High intensity soil mapping for best practice nutrient management in the Wet Tropics

A technique for integrating electromagnetic induction (EMI) into conventional soil survey, to help delineation of soil management boundaries in the Russell River catchment

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Foreword

Jaragun EcoServices is a Wanjuru-Yidinji traditional owner organisation, operating in the Russell River catchment of Far North Queensland. Our organisation is focused on building Wanjuru capacity through employment and skills in agronomy, water quality and natural capital interventions. Jaragun has been working with the sugarcane industry since 2013, to improve water quality flowing to the Great Barrier Reef (GBR). Our applied research projects build the evidence-base needed to deliver local and catchment-wide solutions. Our broader investment goals are achieved through partnerships with industry, scientific, government and non-government organisations which bring expertise and resources to solve complex challenges.

Jaragun is pleased to support Queensland's Department of Resources in delivery of high intensity soil and attribute mapping for the Russell River catchment. The combination of EMI technology and conventional soil survey responds to the need for an efficient means to produce detailed soil mapping that will inform industry best practice and soils based nutrient management. We trust that the work will enable improved farm efficiency, increased profitability, and reduced fertiliser losses to our waterways and the GBR lagoon. This work is the result of the Department's close and direct collaboration with members of the Catchment's cane industry, their advisors and other experts. The underpinning success of the pilot highlights the need to replicate this work in other catchments experiencing similar high nutrient loads.

Jaragun sincerely thanks the Department and their soils team for strong leadership throughout the project, culminating in delivery of detailed mapping products and guidance materials. The foresight to develop a robust and repeatable survey methodology based on EMI will help to improve industry practice and build expertise across the sector. We congratulate the Department on this achievement.

Liz Owen
Director

Dennis Ah-Kee
Director and Wanjuru-Yidinji Elder

Summary

The following report describes the methods and results of a high intensity soil survey undertaken in the Babinda Swamp area of the Russell River Catchment. The work provides detailed and reliable soil information for growers and their agronomists to make informed on-ground nutrient management decisions. Soil attribute layers developed as part of this project have been tailored to align with thresholds set out in the sugar industry best practice program SIX EASY STEPS®. The work aims to bolster uptake of best practice nutrient management by providing improved soil information. The attribute layers will also help growers develop Farm Nitrogen and Phosphorus Budgets to meet current regulatory requirements and help inform variable rate spreading technologies.

The project team employed a range of remote sensing techniques to undertake the soil survey, including use of a detailed LiDAR (light detection and ranging) digital elevation model, and interpretation of both historical and current aerial photography. Whilst these products all proved useful, they were not able to provide the necessary level of detail required for farm and paddock scale nutrient management. To meet higher accuracy and site intensity requirements, an electromagnetic induction (EMI) sensor was used to help delineate soil and attribute boundaries.

The EMI capture revealed important subsurface detail, even within the leached, low conductivity soils of the Babinda Swamp. These EMI patterns enabled more precise soil boundary delineation, helped with site selection, and reduced the potential for site duplication in the same soil unit. This work has shown that EMI is an important tool that can aid with the speed and accuracy of high intensity area-based mapping, provided appropriate consideration is given to data capture conditions and output formats designed to reduce temporal and environmental variation. Workflows and processes developed as part of this project have been provided to help others in the EMI capture space with data management to encourage standardisation of output layers.

In addition to delivery of soil mapping and soil type property or attribute layers, the Department of Resources has also made the EMI mosaic data products available. The decision to release the EMI mosaic datasets was based on strong interest from growers and agronomists seeking to improve on-farm drainage management. There has also been interest in the EMI mosaic datasets from researchers seeking to understand preferential groundwater flow pathways within the paleochannel network uncovered by the EMI capture.

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1. Introduction

Sugarcane is a major agricultural industry contributing over $4 billion to the Queensland economy annually (Queensland Economic Advocacy Solutions, 2019). Approximately 90% of the State's sugarcane production occurs in Great Barrier Reef (GBR) catchments. More than 400 000 ha of land is managed by sugarcane farmers within GBR catchments (Lewis *et al*., 2021).

Nitrogen (N) is an essential crop nutrient, however its application can result in the formation of dissolved inorganic nitrogen (DIN) (Vilas *et al*., 2022), one of the primary risks to water quality in the GBR and coastal ecosystems (Waterhouse *et al*., 2017). Modern DIN loads discharging to the GBR are estimated to be 1.2 to 6 times higher than pre-development conditions (Bartley *et al*., 2017). DIN in agricultural runoff from the sugarcane industry in the Wet Tropics accounts for approximately 80% of the anthropogenic load to the GBR lagoon (Wallace & Waltham, 2021). To implement measures for water quality improvement, the federal and state governments have set a 60% reduction target in end-of-catchment anthropogenic DIN for the Wet Tropics by 2025 (Australian Government & Queensland Government, 2018). This target is modelled on adoption of minimum practice standards.

Efficient and sustainable nutrient management can benefit cane yields and minimise potential off-site impacts (Calcino *et al*., 2022; Larsen & Dougall, 2017). The SIX EASY STEPS® program is the Australian sugarcane industry standard for best practice nutrient management. It is designed to enhance efficiency without impacting crop yield, productivity and farm income (Schroeder *et al*., 2014).

Through this program, the sugarcane industry is working to reduce nitrogenous fertiliser losses to the GBR. Recent Reef Regulations have come into effect requiring sugarcane farmers use prescribed practice standards to develop whole-of-farm nitrogen budgets, based on fertiliser application rates (Queensland Government, 2022). Achieving the outcomes of the SIX EASY STEPS® program will considerably aid in meeting these regulatory requirements.

An understanding of soils and their chemical and physical properties is fundamental for informing profitable fertiliser and farm management programs (Calcino *et al*., 2022). Detailed and industry-relevant soils information is a key element for landholders within GBR catchments to enable the implementation of best practice nutrient management. The success of SIX EASY STEPS® and development of reliable nitrogen budgets relies on access to accurate paddock scale soil information.

Existing soil mapping across much of the Wet Tropical Coast is typically available at a scale of 1:50 000 or coarser. While this medium to low-intensity mapping is suitable for district or catchment wide land use decision making, it is not suitable for management planning at the property or paddock scale (Schoknecht *et al*., 2008). To help fill this soils data gap, the Department of Resources (Resources) and Jaragun Ecoservices (Jaragun), have completed a very high intensity, 1:10 000 scale soil survey across 2025 ha of sugarcane land in the Russell River Catchment. The Russell-Mulgrave catchment was selected due to its relatively high DIN loads. The catchment represents only 9% of the Wet Tropics land area, whilst being the third highest contributor of DIN to the GBR (Department of Environment and Science, 2019).

EMI was chosen to help support development of high intensity paddock scale soil information. Whilst EMI provides excellent information on apparent subsoil conductivity, it is a mapping support tool and does not by itself produce a soil map.

This work delivers a method for integrating EMI into high intensity area based mapping at a scale of 1:10 000 (or better), suitable for property level management planning (Schoknecht *et al*., 2008). The project also delivers important soil information to help growers and their agronomists with adoption of precision soil and landscape limitations based nutrient management. For example, identifying waterlogged areas prone to denitrification. This project was funded with support from the federal government (the Reef Trust and the Great Barrier Reef Foundation) and delivered by the Queensland Department of Resources and Jaragun Ecoservices.

2. Survey project area

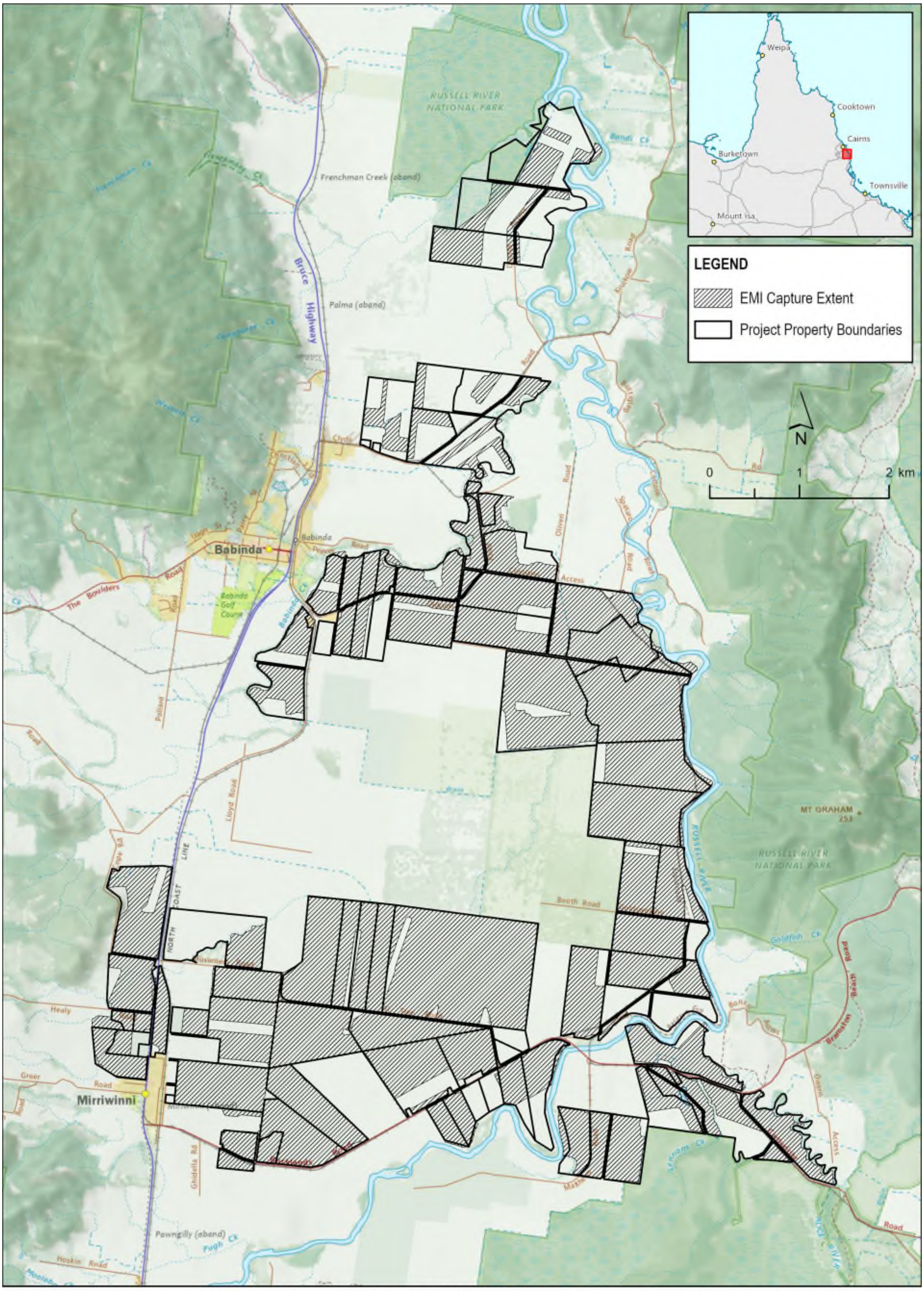
This high intensity soil survey encompasses 2025 hectares of sugarcane growing land in the lower Russell River catchment south of Cairns, Far North Queensland (Figure 1: Location of survey area and EMI capture extent). The nearest townships of Babinda in the north and Mirriwinni to the south are home to around 1700 people (Terrain NRM *et al*., 2021).

The lower Russell River catchment is home to the Wanjuru (Wanyurr) people whose country extends from Wooroonooran National Park to the coast, and from Palmer Point (north) to Coopers Point (south) (Jaragun Ecoservices, 2021). With traditional boundaries identified by language groupings, Wanjuru speak a dialect of Yidi and are also part of the Yidinjii (language group) nation that is found to the north of Cairns, south to the Russell River and west to the Atherton Tablelands. Cultural heritage sites are scattered throughout country, with special significance attached to waterways and the coastline (Jaragun Ecoservices, 2021).

Queensland’s highest mountains, Bartle Frere and Bellenden Ker are situated immediately west of the survey area, generating regular, and often very heavy, orographic rainfall events. This coupled with prolonged rainfall events during the summer wet season results in high energy runoff and extensive flooding across the low-lying floodplains and swamps. Rainfall across the area is summer dominant with 60% occurring between the months of December to March. Significant falls of >100 mm/day can occur at any time of year along the coastal plains (Brodie *et al*., 2011).

The Mulgrave-Russell River catchment is one of the wettest in Australia, with annual rainfall averaging over 3200 mm across the catchment (Department of Environment and Science, 2019). Average rainfall ranges between about 2100 mm around Gordonvale to just over 8000 mm on Mt Bellenden Ker annually, with Babinda experiencing an average of 4265 mm (Bureau of Meteorology, 2021). Over 60% of average annual rainfall in the Mulgrave-Russell becomes surface runoff, resulting in an estimated 4243 gigalitres leaving the catchment annually as discharge into the GBR lagoon (Department of Environment and Science, 2019; Furnas, 2003). The magnitude and intensity of rainfall in this catchment represents is a significant challenge when trying to retain water soluble, applied nutrients within the soil long enough for them to be taken up by the sugarcane crop.

The survey area contained significant extents of granitic alluvial fans around Mirriwinni, levee systems associated with the major watercourses (Russell River, Alice River, Babinda Creek) and parts of the peaty Babinda Swamp that have been drained for sugarcane production.



Map Production: NR914 Date: 17/01/2023 Spatial Reference: GCS GDA2020 MGA Zone 55 © State of Queensland (Department of Resources) 2022

Figure 1: Location of survey area and EMI capture extent

3. Methodology

3.1. EMI equipment and field processes

There are several EMI instruments on the market that measure soil conductivity. This survey was undertaken using a DualEM 21s instrument (DualEM Inc, 2018), which measures apparent electrical conductivity (ECa) in milliSiemens per centimetre (mS/cm). The inbuilt GPS receiver records the location of each data point as a latitude and longitude. Data collection rate was adjusted to a frequency of 1 reading per second. Refer to Appendix A for further information about the DualEM 21s and its use in the field.

At every second the instrument collected ECa readings from four sensors, referred to as PRP1, PRP2, HCP1 and HCP2 (Table 1). These sensors relate to depths of 0.5 m, 1.0 m, 1.6 m and 3.2 m below the instrument (see DUALEM Inc, 2018 for more information). During this survey, the effective depth in all sensors was reduced by 0.5 m, as this was the height of the instrument above the ground, as measured from the interrow (trailer wheel track).

Table 1: DualEM instrument sensor depths

Sensor	Sensor accumulation depth	Depth of investigation below ground (RUSS survey)
PRP1	0.5 m	0 m (surface of raised plant mound only)
PRP2	1.0 m	0.5 m
HCP1	1.6 m	1.1 m
HCP2	3.2 m	2.7 m

The instrument was mounted on a purpose-built trailer made of non-conductive timber, plywood, nylon, and 15 cm diameter PVC (polyvinyl chloride) pipe (Figure 20) and towed behind a rugged terrain vehicle (RTV). The instrument was set back approximately 3.0 m from the vehicle and tow hitch to avoid interference from highly conductive metal components (Figure 2). The trailer was designed to traverse sugarcane paddocks with its wheels straddling the plant row (1.65 m single spacing). The trailer was designed to allow the sensor platform to be raised and lowered to clear obstructions in the paddock, however, to maintain consistency, no adjustments were made during the survey. Traverse spacings were typically every 6th plant row, or approximately 10 m apart (at 1.65 m wide furrow spacings). This separation distance provided adequate data coverage and comfortable turning at the end of each row. Refer to Appendix A for further information regarding trailers and towing vehicles.

Figure 2: The DualEM instrument being towed in the field by an RTV

Data was logged using a rugged, weather, dust and shock-proof field laptop connected to the EMI instrument via a combined data and power cable through a serial RS232 connection. Data logging was supported using QGIS, a freeware geographic information system (GIS) software package. This program allowed real-time tracking and visualisation of the instrument's current location and tracks. The track feature was particularly helpful as it reduced the risk of duplication (traversing the same area twice). Appendix A details how QGIS was used for logging EMI data.

3.2. EMI data and the mosaic products

Following the removal of extraneous data points and outliers, an EMI mosaic dataset was generated using 660 197 individual spatial data points recorded by the EMI survey. Each datapoint contained up to 4 individual depth sensor readings, providing 2 591 951 individual ECa values that were used to develop multispectral mosaic products. Refer to Appendix E for further detail on the post field EMI data processing used for this project.

