Multi-dimensional digital soil mapping: Past, present and future research

John Triantafilis

Talk Outline

What is digital soil mapping DSM?

Digital Soil Mapping
EM Instruments

EM4Soil

Results, Discussion & Conclusions

terraGIS
Digital soil mapping (wikipedia)

What is DSM?

in soil science, or "predictive soil mapping", is the computer-assisted production of digital maps of soil properties and soil type.

0 through 9  1961
Jasper Johns
Oil on canvas painting
Presented by the Friends of the Tate Gallery 1961
What is DSM?

DSM involves the creation and population of spatial soil information by the use of field and laboratory observational methods coupled with Pedometric methods such as spatial and non-spatial soil inference systems.
It applies Pedometrics, which is the use of mathematical and statistical models that combine information from soil observations with information contained in correlated ancillary data proximal instruments and remote sensed images.

What is DSM?

Das Rudel (the pack)

Joseph Beuys

Volkswagen bus with twenty four wooden sleds, each with felt, belts, flashlight, fat and stamped with Braunkreuz (brown paint)

Tate Modern, UK
Semi-automated techniques and technologies are used to acquire, process and visualize information on soil and auxiliary information, so that the end result is obtained at cheaper cost.
Electromagnetic (EM) induction

What is electromagnetics (EM)?
Techniques where induction coils are used to measure magnetic fields associated with current flow in the earth

What is physical property of interest?
Property of interest is CONDUCTIVITY (i.e. apparent electrical conductivity-EC_a)

What units are it measured in?
EC_a - millisiemens/metre (mS/m)
Maxwell’s equations

Why they are important for EM induction
Maxwell's equations describe how electric and magnetic fields are generated by
i) charges,
ii) currents, and
iii) changes of each other.
Electromagnetic (EM) induction

What are components of an instrument?
EM instruments contain two sets of coils located at opposite sides of instrument

Transmitter coil (Tx):
- Driven by AC current
- At audio frequencies
- To generate a sinusoidal time-varying magnetic field

Receiver coil (Rx):
- Positioned on or near surface of the earth some distance away from the transmitter coil
Electromagnetic (EM) induction

How does an EM instrument work?
An alternating current (AC) is introduced into Transmitter coil (Tx)
Electromagnetic (EM) induction

How does an EM instrument work?

AC induces
primary magnetic field
Into/out of soil
Electromagnetic (EM) induction

How does an EM instrument work?
As primary magnetic field passes into/out of soil, eddy currents generated in soil
What conducts a current in soil?

Clay type

Clay content

1:1 Kaolin

2:1 Smectite

Water content

Salt content
Electromagnetic (EM) induction

How does an EM instrument work?
Induces secondary magnetic field into Receiver coil (Rx)
Soil properties that influence EC

- Clay content
- Mineralogy (CEC)
- Water content
- Salt concentration
- Temperature
- Bulk density

Calibration
Applying a mobile electromagnetic sensing system (MESS) to assess cause and management of soil salinization

Triantafilis, J., Huckel, A.I., Ahmed, M.F., Odeh, I.O.A.
DSM of compositional particle-size fractions (PSFs) using proximal and remotely sensed ancillary data

Buchanan S.M., Triantafilis, J., Odeh, I.O.A.

Clay floodplain

Aeolian sand

Clay content

Prior stream

Aeolian sand

Clay floodplain

DSM of a soil property (clay)
Field level DSM of cation exchange capacity using EM and a spatial regression model


Dermosols

Vertosols?
DSM available water content using proximal and remotely sensed data

Gooley, L., Huang, J., Page, D., Triantafilis, J.

Soil Use and Management 30, 139-151
An error budget for mapping field-scale soil salinity at various depths using different sources of ancillary data

Huang, J., Barrett-Lennard, E., Kilminster, T., Sinott, A., Triantafilis, J.
terraGIS: web-based platform for delivery of DSM for cotton growing areas of Australia

Huang, J., Buchanan, S.M.
Bishop, TFA, Triantafilis, J.

