

CONVERTING SENTEK VOLUMETRIC ION CONTENT TO ELECTRICAL CONDUCTIVITY OF THE SATURATED EXTRACT FOR A RANGE OF SOIL TEXTURES

CONVERSION DE LA TENEUR IONIQUE VOLUMIQUE SENTEK EN CONDUCTIVITE ELECTRIQUE DE L'EXTRAIT DE PATE SATUREE POUR DIFFERENTES TEXTURES DE SOL

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ABSTRACT

Since the invention of the term Volumetric Ion Content (VIC) by Sentek Pty. Ltd., the company has endeavoured to relate this unitless measure to the more widely accepted property of soil Electrical Conductivity of the Saturated Extract (EC_e). VIC is calculated by a proprietary model derived from empirical data collected from salinity experiments run in columns of sieved sand in the laboratory. The original electronic circuitry of the sensor was modified to run at two different frequencies (high and low). As the low frequency option of the capacitance sensors react to bulk free ions in the soil, the chemistry of the soil determines the level of reaction observed. The company has long qualified the use of the VIC model, preferring to restrict its use to sandy soil textures only. Despite this, many growers of agricultural products and environmental researchers have sought to extend its use into heavier textured clay soils. So much so, that Sentek produced a work-around in the form of a software module which took VIC values at selected water contents only and plotted them against a timescale. This produced graphed trends containing less detail and simplified the interpretation of the VIC observed in the soil, but anomalies still remained in silt and clay textured soils.

This study describes a more developed process whereby soil salinity benchmarking procedures were conducted in the field on a range of soil textures worldwide to ascertain whether it was possible to validate the use of the VIC model for heavier textured soils in a more precise manner. Simple regression analyses were used to determine a range of possible mathematical relationships between VIC and EC_e . Significant associations were found in linear, power and natural log function relationships for many soil textures including loams and silts. However, the further the investigators ventured away from sandy soils, the less significant the associations became.

Some of the complex chemistries of clays and silts were also investigated using accredited commercial soils analyses and showed that these properties impacted on the standard VIC model. The passage of fertiliser ions through the soil was found to be greatest in sands and much retarded in clays. This was as expected and assumed to be due not only to the greater porosity of the sands but also to the higher chemical interaction between clay particles and the free ionic content in adjacent flowing porewaters. The significance of correlations between VIC and Cation Exchange Capacity (CEC), Sodium Adsorption Ratio (SAR) and Cation Ratio of Soil Structural Stability (CROSS) were varied. In heavier textured soils the CEC varied positively or negatively with VIC and was site-specific. Also in heavier textured soils, the SAR decreased with increasing VIC, indicating that the increasing VIC was not related to sodium or sodicity. The chemistries of heavier textured soils are complex and impact on the calculated VIC value in different ways. Some of this impact appears to be due to the dynamic exchange of ions between porewater and clay particles. The current TriSCAN model may therefore still require some additional calculation adjustments for use in these soils unless the VIC Filter function of IrriMAX[®] software is used.

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Keywords: Volumetric Ion Content (VIC); Salinity; Electrical Conductivity (EC); Calibration; Salt; Fertiliser.

RÉSUMÉ

Depuis la création du terme « teneur ionique volumique » (Volumetric Ion Content, VIC) par Sentek Pty. Ltd., l'entreprise s'efforce de relier cette mesure adimensionnelle à la propriété plus largement admise qu'est la conductivité électrique de l'extrait de pâte saturée du sol (ECe). La VIC est calculée au moyen d'un modèle propriétaire issu de données empiriques recueillies lors d'expériences de salinité menées en laboratoire dans des colonnes de sable tamisé. Le circuit électronique initial du capteur a été modifié pour fonctionner à deux fréquences différentes (haute et basse). Comme l'option basse fréquence des capteurs capacitifs réagit aux ions libres présents dans le volume du sol, la chimie de celui-ci détermine l'intensité de la réponse observée. L'entreprise a longtemps assorti l'utilisation du modèle VIC de réserves, préférant en limiter l'usage aux seules textures de sol sableuses. Malgré cela, de nombreux producteurs agricoles et chercheurs en environnement ont cherché à étendre son utilisation aux sols argileux à texture plus lourde. Cette demande a été telle que Sentek a mis au point une solution de contournement sous la forme d'un module logiciel qui ne retenait les valeurs de VIC qu'à des teneurs en eau sélectionnées et les représentait sur une échelle de temps. Les tendances graphiques ainsi obtenues comportaient moins de détails et simplifiaient l'interprétation de la VIC observée dans le sol, mais des anomalies subsistaient dans les sols limoneux et argileux.

Cette étude décrit un processus plus élaboré dans lequel des protocoles d'établissement de valeurs de référence pour la salinité du sol ont été appliqués sur le terrain à diverses textures de sol partout dans le monde, afin de déterminer s'il était possible de valider plus précisément l'utilisation du modèle VIC pour les sols à texture plus lourde. Des analyses de régression simple ont servi à déterminer un éventail de relations mathématiques possibles entre la VIC et l'ECe. Des associations significatives ont été observées pour les relations linéaires, de puissance et logarithmiques naturelles dans de nombreuses textures de sol, notamment les sols francs et limoneux. Toutefois, plus les chercheurs s'éloignaient des sols sableux, moins les associations étaient significatives.

