}]\}/2}} \quad (4)$$

- We suggest that a measure of electrical conductivity be added to the suite of parameters that winery wastewater is tested for. This can be done on-site using portable meters and should be maintained below 2.0 dS m^{-1} in order to maintain plant health.

- We suggest soils from the winery wastewater disposal area continue to be tested as per current Marlborough District Council guidelines. If an accumulation of soil ESP and/or EPP is detected, hydraulic conductivity should be measured routinely (approx. every 2 years) to assess changes in soil structure due to high Na⁺ and/or K⁺ loading.
- Although we accept there is limited information relating to many soils in the Marlborough region, as a precautionary approach we suggest that CROSS of winery wastewater be maintained below 20, given an assumed EC of approximately 1.4 to 2 dS m⁻¹.

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