Two different EMI mosaics have been developed from this dataset. The first was produced from the absolute values straight from the sensors, while the second was produced from normalised[1] values. The normalising process helped smooth out data variations caused by environmental variables, such as soil moisture, to provide a more 'seamless' layer across the project area.

These intensive, continuous soil ECa datasets helped the survey team with an understanding of soil formation and depositional processes across the project area. The EMI dataset was also useful for identifying soil variation in areas that appeared to be relatively uniform at the surface. Examples of this variation include areas were groundwater moves preferentially or accumulates in the landscape. EMI was particularly useful for delineating subsoil wetness associated with springs and drainage depressions. These features were typically associated with relatively higher ECa values. EMI was also effective for delineating narrow, sinuous, sandy paleochannel features which typically returned a lower relative ECa response.

[1] Normalised values are "phase shifted" values occurring between 0 and 1

The normalised EMI mosaic was used in a qualitive way, in conjunction with the DEM and aerial photography, to aid the delineation of soil mapping boundaries (see section 3.4 for more detail). While this EMI dataset was used extensively to aid soil boundary development, the raw, absolute mosaic product was also consulted regularly to assist in the process.

No attempts were made to correlate normalised EMI values or value ranges to specific soil types. The development of these sorts of relationships is difficult to achieve for large areas when undertaking multiple EMI captures over a broad timeframe. A correlation of differing soil conditions that influence ECa measurements (e.g. moisture) to both the EMI data captured and the spatial extent of soils couldn't be achieved.

The absolute EMI mosaic product proved to be a useful indicator of subsoil moisture conditions. It was used in conjunction with soil site observation data to help with defining key soil and landscape properties (or attributes) important for nutrient management (refer to Section 5). It was found to be useful to use this product to extrapolate soil attributes for areas where no site data was available.

Regular consideration of the absolute intensity (very low or high) amongst the broader pattern helped prevent over-interpretation of relative differences in the normalised mosaic dataset. Over-interpretation can easily occur when using the Dynamic Range Adjustment (DRA) tool as it can make small variations look like significant features.

3.3. Soil characterisation survey

The soil characterisation survey followed established guidelines for soil and land resource survey. Refer to Department of Resources (2021) and McKenzie *et al*. (2008) for detail on the standard procedures for the collection, evaluation and interpretation of soil and land resource information. Soils in the project area were characterised using conventional soil coring, field description and laboratory analysis. Field verification of soil patterns was crucial to ensure appropriate reliability and accuracy of the soil and attribute mapping products.

3.3.1. Desktop assessment and use of remote sensing

Prior to commencing the soil survey, a desktop assessment was undertaken to determine the best available information, including existing soil reports and mapping.[2] The most applicable survey, *Soils of the Babinda - Cairns Area, North Queensland*, was produced by CSIRO in 1996 at a scale of 1:50 000 (Murtha *et.al*. 1996). Review of existing soil reports and information is undertaken to identify known or likely soil types in the study area, the nature of those soils, and their probable distribution.

[2] Published soil reports can be accessed via the Department of Resources' online catalogue (https://www.qld.gov.au/environment/library).

A range of remotely sensed information was also used to inform the soil sampling program.[3] This aerial imagery, including a historical air photo mosaic captured in 1951 showing large tracts of intact native vegetation. The survey team also used several contemporary air photos, encompassing a range of wetter and dryer seasonal conditions to help with our understanding of crop response. Images showing recently cultivated land were also helpful to determine the distribution of peaty soils based on the dark colour. A detailed (light detection and ranging) LiDAR based digital elevation model (DEM) was also used to help separate landscape features based upon small differences in elevation across the alluvial fans and floodplains.

3.3.2.Field collection of profile sites and mapping observations

Collection of soil profile information was undertaken to identify and describe the soils found across the project area, along with the range of attributes and limitations important for land and fertiliser management. Point of truth soil characterisation and chemical testing information was critically important to make linkages and assumptions between observable patterns in EMI and remotely sensed data and real-world soils and attributes.

Site and profile observation descriptions were made in accordance with the *Australian Soil and Land Survey Field Handbook* (NCST 2009). Varying levels of information were recorded at different sites. The minimum level of detail to be collected for different types of site observations is set out in the *Queensland soil and land resource survey information guideline* (Department of Resources, 2021). Site observation types and the level of detail relevant to sites described by this project are listed in **Error! Reference source not found.** below (refer to Schoknecht *et al.*, 2008 and Department of Resources 2021, for more information) .

Table 2: Site observation types and number of associated sites

Site Type	Number of sites	Site type description
Class 1	127	Sites with detailed descriptions of the land and soil profile morphology.
Class 3a	112	Sites with detailed descriptions of the land and soil profile morphology, and limited laboratory analysis (0–0.2 m only).
Class 3b	36	Sites with detailed descriptions of the land and soil profile morphology and full profile laboratory analysis.
Class 4a	161	Brief mapping observations sites with some land and soil profile morphology described to aid soil type attribution of mapping polygons.
Class 4a	56	Brief mapping observations with some soil profile morphological data and limited laboratory analysis only (0–0.2 m).

[3] Mapping resources can be viewed on the Queensland Globe (https://qldglobe.information.qld.gov.au/) or downloaded via QSpatial (https://qldspatial.information.qld.gov.au/catalogue/). Digital aerial photographs can be downloaded from QImagery (https://qimagery.information.qld.gov.au/).

Class 4b	367	Brief mapping observation sites to aid boundary development and identifying presence of various soil attributes and constraints.
Class 4b	106	Brief mapping observation sites to identify the presence various soil attributes and constraints, with limited laboratory analysis (0–0.2 m only).

A total of 965 site observations were made across the Russell Catchment project area, in combination with 2 591 951 individual measurements of ECa, helping to ensure this work meets the recommended standard for a 1:10 000 scale soil survey (Schoknecht *et al*., 2008). All sites and measurements were located using GPS and supported by georeferenced digital photographs.

Soil profile morphology descriptions were taken from relatively undisturbed soil cores sampled on the plant mound within cane paddocks, or from vertical exposures cut into drain walls. Soil cores were collected using a 50 mm soil sampling tube pushed into the ground by a utility mounted hydraulic soil sampling rig (Figure 3). A small number of profile sites were collected and described using hand auguring equipment. Hand augers were used where vehicle access was limited or where soil retrieval was hampered by high groundwater tables.

The extensive drainage network also proved useful to the survey process, helping the survey team to capture of large numbers of brief soil profile mapping observations. These observations typically included basic visual and physical observations including landform, slope, drainage, soil colour, texture and presence of peat.

All site information has been checked as part of the Department's quality assurance (QA) process. An automated quality control (QC) report was also generated to identify errors and omissions. When all identified issues had been remedied (QA/QC processes passed), the site information was released for public consumption via the Queensland Globe.

3.3.3.Soil sampling and laboratory analysis

Sites with full profile laboratory analysis (class 3b) were sampled and analysed following the Paddock to Reef soil sampling protocols of Attard & Shaw (2010). These representative sites were comprehensively tested to inform a wide range of reef science programs and modelling.

Surface samples were typically collected from 0–0.1 m or 0–0.2 m, and subsurface samples at standard depths of 0.2–0.3 m, 0.5–0.6 m, 0.8–0.9 m, 1.1–1.2 m and 1.4–1.5 m. Subsoil sample depths were varied where these ranges crossed significant soil horizon boundaries. In these cases, sampling depths were adjusted to ensure individual samples remained within the identified soil horizon.

Surface 0–0.2 m samples (class 3a) were collected in a manner that was consist with the *Prescribed methodology for sugarcane cultivation, V2* (Department of Environment and Science, 2022). These samples are bulked composites of between 10–15 subsamples taken from within a 20 m radius around a site location (e.g. where full profile description cores were sampled).

Bulk surface sampling was undertaken using a tubular grab-sampler pushed into the shoulder of the plant mound, taking care to avoid any subsoil fertiliser applied within the centre of the mound. Subsamples were mixed in a bucket to form a bulked sample of approximately 1 kg and then bagged for submission to the laboratory. Cation exchange capacity was added to the standard suite required under the *Prescribed methodology for sugarcane cultivation, V2* (Department of Environment and Science, 2022). This inclusion was recommended in consultation with SRA (Sugar Research Australia) based on concerns around calcium deficiency and high aluminium levels.

All samples were submitted to the Department of Environment and Science's Chemistry Centre at Boggo Road, Dutton Park. The suite of analysis applicable to full profile sites is set out in Table 3, whereas the more limited suite of analysis applied to bulked 0–0.2 m samples is presented in Table 4. Laboratory methods are described in Rayment & Lyons (2011).

Figure 3: Collecting a soil profile for description

Table 3: Analytical methods for full profile samples

Laboratory test	Method code
Surface 0–10 cm or bulk 0–20 cm samples	
Organic carbon	6A1
Total organic carbon & total nitrogen (Dumas)	6B2b
BSES (acid) extractable P	9G2
Phosphorus buffer index (PBI) adjusted for Colwell P	9I2b, 9B2
Exchangeable cations (CEC/ECEC)	15A1, 15C1, 15G1
pH 1:5, electrical conductivity, chloride and nitrate (NO3-N)	4A1, 3A1, 7B1, 5A2
Total N & P (Kjeldahl)	7A2a, 9A3a
DTPA extractable B, Cu, Fe, Mn, Zn	12A1
Replaceable K (S_REPK_ICP)	18B1
Air dry moisture (ADM %)	2A1
1/3 and 15 bar moisture	2E2, 2E1
Particle size analysis (PSA)	2Z2
Particle size distribution (selected profiles)	PSD
Loss on ignition pre-treatment (peaty samples)	LOI
All other lower depth samples	
TOC & N Dumas	6B2b
BSES (acid) extractable P	9G2
Total N & P (Kjeldahl)	7A2a, 9A3a
Phosphorus buffer index (PBI) adjusted for Colwell extractable P	9I2b, 9B2
Exchangeable cations, CEC/ECEC	15A1, 15C1, 15G1
pH 1:5, electrical conductivity, chloride and nitrate (NO3-N)	4A1, 3A1, 7B1, 5A2
Air dry moisture (ADM %)	2A1
1/3 and 15 bar moisture	2E2, 2E1
Particle size analysis (PSA)	2Z2
Particle size distribution (selected sites only)	PSD
Loss on ignition pre-treatment (peaty samples)	LOI (600)

Table 4: Analytical methods for other bulk surface (0–20 cm) samples

Laboratory test	Method code
Organic carbon – uncorrected Walkley & Black	6A1
BSES (acid) extractable P	9G2
Phosphorus buffer index (PBI) adjusted for Colwell extractable P	9I2b, 9B2
pH (1:5 water)	4A1
Cations/CEC/ECEC as required	15A1, 15C1, 15G1

3.4. Soil boundary development and attribute assignment

The mapping and related soil information collected for the project area was undertaken at a scale of 1:10 000, which is 25 times more detailed than the existing 1:50 000 mapping by Murtha *et al*. (1996). The basis for the mapping units (polygons) developed is the soil profile class (SPC) which are a grouping of soils with similar profiles and soil properties (Powell, 2008). This project identified and mapped 32 SPCs, including 18 correlated to established Wet Tropical Coast SPCs of Cannon *et al*. (1992), Murtha (1986) and Murtha *et al*. (1996). Four additional SPCs and 10 variants were developed to accommodate soils that did not correlate with established SPCs. Variants developed for this survey differ from the main SPC based on soil texture, soil colour or presence of peat at the surface.

The survey also identified a range of attributes important for land nutrient management, that can be related to each SPC. The reasons behind selecting these attributes and their associated threshold levels are described later in the Soil attributes section. Every soil mapping polygon contains a code for every soil attribute, so that individual attribute maps can be generated in addition to the SPC maps. Attribute maps are designed to assist growers and agronomists determine best practice land and nutrient management strategies. This information, correlated to SPCs, will also allow the formulation of management strategies for similar soil types found elsewhere along the Wet Tropical Coast.

SPCs, mapping, site descriptions and the associated photographs and analysis have been loaded into the State Government's SALI database. This information is publicly available through the Queensland Globe (https://qldglobe.information.qld.gov.au/) and QSpatial (https://qldspatial.information.qld.gov.au/catalogue/).

3.4.1.Map boundary development – SPC related attributes

Boundary development was undertaken by manually drawing polygons around the largest and most significant landforms and features, then further subdividing these as required, based on observed complexity. The historical (pre-clearing) aerial photo mosaic was very useful for delineating both these larger features and some of the smaller features. Figure 4 is an example of a sharp vegetation and soil and boundary, where the alluvial fans in the south-west adjoin peat swamps in the north-east. In this example, the better drained alluvial fans support thick tropical rainforest, compared with the swamp which was sparsely treed with *Melaleuca* spp.

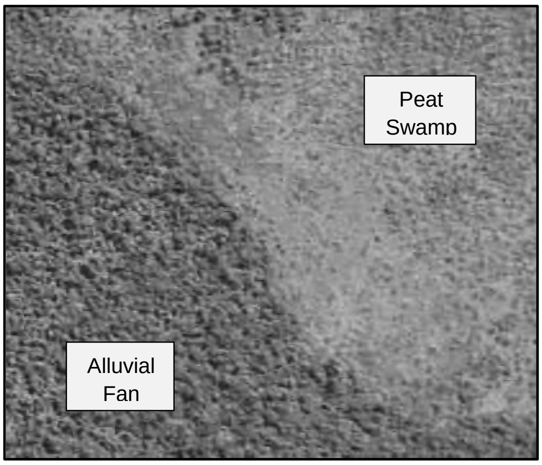


Figure 4: Interpretation of historical imagery (Ca. 1951)

The LiDAR DEM was particularly useful for delineating landforms. Even some of the most subtle features across the alluvial fans and floodplains were able to be interpreted using an ArcGIS Image Analysis tool called Dynamic Range Adjustment (DRA). This tool allows the viewer to zoom in and compare very fine, relative changes in elevation. The example provided in Figure 5 shows low-lying peat swamps (green) being overlain by a sandy alluvial fan termination in the west (red) and part of a clayey, levee system in the east (red and white). This area is one of two additional, historical orientations of Babinda Creek, that can be identified by analysing the LiDAR DEM.

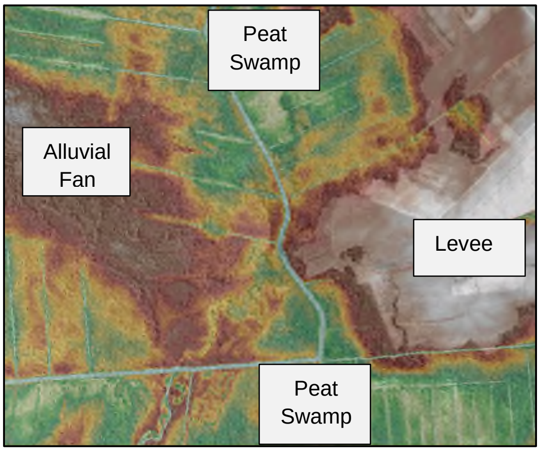


Figure 5: Interpretation of landforms using the DEM

The EMI mosaic dataset was particularly useful in determining boundaries between drier, coarse textured (e.g. sandy) soils and wetter, finer textured soils (e.g. clay). Figure 6 shows a buried sandy paleochannel network as dark sinuous features in contrast with brighter areas of subsoil wetness. The EMI mosaic product proved very useful for identifying areas of relatively higher subsoil wetness. It is important to note that one soil polygon or SPC may have several important, overlapping attributes. For instance, the same soil type may be wetter in one area or be more prone to flooding in another. Conversely, areas with a

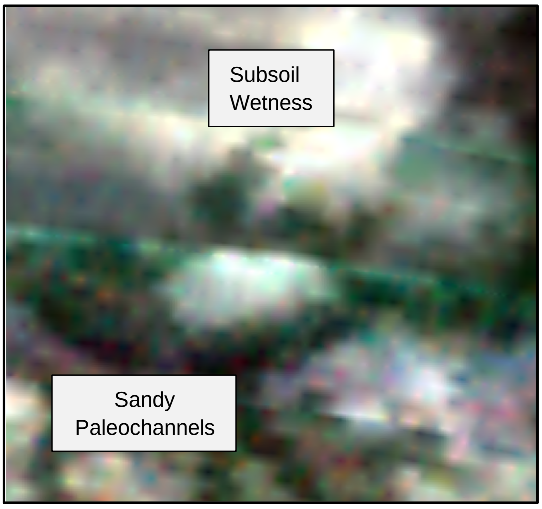


Figure 6: Interpretation of subsoil wetness using EMI

similar EMI response can contain more than one SPC. This high intensity soil survey was sufficient to accommodate greater attribute complexity, enabling delineation of soil attributes that do not always conform with SPC boundaries.