Certaines caractéristiques chimiques complexes des argiles et des limons ont également été étudiées au moyen d'analyses de sols réalisées par des laboratoires commerciaux agréés ; les résultats ont montré que ces propriétés influençaient le modèle VIC standard. La migration des ions fertilisants à travers le sol s'est révélée maximale dans les sables et fortement ralentie dans les argiles. Ce résultat était conforme aux attentes et a été attribué non seulement à la plus grande porosité des sables, mais aussi à l'interaction chimique plus forte entre les particules d'argile et les ions libres contenus dans les eaux interstitielles adjacentes en mouvement. La significativité des corrélations entre la VIC et la capacité d'échange cationique (CEC), le rapport d'adsorption du sodium (SAR) et le rapport cationique de stabilité structurale du sol (CROSS) variait. Dans les sols à texture plus lourde, la CEC variait positivement ou négativement avec la VIC et dépendait du site. Toujours dans ces sols, le SAR diminuait à mesure que la VIC augmentait, ce qui indiquait que l'augmentation de la VIC n'était liée ni au sodium ni à la sodicité. La chimie des sols à texture plus lourde est complexe et influe de différentes manières sur la valeur calculée de la VIC. Une partie de cette influence semble résulter de l'échange dynamique d'ions entre l'eau interstitielle et les particules d'argile. Le modèle TriSCAN actuel pourrait donc encore nécessiter des ajustements de calcul supplémentaires pour être utilisé dans ces sols, à moins d'employer la fonction « VIC Filter » du logiciel IriMAX®.

Mots clés : Teneur ionique volumique (VIC); Salinité; Conductivité électrique (EC); Etalonnage; Sel; Engrais.

INTRODUCTION

Since the invention of Volumetric Ion Content (VIC) growers have been able to track the progression of bulk salts within the soil profile (Buss et al., 2004, Dalton et al. 2004 and McCann et al., 2017). This has been useful in monitoring the movement of applied fertilisers to commercial crops or to observe

the nutrient leaching process after rainfall. It has also been used to monitor the tidal movement of submerged water tables.

The VIC calculation is a proprietary model derived from empirical data collected from salt applications to columns of sand in the laboratory. This media was used for its free draining properties both in terms of water and salts. Unfortunately, these properties also made the model limited in its application in the wider world of differing soil textures. These limitations come about primarily because of the differing levels of complexity in soil crumb chemistries and the variations in soil Bulk Density (BD). The higher Cation Exchange Capacity (CEC) and larger surface area of clays facilitate more opportunities for ions to mobilise and interact between the bound and free states. These free ions are detected by the highly sensitive capacitance sensors, exceeding the known boundaries of the empirical model. The VIC Filter module of IrriMAX software compensates for this to some degree and some growers find they can interpret trends in heavier textured soils with confidence. Many other growers, however, seek to derive a conversion of VIC to soil Electrical Conductivity of the Saturated Extract (EC_e). Sentek designed a methodology called Benchmarking (or Salinity Calibration) to do this. However, in practice it has been found hard to achieve good correlations due to the inherent variability in soil texture and field sample consistency. This study sought to derive a set of reliable regression curves in a range of different soil textures.

METHODS

To support its sensor technologies, Sentek has developed industry specific software to control and interpret the data (IrriMAX®). One of the outputs of its TriSCAN® sensor is a surrogate value for soil salinity called Volumetric Ion Content (VIC). This value is used to monitor and record the trends of salinity and nutrient changes within the soil in near real time.

The current model utilised to calculate VIC is based on laboratory studies in columns of sand which had their water and salinity contents precisely controlled. TriSCAN has only ever been recommended for use in sandy soil textures. There is now a growing market desire to use TriSCAN in heavier textured soils such as clays and silts. To address this need initially, Sentek introduced an additional calculation protocol within its proprietary display software, IrriMAX, making it possible to plot only VIC values at a user-specified, fixed water content (so-called VIC Filter function, refer figure 1). This function produces trending graphs which many operators have found useful in tracking their salinity in clay soils. However, there are some limitations in its use, including gaps in the data and the fact that the data must be calculated retrospectively.

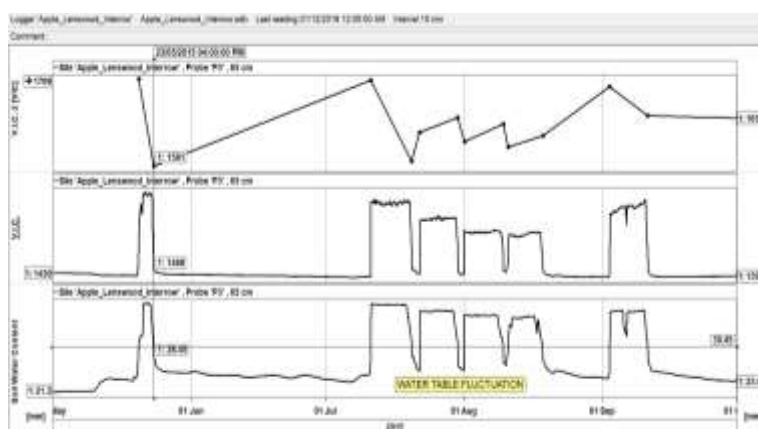


Figure 1: VIC Filter function of IrriMAX. Top pane is VIC at a fixed water content of 28.45mm.

Preliminary work using the VIC Filter function and the Sentek Salinity Calibration protocol (previously called Benchmarking) showed that the VIC calculation could be extended to heavier textures (Biswas et al., 2007). It was uncertain as to how far this could be extrapolated.

To produce regression relationships (Microsoft Excel and DataFit by Oakdale Engineering), Sentek VIC data from Bluetooth enabled Drill & Drop™ probes (30cm or 60cm versions) was compared to independently measured laboratory analyses (Eurofins APAL) of both soil Electrical Conductivity of the Saturated Extract (EC_e) and Particle Size Distribution (PSD, USDA thresholds) from a range of different soil textures treated with differing quantities of soluble THRIVE™ fertiliser (refer figures 2 & 3). The Sentek probe data was transferred to the web using telemetry to allow monitoring on-line with IrriMAX software.



Figure 2: Field setup of Benchmarking site showing 6 different salinity treatments. Data was collected using a Bluetooth Hub Unit via aerial connection to the web.

