Agricultural Water Management 205 (2018) 21–29

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Validating laboratory assessment of threshold electrolyte concentration for fields irrigated with marginal quality saline-sodic water

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ARTICLE INFO

Keywords:
Dispersion
Swelling
Aggregate stability
Threshold turbidity concentration

ABSTRACT

The use of marginal quality saline-sodic (MQSS) water for agricultural production is important in water limited environments and with a growing demand for food and fibre. Soil structural response to irrigation water quality is known to be a function of sodium contained in the irrigation water and the electrolyte concentration of that water. The threshold electrolyte concentration (C_{TH}) is classically used to determine the suitability of water to be applied to a soil, and is usually conducted as a laboratory analysis utilising saturated hydraulic conductivity. This work aimed to validate the laboratory based semi-empirical disaggregation model approach to C_{TH} against field soils where MQSS water had been applied for an extended period of time. Unirrigated locations proximal to long-term irrigation sites were paired to provide control conditions and the C_{TH} was determined. Reduction in hydraulic conductivity from the control was determined as both observed and predicted data. Results supported validation of the approach, indicating the disaggregation model as useful for proactive planning of irrigation systems with regard to water quality and a good measure for identification of MQSS water as a strategic resource. Applicability of the results to irrigation guidelines was discussed with particular focus on removal of generalised guidelines and identification of what constitutes tolerable hydraulic conductivity reduction.

1. Introduction

Marginal quality saline-sodic (MQSS) water is an important resource for agricultural irrigation, be it groundwater, or industry by-product water (Qadir and Oster, 2004). Such waters are generally high in Na, which may cause irreparable soil structural issues *via* the exchange and equilibrium processes that occurs between the soil soluble and solid phases (Ezlit et al., 2010; Raine et al., 2007; Rengasamy and Olsson, 1993). The ensuing instability of soil aggregates leads to clogging of pores, a reduction in soil hydraulic conductivity, reduced nutrient movement and eventual productivity decline (So and Aylmore, 1993). Where the electrolyte concentration (directly proportional to electrical conductivity; EC) is high enough to maintain the clay domain *via* osmotic compression of the diffuse double layer, the hydraulic conductivity and infiltration rate can be maintained to a reasonable extent, albeit still reduced compared to a Ca saturated system (McNeal et al., 1968; Quirk and Schofield, 1955; Shainberg and Letey, 1984). Therefore, the ability of soil to receive MQSS is a function of both the Na concentration and the EC.

Quirk and Schofield (1955) demonstrated that permeability of a soil irrigated with high sodium adsorption ratio (SAR) solution could be maintained provided that the EC was sufficiently high. Notably, where Ca saturated clays were investigated, reduction in EC did not cause hydraulic decline, but maintained a relatively consistent clay platelet spacing, which they termed as a potential minima (absolute stability). On the other hand, the introduction of Na into the system resulted in gradual decline of hydraulic conductivity and was highly sensitive to reduction in EC. They subsequently defined the threshold electrolyte concentration (C_{TH}) as a 10% reduction in saturated hydraulic conductivity (rK_{sat}) from the absolute stability condition. Importantly, from the condition of absolute stability the clay domain gradually expands due to disaggregation processes (intracyrstalline swelling and diffuse double layer development) approaching the threshold turbidity concentration (C_{TU}), which is beyond the C_{TH} and represents the aggregate–dispersion boundary. This insinuates that the rK_{sat} occurring up to the C_{TU} is due to somewhat reversible processes, as dispersion has not yet occurred, which was the premise of the disaggregation model of Ezlit et al. (2013) based on the work of McNeal and Coleman (1966). Ezlit et al. (2013) define the C_{TH} as rK_{sat} = 20% on the basis that departure from absolute stability occurs gradually with Na addition and that the reduction threshold needs to be beyond the measurement error in order to be a practical measure. This concept is applied for beneficial

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https://doi.org/10.1016/j.agwat.2018.04.037
Received 8 December 2017; Received in revised form 21 April 2018; Accepted 27 April 2018

use of industry by-product water (Bennett et al., 2016; Bennett and Warren, 2015; Smith et al., 2015) and is applicable to agricultural water management (Agassi et al., 1981; Frenkel et al., 1977; Marchuk and Rengasamy, 2012; Menezes et al., 2014).

Of great importance is the fact that the C_{TH} is soil-specific (Bennett and Raine, 2012; Marchuk and Rengasamy, 2012; McNeal and Coleman, 1966). This implies that soil characteristics must be understood in order to properly predict the response of a particular soil to MQSS, meaning that modelling approaches based on water quality parameters alone, such as Mallants et al. (2017a) and Mallants et al. (2017b), have considerable potential to result in environmental harm for some soils. The ability to predict the soil-specific response to MQSS application does not yet exist, despite mathematical investigations (Mau and Porporato, 2015) and semi-quantitative clay mineralogical suite investigations (Bennett et al., Submitted). The semi-empirical disaggregation model (Ezlit et al., 2013) compromises between direct measurement of the C_{TH} and complete prediction, relying on rK_{sat} from small core experiments within the laboratory.

While there is some short-term evidence for laboratory C_{TH} assessment reliability in the field (Bennett et al., 2016), it would be desirable to produce a greater body of evidence for longer-term irrigated sites. Given that the C_{TH} varies with soil type, and that clay content (Frenkel et al., 1977; Goldberg et al., 1991; McNeal et al., 1968), clay mineralogy (Churchman et al., 1995), carbonates (Chorom and Rengasamy, 1997), iron oxides (Deshpande et al., 1964; Goldberg, 1989), as well as organic matter type and content (Nelson and Oades, 1998) are suggested to affect C_{TH}, irrigation with MQSS water under field conditions may have unexpected results. Field conditions are very rarely saturated, except within the very near surface during furrow irrigation (Raine et al., 2007), existing as unsaturated environments, which presumably would affect equilibrium conditions. Furthermore, the timescale of the semi-empirical assessment of C_{TH} occurs over a much shorter timescale than the evolution of field soil structure under irrigation with MQSS water and regional rainfall (Minhas, 1996). On this basis, the aim of this study was to validate C_{TH} laboratory assessment against soils that had been irrigated with MQSS water for multiple years.