In press
EM instruments

Application
Root zone
Sub-soil

Depth (m)
0
0.75
1.5

Proximal
EM38
EM38h
EM38v

DSM
clay content,
CEC,
water content and
salinity

Operating Frequency:
14kHz

http://www.geonics.com/
What you can measure…

…with a EM38
EM instruments

Application

- Root zone
- Sub-soil

Depth (m)

- Proximal
  - EM38MK-2
  - EM38h
  - EM38v

- Operating Frequency: 14.5kHz

http://www.geonics.com/
What you can measure…

…with a EM38MK-2
Measurement

Application: Vadose zone, Shallow groundwater tables

Depth (m):
- h: 0
- v: 3
- 6

Proximal:
- Geonics EM31
- EM31h
- EM31v

Operating Frequency: 10kHz
What you can measure…

…with a EM31
EM instruments

Application

Depth (m)

0
7
15
30

Proximal

Geonics EM34

Vadose zone

Shallow groundwater tables

Operating Frequency: 6.4, 1.6 and 0.4 kHz
DUALEM-421

LAMBERT, George, ‘Across the black soil plains’, 1899, Oil on canvas

TRIANTAFILIS, John, ‘Across the clay alluvial plains’, 2009, GEOS3721 Field Trip

http://www.dualem.com/
Operating Frequency: 9.0 kHz

**Theoretical depth of $\sigma_a$ measurement**

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>DUALEM-1</th>
<th>DUALEM-2</th>
<th>DUALEM-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx-1 (0 m)</td>
<td>Rx-1 (1 m)</td>
<td>Rx-2 (2 m)</td>
<td>Rx-3 (4 m)</td>
</tr>
</tbody>
</table>

- **Geonics EM38**
  - 1mHc (0-1.5 m)
  - 0-0.5 m
  - 0-1.5 m

- **Geonics EM31**
  - 2mHc (0-3.0 m)
  - 0-1.0 m
  - 0-3.0 m
  - 0-6.0 m
DUALEM-421

State-of-the-art

http://www.dualem.com/
What you can measure…

…with a DUALEM-421
UNSW-CSSRI collaboration
What you can measure…

…with a DUALEM-421
Commerically available instruments
Seeing is believing: DSM using ancillary data and numerical clustering to identify management zones

Jingyi Huang, Rod Nielson, Michael Sefton, John Triantafilis
Introduction

Australian Sugarcane

Australian sugarcane is grown in alluvial-estuarine areas of NE Queensland, characterised by
i) sodic and/or
ii) infertile sandy soil

From a production perspective there is a need therefore to
i) ameliorate (ie. gypsum) and
ii) fertilise (ie. lime) the soil.

Best-practice amelioration and fertiliser requires knowledge of soil variation to maximise yield and minimise losses
Nutrient Management

BUT this will also require information about
i) soil physical (eg. clay) and
ii) chemical (eg. ESP, Exch. Ca/Mg)
because they determine ameliorant and nutrient availability.
Problem definition

Moreover, samples are required
i) across the field and
ii) at multiple depths
to ascertain what constrains yield and/or productivity

**Nutrient Management**
So how can a farmer manage variation of so many properties when sampling and analysis is expensive ($180/sample)?
Can we use digital soil mapping (DSM)…

1. To value add to limited soil data

2. Using easier to acquire ancillary data

3. And non-spatial inference models

…to make soil management zones
Using easier to acquire ancillary data

Gamma-ray spectrometry: Rx700
Measures $\gamma$-rays in top 0-0.30 m

Electromagnetic induction: DUALEM-421
Measures EC$_a$ at various depths

Table 1. IAEA recommended windows for conventional 3-channel airborne gamma-ray spectrometry (IAEA 1991).