The EMI mosaic product was most often displayed using RGB composite, consisting of the red band PRP2 (0.5 m), green band HCP1 (1.1 m) and blue band HCP2 (2.7 m) together in this order (Figure 7). The PRP1 (plant mound sensor) was not usually selected due to the potential for inaccuracies in this dataset (refer Appendix B). This format enabled viewing of all three sensor depths simultaneously. In areas with a significant change between the patterns at different depths, this was indicative of a change in soil wetness or texture.

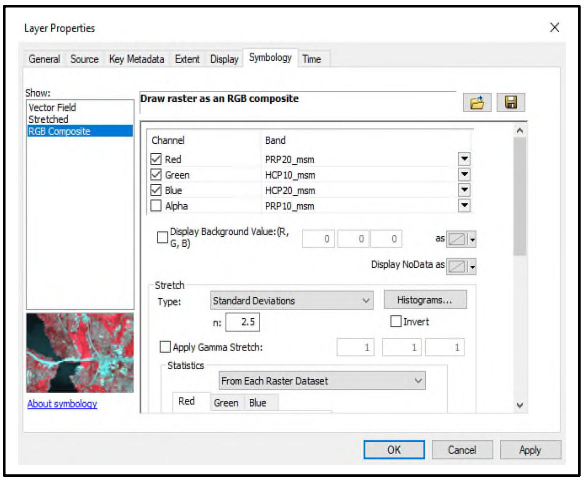


Figure 7: Displaying an individual EMI sensor depth

In the case of significant variation between sensor depths, individual sensor depths were displayed using a stretched, grey scale, with dark colours indicating low ECa response and bright, white colours representing a relatively higher ECa response (Figure 8). Display of individual sensor depths was particularly useful in helping to assign wetness at 0.5 m and 1.0 m, which aligned with PRP2 (0.5 m) and HCP1 (1.1 m). These sensor depths were also of most interest as they were within the depth range of site sampling and analysis.

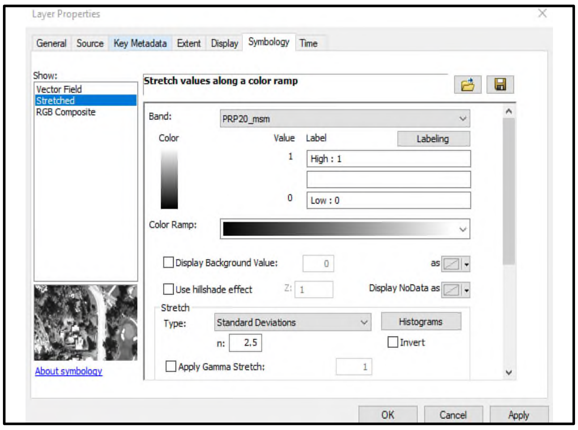


Figure 8: Displaying the EMI mosaic image

3.4.2. Boundary development – Drone DEM and NDVI

The Department of Agriculture and Fisheries (DAF) provided support to the project, by using a drone to capture high-resolution aerial imagery, digital elevation modelling and normalised difference vegetation index (NDVI) mapping across parts of the project area. This work further aided boundary development within the capture area and proved useful in helping to confirm crop response to poor site drainage and subsoil wetness. Figure 9 below shows very subtle changes in elevation across a low-lying paddock. Figure 10 shows vegetative vigour (crop response) with red representing low crop vigour and green representing relatively higher crop vigour.

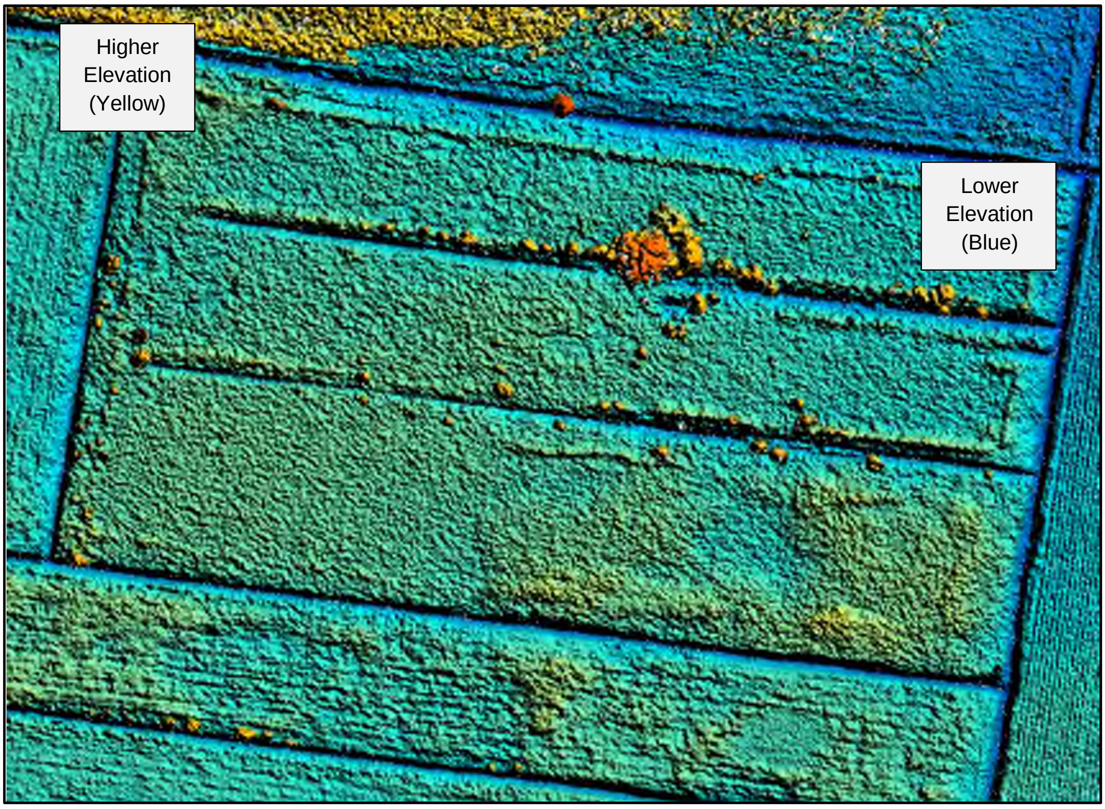


Figure 9: Drone based DEM showing small elevation differences that can affect drainage

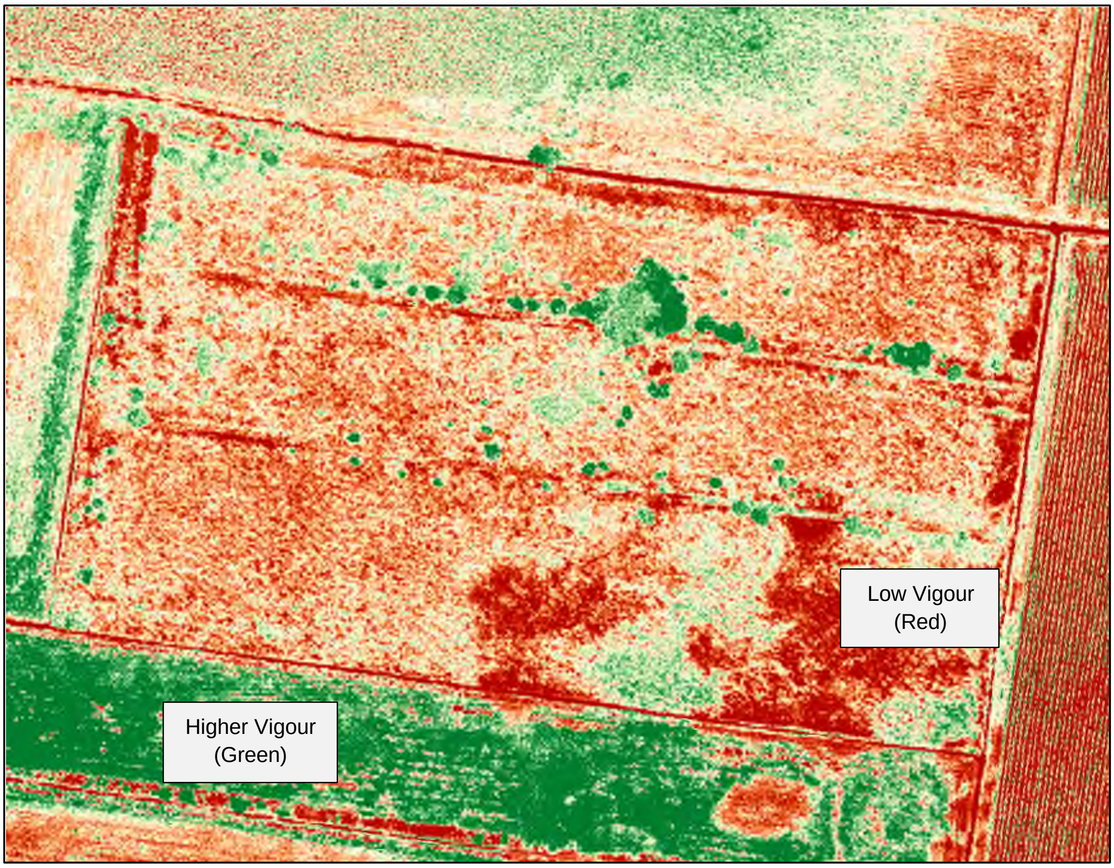


Figure 10: Drone based NDVI showing vegetative vigour

3.4.3. Additional boundary development for non-SPC related landscape attributes

Once the initial SPC map boundaries had been developed, following the above-described processes, additional splitting of the polygons was undertaken due to the need to accommodate important soil and landscape attributes such as flooding and soil wetness. The overall process, at this juncture, resulted in over 7 000 unique mapping areas (UMA) in the polygon dataset.

Other soil related attributes were then assigned to these polygons and the data set was analysed to remove unnecessary landscape mapping complexity. Multiple contiguous polygons with the same SPC and attribute values were merged to form larger individual polygons. Further consideration was then given to the minimum resolvable (displayable) areas of mapping polygons. Very small and isolated polygons were merged with adjacent polygons to ensure the final product is consistent with the standard for minimum resolvable areas to suit 1:10 000 scale mapping. This was a manual process, merging these very small polygons with adjacent polygons with the most similarity in SPC and their attributes.

The final polygonal dataset contains 2954 polygons across the 2025 ha study area. Whilst many polygons remain quite small, this enabled separation of very important soil attributes like wetness. The main consideration in terms of polygon size was based on the aggregated areas that will be provided in the final SPC and attribute layer products.

3.4.4. Polygon development – chemical and quantitative attributes

To assist with decision making on other quantitative soil attributes (i.e. laboratory results), project officers used Microsoft Power BI to summarise all observed and measured soil attributes based on SPC. This allowed a swift comparison of observations and laboratory results for each SPC along with their spatial location. Figure 11 provides an example of the Power BI interface used to summarise organic carbon % for the Russell SPC. The right-hand pane shows the results for organic carbon testing (laboratory method 6A1) within the upper 0.2 m. Site locations for each test are also visible on the map in the bottom left. The top left pane provides a median result for organic carbon presented in terms of its nitrogen mineralisation index. In this case, median organic carbon levels within the Russell SPC were found to be between 1.21 – 1.6%, equating to a Moderate (M), class 4, nitrogen mineralisation index.

This process was repeated for each SPC and attribute listed in the tabs along the bottom of the report including nitrogen mineralisation, effective CEC (cation exchange capacity), pH, PBI, calcium deficiency, surface texture, drainage to 0.5 m, drainage to 1.0 m and aluminium saturation. These median (typical) attribute values were then applied to the polygonal dataset based on the SPC. The site laboratory dataset was then used to make finer adjustments where laboratory results fell outside the typical attribute range. For some attributes like pH, calcium deficiency and aluminium saturation, these outliers sometimes related to differences in land management, particularly the rate and frequency of agricultural lime.

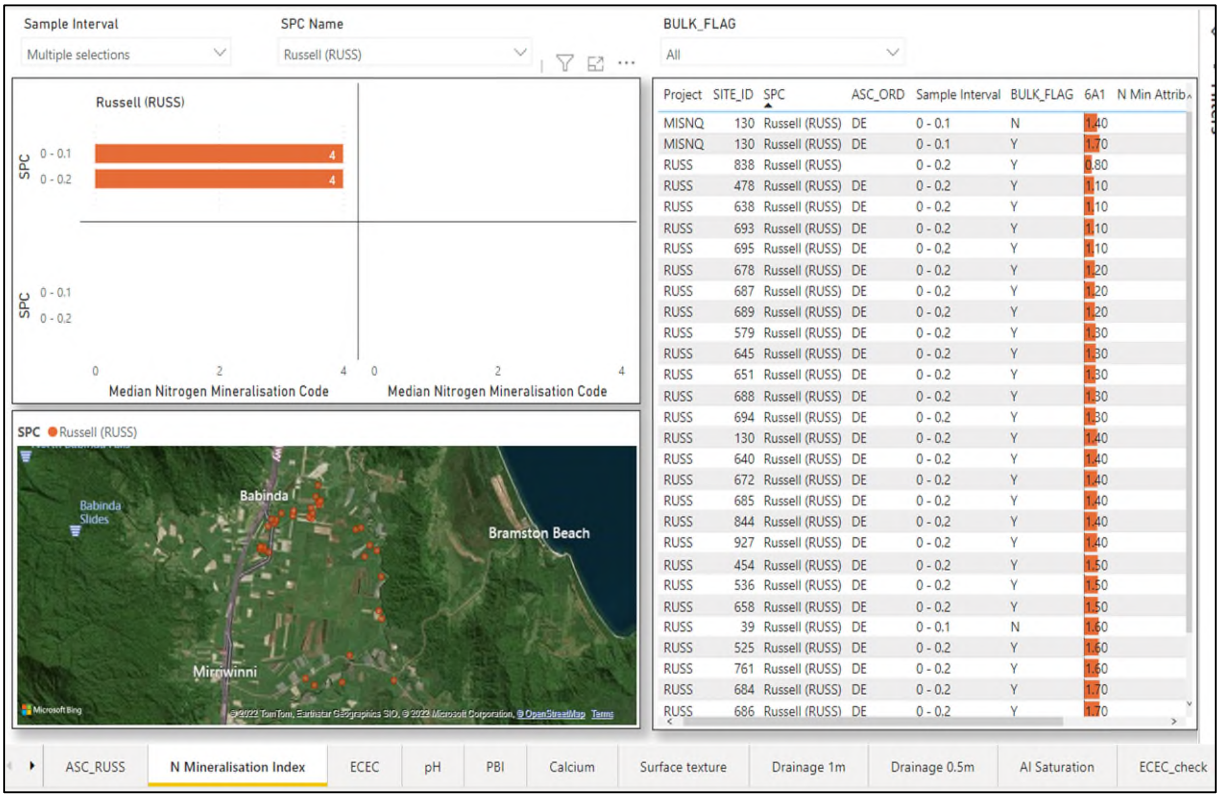


Figure 11: Power BI summary of site and laboratory data

4. Soil profile classes

The soil profile classes (SPC) identified and mapped across the project area are described here, grouped according to their geology, landform, and drainage conditions. The SPCs have been classified into seven Soil Orders defined within the Australian Soil Classification (Isbell & NCST 2016) Soil Orders identified in the project area include:

Dermosols	Soils that lack a strong texture contrast between the A and B horizons and have a moderate to strong grade of pedality (structure) in the major part of the B2 horizons.
Hydrosols	Soils that are seasonally (no less than 2–3 months) or permanently saturated in the major part of the soil profile.
Kandosols	Soils that lack a strong texture contrast between the A and B horizons, have a massive or weak grade of structure in the major part of the B2 horizons, a clay content >15% in any part of the B2, and are not calcareous throughout.
Organosols	Soils with more than 0.4 m of organic material (peat) within the upper 0.8 m of the profile.
Rudosol	Soils with little, if any, pedological organisation (soil development) apart from minimal development of an A1 horizon.
Tenosols	Soils with a generally a weak grade of pedological organization apart from A horizons and do not meet the requirement for any other Soil Order. Includes soils with a sandy textured (≤15% clay) colour B horizon.