2. Methodology

2.1. Experimental design

This work used uncultivated and unirrigated soil proximal to long-term cultivated and irrigation sites as the basis of comparison. The principal issue in validating the Ezlit et al. (2013) approach is that direct measurement under field conditions would require the saturated hydraulic conductivity to be assessed initially as a benchmark condition prior to an irrigation regime commencing and these points within a field tracked over multiple seasons. Field variability, compaction due to traffic, and shrink-swell structural conditions would all introduce vast error. However, the direct in-field comparison of uncultivated land to cultivated and irrigated land presents confounded conditions in terms of soil hydraulic network continuity and bulk density. For this reason, soils were sampled from either irrigated or unirrigated regions, homogenised (within region, not between region), and then brought back to the laboratory for comparison as reconstituted cores.

The unirrigated samples were used for C_{TH} assessment consistent with the method of Ezlit et al. (2013). Replicated subsamples (5) of each irrigated soil were wet to a nominal field capacity of -10 kPa using a hanging column and then subject to centrifuge drainage to obtain the soil solution at this suction, consistent with the method described in Bennett et al. (2016). These data were used to prepare field condition equilibrium treatment irrigation solutions. All soil samples were taken uniformly from 0 to 0.2 m to ensure the highly dynamic surface conditions (influenced greatly by small rain events) did not override the long-term unsaturated conditions. Additionally, irrigation water records over the lifetime of irrigation application were used to produce a weighted mean water quality treatment; weighted in terms of poorest quality as a function of magnitude of application. The true equilibrium condition would lie between the field capacity and weighted mean irrigation water qualities. Hence, these treatments were used to generate a steady state saturated hydraulic conductivity and subsequently compared to the C_{TH} assessment of unirrigated soils to test the hypothesis and seek to validate the Ezlit et al. (2013) approach.

2.2. Soil selection and characteristic analysis

Eight cotton farms in southeast Queensland that had undertaken irrigation with marginal quality water were selected. From each farm, a sample was collected from the irrigated site, and a sample was also collected from a nearby plot that had never been irrigated. A total of 16 soil samples (two from each farm) were collected from a 0–0.2 m depth, air-dried and gently ground to pass a 2 mm sieve. Bulk sample to fill a 44 gallon drum was taken from throughout the field using the uniform sampling method to provide a representative sample.

Soil pH and electrical conductivity (EC) were determined in 1:5 soil:deionised (DI) water using a Radiometer analytical ION 450 m. Exchangeable cations were determined using a Perkin Elmer NexIon-ICP MS (Inductively Coupled Plasma – Mass Spectrometer). For exchangeable cations, the soluble salts were washed with deionised water and then the samples were extracted with 0.5 M NH_4Cl pH adjusted to 7.2 or 8.2 to match the pH of the soil analysed (Marchuk and Rengasamy, 2012). The extracted soluble cations were put through a centrifuge for 30 mins, and analysed on the ICP-MS to calculate SAR (Rayment and Lyons, 2011).

The tendency of clay colloids to disperse was assessed as electrophoretic mobility by use of zeta potential (ζ) measured using a Malvern Zetasizer (Marchuk and Rengasamy, 2012). For spontaneous dispersion in water, 1:5 soil:DI water suspensions were prepared and upended carefully three times. These were left to sit for 4 h before extraction of the suspended clay in solution and measurement of this *via* a Malvern Zetasizer. Turbidity (NTU) was also measured on this clay suspension using a NACH 2100N turbiditimeter. The clay mineral suite was semi-quantitatively determined consistent with the methods presented in Marchuk et al. (2016) using the sedimentation method of Jackson (2005) for clay separation without addition of dispersing agents or chemical treatments (such as for organic matter or oxide removal). Interpretation of data was also consistent with Marchuk et al. (2016) using CSIRO software XPLOT for Windows (Raven, 1990) comparing the XRD patterns with the International Centre for Diffraction Data (ICDD) database of standard diffraction patterns using computer aided search/match algorithms.

All 5 soils had a two-component clay mineral suite of montmorillonite (d ≈ 15.8 Å) and kaolinite (d ≈ 7.15 Å) dioctahedral types (060 patterns not shown) in addition to accessory minerals anatase (d ≈ 3.52 Å), hematite (d ≈ 2.70 Å) and the primary mineral quartz (d ≈ 3.34 Å). The quantitative estimation of clay phases for all 5 soils are presented in Table 1. Soils were generally Montmoriilonite

Table 1
Mineralogical composition of clays (%) from XRD analysis. No difference between irrigated and unirrigated soils were evident in terms of mineralogy so a single suite is provided below per soil.

Soil	Montmorillonite	Kaolinite	Anatase	Hematite	Quartz
Soil 1	76	10	4	1	9
Soil 2	23	21	4	0	52
Soil 3	72	7	3	1	17
Soil 4	62	6	3	0	29
Soil 5	60	7	4	1	28
Soil 6	1	29	0	0	63
Soil 7	13	34	0	0	53
Soil 8	79	6	0	0	15

Table 2
Selected physicochemical properties of the 8 soils; U – unirrigated soil initial field conditions; I- irrigated soil initial field conditions; EC- electrical conductivity; TCC – total cation concentration; SAR – sodium absorption ratio; ESP – exchangeable sodium percentage; CEC – cation exchange capacity; ASC – Australian Soil Classification (Isbell 2002).