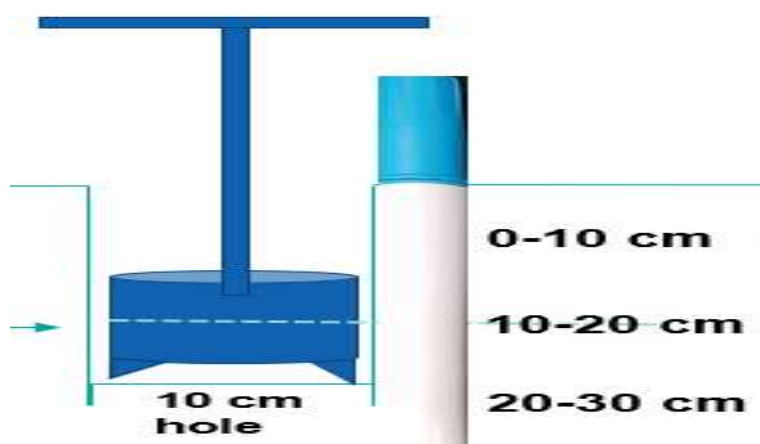


Figure 3: Sampling auger and Bluetooth probe.

Soils were also analysed for their chemical properties through professional laboratory testing (Eurofins APAL) of Cation Exchange Capacity (CEC), Sodium Adsorption Ratio (SAR) (Saidi, 2012) and Cation Ratio of Soil Structural Stability (CROSS) (Rengasamy and Marchuk, 2011). CEC uses measures of Ca^{2+} , Mg^{2+} , Na^{+} and K^{+} to calculate a value expressed in cmol of cations per kg. SAR uses measures of Na^{+} , Ca^{2+} and Mg^{2+} to arrive at a unitless index. The CROSS calculation is analogous to SAR but expresses a ratio between dispersive Na^{+} and K^{+} ions over differential flocculation of Ca^{2+} and Mg^{2+} . CROSS is a similarly unitless index used in Australia to diagnose common sodic soils. These Additional laboratory analyses were performed to gain further understanding of the soil chemistries of the different test sites. The aim here was to use these measures to inform the choice of calibration equation most appropriate for the different textures of soil. Overseas soils analyses were analysed separately due to variations in methodologies and quality control protocols.

RESULTS AND DISCUSSION

Soil Texture and Particle Size Distribution

The calculated regression analyses showed that it was not always possible to obtain significance in the null hypothesis with combined data over many different sites. It was sometimes necessary to separate the data sets into their respective sites and even into their separate textures within those sites (refer figures 4 – 13). This showed that there were other factors besides soil texture and Bulk Density impacting on the capacitance sensors. Some of this can be explained in terms of differences in soil chemistries. These Salinity Calibration equation details are summarised in Table 1.

Some significances in linear regression relationships were found using sandy and silty soil textures, but not in those containing appreciable amounts of clay. The highest r^2 values were found in the most sandy soil textures. Any relationships showing r^2 values of less than 0.600 and p values greater than 0.05 were rejected and are not shown here unless their negative result was deemed relevant to the discussion. Regression relationships using second order or higher polynomials, were deferred in favour of the simplest calculations possible.

Linear Regression Salinity Calibration Relationships

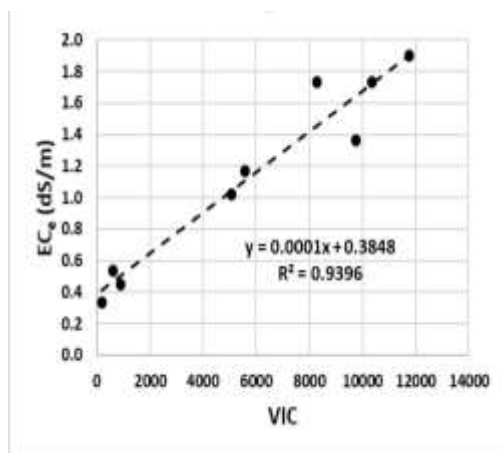


Figure 4: VIC vs EC_e in Sand (Forster, Barley, $p < .001$, SE 0.1567).

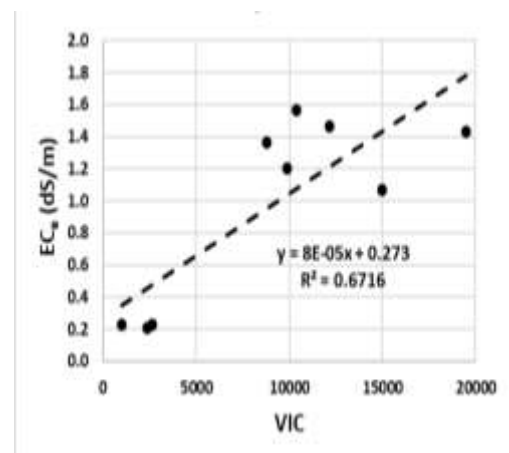


Figure 5: VIC vs EC_e in Sand (Forster Hill, $p = .007$, SE 0.3572).

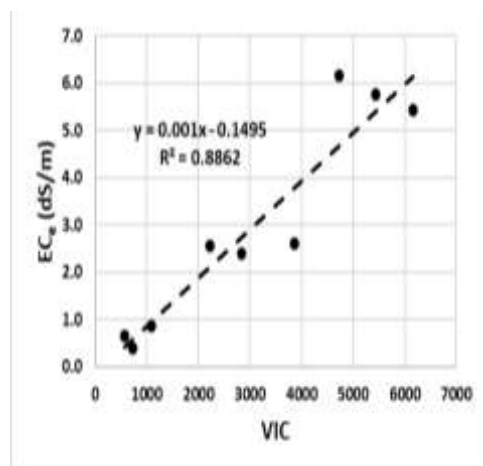


Figure 6: VIC vs EC_e in Sand (Walker Flat, Almond, $p < .001$, SE 0.8181).