4.1. Soils formed from metamorphic rock

One SPC formed from basic metamorphic rock has been described and mapped within the Russell catchment project area. It is found on gently to moderately inclined mid to lower slopes of the foothills of the Wooroonooran (Bellenden Ker) Mountain Range which bounds the project area to the west.

Kimberley (Red Dermosol) is a deep (>1.0 m) to very deep (>1.5 m), well drained, whole-coloured[4], red, gradational to uniform, strongly structured, light to medium clay soil, formed from basic metamorphic rock (amphibolite or metamorphosed basalt) of the Barnard and Hodgkinson Formations. Kimberley soils were found on the footslopes of hills, northwest of Mirriwinni.

Murtha, Cannon and Smith (1996) originally classified this soil as a Ferrosol, due to it being derived from basaltic origins. These authors recognised that basaltic influence within these metamorphic rock units could be variable and that the associated differences in free iron content could result in an alternate Red Dermosol classification. We noted that the *Galmara* SPC would also fit this soil, though for consistency, the Kimberley classification was retained.

[4] Nil, or few if any (<10%) mottles

4.2. Soils of the granitic alluvial fans

These are soils found on low angle alluvial fans between the steeper metamorphic foothills along the western project area boundary, and the floodplain and swamp soils dominating the eastern half of the project area. These fans comprise granitic material of the Bartle Frere Granite formation, washed from the slopes of Mt Bartle Frere, which dominates the Wooroonooran Range behind Babinda and Mirriwinni. These materials have been deposited from overland sheet wash processes.

At the lower (distal) ends of these fans, the sandy alluvial fan materials have been found to overlay finer textured floodplain deposits. In the valley floor, these fans have been buried by thin to moderately thick peats deposited by more recent freshwater swamps.

Soils of the granitic alluvial fans are described here according to their dominant landform. These soils are sandy throughout and contain angular, fine to medium size quartz gravels. They can be readily distinguished from other sandy soils found on the floodplain and within prior streams by the angular nature of the sands and gravels.

4.2.1. Well drained soils of the alluvial fans (>1% slope)

Tyson (Red Kandosol) is a deep (>1 m), well drained, red, massive to weakly structured, whole coloured, gradational soil, found on the mid to upper slopes of fans with slopes up to 5%. Only two polygons of this soil type have been mapped in the project area. The soil grades from a dark brown sandy loam topsoil into a red, massive, sandy clay loam subsoil. Deeper subsoils become browner, with a lighter sandy loam texture. Few (2-10%) to common (10-20%) fine to medium angular quartz gravels are found throughout the profile.

Within the project area, this soil is found to be a lighter textured variant of the *Tyson* described in Murtha, Cannon and Smith (1996). These authors described *Tyson* as typically having a heavier grade of texture throughout, ranging from a sandy clay loam topsoil to a sandy medium clay in the upper part of the subsoil.

Tyson Brown Variant (Brown Kandosol). This soil occupies a small area immediately downslope of *Tyson* (three polygons) and appeared to be a browner, moderately well drained variant of the SPC. The surface has a brown to greyish brown sandy clay loam grading to reddish brown sandy clay loam subsoil. This soils is expected to be slightly heavier textured than Tyson and contain slightly more organic carbon. Subsoils were reddish brown and sand, and gravel content did not appear to increase with depth, distinguishing it from *Thorpe*. Very little is known about this soil and its presence is based on surface observations and drain cuttings.

Thorpe (Brown Kandosol) is a deep to very deep, moderately well to well drained, brown, massive to weakly structured, whole coloured uniform to gradational soil that dominates the mid slopes of the granitic alluvial fans. *Thorpe* has a dark grey to brown sandy loam to sandy clay loam topsoil that grades into yellowish brown or brownish yellow sandy clay loam to sandy clay subsoils. Sand and gravel content typically increases with depth and the soil frequently overlies buried sandy C/D horizons. Fine to medium angular gravels can be found throughout the profile.

Thorpe differs from *Tyson Brown Variant* by its paler or more yellow-brown subsoil colour. *Thorpe* is also usually found in lower slope positions to *Tyson*

Thorpe Sandy Variant (Brown Kandosol) is a well-drained soil found in association with *Thorpe*, although profiles contain a greater abundance of coarse sands and fine gravels throughout.

Thorpe heavy variant (Brown or sometimes Grey Dermosol) occupies relatively lower landscape positions within the alluvial fan. *Thorpe heavy variant* is a structured clay soil, containing a much lower abundance of coarse sands and fine gravels. This soil has dark grey clay loam sandy to sandy light clay topsoil over a yellow brown to greyish brown sandy light to medium clay subsoils.

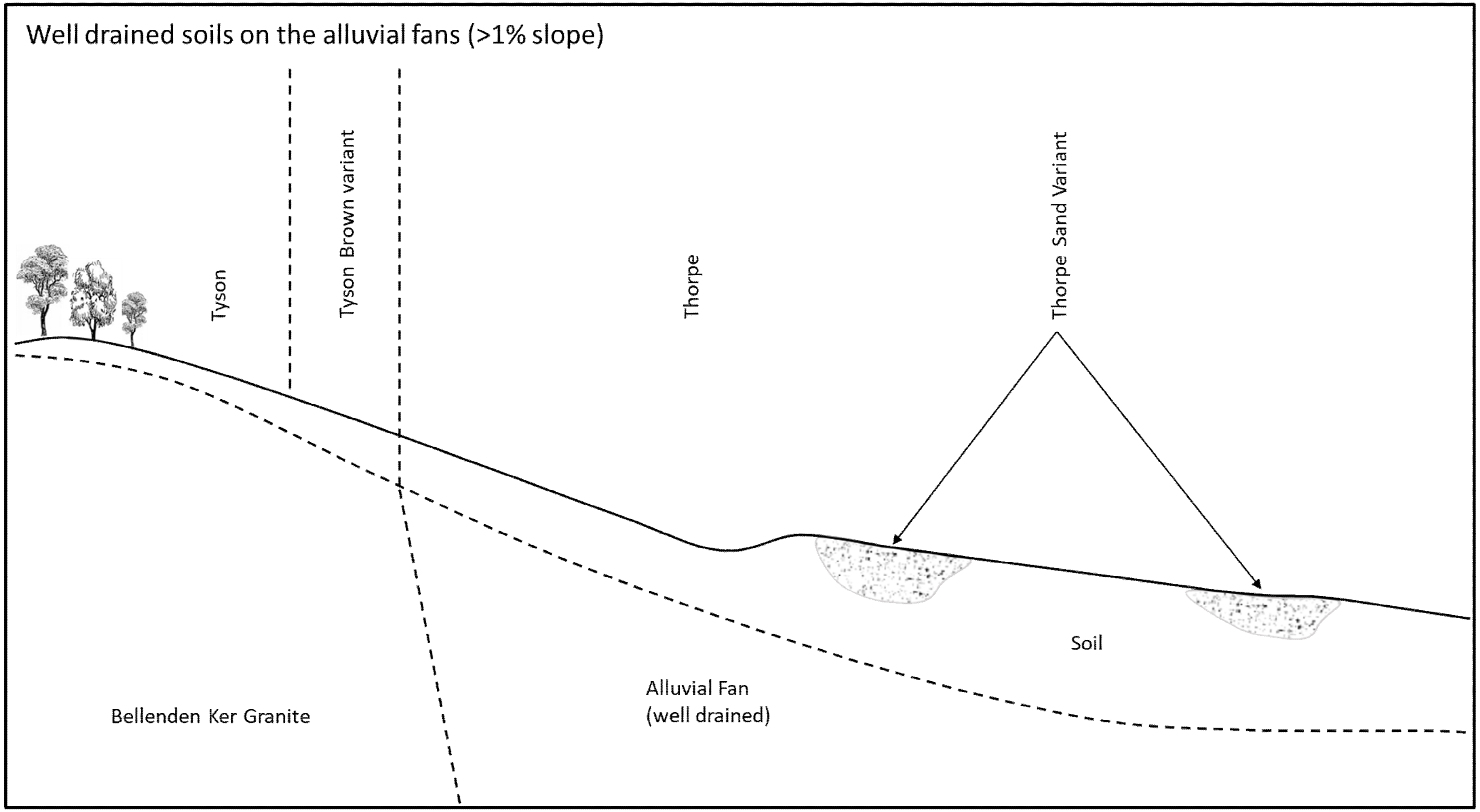


Figure 12: Well drained soils of the alluvial fans

4.2.2. Imperfectly to poorly drained soils of the alluvial fans (<1% slope)

Due to the low slope of areas with these soils, the transition into the floodplain soils can be difficult to determine. Observations have shown that the broader landform tends to be concave, or waning, between upper and lower slope positions rather than the more planar form of the adjacent floodplain soils.

The active nature of stream development and watercourse migrations across the landscape over time has resulted in numerous isolated portions, dissected from the main part of the fans. These can occur as small, almost imperceptible, rises or hummocks with very low elevation, surrounded by lower lying floodplain alluvium or peaty, organic rich soils. In some areas, the extremities of these alluvial fans have been overlain by thin to moderately thick organic (peaty) materials deposited in the former freshwater swamps.

Prior (Yellow or Grey Kandosol) is a deep to very deep, imperfectly drained, massive to weakly structured, uniform, to gradational soil found in imperfectly drained areas on mid to lower slopes of the granitic alluvial fans. *Prior* has a dark grey, sandy loam to sandy clay loam topsoil, and grades to yellow and yellowish grey and grey sandy clay loam subsoils. Subsoils are frequently mottled. Sand and gravel content typically increases with depth and the soil frequently overlies buried sandy C/D horizons. Fine to medium size angular gravels can be found throughout the profile. *Prior* is an imperfectly drained yellow-grey and mottled version of the well-drained, brown *Thorpe*.

Prior sandy variant (Yellow or Grey Kandosol) is an imperfect to well-drained soil found in association with *Prior*, although profiles contain a greater abundance of coarse sands and fine gravels throughout.

Bartle (Brown Kandosol) is a moderately deep to deep, moderately well to imperfectly drained, brown, uniform, massive, sandy clay loam soil associated with infilled prior stream channels on level to very gently inclined alluvial fans. Upper parts of the solum are typically moderately well drained, although subsoils can be imperfectly drained due to being underlain by heavier textured, imperfect to poorly drained alluvium.

Malbon (Yellow or Brown Kandosol) is a deep to very deep, imperfectly drained, gradational, massive to weakly structured soil found on mid to lower slopes of the granitic the alluvial fans. Similar in appearance to the lighter textured *Prior*, *Malbon* comprises dark grey sandy clay loam topsoil, grading to yellow, olive and grey sandy light clay subsoils. Fine gravels occur throughout the profile and mottles are a common feature. In some instances, *Malbon* was found to overlie heavier textured grey clay D horizons or stratified layers of sands and gravels.

Mirriwinni (Grey Kandosol) is a deep to very deep, imperfectly drained, whole coloured grey, uniform to gradational, massive to weakly structured soil found in mid to lower parts of the granitic alluvial fans. The soil comprises a brownish grey clay loam sandy to sandy light clay surface, grading to grey sandy clay loams to sandy light medium clays. Deeper soils comprise stratified grey coarse sandy clay loams and clayey sands. *Mirriwinni* is a gravelly soil containing at least 10–20% abundance of fine and some medium gravels throughout the profile. Three variants of *Mirriwinni* have been identified and mapped.

Mirriwinni Sandy Variant (Grey Kandosol) is an imperfect to moderately well drained, grey, whole coloured, gravelly soil, found in association with *Mirriwinni. Mirriwinni Sandy Variant* appears to be formed on infilled prior streams which have reworked the alluvial fan. The soil comprises a brownish grey sandy loam to sandy clay loam surface, grading to grey sandy clay loams. Deeper soils comprise stratified grey coarse sandy clay loams and clayey sands. This soil contains a higher abundance (20–50%) of coarse sands and fine gravels than *Mirriwinni*.

Mirriwinni Heavy Variant (Grey Dermosol or Grey Hydrosol) is an imperfect to poorly drained, grey, uniform to gradational, clay textured soil found in low-lying, low energy areas about the periphery of the granitic alluvial fans. The soil comprises a brownish grey, sandy light to light-medium clay topsoil over structured sandy light-medium to medium-heavy clay. This soil contains significantly less coarse sand than *Mirriwinni* and only a few (2–10%) fine gravels. Subsoils are typically whole coloured, however a few to common mottles were found at depth in some profiles. Stratified gravelly sands and or clayey textured D horizons have been found to underly this soil at depth.

Lugger (Grey Kandosol or Kandosolic Hydrosol) is a deep to very deep imperfectly drained, grey uniform to gradational, massive to weakly structured soil found in drainage depressions and on the lower terminal margins of the alluvial fans. The soil comprises a very dark to black (non-peaty) sandy clay loam surface, overlying frequently mottled, grey sandy loam to coarse sandy clay loam subsoils. *Lugger* contains few to many fine gravels throughout the profile and typically overlies coarse sandy and gravelly C/D horizons, often stratified. *Lugger* can be likened to a *Mirriwinni*, with a very dark, organic rich surface.

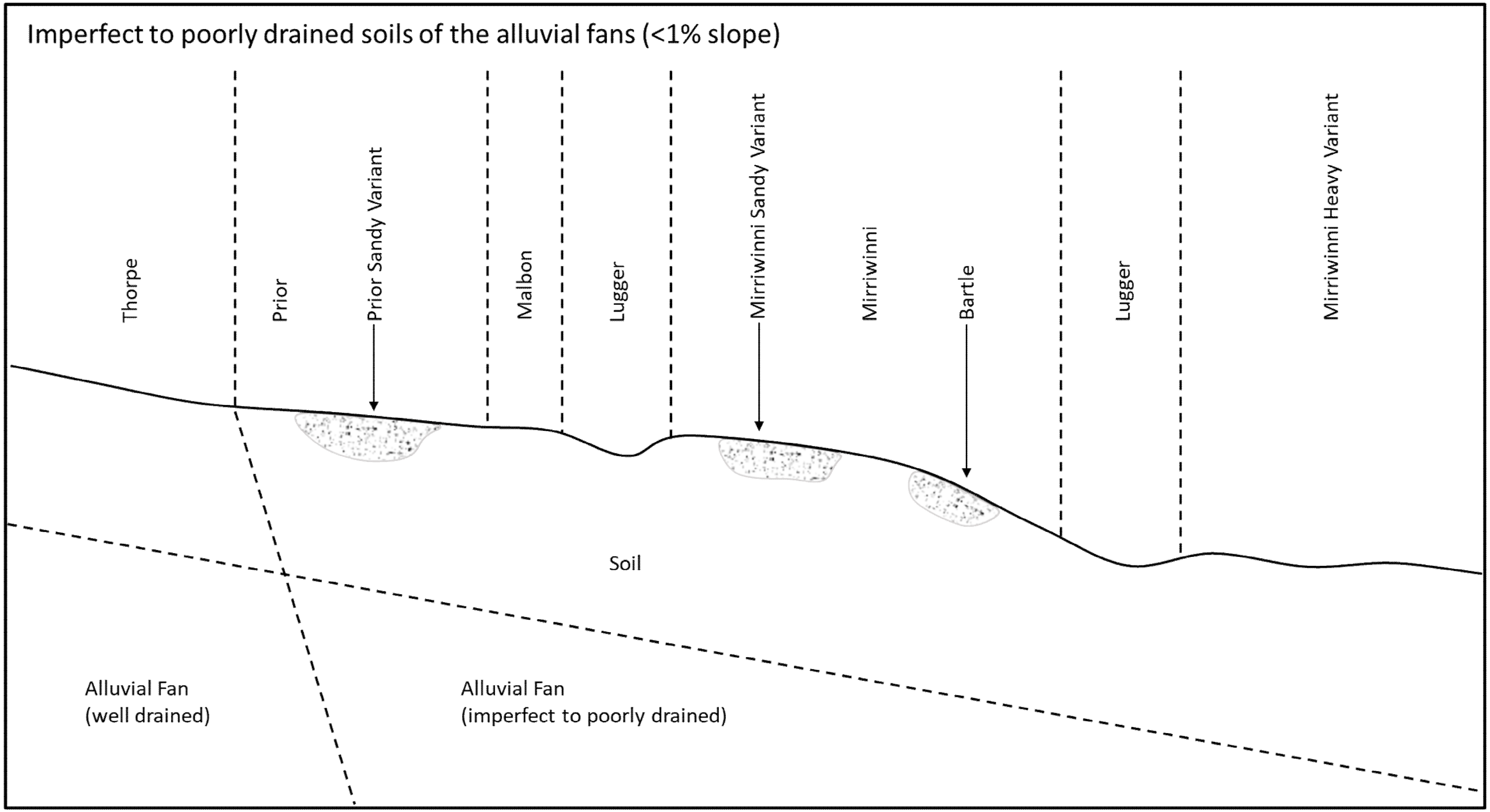


Figure 13: Imperfect to poorly drained soils of the alluvial fans

4.2.3 Poorly drained soils of the buried alluvial fans (<0.5% slope)

These soils were originally formed on very low-angle alluvial fans, however past river migration and associated changes in catchment hydrology have led to extensive areas being overlain by freshwater swamps. Surface organic deposits typically range from thin (around the edges of the former swamp) to moderately deep toward the centre of the swamp.