<table>
<thead>
<tr>
<th>Element analysed</th>
<th>Isotope used</th>
<th>Gamma ray energy MeV</th>
<th>Energy window MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium</td>
<td>$^{40}$K</td>
<td>1.46</td>
<td>1.370–1.570</td>
</tr>
<tr>
<td>Uranium</td>
<td>$^{214}$Bi</td>
<td>1.76</td>
<td>1.660–1.860</td>
</tr>
<tr>
<td>Thorium</td>
<td>$^{208}$Tl</td>
<td>2.61</td>
<td>2.410–2.810</td>
</tr>
</tbody>
</table>
In a sugarcane field in Herbert Valley:

a) Can we use easier to acquire ancillary data such as proximal sensing
   i) $\gamma$-ray (RS-700) and
   ii) EM - DUALEM-421 data to identify soil management zones;

b) Do these DSM derived Soil management zones relate to differences in topsoil (0-0.3 m) and subsoil (0.6-0.9 m) properties;
   i) Clay, CEC, ESP, pH
   ii) Exch, Ca, Mg, Na and K
   iii) or yield percent variation.
Easier to acquire ancillary data

$\gamma$-ray (RS-700)

- High - K
- Int. - K
- Low - K
- Int. - Th
- Low - Th
- Int. - U
- Low - U
- High - Th
- High - TC
- High - U
Easier to acquire ancillary data

**DUALEM-421**
- 1mPcon
- 1mHcon
- 2mPcon
- 2mHcon

Int. - ECa

High - ECa

Low - ECa
Easier to acquire ancillary data

Yield percent variation

- 2014
- 2015
- 2016
Objective management zones

How many classes \((k)\)/management zones?

- \(k = 2\)
- \(k = 3\)
- \(k = 4\)
- \(k = 5\)
The best number of zones

How many classes ($k$)/management zones?

$$y = X\tau + Zu + \varepsilon$$

When $k = 3$,
Topsoil (0-0.3m)
- clay, sand,
- CEC,
- ESP,
- Exch. Ca, Mg
are all minimised