Soil	Units	Soil 1		Soil 2		Soil 3		Soil 4		Soil 5		Soil 6		Soil 7		Soil 8	
Field state		U	I	U	I	U	I	U	I	U	I	U	I	U	I	U	I
pH		8.57	8.83	7.24	8.74	7.95	8.87	7.98	8.47	7.27	8.92	7.49	7.99	8.44	8.55	8.26	8.60
EC	dS/m	0.10	0.45	0.21	0.13	0.13	0.19	0.36	0.43	0.19	0.30	0.04	0.04	0.96	1.17	0.14	0.17
Organic matter	%	1.06	0.8	1.01	1.09	1.02	0.95	0.98	1.11	1.31	1.54	0.69	0.92	1.56	1.86	1.02	1.23
Soluble Cations (mmol$_c$/L)	Na	0.86	4.43	0.77	1.05	1.73	1.05	3.66	1.36	1.87	0.57	0.08	0.05	4.66	4.96	1.33	1.01
	Mg	0.63	0.40	0.52	0.31	0.26	0.30	0.38	0.58	0.27	0.70	0.07	0.06	0.71	0.47	0.36	0.34
	K	0.09	0.09	0.10	0.09	0.08	0.10	0.10	0.32	0.10	0.22	0.21	0.23	0.45	0.49	0.09	0.10
	Ca	1.03	0.10	0.76	0.62	0.26	0.45	0.84	0.73	0.45	1.99	0.16	0.24	3.74	2.05	0.49	0.65
TCC	mmol$_c$/L	2.61	5.02	2.16	2.07	2.33	1.91	4.98	3.00	2.69	3.48	0.52	0.59	9.57	7.97	2.27	2.10
Exchangeable Cations (cmol$_c$/k g)	Na	0.40	2.53	0.39	0.14	0.94	2.88	1.03	3.25	3.73	0.93	0.01	0.00	0.14	0.20	0.69	1.00
	Mg	8.67	9.01	2.87	3.53	13.70	11.30	14.81	13.18	14.52	15.47	0.76	0.67	1.72	1.99	11.33	13.58
	K	2.95	1.50	0.66	0.48	1.00	1.32	0.96	0.99	1.12	1.56	0.61	0.91	0.82	0.95	0.81	0.83
	Ca	25.52	25.12	11.66	9.52	20.87	20.31	24.30	24.93	19.87	17.32	2.04	3.61	10.67	9.64	18.35	22.10
CEC		37.54	38.16	15.58	13.67	36.51	35.81	41.10	42.35	39.24	35.28	3.41	5.20	13.35	12.77	31.19	37.51
SAR		0.98	5.84	0.96	1.54	3.36	1.71	4.69	1.68	3.09	0.49	0.23	0.13	3.13	4.42	2.04	1.43
ESP	%	1.07	6.62	2.50	1.06	2.57	8.04	2.51	7.67	9.51	2.64	0.16	0.10	1.03	1.56	2.22	2.66
Texture		Clay		Clay		Clay		Clay		Clay		Sandy loam		Silty clay loam		Silty clay	
ASC		Black Vertosol		Black Vertosol		Black Vertosol		Black Vertosol		Black Vertosol		Red Kandosol		Brown Vertosol		Brown Dermosol	
Clay content	%	75	76	52	58	60	62	61	62	62	63	12	11	23	24	53	52
Zeta Potential	mV	−23	−25	−23	−24	−29	−29	−27	−25	−16	−28	−33	−32	−19	−22	−29	−31

dominant, with exception of Soil 2, Soil 6 and Soil 7, which were Quartz dominant.

Soil 1–5 were all black Vertosols, Soil 6 was a red Kandosol, Soil 7 was a brown Vertosol, and Soil 8 was a Dermosol. The soils had varying amounts of organic carbon, soluble cations and exchangeable cations (Table 2) thus providing a range of physico-chemical properties to evaluate soil-specific response.

2.3. Saturated hydraulic conductivity measurement and solutions

The C_{TH} analysis was conducted as per Ezlit et al. (2013) for the unirrigated soils using two soil core replicates per soil, and assessed *via* saturated hydraulic conductivity. The benchmark conditions (absolute stability) was determined using a $CaCl_2$ solution prepared at the respective EC the soil core was designed to be fixed at (0.5, 1.0, 2.0, 4.0, or 8.0 dS/m) and progressive treatment solutions were applied with increasing SAR (Table 3). Steady state conditions were obtained for each treatment solution applied during C_{TH} assessment, defined as less than 3% variation in the volume between consecutive measurements after a 10 min interval for at least 1 h (Reading et al., 2012). During the entire experimental process soil cores were kept saturated. The rK_{sat} was calculated for each soil core used to create a three dimensional response surface using TableCurve 3D (SYSTAT Software Inc., 2002) for rK_{sat} as a function of solution SAR and EC:

Absolute stability condition:

$$rK_{sat} = 1, \quad at \quad x \leq 0 \tag{1}$$

Disaggregation condition:

$$rK_{sat} = 1 - \left[\frac{ge^{m\frac{ESP}{100}}(x_0)^{\left[\left(\frac{ESP}{100}\right)^a + b\right]}}{\left\{1 + ge^{m\frac{ESP}{100}}(x_0)^{\left[\left(\frac{ESP}{100}\right)^a + b\right]}\right\}} \right] \text{at} \quad x \; > 0 \tag{2}$$

where rK_{sat} is the reduction in saturated hydraulic conductivity; *ESP* is exchangeable sodium percentage; x_o is the adjusted effective swelling factor which takes account of the swelling and dispersion that controls rK_{sat} dynamics; and, *a, b, g, m* are all optimisable empirical fitted parameters dependent on soil type.

For the irrigated soils, both the field capacity and groundwater irrigation solutions were prepared on a soil-specific basis (Table 4), as outline in the experimental design. Soil cores were prepared as for C_{TH} analysis, with five replicates per treatment, per soil (ten cores per soil). Solutions were prepared to reflect the SAR and EC of the water available to the farmer's from their bores. Soil cores were saturated slowly from the bottom over a period of one hour, after which they were removed and placed into leaching racks where a constant hydraulic head was applied using the respective treatment solution. These soils were run with this solution until steady state was achieved using the same definition as per C_{TH}.