Lugger peaty variant (Peaty Grey Hydrosol or Organosol) is a deep to very deep, moderately well to poorly drained, *Lugger* soil that has been buried by shallow to moderately deep peaty materials. The peaty overlay is the result of expansion of stagnant swampy conditions over low parts of the alluvial fan. Subsoils contain significant sand and fine gravels, deposited through higher energy sheet wash and alluvial depositional processes. This soil is much more permeable than *Mirriwinni peaty variant* and other surrounding soils of the former freshwater swamps, particularly in areas subject to artificial drainage. Sandier textured subsoils differentiate *Lugger peaty variant* from *Mirriwinni peaty variant.*

Mirriwinni peaty variant (Peaty Grey Hydrosol or Organosol) is a deep to very deep, imperfectly to very poorly drained, *Mirriwinni Heavy Variant* soil that has been buried by shallow to moderately deep peaty materials. The peaty overlay is the result of expansion of stagnant swampy conditions over low parts of the alluvial fans. Subsoils consist of finer textured clay loams and clays, deposited through lower energy sheet wash and alluvial depositional processes on the alluvial fan. *Mirriwinni Peaty Variant* is found in association with the lighter textured, buried, alluvial fan soil, *Lugger Peaty Variant.* Presence of fine angular and subangular gravels throughout the subsoil differentiates *Mirriwinni peaty variant* from *Hewitt*, on buried alluvial backplains (i.e. buried *Timara*).

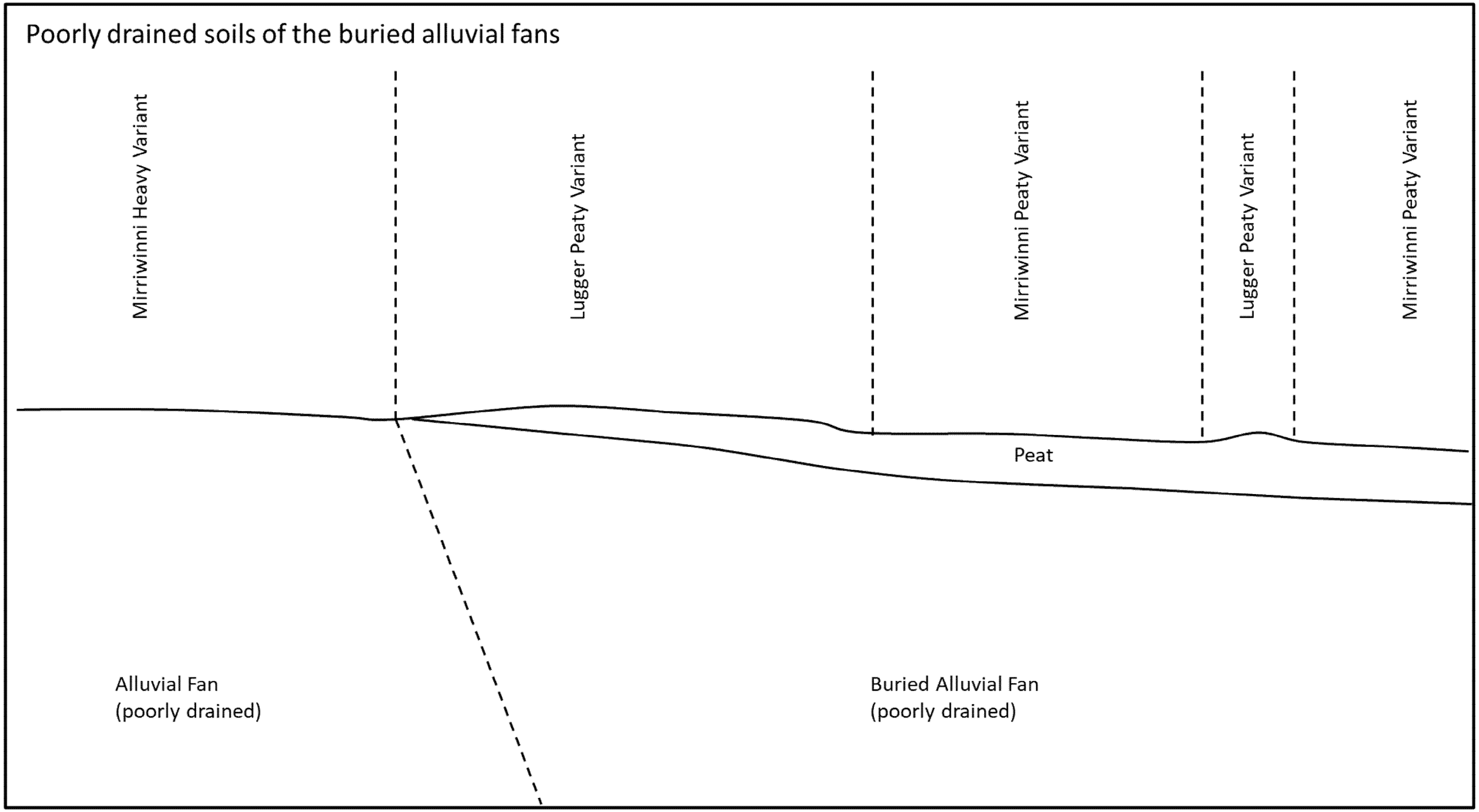


Figure 14: Poorly drained soils of the buried alluvial fans

4.3. Alluvial soils of the levees and backplains

4.3.1 Well drained soils of the levees, terraces and channel benches

Some of the most versatile and resilient soils within the study area occur on the broad, high levees formed by the Russell River and Babinda Creek. These elevated, mostly clay textured soils enjoy favourable drainage and are subject to few or infrequent flooding events or trafficability limitations.

Russell (Brown Dermosol) is a deep to very deep, moderately well drained, brown, whole coloured, uniform to gradational, structured soil found on the undulating crests and backslopes of wide levees formed by the Russell River and Babinda Creek. The soil comprises a dark brown clay loam to light clay topsoil grading to yellowish brown, well-structured clay loam to medium clay subsoils. *Russell* is a newly described SPC analogous to the *Innisfail* soil of Murtha (1986), however the *Innisfail* soil has higher phosphorus buffering capacity *Russell*, which indicates that it may be more influenced by basaltic geology. *Russell* has been mapped across the extent of land originally identified as *Tully* by Murtha, Cannon and Smith (1996).

Russell sites were consistently browner than the yellow *Tully* SPC. Only a few described sites could fit the concept of a *Tully* soil and no polygons have been mapped by this project. These yellower soils may occur as a narrow intergrade between the better drained *Russell* and imperfectly to poorly drained *Coom*.

Russell Mottled Variant (Brown Dermosol) is a deep to very deep, imperfectly drained, brown, uniform to gradational, structured soil found on the backslopes and drainage depressions of wide levees formed by the Russell River and Babinda Creek. A few instances of this soil were also found on older stranded levees within the floodplains and backplains. Upper parts of the profile are moderately well drained and whole coloured brown. Subsoils contain common to many distinct red, orange or yellow mottles, reflecting imperfect drainage conditions. Ferruginous and manganiferous soft segregations were a regular feature in deeper subsoils. *Russell mottled variant* topsoils can in some instances be darker and thicker than the typical *Russell*, particularly where the soil is situated in a swale or drainage depression.

Canoe (Brown Kandosol or Brown Dermosol) is a moderately deep to very deep, well drained, brown, whole coloured, uniform to gradational soil found on gently inclined channel benches, infilled prior streams and undulating levees and scroll plains along Babinda Creek and the Russell River. *Canoe* is a lighter textured and typically massive (apedal) variation of the Russell SPC. This SPC has been expanded to include some shallow structured clay loam textured topsoils overlying sandy to sandy clay loam textured sediments. The soil comprises a brown sandy loam to sandy clay loam topsoil grading to a massive, yellowish-brown or brownish-yellow sandy clay loam to sandy light clay subsoil. It typically overlies buried stratified layers of sands, sandy loams or sandy clay loams within 1.0 m of the surface.

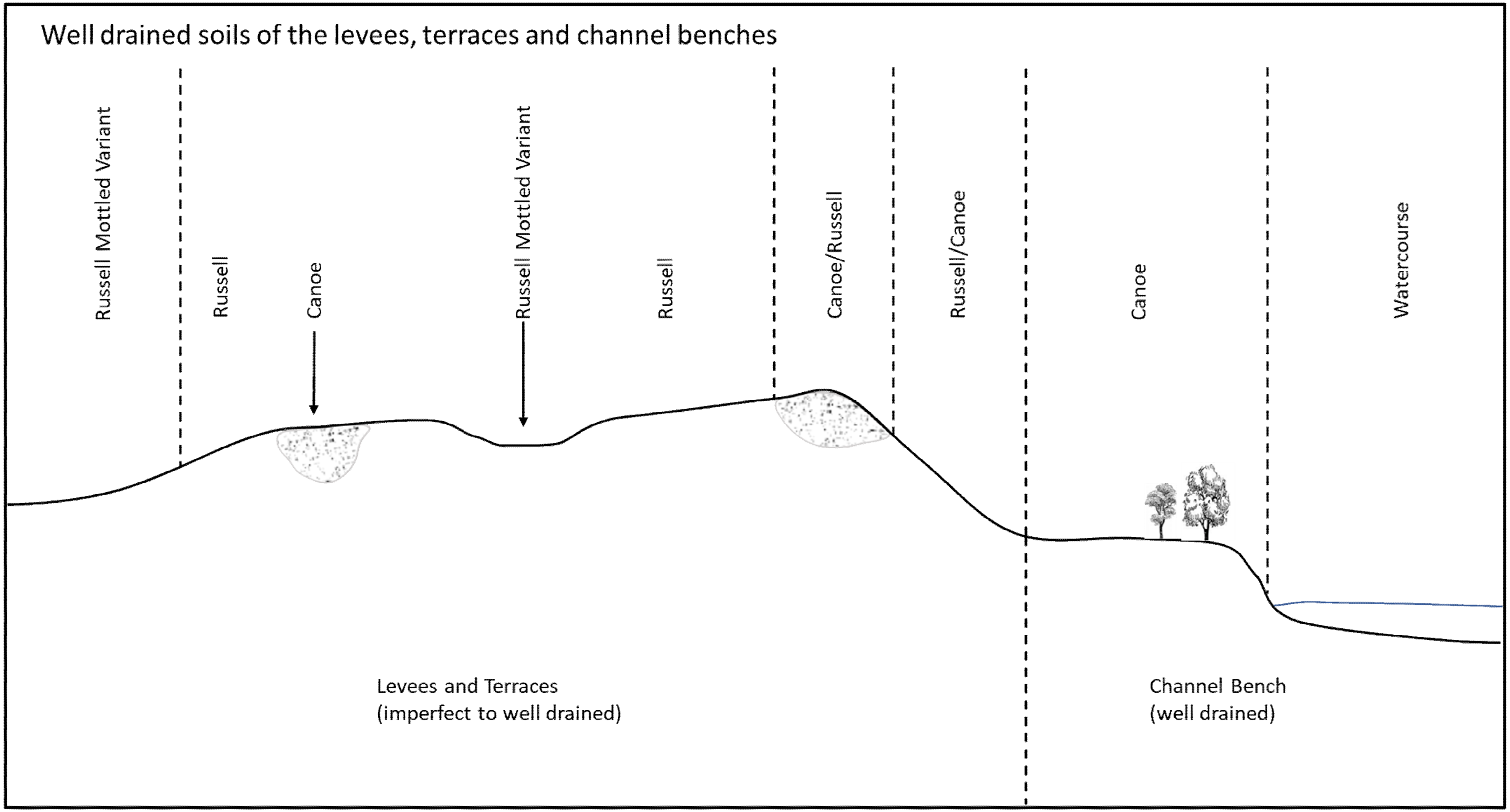


Figure 15: Well drained soils of the levees, terraces, and channel benches

4.3.2. Imperfectly to poorly drained alluvial soils of the levees and backplains

These are the alluvial floodplain soils which, along with the Organosols of the freshwater swamps, form the largest extent of soils found across the project area. Numerous sites had a massive or weak grade of structure in the clayey subsoil. However, this can be attributed to the wetness of the soil masking their structure at the time of their description, as a moderate to strong structure is evident in other drier profiles.

Coom (Dermosolic Grey Hydrosol or Grey Dermosol) is a deep to very deep, imperfectly to poorly drained, greyish brown to grey, uniform to gradational, structured soil, occupying the mid to lower back slopes of levees. *Coom* is an intergrade between the *Russell* or *Russell mottled variant* (levee crests) and *Timara* (levee toeslopes and backplains). The soil comprises dark greyish-brown to brown topsoil grading to mottled, brownish grey, grey or occasionally yellowish brown subsoils. Upper parts of the solum (0–0.5 m) are typically brown and moderately well drained, while subsoils (0.5–1.0 m) are typically mottled, grey and poorly drained. Grey mottles are typical of the subsoil in the upper slope positions, while yellow, red, orange or brown mottles are often encountered throughout the subsoil in the poorer drained areas.

Timara (Dermosolic Grey Hydrosol) is a moderately deep to very deep, poorly drained, grey, uniform to gradational, structured soil, occupying the broad low energy backplains behind the levees. *Timara* is typically found between *Coom* (levee backslopes) and *Bulgun or Hewitt* (periphery of the former freshwater swamps). *Timara* comprises a grey to brownish grey, whole coloured, silty light to medium heavy clay topsoil, overlying grey silty clay subsoils containing yellow, red, brown or orange mottles, that increase in abundance with depth. *Timara* has been found to overlie peat in lower lying positions, adjacent to the former freshwater swamps.

Bulgun (Dermosolic Grey Hydrosol) is a moderately deep to very deep, poorly to very poorly drained, uniform to gradational, structured soil, found in depressions and lower lying poorly drained positions on the floodplain and about the swamp margins. *Bulgun* is typically found between *Timara* and peaty soils of the freshwater swamps. *Bulgun* comprises a very dark and thick, organic rich, clay textured (non-peaty) surface overlying grey, structured, mottled, clay loam to medium clay subsoils. *Bulgun* has been found to overly peat in lower lying landscape positions, adjacent to the freshwater swamps.

Lee (Brown Kandosol or Tenosol) is a shallow to very deep, imperfect to moderately well drained brown to brownish grey, whole coloured, sandy soil on recent alluvium found within the floodplains and swamps. *Lee* appears to be formed on the small low bars and levees of abandoned (prior) streams and may still be forming adjacent some of the larger, present-day drains. *Lee* has been grouped with the poorly drained backplain soils due to its landscape position away from the major watercourses and typical drainage conditions within these low-lying landscapes. *Lee* comprises a uniform brown to greyish brown sandy loam to sandy clay loam. *Lee* is most often found as a thin to moderately deep soil, overlying other poorly drained floodplain soils or peat. Two variants of *Lee* have also been described.

Lee heavy variant (Brown Dermosol) is a shallow to very deep, imperfectly drained, brown to greyish brown, uniform to gradational, structured soil formed on abandoned levees within the backplains and floodplains. Lee heavy variant comprises a moderately deep, dark brown to greyish brown medium clay to 0.5 m, grading to a brownish grey to grey medium clay by 1.0 m. *Lee heavy variant* is most often found as moderately deep soil, overlying other poorly drained floodplain soils or peat. This soil is similar in appearance to the other imperfectly drained levee soil *Coom. Lee* heavy variant can be differentiated from *Coom* by its landscape position within the floodplain and its darker brown, heavier textured and strongly structured surface.

Lee grey variant (Grey Hydrosol) is a shallow to very deep, poorly drained, brownish grey to grey, uniform to gradational, structured soil formed on abandoned levees within the backplains and floodplains. *Lee grey variant* occurs in poorer drained landscape positions in conjunction with *Lee* and *Lee heavy variant.* The soil comprises a grey to dark grey, light to medium clay, grading to grey mottled clay. *Lee grey variant* is most often found as moderately deep soil, overlying peat. This soil is similar in appearance to *Timara. Lee grey variant* can be differentiated from *Timara* by its landscape position, connectivity with other abandoned levees and its strong structure.