Subsoil (0.6-0.9m)
- clay,
- ESP,
- exch. Ca, Na,
are all minimised

<table>
<thead>
<tr>
<th>Topsoil</th>
<th>$k = 2$</th>
<th>$k = 3$</th>
<th>$k = 4$</th>
<th>$k = 5$</th>
<th>$k = 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of zones</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>8.3</td>
<td>7.73</td>
<td>8.13</td>
<td>8.09</td>
<td>7.88</td>
</tr>
<tr>
<td>Silt</td>
<td>704 242.6</td>
<td>108 761.1</td>
<td>301</td>
<td>132.1</td>
<td>125.14</td>
</tr>
<tr>
<td>Sand</td>
<td>–</td>
<td>64.15</td>
<td>677 129</td>
<td>152.96</td>
<td>132.98</td>
</tr>
<tr>
<td>CEC</td>
<td>1.9</td>
<td>0.69</td>
<td>0.75</td>
<td>2.12</td>
<td>0.8</td>
</tr>
<tr>
<td>ESP</td>
<td>26.97</td>
<td>26.67</td>
<td>27.31</td>
<td>43.67</td>
<td>38.6</td>
</tr>
<tr>
<td>pH</td>
<td>0.452</td>
<td>0.255</td>
<td><strong>0.202</strong></td>
<td>0.266</td>
<td>0.322</td>
</tr>
<tr>
<td>Exch. Ca</td>
<td>0.51</td>
<td>0.27</td>
<td>0.29</td>
<td>0.43</td>
<td>0.31</td>
</tr>
<tr>
<td>Exch. Mg</td>
<td>0.151</td>
<td>0.115</td>
<td>0.122</td>
<td>0.128</td>
<td>0.144</td>
</tr>
<tr>
<td>Exch. Na</td>
<td>0.016</td>
<td>0.014</td>
<td><strong>0.012</strong></td>
<td>0.016</td>
<td>0.015</td>
</tr>
<tr>
<td>Exch. K</td>
<td>0.099</td>
<td>0.111</td>
<td>0.074</td>
<td>0.129</td>
<td>0.126</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subsoil</th>
<th>$k = 2$</th>
<th>$k = 3$</th>
<th>$k = 4$</th>
<th>$k = 5$</th>
<th>$k = 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of zones</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>259.23</td>
<td>196.8</td>
<td>264.27</td>
<td>274.43</td>
<td>274.22</td>
</tr>
<tr>
<td>Silt</td>
<td>–</td>
<td>365 829.8</td>
<td>1100 022</td>
<td><strong>112.11</strong></td>
<td>118.13</td>
</tr>
<tr>
<td>Sand</td>
<td>430.78</td>
<td>452.43</td>
<td>634.02</td>
<td><strong>381.09</strong></td>
<td>392.84</td>
</tr>
<tr>
<td>CEC</td>
<td>137 489.8</td>
<td>60 254.34</td>
<td>93 325.61</td>
<td><strong>16 160.12</strong></td>
<td>47 366.91</td>
</tr>
<tr>
<td>ESP</td>
<td>165.13</td>
<td>155.19</td>
<td>167.52</td>
<td>189.2</td>
<td>179.16</td>
</tr>
<tr>
<td>pH</td>
<td>5.423</td>
<td>2.927</td>
<td>11528.94</td>
<td>1.564</td>
<td><strong>0.914</strong></td>
</tr>
<tr>
<td>Exch. Ca</td>
<td>7.76</td>
<td>1.65</td>
<td>1.86</td>
<td>2.36</td>
<td>2.36</td>
</tr>
<tr>
<td>Exch. Mg</td>
<td>10 612.55</td>
<td>20 075.53</td>
<td>8 281.63</td>
<td><strong>2.37</strong></td>
<td>11 083.97</td>
</tr>
<tr>
<td>Exch. Na</td>
<td>2.13</td>
<td>0.97</td>
<td>20 479.47</td>
<td>2.21</td>
<td>1.23</td>
</tr>
<tr>
<td>Exch. K</td>
<td><strong>0.045</strong></td>
<td>0.047</td>
<td>0.046</td>
<td>0.047</td>
<td>0.047</td>
</tr>
</tbody>
</table>
Just add gypsum

Topsoil (0-0.3m) properties

Clay (%)
CEC (cmol(+/kg))
ESP (%)
pH

Gypsum (6 easy steps)

2 t/ha
4 t/ha

4 t/ha
Can we upscale to a farm scale?

Research Question
Gamma-ray and EM data coupled with clustering produce soil management zones related to differences in soil properties important for amelioration and fertilisation.

Implications including;
(i) more efficient application of gypsum to ameliorate topsoil sodicity,
(ii) more efficient application of lime to improve topsoil infertility, and
(iii) potential to define zones which can be used to develop strip trials of;
   a) varieties, and
   b) gypsum and fertiliser requirement
DSM of soil landscape units at the district scale

Zare, E., Huang, J., Triantafilis, J.,

clay floodplains

Aeolian sand

DSM of a soil type (40,000ha)
Develop a visNIR spectral library

To predict

i) soil physical
   (eg. Clay and sand) and
ii) chemical
   (eg. CEC, ESP, Exch. Ca/Mg
   pH
   Organic Carbon)

because they determine
ameliorant and
nutrient availability.
Research Questions and partners
Can we
- upscale farm scale zoning
- improve water use efficiency
- develop industry spectral index

Partner cash (/annum)
Herbert Cane Productivity Services Ltd
  – Salary of Michael Sefton ($100k)
DAVCO Farming Pty Ltd
  – Usual consulting/surveys ($50k)
Mirawhinney Lime/Gypsum
  – Fertiliser ($50k)
Backpaddock (Soil analysis)
  – Fertiliser recommendation ($50k)
Now you see it…now you don’t: Time-lapse imaging of soil moisture

Huang J, Scudiero E, Choo H, Clary W, Corwin D, Triantafilis J
Problem definition

A constant need to measure/monitor?