The $CaCl_2$ benchmark conditions of the unirrigated soil were used to determine the expected benchmark conditions for the irrigated soils fixed at the respective treatment EC using the following equation (Table 5):

$$K_{sat} = a \quad \ln \quad EC + b \tag{3}$$

Where K_{sat} is the saturated hydraulic conductivity at the benchmark condition respective to the solution electrical conductivity (*EC*), which was determined as either the soil solution or irrigation solution EC depending on the treatment. Parameters '*a*' and '*b*' are optimisable parameters determined by the soil specific response to $CaCl_2$ (over EC = 0.5–8.0 dS/m) for the unirrigated soils. The observed steady state saturated hydraulic conductivity was subsequently used with the expected benchmark condition and reduction in hydraulic conductivity calculated.

Table 3
Required amounts of NaCl and $CaCl_2$ for solution preparation for EC sequence 0.5, 1, 2, 4 and 8 dS/m; SAR, sodium adsorption ration; Treat., treatment; TCC, total cation concentration.

SAR Treat.	Na (mmol$_c$/L)	Ca (mmol$_c$/L)	SAR (mmol$_c$/L)	Final TCC (mmol$_c$/L)	SAR Curve	Na (mmol$_c$/L)	Ca (mmol$_c$/L)	SAR (mmol$_c$/L)	Final TCC (mmol$_c$/L)
0	0	80	0	80	**5**	75.00	5.00	47.43	80
	0	40	0	40		37.50	2.50	33.54	40
	0	20	0	20		18.75	1.25	23.72	20
	0	10	0	10		9.37	0.63	16.77	10
	0	5	0	5		4.69	0.31	11.86	5
1	30.00	50.00	6.00	80	**6**	77.00	3.00	62.87	80
	15.00	25.00	4.24	40		38.50	1.50	44.45	40
	7.50	12.50	3.00	20		19.25	0.75	31.43	20
	3.75	6.25	2.12	10		9.62	0.38	22.23	10
	1.87	3.13	1.50	5		4.81	0.19	15.72	5
2	50.00	30	12.91	80	**7**	78.10	1.90	80.12	80
	25.00	15	9.13	40		39.05	0.95	56.66	40
	12.50	7.5	6.45	20		19.52	0.48	40.06	20
	6.25	3.75	4.56	10		9.76	0.24	28.33	10
	3.12	1.875	3.23	5		4.88	0.12	20.03	5
3	63.00	17.00	21.61	80	**8**	78.80	1.20	101.72	80
	31.50	8.50	15.28	40		39.40	0.60	71.93	40
	15.75	4.25	10.80	20		19.70	0.30	50.86	20
	7.87	2.13	7.64	10		9.85	0.15	35.97	10
	3.94	1.06	5.40	5		4.92	0.08	25.43	5
4	71.00	9.00	33.47	80	**Infinity**	80.00	0	∞	80
	35.50	4.50	23.67	40		40.00	0	∞	40
	17.75	2.25	16.73	20		20.00	0	∞	20
	8.87	1.13	11.83	10		10.00	0	∞	10
	4.44	0.56	8.37	5		5.00	0	∞	5

Table 4
EC and SAR of solutions used to calculate the reduction in hydraulic conductivity after irrigating with marginal quality water.

Soil	Soil-water solution		Irrigation solution	
	EC	SAR	EC	SAR
1	3.64	10.98	2.28	8.35
2	0.87	3.41	2.57	14.39
3	0.89	3.38	3.61	12.46
4	0.71	4.71	3.94	12.20
5	1.96	8.25	2.67	14.33
6	0.61	1.04	2.25	14.32
7	0.83	7.40	0.72	15.15
8	0.85	2.66	0.60	2.92

Table 5
Benchmark condition equations for the eight soils obtained from the $CaCl_2$ solutions of the soils with unirrigated initial field condition where variables ‘a’ and ‘b’ from Eq. (3) have been parameterised on a soil-specific basis.

Soil	Equation
Soil 1	$K_{sat} = 8.5883\ln(EC) + 57.466$
Soil 2	$K_{sat} = 40.823\ln(EC) + 119.13$
Soil 3	$K_{sat} = 19.556\ln(EC) + 47.018$
Soil 4	$K_{sat} = 32.57\ln(EC) + 47.719$
Soil 5	$K_{sat} = 8.8717\ln(EC) + 31.844$
Soil 6	$K_{sat} = 6.9844\ln(EC) + 56.134$
Soil 7	$K_{sat} = 1.7576\ln(EC) + 22.414$
Soil 8	$K_{sat} = 0.7088\ln(EC) + 15.365$

3. Modelling

TableCurve 3D software facilitated the modelling of data into a three dimensional surface using Eqs. (1) and (2) for hydraulic reduction (Ezlit et al., 2013). For all eight soils, data from the C_{TH} analysis was modelled using TableCurve 3D. The 20%, 40%, 60% and 80% rK_{sat} contour were extracted and plotted for each soil. TableCurve input parameters for the Ezlit et al. (2013) equation and the associated model statistics are provided in Table 6.

4. Results

4.1. Threshold electrolyte concentration analysis of the unirrigated soils

For the eight soils at least 80% of the variation in rK_{sat} was explained by the fitted surface as a function of ESP and EC, with the majority of the soil having > 90% of the variation explained (Table 6). Deviation of the surface from the data points is depicted in Fig. 1. The predicted R^2 for the eight soils provides a very good indication of predictive capability of the surface for non-data point regions within the bounds. Additionally, the fitted standard errors for the eight surfaces are small. These statistics indicate that the surfaces explain the data well and are useful for prediction of rK_{sat} for changes in irrigation water quality.