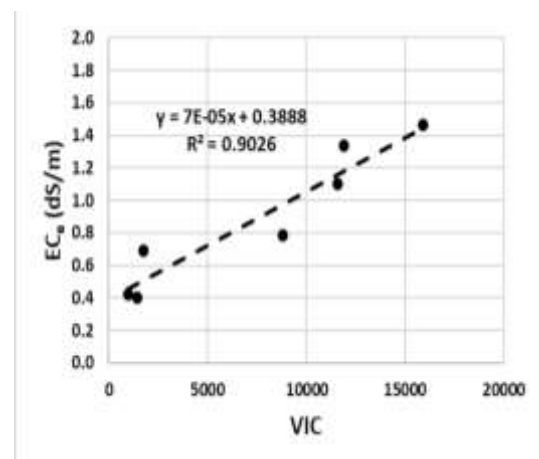


Figure 7: VIC vs EC_e in Sand (Walker Flat, Scrub, $p = .00104$, SE 0.1451).

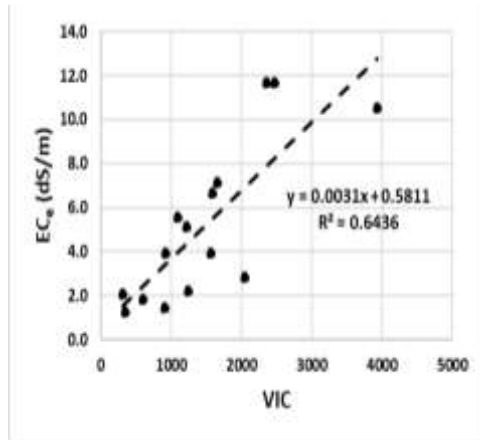


Figure 8: VIC vs EC_e in Sandy Loam to Loam (Langhorne Creek, $p < .001$, SE 2.2621).

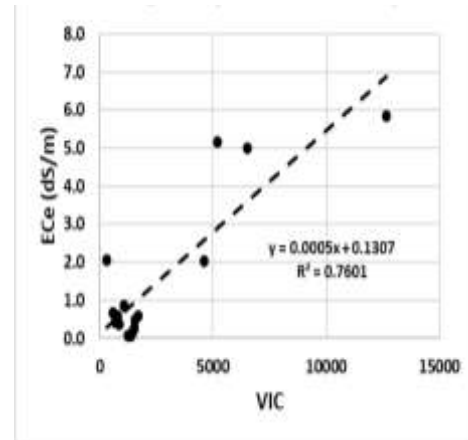


Figure 9: VIC vs EC_e in Loamy Sand (Australia & USA, $p < .001$, SE 0.9784).

Anything containing significant amounts of clay (>41%) or silt (>62%) required more complex calibration curves involving natural log or exponential functions (figures 10 – 13). Some clay containing sites produced limited ranges of salinity and VIC values during treatment with the salt solutions. This reflects the more complex buffering chemistries in clays and the greater surface areas available for chemical reactions and isomorphous substitution of ions.

Natural Log and Exponential Calibration Relationships

Some sites produced multiple forms of significant regression relationships, as in the case of Forster Hill, which showed that both linear and natural log functions could be derived (figures 5 & 10). On the other hand, a site containing high silt content produced a significant association in a natural log function (figure 11). Some sites containing clays produced significant associations in exponential regression relationships but these were the exception and were limited to soil layers near the surface (figures 12 & 13).

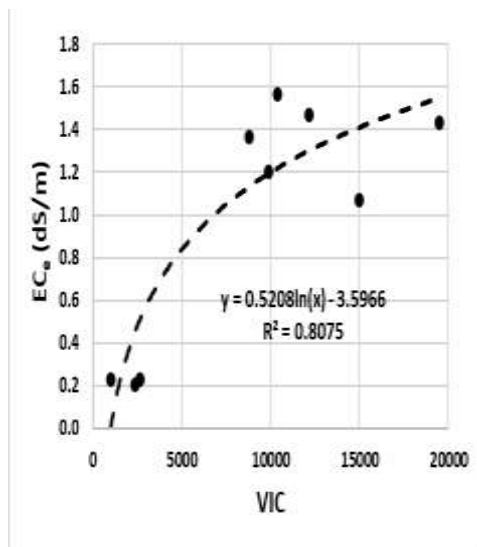


Figure 10: VIC vs EC_e in Sand (Forster Hill, $p < .001$, SE 0.2736).

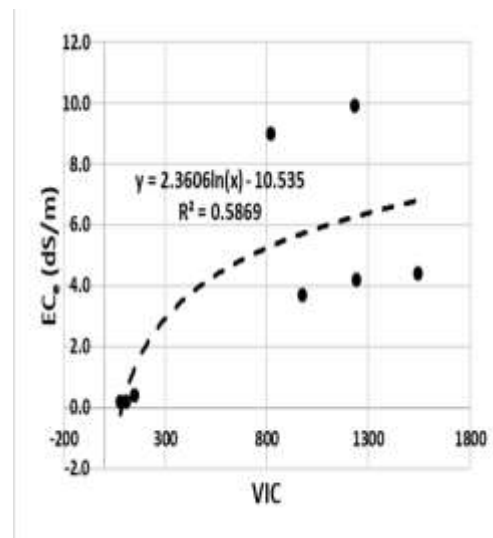


Figure 11: VIC vs EC_e in Silt Loam (New Zealand, $p = .0266$, SE 2.6489).