Soil water content ($w$) is required for crop yield optimization and water use efficiency improvement.

Unfortunately, *thermogravimetric* ($w$) method is too labour intensive, time-consuming, and expensive ($\rho$ needs measuring) to be practical at the field scale.

To improve efficiency, instruments have been developed to measure temporal variation of $\theta$ at point locations:

- TDR
- Capacitance probes
- Neutron probe
What would be ideal?

If you could afford the time and money?
Can we map $\theta$ using EM?

Many have shown potential, for example

Stanley et al., Soil Research, 2014, 52, 373–378

Operating Frequency: 9.0 kHz

<table>
<thead>
<tr>
<th>Transmitter Tx-1 (0 m)</th>
<th>DUALEM-1 Rx-1 (1 m)</th>
<th>DUALEM-2 Rx-2 (2 m)</th>
<th>DUALEM-4 Rx-3 (4 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geonics EM38</td>
<td>0-0.5 m</td>
<td>0-1.0 m</td>
<td>0-2.0 m</td>
</tr>
<tr>
<td></td>
<td>0-1.5 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0-3.0 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0-6.0 m</td>
<td></td>
</tr>
</tbody>
</table>

Theoretical depth of $EC_a$ measurement
What you can measure…

…with a DUALEM-421
Inverted $EC_a(\sigma)$

Electromagnetic conductivity image
Materials and methods

Research Question
Can we use a single frequency and multiple array

DUALEM-421

1-dimensional inversion software

EM4Soil

To generate EMCI to represent time-lapse soil moisture status
Field is 32 ha and farmed with irrigated alfalfa (*Medicago sativa* L.), used for consumption on-farm in a dairy feed lot.

Average properties of dairy lagoon water from March 2008 to June 2009 were:

- pH water is slightly alkaline (pH = 7.8)
- slightly saline $EC_{iw}$ (1.63 dS/m) and $SAR_w$ (4.3), water infiltration problems unlikely

Centre pivot irrigation:

- Sprinklers (~ 2 m)
- Wheel tracks (~48 m)
Measurements

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(28 August, 2014)</td>
</tr>
<tr>
<td>2</td>
<td>(29 August)</td>
</tr>
<tr>
<td>3</td>
<td>(30 August)</td>
</tr>
<tr>
<td>4</td>
<td>(31 August)</td>
</tr>
<tr>
<td>6</td>
<td>(2 September)</td>
</tr>
<tr>
<td>8</td>
<td>(4 September)</td>
</tr>
<tr>
<td>12</td>
<td>(8 September)</td>
</tr>
</tbody>
</table>
# Measurements

<table>
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<tr>
<th>Day</th>
<th>Date</th>
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<tbody>
<tr>
<td>1</td>
<td>(28 August, 2014)</td>
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<tr>
<td>2</td>
<td>(29 August)</td>
</tr>
<tr>
<td>3</td>
<td>(30 August)</td>
</tr>
<tr>
<td>4</td>
<td>(31 August)</td>
</tr>
<tr>
<td>6</td>
<td>(2 September)</td>
</tr>
<tr>
<td>8</td>
<td>(4 September)</td>
</tr>
<tr>
<td>12</td>
<td>(8 September)</td>
</tr>
</tbody>
</table>
Laboratory analysis

Particle size analysis (Soil texture)
- Clay
- Silt
- Sand
- Gravel

$EC_e \text{ -- dS/m}$

$\rho \text{ -- g/cm}^3$

$\theta \text{ -- cm}^3/cm^3$
Results

Particle size analysis

Clay

Silt

Gravel

Sand

θ – cm³/cm³
Results

DUALEM421 EC<sub>a</sub> measurements (only day 1)