Soil 6, a Red Kandosol, and Soil 7, a Brown Vertisol, had rK_{sat} at SAR = infinity of 80 and 60% at high EC solutions, respectively, indicating a greater resilience to dispersion; the remaining soils decreased by > 95% at the same solution. Such results may be consistent with the high sand content of the Kandosol, whereby clay dispersion even at extreme SAR is insufficient to completely block conducting pores. At the Brown Vertisol site there was an abundance of ironstone, which may support resistance of aggregates to dispersion due to iron oxides. This reasoning was unable to be tested, but is presented here as a matter of consideration; as discussed above, the disaggregation model fitted-surface and predictive capability for both soils was very good.

The C_{TH} of the soils varied between soil classification, and within the Vertisol classification (Figs. 1 and 2). Soil 4, a Black Vertisol, had very rapid reduction to rK_{sat} = 20%, with the C_{TH} curve (Fig. 2) substantially different to the other 5 Vertisol soils.

4.2. Reduction in soil hydraulic conductivity of the irrigated soils

Fig. 2 depicts the soil-water and irrigation solutions used to assess the rK_{sat} due to the use of MQSS water, with the true reduction existing

Table 6
Model parameters for the fitted surface predicted through TableCurve.

Model parameters	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5	Soil 6	Soil 7	Soil 8
a	0.514	1.723×10^{-4}	0.459	0.512	0.96	0.379	0.068	2.278×10^{-6}
b	2	1.919	1.319	0.466	1.999	1.692×10^{-6}	0.391	0.423
g	38	0.426	13.96	11.676	14.579	0.556	2.626	3.821
m	7.117	13.769	5.594	4.415	9.932	5.034	0.756	8.605
s	1.154	4.032	0.077	5.106×10^{-5}	1.887	2.347	7.001	7.733
l	−4.708	−28.604	−0.681	1.592×10^{-5}	−11.311	0.387	−11.268	−20.234
F value	0.363	0.783	0.515	0.143	0.276	0.079	0.086	0.054
R^2	0.962	0.967	0.928	0.854	0.969	0.843	0.80	0.89
Predicted R^2	0.956	0.961	0.915	0.827	0.964	0.813	0.752	0.871
Fitted standard error	0.014	0.011	0.006	0.036	0.070	0.056	0.012	0.013

on the line bounded by these points. For Soils 2–6 the soil-water solution had both a lower SAR and EC than the irrigation solution, indicating that the soil water system was diluted within the top 0.2 m of the soil. Soil 1 and 8 had the reverse, with the soil-water solution having both SAR and EC greater than for the irrigation solution, consistent with solute concentration within the top 0.2 m of soil. Soil 7 soil-water solution had a lower SAR and higher EC than for the irrigation solution; this may suggest initial dilution followed by concentration, due to rainfall and evaporation sequences. The true rK_{sat} was therefore predicted with variation between soil-water and irrigation solutions of 3–17%, which corresponded to variation for observed soil-water and irrigation solution variation of 1–19% (Table 7).

The observed rK_{sat} for the eight soils ranged from 1 to 87%, while the predicted rK_{sat} ranged from 2 to 66% (Table 7). This discrepancy was due to Soil 3 where the observed $rK_{sat} = 87$ and 83% as compared to the predicted $rK_{sat} = 21$ and 34% for the soil-water and irrigation solution treatments, respectively. This resulted in an observed to predicted rK_{sat} difference of 66 and 48% for the soil water and irrigation solution treatments, respectively. For all other soils, the difference between the observed and predicted results for soil-water and irrigation solution treatments was $< 9\%$. For this reason, Soil 3 was considered an outlier and was removed from the direct comparison of observed and predicted data used for model validation (Fig. 3). While Soil 3 was removed from the validation data set these points are still depicted in Fig. 3 in order to demonstrate how different they were from the remaining 7 independent soil samples. The regression line for the 7 soils was very close to the 1:1 observed versus predicted data line (gradient of 0.97) and explained 96% of the data variation indicating a very good fit. Therefore, these data support validation of the model results.

5. Discussion

5.1. Model validation

With the exception of the observed results for Soil 3, the results support validation for the use of the Ezlit et al. (2013) disaggregation model in determining the C_{TH} with relevance to field application of MQSS water. It is likely that Soil 3 was subject to irrigation with MQSS groundwater followed by irrigation with good quality, low EC, captured rainfall. Thus, removal of the data as an outlier was warranted, especially given the obvious trend of the remaining 7 soils. From Tables 1 and 2 the key parameters of CEC, clay content, mineralogy and Australian Soil Classification were used to determine the similarity of the proximally located irrigated and unirrigated soil samples. In all cases no significant differences were found between irrigated and unirrigated soils for these parameters, confirming that the soils were fair in comparison. Therefore, given the relationship between observed and predicted rK_{sat} ($R^2 = 0.96$) in Fig. 3, it is deduced that laboratory assessment of C_{TH} is relevant in informing changes in field condition. Similar results were obtained by Bennett et al. (2016) for reuse of coal seam gas on a red Vertosol where no significant change in K_{sat} was observed for soil irrigated with SAR = 24 and EC = 3.2 dS/m, as predicted by C_{TH} analyses carried out for that site.

In the current work, it was not feasible to identify new areas for irrigation and then subject these to irrigation with MQSS water. For this reason the experimental design focused on proximally paired sites that were subsequently relocated and reconstituted as short leaching columns. We acknowledge that the soils *in situ* would not be subject to saturated conditions under the majority of rainfall and irrigation events, but contend that the true soil-water concentration and cation suite is reflected by the experimental approach in this work. In the case of Bennett et al. (2016), the C_{TH} was conducted to inform water treatment targets for application to land, prior to irrigation system installation and operation. Their results therefore directly tracked *in situ* changes throughout time. Shainberg and Letey (1984) suggest that the soils irrigated with MQSS water in a laboratory are usually more sensitive than those within a field, which may have occurred in the Red Vertosol of Bennett et al. (2016). The current work might be furthered by use of in-tact large columns (large to account for macroposrosity variation spatially). However, we suggest that the validation of the disaggregation model still holds as the use of laboratory soil cores, while potentially more sensitive than *in situ* field soils, at an $rK_{sat} = 20\%$ as the reduction threshold provides a safety factor protecting soils from undue degradation (Quirk, 2001).