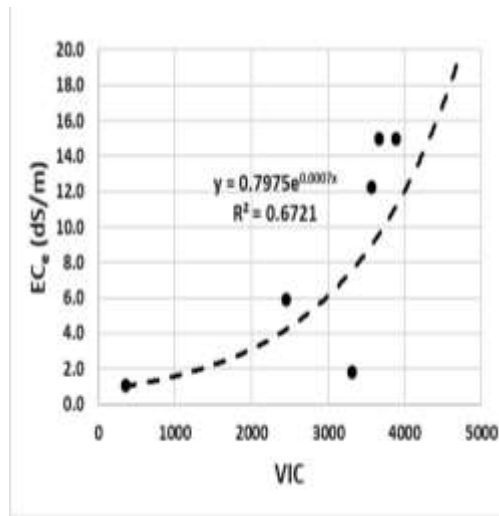


Figure 12: VIC vs EC_e in Silty Clay Loam (Aldinga, $p=0.0329$, SE 3.7995).

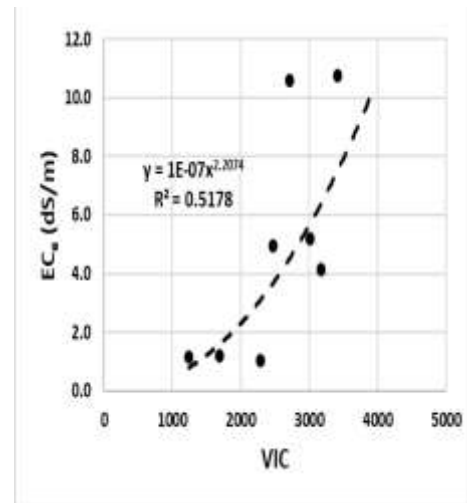


Figure 13: VIC vs EC_e in Clay to Clay Loam, 5-25cm depths (Ripabianca, Italy, $p=0.0444$, SE 2.9691).

Equation ID	a	b	r^2	P	SE	Sample Number (n)	Sand:Silt:Clay (USDA)	Country
Linear: $EC_e = a \times VIC + b$								
Sand (Forster Barley)	0.0001	0.3848	0.9396	<0.001	0.1567	9	94:3:3	Australia
Sand (Forster Hill, Linear)	0.00008	0.273	0.6716	0.007	0.3572	9	96:1:2	Australia
Sand (Walker Flat Almond)	0.001	0.1495	0.8862	<0.001	0.8181	9	91:4:5	Australia
Sand (Walker Flat Scrub)	0.00007	0.3888	0.9026	0.00104	0.1451	7	96:1:3	Australia
Sandy Loam to Loam (Langhorne Creek)	0.0031	0.5811	0.6436	<0.001	2.2621	15	57:31:12	Australia
Loamy Sand (Australia/USA)	0.0005	0.1307	0.7601	<0.001	0.9784	17	84:10:6	Australia & USA
Natural Log: $EC_e = a \times \ln(VIC) + b$								
Sand (Forster Hill, Log)	0.5208	-3.5966	0.8075	<0.001	0.2736	9	96:1:2	Australia
Silt Loam (Kirwee)	2.3606	-10.535	0.5869	0.0266	2.6489	8	13:64:23	New Zealand
Exponential: $EC_e = a \times e^{b \times VIC}$								
Silty Clay Loam (Aldinga)	0.7975	0.0007	0.6721	0.0329	3.7995	6	17:48:36	Australia
Power: $EC_e = a \times VIC^b$								
Clay to Clay Loam (Ripabianca)	1.00E-07	2.2074	0.5178	0.0444	2.9691	8	25:29:46	Italy

Table 1: Summary of Salinity Calibration VIC vs EC_e regression curves.

Figure 14 shows representative textures of soils for which significant associations between VIC and EC_e were found. The United States Department of Agriculture (USDA) particle size thresholds were used in these characterisations for consistency of comparison and current market need. Figure 15 shows the over-arching extent of VIC and EC_e possible with the treatments applied in a range of different soil textures. Firstly, it showed that applied salts moved freely through sands but were impeded in clay soils. The Sentek TriSCAN model detected the applied salts as a higher range of VIC in sand than in all other textures. This also means that the greatest VIC resolution is achieved in sandy soil textures.

The heavier soil textures hold on to their adsorbed salts while the sands conduct them suspended in their porewaters, making them easier to detect by the capacitance model. The calculated salinity calibration equations now become tools for converting Sentek VIC data to soil EC_e with the proviso that individual site chemistry variations may affect the outcome.



Figure 14: Soil Textures defined by Salinity Calibration equations (shaded).

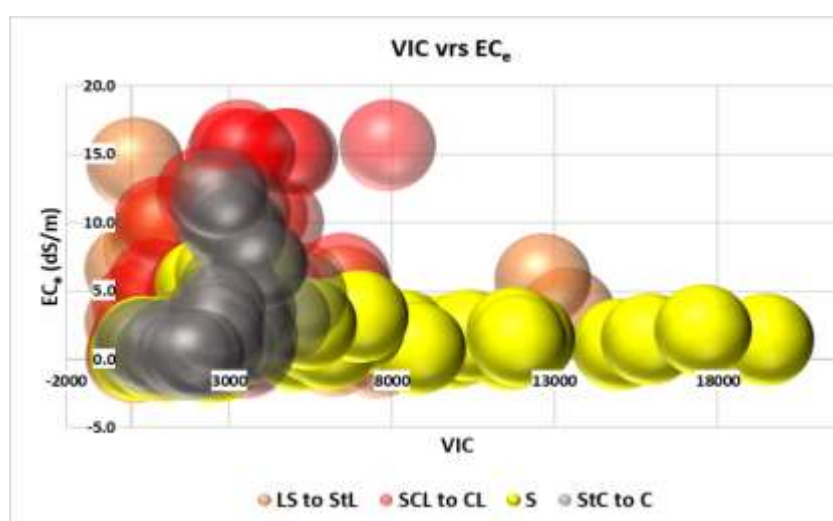


Figure 15: VIC range with various soil textures (S=Sand, L=Loam, St=Silt and C=Clay).