- **DUALEM-1**
  - Root zone: 0.5
  - Profile: 1.5
  - Subsoil: 2.0

- **DUALEM-2**
  - Vadose Zone

- **DUALEM-4**
  - Vadose Zone
  - Hcon: 3.0
  - Pcon: 6.0

![Graph showing EC<sub>a</sub> measurements](image.png)
Results

DUALEM421 $EC_a$ (1mHcon – all days)
Estimated $\sigma$ versus $\theta$
Calibration / Validation

\[ \sigma \,(\text{mS/m}) \text{ versus } \theta \,(\text{cm}^3/\text{cm}^3) \]

![Diagram showing calibration and validation plots for electrical conductivity (\(\sigma\)) versus water content (\(\theta\)).](image)
Predicted

θ verse soil texture

Day 1

Loam
Saturated soil (?)
Sandy Loam
Wetting front (?)
Loamy sand
Deep drainage (?)

Depth (m)

Day 1
θ (cm³/cm³)

0.0
-0.3
-0.6
-0.9
-1.2
-1.5

Eastings (m)

499270 499320 499370 499420 499470 499520 499570
Predicted

Depth (m)

Day 12

\( \theta \) (cm\(^3\)/cm\(^3\))

- Day 12
- Eastings (m)

- Site 1
- Site 2
- Site 3
- Site 4
- Site 5

Tire tracks

Day 12
Available water content (~)

Day 1 - Day 12

Depth (m)

$\Delta \theta$ (cm$^3$/cm$^3$)

- $\leq 0.03$
- $\leq 0.05$
- $\leq 0.07$
- $\leq 0.09$
- $> 0.09$

Eastings (m)
Conclusion

Research Question

**YES WE CAN** use a single frequency and multiple array

**DUALEM-421**

+ 1-dimensional inversion software

**EM4Soil**

To generate EMCI to represent time-lapse soil moisture status
Research Question
EMCI is capable of predicting field-scale $\theta$ at any depth and on different days with one predictive model and with sufficient resolution and efficiency.

Implications including;
(i) improved timing of irrigations at planting and germination,
(ii) evaluation of uniformity of irrigation across a field, and
(iii) sufficient control of site-specific irrigation to optimize water use efficiency and match the leaching requirement throughout a field.
Now you see it…now you don’t: Time-lapse imaging of soil moisture

Huang J, Scudiero E, Clary W, Corwin D, Triantafilis J

DSM in 2-d with time-lapse (θ)
Mapping soil moisture across an irrigated field using electromagnetic conductivity imaging

Huang J, Scudiero E, Choo H, Corwin DL, Triantafilis J

Agricultural Water Management 163, 285-294
Temperature-dependent hysteresis effects on EM induction instruments

Jingyi Huang, Budiman Minasny, Brett Whelan, Alex B. McBratney, John Triantafilis
Monitoring soil water dynamics using electromagnetic conductivity imaging and the ensemble Kalman Filter

Jingyi Huang, Alex B. McBratney, Budiman Minasny, John Triantafilis

DSM in 2-d with time-lapse (θ)
3D soil water nowcasting using electromagnetic conductivity imaging and the ensemble Kalman filter

Jingyi Huang, Alex B. McBratney, Budiman Minasny, John Triantafilis

DSM in 3-d with time-lapse (θ)
Digital soil mapping of available water content using proximal and remotely sensed data.

Huang, J, Davies, G.B., Bowd, D., Monteiro Santos, F.A., Triantafyllis, J.

DSM in 2d (ESP)
An inversion approach to generate electromagnetic conductivity images from signal data

Triantafilis, J.
Monteiro Santos, F.A.,

clay floodplain
prior stream
palaeochannel

Env. Mod. Software 43: 88-95
Quasi-3D modelling of dryland and irrigation salinity using a DUALEM data and EM4Soil inversion modelling

Huang J, Kiliminster T, Zare E
Barrett-Lennard E, Monteiro Santos FA, Triantafilis J

Problem Definition?

Materials and Methods

EM4Soil

Results, Discussion & Conclusions
Problem definition (dryland salinity)

Significance of soil salinisation

In the wheat-sheep belt of WA a substantial area of land is affected by dryland salinity, due to saline shallow watertables. This is because perennial native vegetation that used most rainfall, replaced with annual crops/pastures, that use less.