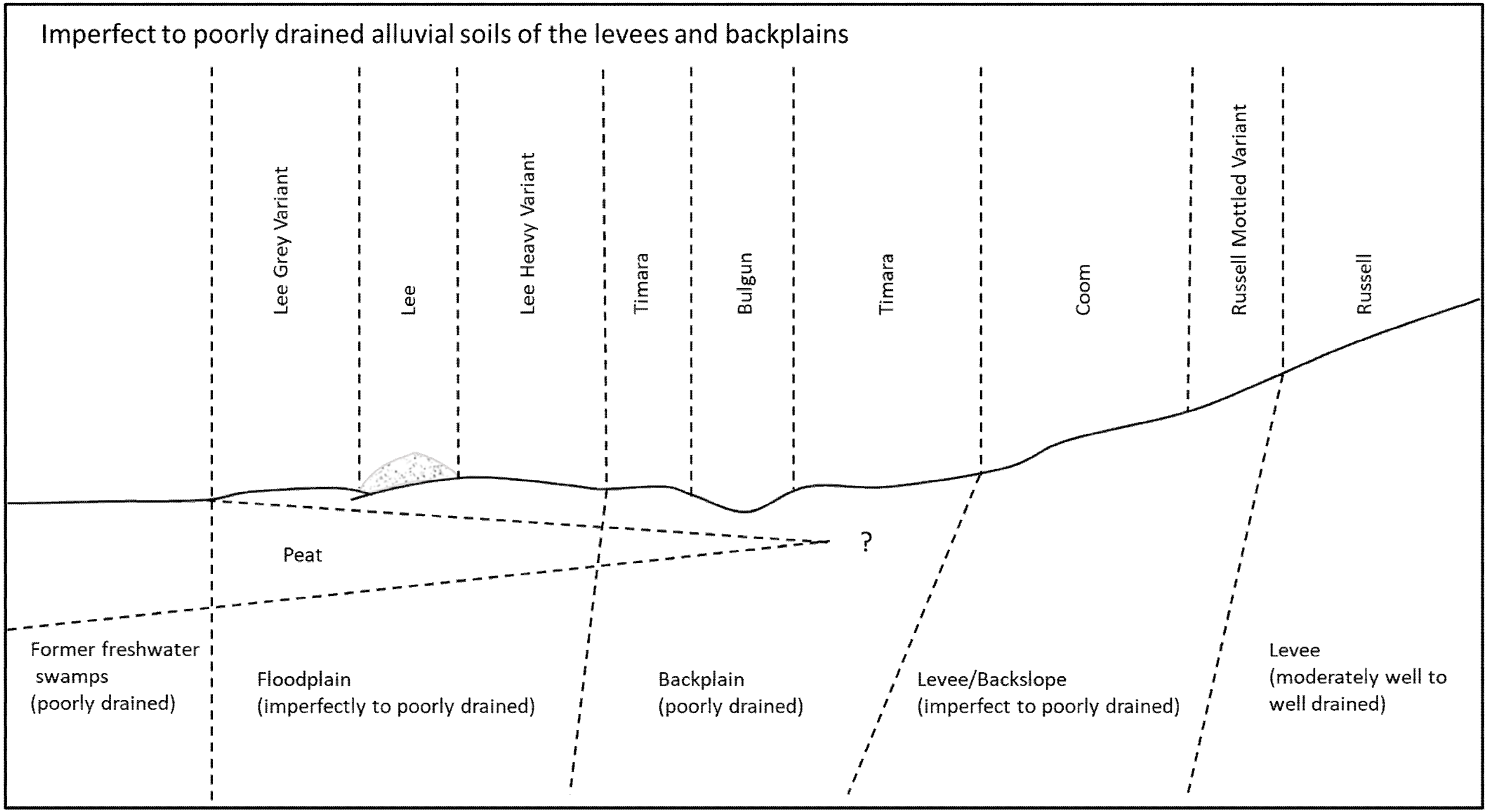


Figure 16: Imperfect to poorly drained soils of the levees and backplains

4.4. Soils of the prior streams

These soils occupy former stream channels or paleochannels that previously dissected the alluvial fans and floodplains. Watercourse migration and associated infilling of these channels has resulted in map units that are typically long, narrow, and sinuous. Coarse textured and highly permeable, sandy, gravelly and peaty textured materials are frequently encountered within the solum. These highly permeable materials can operate as effective conduits for the transmission of subsoil moisture.

Paleochannels are strongly evident in the EMI mapping and typically return a relatively lower ECa response. Sandy and peaty infilled channels are also visible in the walls of deeper drains, where they intersect these features. Paleochannels typically occur as a narrow, in-filled, sandy channels surrounded by broader areas of finer textured materials consistent with paleo-levees. Many of these features have been buried by peat and other floodplain alluvium and would be difficult to delineate without the aid of EMI technology.

In a few locations, these stream-like features returned relatively higher ECa responses than the surrounding landscape. In these areas, subsoils were either wet or contained moist, finer textured materials. Perusal of the historical imagery shows that some of these features correlate with modern waterways that were levelled and straightened in modern times as part of farm development.

Goolboo (Yellow or Brown Tenosol or Kandosol) is a moderately deep to very deep, rapidly drained, brown to yellowish brown, uniform, massive, sandy soil containing common to abundant fine to medium gravels. The soil texture typically ranges between loamy to clayey sands and coarse sands to sandy or coarse sandy loams. In some areas, *Goolboo* was found to overly grey clayey sand or clay C or D horizons.

Derra (Peaty Dermosolic Grey Hydrosol) is a deep to very deep imperfect to poorly drained, yellowish brown to grey, structured, fine sandy clay loam to fine sandy clay soil associated with levees on abandoned, infilled prior streams that have been overlain by shallow to moderately deep peat. This soil comprises a black, granular structured sapric peat, overlaying structured, mottled, yellowish brown to yellowish grey and grey fine sandy light to medium-heavy clay. Due to better structured subsoils, *Derra* tends to be slightly better drained than surrounding peaty soils such a *Hewitt and Wanjuru*. Several *Derra* sites were described as massive, rather than structured. This is the result of subsoil wetness, masking structure that would be present if the soils were dry when described.

Niringa (Hydrosol, Tenosol or Organosol) is a moderately well to poorly drained, sandy textured soil associated with prior stream channels that have been infilled by coarse sandy textured materials and overlain by shallow to moderately deep peat. *Niringa* comprises thin to moderately deep, black granular structured peat to sandy peat overlying grey, greyish brown or brown sand to coarse light sandy loam subsoils. *Niringa* is distinguished from *Derra* by its sandier textured subsoils. In most profiles, a thin horizon of silty grey clay occurs between the peat and sand indicating a brief period of low-energy floodplain deposition prior to deposition of the peat under stagnant conditions.

Niringa is typically classified as a Hydrosol with Tenosolic profile characteristics, or a Tenosol where it cannot meet the wetness requirements for a Hydrosol. It is also classified as an Organosol where it meets the requirement for this Soil Order due to the thickness of the peaty topsoil.

Canoe (Brown Kandosol or thin Brown Dermosol) occurs on channel benches, levees and infilled prior streams. A full description of this soil is provided under well drained soils of the levees, terraces and channel benches (refer to section 4.3.1).

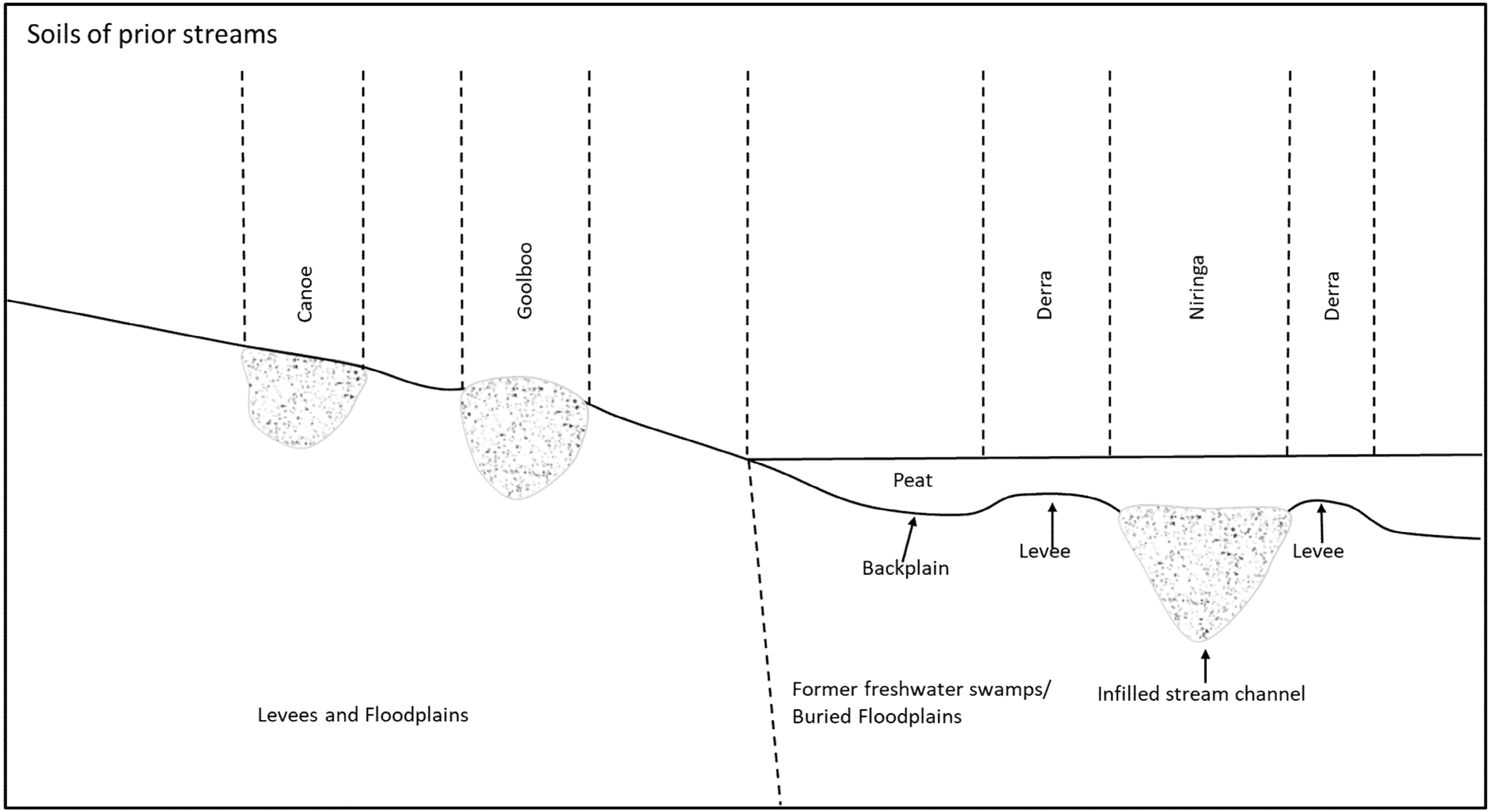


Figure 17: Soils of the prior streams

4.5. Soils of the former freshwater swamps

These soils of the former freshwater swamps contain appreciable peaty organic materials that have accumulated under regular or permanent inundation, prior to drainage for farm development. Soils have been subdivided based on depth of peat overlying the former floodplain landscape. Peaty deposits were typically shallower around the swamp margins and increased in depth toward central parts of the swamp and parts of the floodplain that had had been incised by waterways. These former swamps have been heavily modified with intensive table drainage.

Hewitt (Peaty Hydrosol) is a deep to very deep, poorly to very poorly drained, very dark grey to black, gradational to texture contrast, organic rich, peaty soil, formed around the edges of the former swamps, where silty clay textured backplain soils (e.g. *Timara*) have been overlain by very thin to moderately deep peat infill. This soil comprises moderately thick to thick (≤ 0.4 m), very dark grey to black, silty clay loam to silty clay textured sapric[5] peat with strong granular structure, over grey, structured, and frequently mottled, silty light to medium heavy clay. Observations about the drains indicate that the grey clay subsoils contain a coarse prismatic or columnar structure when dry.

Wanjuru (Organosol) is a deep to very deep, poorly to very poorly drained, very dark grey to black, structured, organic rich, peaty soil, formed around the edges of the former swamps, where silty clay textured backplain soils (e.g. *Timara*) have been overlain by thick peat infill. A deeper version of *Hewitt*, this soil comprises a thick, black, silty clay loam to silty clay sapric peat with strong granular structure to 0.4–0.6 m over mottled, grey or gley, light to medium clays. Thin layers of brown, moist and unstructured hemic or fibric peat were frequently encountered/preserved in this soil between the sapric peat and clay, indicating moist reducing conditions for much of the year.

Layers of yellow to reddish, ashy or black, fusic (charcoal like) material were also encountered in numerous sites. This ash or fusic material was typically found below 0.3 m and is evidence of widespread peat fires that appear have occurred during atypically dry climatic conditions. *Wanjuru* is typically found in toposequence between *Hewitt* (shallow peat) and *Wyvuri* (moderately deep peat).

Wyvuri (Organosol) is a deep to very deep, poorly to very poorly drained, black, structured, organic rich, peaty soil. It is a deeper version of *Wanjuru*, with a moderately deep, black, strong granular structured, sapric peat overlying mottled grey or gley clay between 0.6–1.0 m. Moderately thick layers of brown, moist, unstructured hemic[6] and fibric[7] peat were typically found between the sapric peat and clay, indicating moist, reducing conditions for much of the year. Stratified grey silts and clays may also be present within the peats. Ash or fusic layers like those found in *Wanjuru* were also observed in multiple locations.

Babinda (Organosol) is a deep to very deep, very poorly drained peaty soil overlying stratified gley sands, silts or clays at depths >1.0 m. *Babinda* dominates central parts of the swamp, although, like

[5] Sapric peat – strongly to completely decomposed organic material, plant remains are indistinct to unrecognisable.
[6] Hemic peat – moderately to well decomposed organic material, remains can be recognised as plant material.

Wanjuru and *Wyvuri*, this soil can also be found in depressions and incisions associated with prior streams or paleochannels about the edges of the former swamp.

Babinda comprises a thick to very thick, black, sapric peat with strong granular structure, overlying thick to very thick horizons of brown hemic and fibric[7] peats about the permanent water table. Identifiable plant remains (fibric peat) such as branches, tree and palm trunks were frequently encountered throughout the subsoils. Logs and larger organic detritus were present in drain batters and on the soil surface after deep ripping.

Thin, stratified layers of grey silts and clays were common throughout the solum within these deep peaty soils. These thin clayey textured horizons may have been deposited during larger flood events. High permanent watertables are a common feature of the *Babinda* soil, despite extensive drainage works.

[7] Fibric peat – undecomposed or weakly decomposed organic material, fibrous plant remains can be readily recognised.