Soil Chemistry

It was found that much of the applied ionic fertiliser was washed through very quickly in sandy soil textures and was poorly retained, depending upon grain size. In heavier soil textures it could be seen that the fertiliser was slower to move through the soil profile, in part due to the increased chemical interaction. Some losses were also noted as runoff due to lower soil permeability.

It was often found necessary to analyse discrete soil textures separately when comparing relationships between VIC and CEC or SAR. These methods are notoriously confounded by variations in soil pH and the presence of contaminating ions during the laboratory dissolution and handling

procedures. CEC and SAR are also governed by the parent source of the clay minerals, predominantly the number of charged ions incorporated into the multilayered silicate sheets. Some of these inclusions form permanently charged areas on soil particles while some are exchangeable. Figure 16 shows a regression analysis of VIC vs CEC for a pooled group of soils with clay or silty clay loam textures in South Australia. An $r^2 = 0.6459$ and a $p = .002$ showed that changes in VIC were likely associated with changes in CEC.

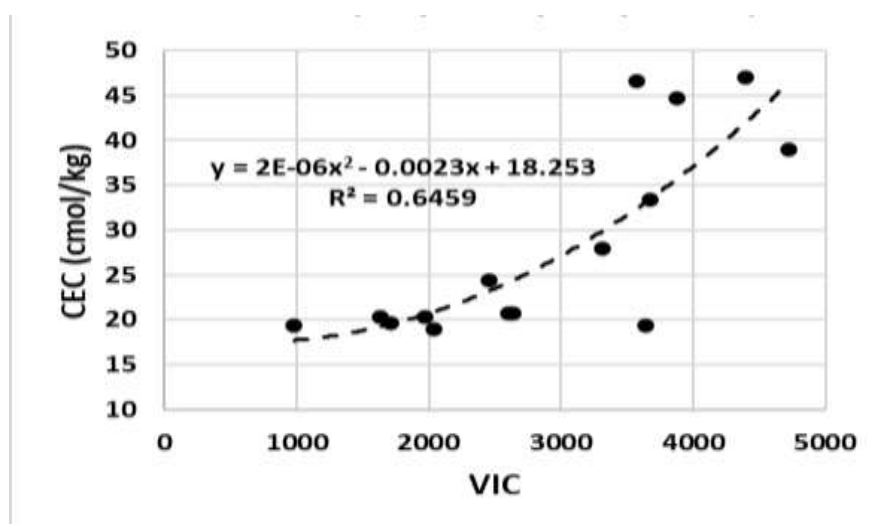


Figure 16: VIC vs Cation Exchange Capacity (CEC) of a Clay / Silty Clay Loam from Australia, $p = .002$, SE 7.042

The relationship between soil constituents and CEC in a combination of Australian soils from Langhorne Creek, Nuriootpa and Aldinga is shown in figures 17-19. These figures demonstrate the different chemistries, particularly between sand and both clay and silt. As the sand content increased, the CEC decreased (figure 17). By contrast, as the clay and silt contents increased, the CEC increased (figures 18 and 19). Although the regression relationships showed significant associations for the cases of clay and silt, the r -squareds were not high and the curves went in directions opposite to the trend found in sand. These results were fuelled by the high sample number ($n = 54$). Hence, these results add some credence to the recommendation that the VIC model be used with caution for anything other than sandy soil textures.

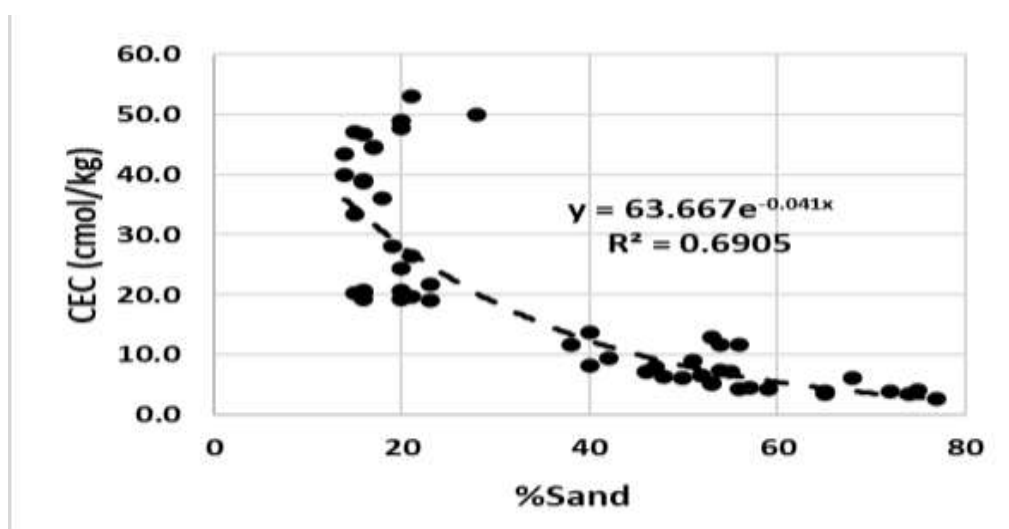


Figure 17: %Sand vs CEC for Australian soils, $p < .001$, SE 8.948.