5.2. Soil-Specific threshold electrolyte concentration

The results for the eight soils provide further evidence for the C_{TH} being soil-specific, even within the same soil classification and where soil characteristics such as pH, organic matter, clay content, CEC and mineralogical suite were highly similar for the Vertosol soils. Quirk and Schofield (1955) and Quirk (1971) initially suggested that the C_{TH} relationship was universal an able to be described by a generalised equation. Various authors (Bennett and Raine, 2012; Marchuk and Rengasamy, 2012; McNeal and Coleman, 1966; McNeal et al., 1968; Shainberg and Letey, 1984) have demonstrated that a universal approach to describing C_{TH} is not appropriate. Quirk (2001) later concedes that variation in C_{TH} should be expected, but that the equations presented by Quirk and Schofield (1955) describe the general relationship. For the Vertosol soils in this work, Soils 1, 2, 3, 5 and 7 generally have similar C_{TH}, although the standard error for the relationships was by and large SAR $\pm / -6.8$. Such variation from a general relationship may have significant practical implications. Importantly, Soil 4 was distinctly different from the remaining Vertosols, but highly similar in terms of its physical, chemical and mineralogical characteristics. We contend that intricacies within the mineralogy likely explain this result, demonstrating that future work should seek to quantifiably determine clay mineralogy, its size range, and differences in charge interactions. Use of a general relationship for such a soil would likely result in 50–60% rK_{sat}. Hence, use of the disaggregation model with soil-specific observed data to inform irrigation of MQSS water is advised.

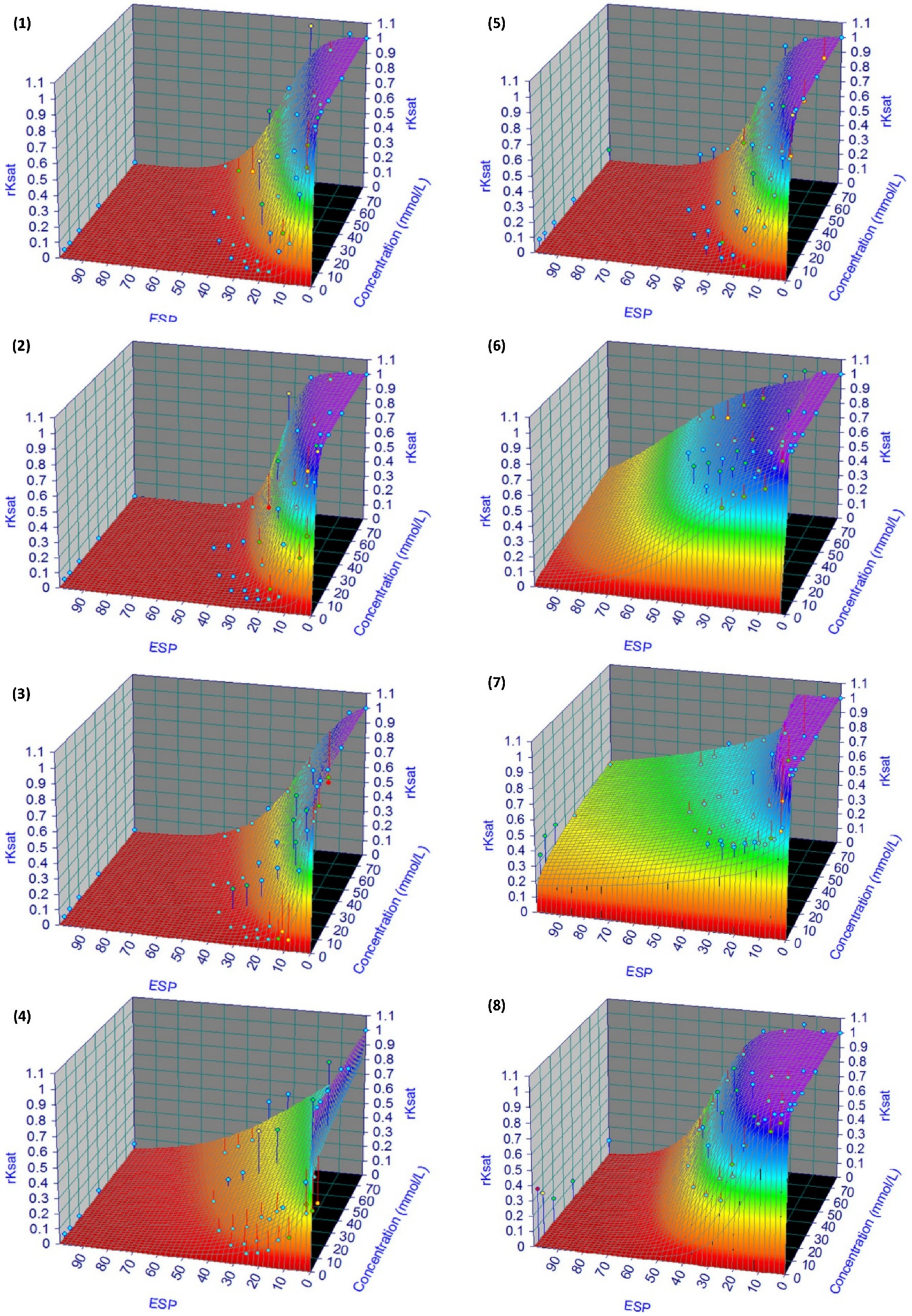

Fig. 1. Reduction in saturated hydraulic conductivity (rK_{sat}) for eight southeast Queensland soils (1–8). The 3-Dimensional surfaces are function of the exchangeable sodium percentage (ESP) and solution concentration ($mmol_c/L$) as calculated using the approach of Ezlit et al. (2013). Model parameters and associated statistics are presented in Table 6.