To understand limitation and determine best management, concentrations of salt needs determination with variation mapped.
Problem definition (dryland salinity)

This is because it is insidious

Meredin WA: dryland salinity
Problem definition (irrigation salinity)

Significance of soil salinisation
In many part of the highly productive Murray-Darling Basin irrigation salinity, due to saline shallow watertables.

This is because irrigation inefficiencies have resulted in mobilisation of stored Aeolian, cyclical and connate salts.

To understand limitation and determine best management, concentrations of salt needs determination with variation mapped.
Problem definition (irrigation salinity)

This is because it is insidious
Problem definition

This is because it is insidious

Meredin WA:
- dryland salinity

Bourke NSW
- irrigation salinity
Use of EM instruments and LR

Proximal EM instruments are being used because they enable efficient mapping without extensive soil sampling.

One approach is to make LR between $EC_a$ and average $EC_e$ (e.g. 0-1.0 m) (e.g. Amezketa and del Valle de Lersundi, 2008).

Another is to use $EC_a$ to make relationships with $EC_e$ at various depths of interest. For example (Yao and Yang, 2010).
Materials and methods

Research Question
Can we use a single frequency and multiple array

DUALEM-1 DUALEM-421

+ 1-dimensional inversion software

To generate quasi-3d EMCI to represent dryland and irrigation salinity status

Meredin WA

Bourke NSW

EM4Soil
Operating Frequency: 9.0 kHz

Theoretical depth of $\sigma_a$ measurement
Average properties of dairy lagoon water from March 2008 to June 2009 were:

- pH water is slightly alkaline (pH = 7.8)
- Slightly saline ECw (1.63 dS/m) and SARw (4.3), water infiltration unlikely

DUALEM-1 Survey

Area: 36 ha.
Sites: 10,000
Spacing: 20 m

Materials & methods (dryland salinity)
Materials & methods (dryland salinity)

Soil sampling
Sites: 15 (7th percentile)
Depths: 0.00-0.25 m, 0.25-0.50 m, 0.50-0.75 m, & 0.75-1.00 m
Materials & methods (irrigation salinity)

DUALEM-421 Survey

Area: 30 ha
Sites: 5,000
Spacing: 50 m
Materials & methods (irrigation salinity)

Soil sampling

Sites: 20 (5th percentile)
Depths: 0-0.3, 0.3-0.6 m, 0.6-0.9 m, and 0.9-1.2 m
Materials & methods

Laboratory analysis

$\text{EC}_e$ – dS/m
Results & Discussion (dryland salinity)
Results & Discussion (irrigation salinity)

DUALEM-421 Survey

Transmitter

<table>
<thead>
<tr>
<th>Tx-1</th>
<th>DUALEM-1 Rx-1</th>
<th>DUALEM-2 Rx-2</th>
<th>DUALEM-4 Rx-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0 m)</td>
<td>(1 m)</td>
<td>(2 m)</td>
<td>(4 m)</td>
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</tbody>
</table>

1mHcon

1mPcon

2mPcon

4mPcon

Northings (m)

Eg (mS m⁻¹)

≤ 250

≤ 500

≤ 750

≤ 1000

> 1000

Eg (mS m⁻¹)

≤ 250

≤ 500

≤ 750

≤ 1000

> 1000

1mHcon

1mPcon

2mHcon

2mPcon

4mHcon

4mPcon

(0-0.8 m)

(0-1.2 m)

(0-3.0 m)

(0-6.0 m)
EM4Soil

Quasi-2d and 3d inversion software

http://emtomo.com

EM4Soil

EMTOMO – Software for ElectroMagnetic Tomography
Results & Discussion

Predicted $\sigma$ from EM4Soil modelling

Soil sampling and laboratory $EC_e$
Results & Discussion (dryland salinity)