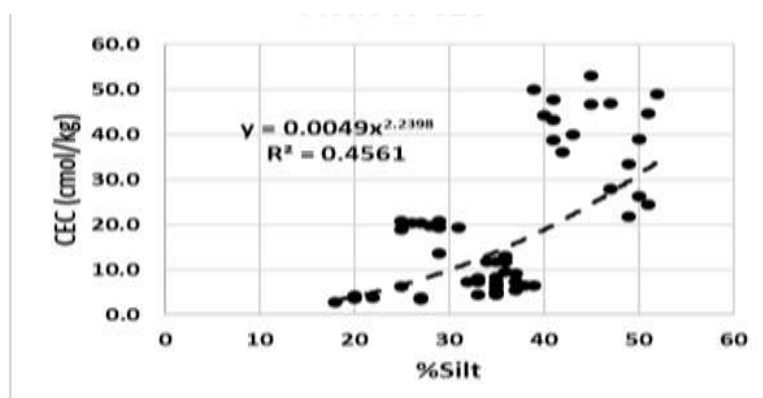


Figure 18: %Silt vs CEC for Australian soils, $p < .001$, SE 11.849.

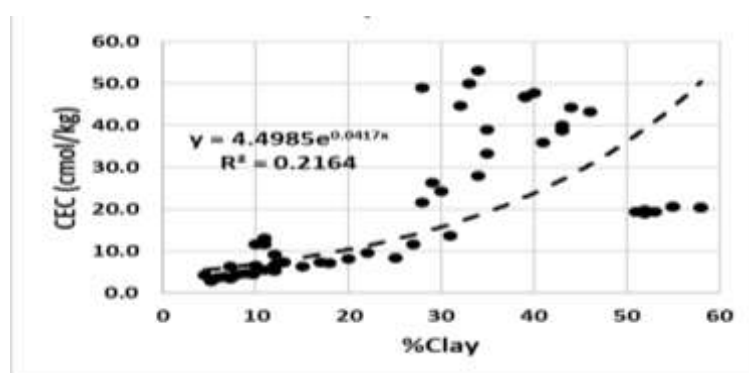


Figure 19: %Clay vs CEC for Australian soils, $p < .001$, SE 13.399.

By comparison, SAR showed only significant associations with soil texture particle size measures at highly complex relationships in the Australian samples (figures 20 (a, b and c)). Bell curves were noted with normal distributions around percentage values. Peak textural measures were observed at: 18%Sand; 42%Silt and 41%Clay. Hence, SAR was not seen as a reliable dependant variable across different soil textures. A similar outcome was seen in the CROSS analyses (not shown). These findings are to form the basis for further investigations.

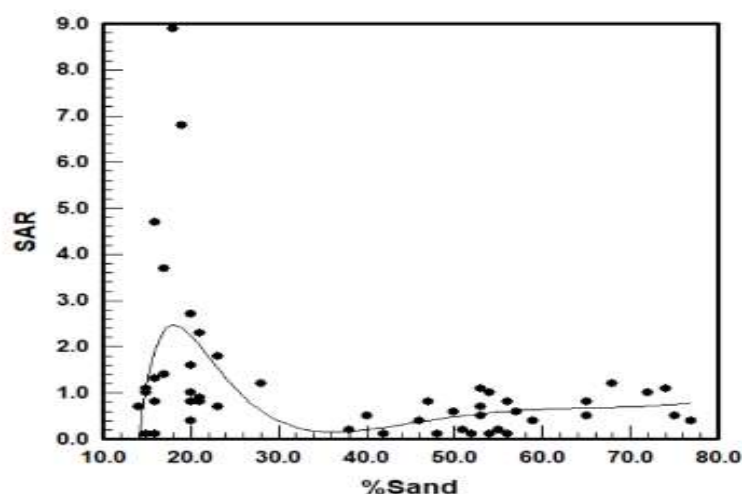


Figure 20 (a): %Sand vs SAR for Australian soils, fifth order logarithm, $r^2 = 0.2558$, $p = .0122$, SE 1.4487.

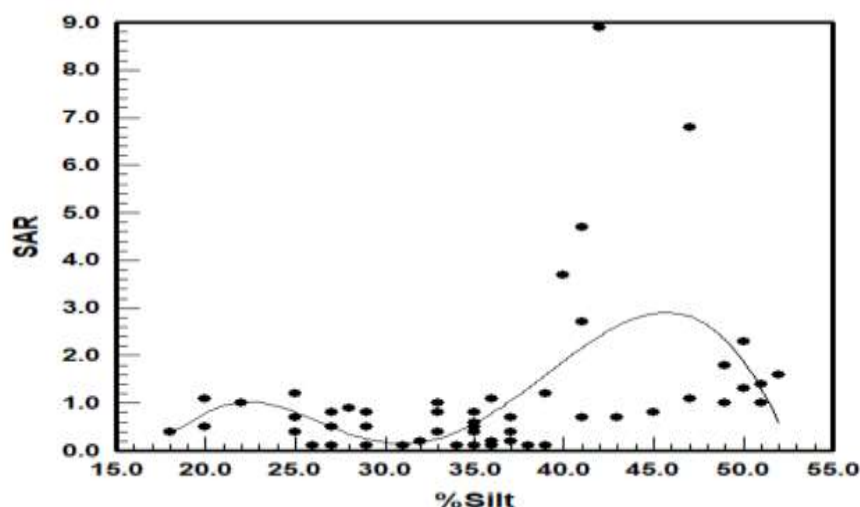


Figure 20 (b): %Silt vs SAR for Australian soils, fifth order logarithm, $r^2=0.2747$, $p=.0072$, SE 1.4302.