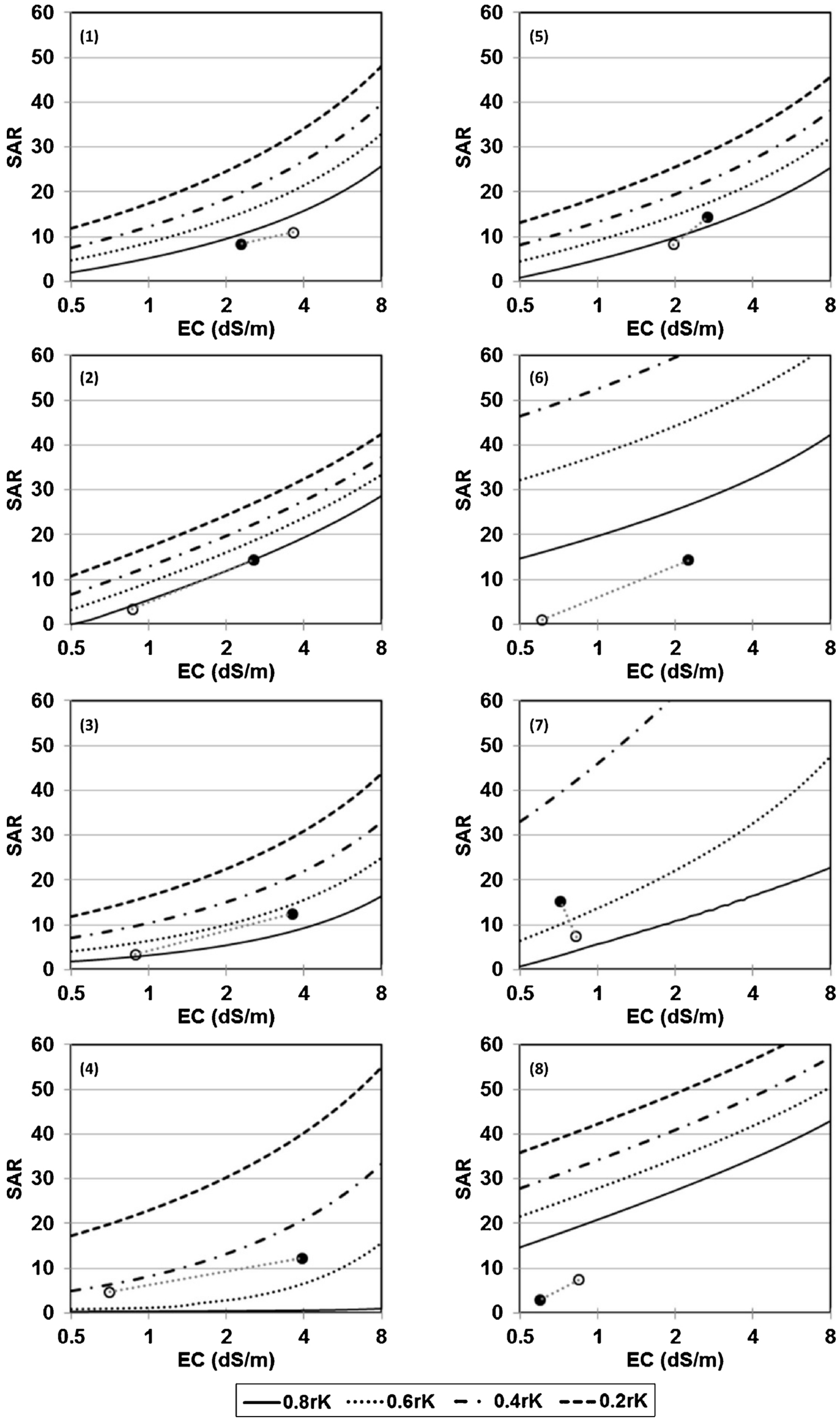

Fig. 2. Reduction in saturated hydraulic conductivity (rK) as a function of solution sodium adsorption ratio (SAR) and electrolyte concentration (EC). Threshold electrolyte concentration is defined as a 20% reduction in hydraulic conductivity (0.8rK). The hollow circle represents the soil solution and the solid circle represents the irrigation solution, with the true field condition existing on the hashed line between these points; 0.2rK curves for Soil 4, 6 and 7 occur at SAR greater than the graphical domain presented.

Table 7
Reduction in hydraulic conductivity from benchmark conditions after irrigation with two different treatments; Benchmark – benchmark condition saturated hydraulic conductivity determine using $CaCl_2$ to represent the most stable condition of the soil at a given electrical conductivity K_{sat} – saturated hydraulic conductivity; rK_{sat} – reduction in saturated hydraulic conductivity; Pred – predicted; Obs Treat Range, Pred Treat Range – rK_{sat} variation between soil–water and irrigation solutions (Treat) as observed (Obs) and predicted (Pred); Difference – difference between the observed and predicted rK_{sat}.