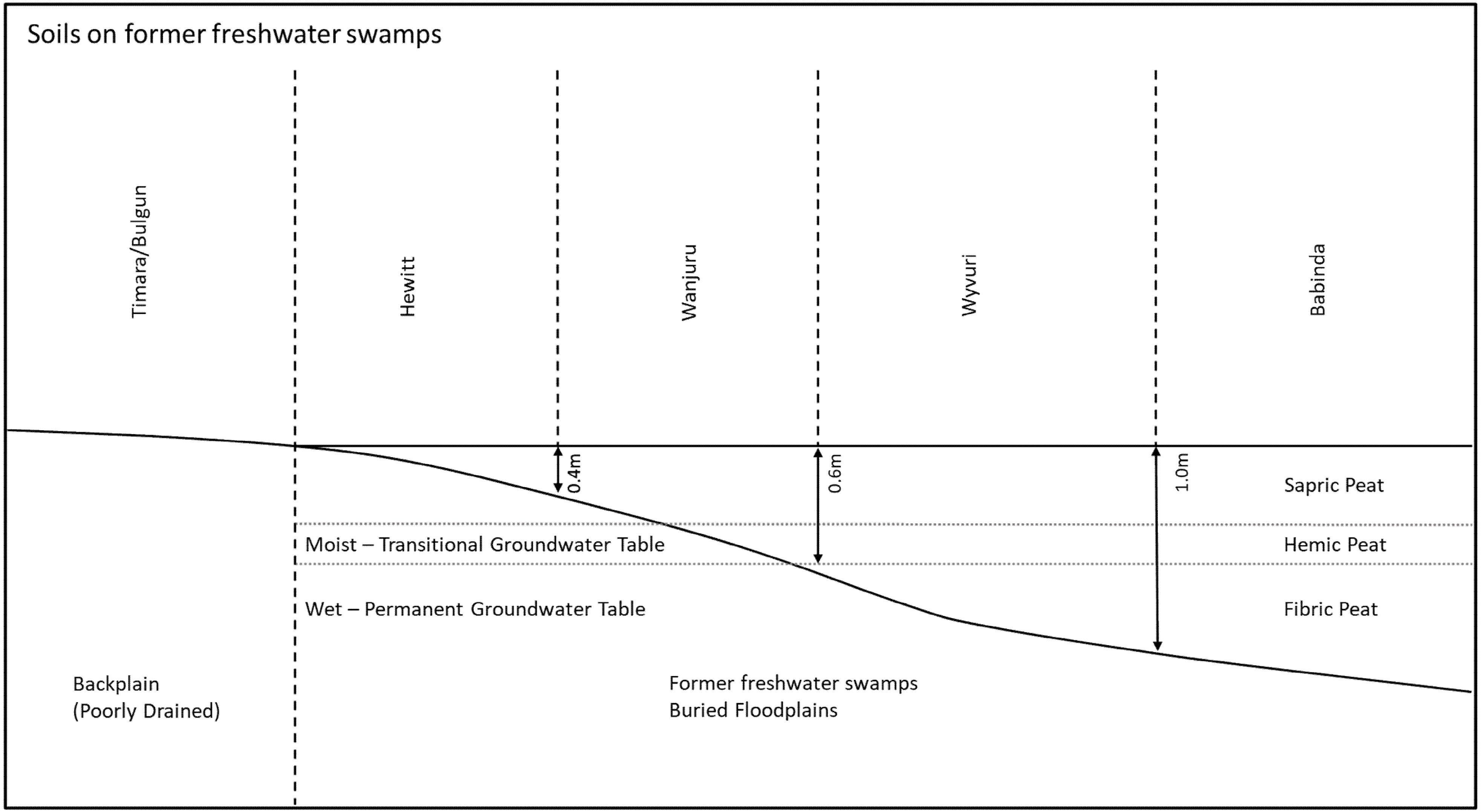


Figure 18: Soils of the former freshwater swamps

5. Soil attributes

This section describes the range of physical and chemical properties that are relevant to land and nutrient management across the study area. A soil attribute is an inherent property of the soil/landscape that can influence land use, land management and inputs (e.g. fertiliser). The eleven attributes described below have been selected to help growers and agronomists manage on-farm land management along with fertiliser and soil conditioner inputs. These attributes were developed in consultation with sugar industry scientists, agronomists, soils personnel and other land management experts. Several of these have been adapted from Calcino *et al*., 2022; Schroeder *et al*., 2007; Sugar Research Australia, 2022. The attributes are:

- Soil organic carbon (SOC)
- Nitrogen leaching potential (NL)
- Denitrification potential (ND)
- Phosphorus sorption (PS)
- Cation exchange capacity (CEC)
- Soil pH (pH)
- Aluminium saturation (AS)
- Calcium deficiency (CD)
- Surface soil texture (ST)
- Wetness (W)
- Flooding (F)

As part of the mapping process, soil attribute information was added to the soil mapping polygons, to enable generation of individual soil attribute layers. The intensive mapping and detail provided in these layers has been designed to assist growers and their advisors with development of soil and landscape attribute-based application rates for fertilisers and other inputs. It is noted that whilst many of these soil attributes are relatively stable, or change very slowly over time, others such as pH, CD and AS can be transient, and depend heavily upon practice and inputs (e.g. agricultural lime). This information should be considered as baseline data, collected at a point in time, and does not replace requirements for ongoing soil testing.

5.1. Soil organic carbon (SOC)

Organic matter (OM) is crucial to the maintenance of soil health, productivity, and profitability. The soils of the Wet Tropical Coast tend to be acidic and strongly leached, with a low CEC and limited ability to retain applied nutrients. The very wet, humid conditions experienced across the area are conducive to the build-up of large amounts of organic matter. Soils with higher levels of OM generally have a higher CEC, with a greater capacity to hold onto and subsequently make applied nutrients available for crop use (Calcino *et al*., 2018). This process occurs through direct adsorption into soil organic matter via plant growth, and the cycling of detritus (e.g. green cane trash, legume cover crop residue) by soil biota. The decay of the organic detritus slowly liberates nutrients, including dissolved inorganic nitrogen (DIN) and helps to supply the crop with nutrients over the growing season. This is an important component of nitrogen (N) mineralisation.

OM levels in the soil can be difficult to quantify, however SOC is used as a surrogate measure (Calcino *et al*., 2022). It is an important attribute as a direct relationship has been established between SOC and N mineralisation occurring during the process of OM break down.

The N mineralisation potential of soil is reasonably well understood. SRA has developed thresholds and suggested N application rates for sugarcane crops based on organic carbon (OC) percentages in topsoil. The categories of the SOC attribute layer applied here are based on the N mineralisation index identified in Schroeder *et al*. (2007) for the Johnstone River Catchment. This attribute uses SOC % in the topsoil (plough layer).

The N mineralisation indices from Schroeder *et al*. (2007) were chosen as most appropriate, as the Johnstone River Catchment adjoins the Russell Catchment. Both have similar climatic conditions and crop production potentials. Research underpinning these indices shows that where appreciable levels of organic carbon are present in topsoil, productivity can be maintained with lower inputs of N fertilisers. Maintaining yields with less fertiliser N inputs is important in terms of improving industry profitability and sustainability while minimising potential offsite DIN losses. The N mineralisation index for different levels of topsoil SOC is set out in Table 5 below.

The SOC lookup table (Table 5) is designed to aid in identifying recommended N applications rates, matching N mineralisation index to organic carbon %. Refer to Schroeder *et al*. (2007) or Sugar Research Australia (2022) to identify the recommended N application rates for the corresponding SOC category.

The presence of higher SOC levels can result in appreciable savings in terms of lower N inputs, whilst returning similar yields. There is a greater availability of N present in soils with higher SOC, resulting in less N fertiliser application requirements. In cases where SOC exceeds 2.4%, this can equate to an estimated saving of 60 kg/ha/year or as much as 37.5% on N fertiliser costs.

The SOC layer can be used to guide N application rates as part of whole of farm nutrient management plans. However, it does not replace the requirement for regular soil testing and specialist nutrient management advice. Specialist advice should be sought where the presence of other limitations may reduce crop responsiveness to applied N.

For instance, soils with low or very low organic carbon levels may be sandy and rapidly drained, and subject to other soil limitations. In these circumstances, low soil moisture content and nutrient leaching could be the dominant factors limiting yield potential. Soils with very high OC also tend to be prone to other severe limitations like waterlogging or flooding. These deep accumulations of organic matter are only possible under very wet or saturated conditions. Nitrogen efficiency in these soils can be highly variable depending on drainage status in the upper 0.5m.

Where compounding limitations apply in the paddock, consideration should be given to additional management practices needed to overcome these other limitations. This should be undertaken in conjunction with practices aimed at the continual build-up of OM from cane trash, green manure cover crops, and other sources (e.g. mill by-products). Practices that could result in a reduction or removal of organic matter should be minimised or avoided. Minimum tillage or zonal tillage practices and permanent bed systems can minimise losses of organic SOC at planting. On-farm evaluations of N requirements should also be considered and are an important component of adopting the SIX EASY STEPS® approach to sustainable nutrient management.

Table 5: Soil organic carbon (SOC) categories

SOC category	Topsoil organic carbon % (Walkley and Black method 6A1)	N mineralisation Index
1	<0.4%	Very low (VL)
2	0.4–<0.8%	Low (L)
3	0.81–<1.2%	Moderately low (ML)
4	1.21–1.6%	Moderate (M)
5	1.61–2.0%	Moderately high (MH)
6	2.01–2.4%	High (H)
7	>2.4%	Very high (VH)

Note: Modified from Table 2.1. N mineralisation index of Schroeder *et al*. (2007).

5.1.1. Determining soil polygon SOC category

Analytical results of topsoil OC % (Walkley-Black method) were used to identify the applicable median SOC category for each soil profile class. Atypical results, found in certain areas were adjusted manually based on the chemistry data. In areas cases, and where measurements of OC % were not available, polygons were adjusted according to site observations of topsoil colour and texture from the site data and photos of the profile

5.2. Nitrogen (N) loss

Identifying the potential for N loss is a qualitative assessment of two important N loss pathways in soils. The first relates to how susceptible a soil is to the leaching of water-soluble N fertiliser beyond the root zone—nitrogen leaching potential (NL). The second relates to the potential for denitrification and atmospheric losses from soils that experience prolonged saturation—denitrification potential (ND).

Monitoring and trials carried out in the nearby Silkwood area (Masters *et al*., 2017) found that deep drainage (leaching) is an important N loss pathway. However, a significant decrease in this type of loss was observed between planting and ratoon crops, attributed in part to better plant root development with increased N uptake in later ratoon crops. Like the Babinda Swamp area, a high seasonal water table is characteristic of the Silkwood study area, where much of the N lost to leaching was found to be entering the local drains through lateral flow. While leaching losses proved to be significant, greater losses were attributed to denitrification due to prolonged seasonal saturation.

The NL and ND categories allocated to soil mapping polygons are outlined in Table 6 and Table 7. NL considers the potential for N losses leaching down through the soil profile to a depth that is beyond the crop's main uptake root zone (>0.5 m). Soluble N-based fertilisers can move more readily through highly permeable, low CEC soils, presenting a higher risk from leaching.

The ND attribute is the potential for denitrification losses within the upper 0.5 m of soil due to prolonged wetness or waterlogging. Denitrification can occur under anaerobic (low oxygen) conditions, causing microbial activity to convert inorganic N into a gas, and allowing it to escape into the atmosphere. Denitrification will be more pronounced in areas that experience prolonged seasonal saturation due to relatively low landform, high groundwater tables or flooding.

To reduce the potential or NL and ND losses, and to improve crop N uptake efficiency, growers and agronomists are encouraged to consider adjusting management practices where the potential for NL or ND losses are high or very high. Various techniques are available to minimise N losses (Danielle Skocaj, SRA, personal communication, August 2022). These include: applying fertiliser when the risk of heavy rainfall is low, split applications and timing applications to match crop N demand; use of slow-release granular fertilisers; subsurface fertiliser application; and improvements to drainage such as land levelling and increasing plant mound height.

Table 6: Nitrogen leaching potential (NL) categories

NL category	Potential for N loss by leaching below 0.5 m
1	Very low
2	Low
3	Moderate
4	High
5	Very high

5.2.1. Determining soil polygon nitrogen loss (NL) category

The applied NL categories consider the potential for losses from deep drainage and leaching, based on observations of soil properties used to determine permeability (rate of water transmission) through the soil profile. Both the soil physical indicators of permeability (texture and structure) and chemical properties that can indicate the soil's capacity to adsorb applied nutrients (pH, CEC, organic carbon) were considered during the assignment process. In this catchment, soils with a high NL potential tend to be those well drained, sandy soils with low CEC and OC. It is noted that strongly structured clay soils can also be prone to nutrient leaching.

Categories applied to the mapping polygons are based on the likelihood that N would leach beyond the main uptake root zone (greater than 0.5 m). SPCs were used to populate the NL categories in the first instance, however consideration was also given to site permeability and areas with a low ECa response in the EMI mosaic (PRP2 & HCP1).

Table 7: Denitrification potential (ND) categories

ND category	Potential for N loss by denitrification in the upper 0.5 m
1	Very low
2	Low
3	Moderate
4	High
5	Very high

5.2.2. Determining soil polygon denitrification (ND) category

The ND category was based on an assessment of the likelihood of prolonged wetness in the upper 0.5 m of the soil profile, where N fertiliser is applied. The assessment was made using soil properties indicating wetness within the top 0.5 m of the soil profile. These properties included soil colour, mottling and drainage characteristics. Relative landscape position and observations of the water table in adjacent drains were also considered.

Observations were considered alongside EMI measurements from the upper two EMI sensor depths (PRP1 - plant mound, and PRP2 - 0 to 0.5 m). High ECa responses, indicating soil wetness in the dry season, assisted with delineating areas prone to prolonged wetness in upper parts of the profile.

5.3. Phosphorus sorption (PS)

Phosphorus (P) sorption, often termed fixation, influences the availability of P in soils for plant use. A soil with high P sorption will require higher P fertilizer applications to ensure sufficient P is available to meet crop requirements. The strength of a soil's P sorption is determined by analysing its phosphorus buffering index (PBI).

For ease of management, five P sorption categories have been adopted (Table 8) based on the PBI and sorption classes of Calcino *et al*. (2022) and Schroeder *et al*. (2007).

For guidance on P application rates, the sorption categories should be used in conjunction with plant available soil P tests (P_{BSES}) to determine the recommended rates suggested in Calcino *et al*. (2022) or Schroeder *et al*. (2007). Growers should seek specialist advice if soils are found to be in the very high category.

Table 8: Phosphorus sorption (PS) categories

PS category	PBI	P sorption class
1	<140	Low
2	140–280	Moderate
3	281–420	High
4	421–1000	Very high

5.3.1.Determining soil polygon phosphorus sorption (PS) category

The PS attribute layer was created based on laboratory results (PBI) from bulked 0-0.2 m depth sampling across the project area. Areas with no sample sites were extrapolated based on soil profile class with added consideration given to other important, related attributes, including OC, texture, and pH.

5.4. Cation exchange capacity (CEC)

Cation exchange capacity (CEC) is a measure of a soil's capacity to hold exchangeable cations (Rengasamy & Churchman, 1999). It is an indicator of the general fertility of a soil, and its capacity to supply nutrients for cycling and plant uptake. CEC affects a soil's nutrient availability, structural stability, pH, buffering capacity and the effectiveness of fertilisers or ameliorants (Calcino *et al*., 2022).

CEC is influenced by many factors including clay content (%), clay type, soil pH and organic matter content (Brown & Lemon, 2019). In general terms, soils with high organic matter or those dominated by finer clay sized and silt sized particles will have higher CEC's. CEC is typically lower in soils with low organic matter or those dominated by sandier, coarser sized particles.

CEC is used here as a generic term. It may be directly measured in the laboratory as a total of all exchangeable cations along with the four major exchangeable cations—calcium (Ca^{2+}), magnesium (Mg^{2+}). potassium (K^{+}) and sodium (Na^{+}). In the absence of a total CEC measurement, it is estimated by summing the individual analysed cations.

CEC is expressed as an effective cation exchange capacity (ECEC) in strongly acidic soils (pH 1:5 soil:water <5.5). This calculation is made by summing the four major cations together with exchangeable aluminium (Al^{3+}) and hydrogen (H^{+}) to account for the contribution of exchangeable acidity. These latter cations become the dominant ions with increasing acidity. For other soils that are not strongly alkaline, the sum of the four major cations will typically be close to the actual measurement of CEC. However, in this case it should be expressed simply as a total of the base cations.

Other cations often found with the laboratory analysis include the micronutrients copper (Cu^{2+}), zinc (Zn^{2+}), manganese (Mn^{2+}) and iron (Fe^{2+}). These micronutrients are reported in milligrams per kilogram (mg/kg) rather than the centimoles per kilogram (cmol/kg)[8] used for the major cations. They are not usually discussed in terms of CEC and tend to only be measured at the surface. These and any other minor cations can make up the difference between a direct measurement of CEC and the sum of the major cations. Determining their contribution to CEC will need a conversion of their units of concentration, however it will typically be very low or negligible.

Four CEC categories have been used to represent CEC in this study (Table 9), following the classes set out in Schroeder *et al*. (2007). The soils across the Wet Tropical Coast are generally found to have low CECs compared to drier, inland areas. This is due to sandy textures and the high rate of weathering these soils are subjected to in the study area (Schroeder *et al*., 2007).

Table 9: Cation exchange capacity (CEC) categories

CEC category	Topsoil CEC (cmol/kg)	CEC class
1	≤2	Very Low
2	2.01–4	Low
3	4.01–8	Medium
4	>8	High

Note: 1 cmol /kg = 1 meq/100g = 1 me%

5.4.1.Determining soil polygon CEC category

The CEC attribute layer was created based on laboratory results from bulked 0-0.2 m depth sampling across the project area. Polygons were first assigned based on the median value for each SPC, Polygons containing outlier values that fell outside the median category were then adjusted manually along with any immediately adjoining areas of the same SPC. In some areas, consideration was also given to grower liming practice as high calcium levels in some areas strongly influenced CEC.