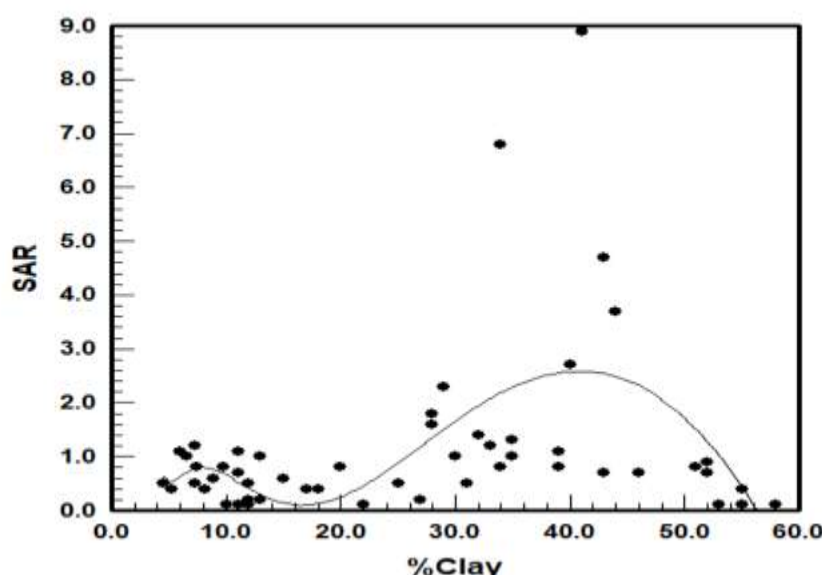


Figure 20 (c): %Clay vs SAR for Australian soils, fifth order logarithm, $r^2=0.301$, $p=.0033$, SE 1.404.

By contrast, figure 21 shows that by separating the Italian site data into Clay and Clay Loam, it was possible to see significance in the associations of VIC and SAR in both soil textures. The SAR decreased with increasing VIC, indicating that the increasing VIC was not related to sodium, but to other ions. These ions were from the fertiliser treatments applied. By adding more fertiliser to the treatment sites, we may have bound more non-sodium cations to the soil particles. They then compete with the sodium added during the laboratory testing and return a reduction in SAR. The soils were not shown to be sodic.

Figure 22 shows a regression analysis of VIC vs CEC for a silt loam at Kirwee, New Zealand. The relationship indicates a negative trend between VIC and CEC ($r^2= 0.6014$ and $p=0.0141$). VIC vs SAR did not show significant associations for the two represented soil textures (not shown). The pH range of this soil was from 4.5 to 6.2. Regression analyses of both CEC and SAR with pH also did not show any significance in associations (not shown).

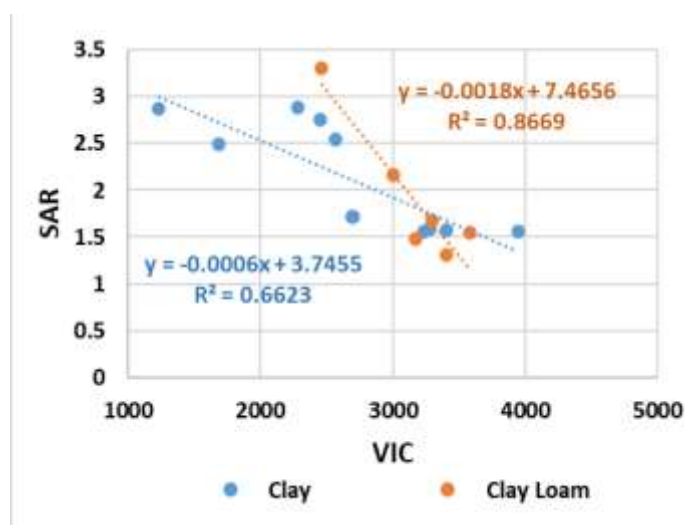


Figure 21: VIC vs Sodium Adsorption Ratio (SAR) of a Clay and Clay Loam at Ripabianca, Italy, Clay: $p=.0023$, SE 0.3578, Clay Loam: $p=.007$, SE 0.3017.

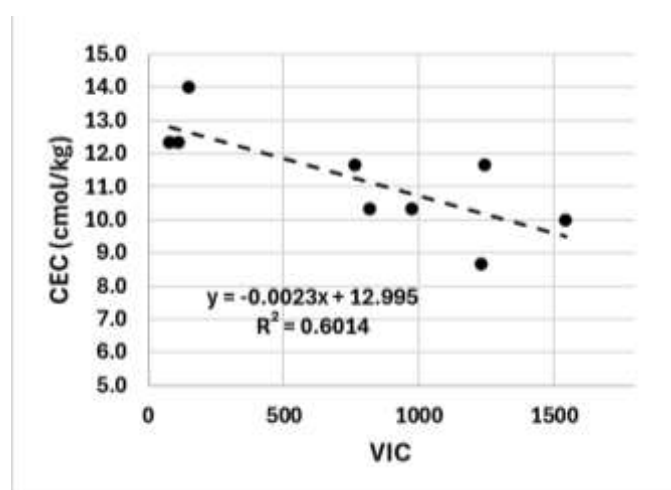


Figure 22: VIC vs Cation Exchange Capacity (CEC) of a Silt Loam at Kirwee, New Zealand, $p=0.0141$, SE 1.0718.

CONCLUSIONS

The application of the Sentek TriSCAN calculation model has been extended for use in many different soil textures. A total of ten (10) VIC to EC_e calibration equations were found. Simple linear regressions were sufficient for many sandy soil textures, but textures containing clay or silt were found to require more complex natural log or exponential functions. The VIC vs EC_e regression r^2 values lessened with increasing clay content. The CEC of sands was found to be associated positively with VIC in sandy soil textures. In heavier textured soils the CEC may vary positively or negatively with VIC. This property was found to be site-specific.

Overall, neither SAR nor CROSS were found to be useful measures in characterising VIC trends in saline soils. In heavier textured soils only the SAR decreased with increasing VIC, indicating that the increasing VIC was not related to sodium or sodicity. The chemistries of heavier textured soils are complex and impact on the calculated VIC value in different ways. The current TriSCAN model may therefore require some additional calculation adjustments for use in these soils unless the VIC Filter trending only function of IrriMAX is employed.

ACKNOWLEDGEMENTS

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