Soil	Treatment	Benchmark (mm/h)	K_{sat} (mm/h)	rK_{sat} (%)	Pred rK_{sat} (%)	Obs Treat Range (%)	Pred Treat Range (%)	Difference (%)
1	1	69	55	20	18	8	3	1.8
	2	65	57	12	15			3.3
2	1	113	89	21	19	2	3	2.4
	2	158	121	23	22			1.2
3	1	13	2	87	21	4	13	66.1
	2	21	4	83	34			48.7
4	1	36	13	64	66	8	16	1.7
	2	92	40	57	50			6.7
5	1	38	28	27	19	1	10	8.3
	2	41	29	28	29			0.9
6	1	53	52	1	3	19	13	1.7
	2	62	49	21	16			4.7
7	1	37	25	32	28	17	17	3.9
	2	24	12	49	45			4.3
8	1	16	14	10	2	7	14	8.2
	2	16	13	17	16			1.4

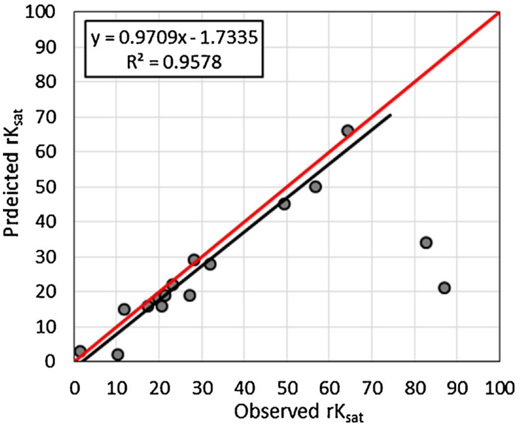

Fig. 3. The reduction in hydraulic conductivity as predicted using threshold electrolyte concentration analysis semi-empirical modelling for previously unirrigated soils versus the observed reduction in saturated hydraulic conductivity for soil previously irrigated with marginal quality saline sodic water. The diagonal red line represents the 1:1 line, while the black line is the regression fit for the observed data ignoring the two outliers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. Irrigation and soil management implications

Validation of the Ezlit et al. (2013) semi-empirical disaggregation model for the field soils suggests that irrigation systems can be adequately planned for in terms of water quality and soil structural degradation. Current guidelines for Australian irrigation (ANZECC, 2000) utilised generalised equations for the use of MQSS water, which is advised against by both literature and the results of this work. Similar to general use guidelines for wastewater and groundwater associated with the coal seam gas industry, it would be advisable to set a lower limit for SAR at a specified EC where the 80–90% have $rK_{sat} < 20\%$ with the majority of the remaining soils (*e.g.* Soil 4) not decreasing by > 40%.

Shainberg and Letey (1984) proposed the use of an $rK_{sat} = 50\%$ as the C_{TH} on the basis that laboratory testing of soils is generally more sensitive than for the same soils under field condition. However, this assertion is made on a limited data set and with the assumption that the selection of the rK_{sat} is arbitrary. While the rK_{sat} is somewhat arbitrary, it is linked to physicochemical phenomena, whereby K_{sat} reduction is gradual as sodium concentration increases and/or electrolyte concentration decreases, and the stability condition departs occurs from is a potential minima (Quirk, 2001). The initial selection of $rK_{sat} = 10\%$ (Quirk and Scofield, 1955), and the current use of $rK_{sat} = 20\%$ (Ezlit et al., 2013), are based on measureable departure from this potential minima taking into account the extent of error associated with the measurement method, while seeking to limit undue soil structural deterioration. Increasing the rK_{sat} that defines the C_{TH} is a worthy discussion in terms of ability to use MQSS water as a strategic irrigation resource, particularly in water limited environments. Shainberg and Letey (1984) and Menezes et al. (2014) both point out that if initial K_{sat} is substantial, then $rK_{sat} > > 20\%$ may well be tolerable. However, the definition of tolerable requires further consideration. Quirk (2001) wrote his review with a particular focus on misunderstanding of the C_{TU}, which occurs at the aggregate-dispersion boundary and is considered to be where hydraulic reduction is no longer reversible to any extent. This definition acknowledges that intercyrstalline swelling is a reversible process, as is the development of a diffuse double layer (intracyrstalline swelling), provided the diffuse double layer does not overcome the attractive forces within the clay domain. On this basis, we emphasize that '*tolerable*' reduction in K_{sat} could be defined as the rK_{sat} occurring at the C_{TU}. However, caution is needed in this approach as there is no safety buffer, which the C_{TH} effectively provides (Quirk, 2001). Rapid dilution during rainfall could completely negate the aggregated condition, under such definition of '*tolerable*', and result in irreparable damage even where systems are buffered with an electrolyte source, such as gypsum (Ali et al., 2018). It is worth noting that the C_{TU} occurs at approximately $rK_{sat} = 56\%$ at SAR = 21 in the pioneering work of Quirk and Schofield (1955), which is very close to the $rK_{sat} = 50\%$ at C_{TH} recommended by Shainberg and Letey (1984) and similarly very close to irreparable damage to the soil resource. The current work demonstrates the soil-specific nature of the C_{TH}, and similarly we should expect the C_{TU} to be soil-specific with potential to occur at $rK_{sat} < 50\%$. There appears to be very little information on the rK_{sat} associated with the C_{TU} indicating further investigation is required (Dang et al., 2018). Hence, where the rK_{sat} associated with the C_{TH} is to be increased for practical irrigation reasons, it needs to be done where the C_{TU} is known and some level of safety factor has been applied.

6. Conclusion

The semi-empirical approach to C_{TH} determination used in the disaggregation model of Ezlit et al. (2013) was validated against seven soils where MQSS water had been used for irrigation of soil under field conditions. This indicates that C_{TH} determination *via* the disaggregation model will allow proactive planning of irrigation systems with regard to water quality and is a good measure for identification of MQSS water as a strategic resource. The C_{TH} was further supported as being soil-specific, even within soil classification, demonstrating that it is important to move on from generalised guidelines for water quality in agricultural production. Discussion was subsequently presented to aid in the development of such guidelines and for the increase of saturated hydraulic reduction that is considered tolerable.

Acknowledgements

The authors wish to acknowledge the Cotton Research and Development Corporation for funding the work. Additionally, technical assistance from Mr David West was appreciated. The authors declare no conflicts of interest.

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