**Validation**

**Quasi-3D**

- Lin's concordance = 0.9412
- Pearson's r = 0.9415
- RMSE = 2.24 dS/m
- ME = -0.03 dS/m

- \( \text{EC}_\text{e} = -0.4807 + 0.0339 \times \sigma \)

**MLR**

- Lin's concordance = 0.9396
- Pearson's r = 0.9404
- RMSE = 2.26 dS/m
- ME = 0.00 dS/m

- \( \text{EC}_\text{e} = -1.8156 + 0.0675 \times 1 \text{MPcon} \)
- \( \text{EC}_\text{e} = -1.5218 + 0.0350 \times 1 \text{mHcon} \)
- \( \text{EC}_\text{e} = -0.4178 + 0.0335 \times 1 \text{mHcon} \)
Results & Discussion (dryland salinity)

0.00 - 0.25 m
0.25 - 0.50 m
0.50 - 0.75 m

16 - 24 dS/m
2 - 4 dS/m
0 - 2 dS/m
Results & Discussion (irrigation salinity)

- 0 - 2 dS/m
- 2 - 4 dS/m
- 16 - 24 dS/m
Results & Discussion (irrigation salinity)

EC_e = 4.12 + 0.017 σ

R^2 = 0.89
Results & Discussion \textit{(irrigation salinity)}

Validation

\textbf{Quasi-3D}
Lin's concordance = 0.93
$R^2 = 0.88$
RMSE = 5.28 dS m\(^{-1}\)
ME = -0.03 dS m\(^{-1}\)

\textbf{MLR}
Lin's concordance = 0.96
$R^2 = 0.92$
RMSE = 4.35 dS m\(^{-1}\)
ME = 0.17 dS m\(^{-1}\)
Results & Discussion (irrigation salinity)

[Map showing different ECe (dS/m) levels]

- 0.00 - 0.25 m
- 0.25 - 0.50 m
- 0.50 - 0.75 m
- 0.75 - 1.00 m
- > 32 dS/m
- 16 - 32 dS/m
- 4 - 8 dS/m

(Northing: 6673800 - 384300, Easting: 384300 - 384700)
Results & Discussion (irrigation salinity)

- Measured ECa (ds/m)
- Predicted ECa (ds/m)

- > 32 dS/m
- 16 - 32 dS/m
- 4 - 8 dS/m
**Research Question**

YES WE CAN use a single frequency and multiple array

DUALEM-1 DUALEM-421

+ 1-dimensional inversion software

To generate quasi-3d EMCI to represent dryland and irrigation salinity status
EMCI is a viable means of mapping $EC_e$ at field scale with sufficient resolution and accuracy for dryland/irrigation management.

Capability has ramifications including ability to monitor salinity using time-lapse for;
(i) Revegetate landscape upslope, and
(ii) Rotation cropping to use water in landscape year round.

Capability has ramifications including ability to monitor salinity using time-lapse for;
(i) improved timing and uniformity of irrigation across a field, and
(ii) sufficient control of site-specific irrigation to optimize water use.
Mapping salinity in three-dimensions using a DUALEM-421 and EM inversion software

Zare, E., Huang, J., Monteiro Santos, F.A., Triantafilis, J.

79, 1729-1740
Potential to map depth-specific soil OM across an olive grove using quasi-2d and quasi-3d inversion of DUALEM-21 data

Huang J, Pedrera-Parrilla A, Vanderlinden K, Taguas EV, Gómez, JA, and Triantafilis J

Catena, 152, 207-217
Inferring leachate plume preferential flow paths using a DUALEM-421 and quasi-3 dimensional inversion model.

Triantafilis, J., Ribeiro J, Page, D., and Monteiro Santos, F.A.

$\sigma = 22.5$
Modelling coastal salinity using a DUALEM-421 and inversion software.

Davies, G.B., Huang, J, Monteiro Santos, F.A., Triantafilis, J.

Low tide

High tide

DSM in 4d (EC$_w$)