5.5. Soil pH

Wet and humid conditions of the Wet Tropical Coast have resulted in soils that are typically acidic. This condition is exacerbated by conventional farming practices, leading to the further acidification of the soil. For example, by the addition of acidifying fertilisers such as urea or ammonium-based N fertilisers (Gazey & Azam, 2018; Moody & Aitken, 1997). These wet conditions are also conducive to accumulations of organic matter and organic acids formed during decomposition, and the replacement of other cations with acidifying ions such as H^+.

Soil pH is the single most important soil chemical property indicative of a soil's health and productive capability. Measures to address pH imbalances have both a direct and indirect effect on a range of

[8] Laboratory analysis of soil CEC, and major cations, is reported in centimoles per kg of soil (cmol/kg) (Rayment & Lyons, 2011). In the past it has been expressed in milli-equivalents per 100 grams (meq/100g) of soil, such as with the CSIRO soil surveys undertaken across the Wet Tropical Coast. Meq/100g is equivalent to cmol/kg, which are also equivalent to me% used in publications such as Schroeder *et al*. (2007) and Calcino *et al*. (2022).

other soil conditions which affect crop growth. pH is considered here in conjunction with two other important and interrelated properties that can act as constraints to sugarcane production systems: aluminium saturation (AS) and calcium deficiency (CD).

Soil pH extremes can result in a reduced availability of many important plant nutrients. Soils with a pH (1:5 soil:water) <5.5 are also associated with increasing levels of elemental toxicity, for example toxic concentrations of aluminium (Al) and manganese (Mn).

Regular soil testing is important to ensure that rates of neutralising soil conditioners (e.g., agricultural lime) are sufficient to maintain soil pH within the target range. In addition to direct interventions with neutralising agents, use of nitrate-based fertilisers and split applications should also be considered to reduce the rate of soil acidification.

The purpose of the pH attribute is to provide a baseline from which the monitoring of this condition and the effectiveness of management measures can be undertaken. Six categories for the soil pH attribute have been identified (Table 10) based on the pH ratings of Rayment & Lyons (2011).

Table 10: pH categories

pH category	Topsoil pH range (1:5 soil:water)	pH rating
1	<4.5	Extremely acid
2	4.5–5.5	Strongly acid
3	5.51–6.5	Acid
4	6.51–7.3	Neutral
5	7.31–8.4	Alkaline
6	>8.4	Strongly alkaline

5.5.1.Determining soil polygon pH category

Soil pH categories were assigned to soil mapping polygons based on laboratory results and field tests of soil pH for sampled and described sites. Areas with no sample sites were extrapolated based on SPC. In some instances, farm boundaries were considered due to differences in liming practices between growers.

5.6. Aluminium saturation (AS)

Aluminium saturation (AS) is included in this study to indicate the risk of aluminium (Al^{3+}) toxicity as a constraint to crop growth in acidic soils. A strong relationship between pH and exchangeable aluminium percentage has been found to occur (Ringrose-Voase *et al*., 1997). Strongly acidic soil conditions deleteriously impact nutrient availability, and when soil pH falls below 5.5 (1:5 soil:water), availability of the phytotoxic Aluminium (Al^{3+}) cation increases. AS is the degree to which the 'exchange complex' is dominated by Al^{3+}. It is determined numerically by calculating the percentage of exchangeable Al^{3+} as a proportion of the Effective Cation Exchange Capacity (ECEC).

Aluminium toxicity impacts shoot and root growth and development, plant cell division, cellular respiration and function, photosynthesis, and the uptake of water and nutrients (Mantovanini *et al*., 2019; Oliveira *et al*., 2021; Pimenta *et al*., 2020). While sugarcane itself is relatively tolerant to aluminium, legumes commonly used as rotational cover crops can be severely affected (Calcino *et al*., 2022; Di Bella *et al*., 2009; Schroeder *et al*., 2007).

Nutrient availability varies with pH. At low pH, some nutrients become available and some become highly available to the point of toxicity. In strongly to extremely acidic soils, Al^{3+} and H^{+} (exchangeable acidity) become the dominant cations. Beneficial cations such as calcium (Ca^{2+}) are replaced on the 'exchange complex' and may then become susceptible to leaching losses (Calcino *et al*., 2022; Schroeder *et al*., 2007). Aluminium, in addition to iron, also contributes to P sorption, reducing this nutrient's plant availability (Hall, 2008).

The AS categories used in this study are shown in Table 11. These were determined in consultation with SRA. For most plant species, the optimal plant health and growth threshold regarding aluminium saturation is around 5% or less (Di Bella *et al*., 2009; Hazelton & Murphy, 2007). This project has applied 10% aluminium saturation as a minor constraint as this is an approximate threshold for soybeans, a rotational legume crop commonly grown between sugarcane cropping cycles. The 20% threshold was assigned as cowpea and other more tolerant legumes are constrained beyond this level. The performance of sugarcane crops is likely to be affected where aluminium saturation exceeds 50% (partly in response to greatly reduced levels of Ca in the soil which is essential for sugarcane growth). However, more research into sugarcane yield response in relation to aluminium saturation would be beneficial to further refine these thresholds.

Table 11: Aluminium saturation (AS) categories

AS category	Topsoil aluminium saturation %	Aluminium saturation constraint rating
1	≤5%	Nil, no constraint
2	5.01–10%	Minor
3	10.01–20%	Moderate
4	20.01–50%	Severe
5	>50%	Very Severe

5.6.1. Determining soil polygon aluminium saturation category

Analytical results of topsoil AS were used to identify the applicable median AS category for each soil profile class. Atypical results found in certain areas were dealt with through manual adjustments to the polygon attribute code. In some areas, where measurements of AS were not available, polygons were adjusted according to field pH.

If pH is above 5.5, it was assumed that the AS was category 1 or less than 5%. AS was calculated for samples tested for exchangeable Al, where pH (1:5 soil:water) was <5.5. For polygons where exchangeable Al was not measured, this attribute was estimated by correlation with available pH test results based on pH 5.0-5.5 as minor (category 2), pH 4.5-5.0 as moderate (category 3), and anything less than pH 4.5 as severe (category 4). In the absence of chemistry or site data, AS was based on the median value for that SPC.

5.7. Calcium deficiency (CD)

Calcium (Ca) is essential for soil health, helping maintain good soil structure and providing plants with essential nutrients (Hall, 2008). Ca is a common exchangeable base cation found in soils which can be readily supplemented from sources such as limestone and gypsum (Schroeder *et al*., 2007). Exchangeable Ca is influenced by several factors including parent material, soil type and texture, agricultural applications, crop uptake and removal, rainfall, soil pH or acidification (Di Bella *et al*., 2009; Jacobsen *et al*., 1992; Schroeder *et al*., 2007). In strongly acidic (pH 1:5 soil:water <5.5) soils, Ca becomes readily replaced on the cation exchange sites by Al and H, leading to deficiencies.

Sugarcane requires Ca as it forms part of the cell walls, helps genes operate, supports the growth and development of the plant, leaves and roots, assists nitrogen metabolism and is required by legume break crops for nodulation and nitrogen fixation (Calcino *et al*., 2022; Jacobsen *et al*., 1992; Schroeder *et al*., 2007). Many sugarcane growing regions are commonly deficient in Ca (Calcino *et al*., 2022).

Exchangeable calcium is used as a measure of Ca deficiency here as it was found to provide a more reliable indicator of potential sugarcane yield response to lime applications than pH or acidity through the Mossman to Tully region (Calcino *et al*., 2022). This is due to the region’s lower levels of subsoil Ca than generally found across other cane growing regions, where both pH and Ca need to be considered.

Calcino *et al*. (2022) and Sugar Research Australia (2022) provide recommended liming rates based on exchangeable Ca. Yield response curves presented by Calcino *et al*. (2022) identified a critical Ca lower level as 0.65 meq%, and an upper marginal benefit level of 2.0 meq%. Below 0.65 meq%, a response to liming will occur, between 0.65 and 2.0% maintenance applications are recommended to avoid limiting yields. There is no liming requirement recommended for Ca levels >2.0 meq%. Liming rates are also recommended to be reduced when mill mud or mill ash is also being applied.

Based on the information presented by (Calcino *et al*., 2022), four CD categories have been applied by this study (

Table 12). The aim was to identify where liming effort should be concentrated. Refer to Calcino *et al*. (2022) or Sugar Research Australia (2022) for recommended liming requirements specific for measured exchangeable Ca.

Table 12: Calcium deficiency (CD) categories

Category	Topsoil Ca (cmol/kg)	Calcium deficiency rating
1	<0.65	Critical
2	0.65–1.5	Deficient
3	1.51–2.0	Marginal
4	>2.0	Sufficient

Note: 1 cmol /kg = 1 meq/100g = 1 me%

5.7.1. Determining soil polygon calcium deficiency category

To populate the CD layer, laboratory results were divided into the

Table 12 categories that were then applied to respective soil polygons with sample sites. For polygons where calcium measurements were not available, the category was estimated based on a correlation to observations of soil type, texture and pH. In some instances, farm boundaries were considered due to differing liming practices between growers.

5.8. Surface soil texture (ST)

Surface soil texture (ST) is useful in terms of communicating aspects important to land and nutrient management practice. Texture is a key property influencing nutrient loss pathways. It aids the determination of other attributes, limitations or constraints, such as CEC, in the absence of direct measurements. It can be used to guide machinery access and cultivation decisions. For instance, heavy machinery access may be constrained on some peaty soils, and interrow ripping to improve water penetration may not be necessary on deep, permeable sandy or peaty soils.

Four ST categories are used (Table 13Table 13), relating to the broad texture groupings applicable to the topsoil found in the soil mapping polygons.

Table 13: Surface soil texture (ST) grouping

ST category	Soil texture group
1	Peaty, dominated by organic materials
2	Sands to sandy loams (<20% clay)
3	Loam to clay loams (20–35% clay)
4	Silts and clays (>35% clay)

5.8.1. Determining soil polygon surface texture category

The ST attribute was populated from soil field textures undertaken at soil observation sites along with textures derived from particle size analysis. Where mixing between surface and subsurface soil had occurred, an ‘averaged’ texture of the mixed material was used. Where no texture observations were available, texture was assigned based on observations and modal texture for the soil profile class allocated to the mapping polygon.

5.9. Wetness (W)

Soil wetness or waterlogging is a significant limitation to sugarcane in some parts of the Wet Tropics. Under wet conditions, root systems are typically shallower, experience poor aeration, increased disease pressure, and temperatures up to 4 degrees cooler than in well-drained soils. In addition, nitrification of soil organic matter is likely to be supressed and denitrification of nitrate from applied fertiliser increased, resulting in reduced nitrogen uptake by the crop. This is primarily responsible for yellowing in waterlogged cane (Ridge & Reghenzani, 2000).

Sugarcane is a crop that can tolerate wet conditions and some periods of saturation, however prolonged waterlogging will result in significant yield decline. Young roots of plant and early ratoon cane can be permanently injured by relatively short (approximately one week) periods of waterlogging (Rudd & Chardon, 1977). A productivity review conducted by Leslie & Wilson (1996) stated an environment of extreme soil wetness at Babinda was having a major influence on cane growth. This especially affected early ratoon sugarcane up to 1 m high.

Rudd & Chardon (1977) studied the effect of waterlogging by flooding on sugarcane productivity. A pronounced cumulative cane and sugar yield decline of 36% occurred from early flooding before the crop had fully established. A considerably lower effect (12% loss) from flooding occurred on more established cane later in the season.

The Rudd & Chardon (1977) study also identified the importance of a high water table, particularly within 0.5 m of the surface. Crop losses of ~0.46 tonnes cane/ha/day can occur for every day the water table is 0.5 m of the soil surface. Other work in this area showed that root-zone waterlogging can cause even greater yield reductions in very young cane, particularly in the early growth stage (Salter *et al*., 2018). This trial identified losses up to 0.83 tonnes cane/ha/day over a 19-day period.

In addition to crop and yield effects, soil wetness is also a serious management constraint, limiting vehicular access for cultivation, fertilizer application and plant uptake, weed and pest control and harvesting. Traversing wet or waterlogged paddocks often results in compaction and soil structural damage, and sometimes bogging.

Six wetness categories have been identified for this limitation, following the drainage classes of National Committee on Soil and Terrain (2009), which are applied over two depth ranges (Table 14 and Table 15). The first (W1), is concerned with wetness conditions below the main uptake root zone (>0.5m), to consider likely impacts on the plant from waterlogging in the deeper subsoil. Root senescence or barriers to root development caused by waterlogging at depth would impact the crop's ability to access deeper subsoil sources of nutrients. Access to deeper sources of soil moisture supply during dry periods will also become limited unless the root system can recover.

Table 14: Soil wetness to 1.0m (W1)

Wetness category	Soil drainage and wetness to 1.0m
1	Very poorly drained (water table present most of year)
2	Poorly drained (mottled/gley horizons, wet for several months)
3	Imperfectly drained (mottled, wet for several weeks)
4	Moderately well drained (wet for up to a week)
5	Well drained (wet for several days)
6	Rapidly drained (wet for several hours after rainfall)

The second wetness limitation (W2), which is more critical, considers the direct impact of waterlogging within the main crop root-zone or upper 0.5 m. As noted above, significant impacts will occur upon the plant, resulting in production losses from prolonged waterlogging within this part of the soil profile. This is because most of the crop's root biomass is found near the surface, with as much as 85% found in the top 0.6m of soil (Smith *et al*., 2005).

Table 15: Soil wetness to 0.5m (W2)

Wetness category	Soil drainage and wetness to 0.5m
1	Very poorly drained (water table present most of year)
2	Poorly drained (mottled/gley horizons, wet for several months)
3	Imperfectly drained (mottled, wet for several weeks)
4	Moderately well drained (wet for up to a week)
5	Well drained (wet for several days)
6	Rapidly drained (wet for several hours after rainfall)

5.9.1.Determining soil polygon wetness (W) category

The wetness categories were allocated to soil mapping polygons based on site drainage characteristics observed in soil profile and during traverses across the landscape. Considerations included the presence and depth of mottling and/or segregations, soil colour, soil structure and texture, moisture levels in the profile, permeability, and the presence of water tables in nearby drains.

EMI data, captured during the dry season was also used to help with attribution of wetness categories in areas where there was no site data. This was a qualitative approach based on the relative brightness of the EMI response from specific sensor depths. The PRP2 sensor, with a nominal depth of 0.5 m, was used to assist with attribution of the W2 limitation. The HCP1 sensor (to 1.2 m) was used to assist with attribution of the W1 limitation. The HCP2 sensor (to 2.7 m) aided with information on deeper subsoil moisture conditions.

5.10. Flooding (F)

Flooding is a significant management issue in the Wet Tropics that can cause a range of impacts. These typically include physical damage to crops, yield decline, soil erosion, nutrient losses, along with site access and harvesting challenges. Whilst flooding can result in thick deposits of silt which could smother the plant, this silt can also contain beneficial plant nutrients. It is important to undertake regular soil testing in areas that are regularly submerged so that fertiliser inputs and management practices can be adjusted accordingly.

The net effect of flooding on sugarcane yields depends on several factors, including age and height of the crop, period of submergence of the growing point, stalk breakage and the silt load in the floodwater. A study of the effects of flooding in the Mulgrave-Babinda areas in 1977 found a relationship between crop yield, stalk height and period of submergence (Ridge & Reghenzani, 2000). The regression analysis undertaken was most accurate for periods of flooding greater than 5 days. The study found that cane with stalk heights between 2.5 and 0.5 m may suffer yield losses, respectively, of around 15–20% after 5 days of submergence, between 30% and 60% after 10 days and between 37% and 100% after 15 days. This analysis was used to create the four flooding limitation categories used in this study, shown in Table 16 below.

Table 16: The flooding (F) categories

Flooding categories	Description
0	Inundated less than 5 days in most years
1	Inundated for 5–10 days in most years
2	Inundated for 10–15 days in most years
3	Inundated for >15 days in most years

5.10.1. Determining soil polygon flooding (F) category

Flooding categories were applied to polygons following consultation with landholders regarding known flood levels and residence times. This local knowledge was then extrapolated using the LiDAR digital elevation model areas into areas where flooding extents are less well understood. Consideration was also given to the flood studies of the Babinda Swamp area (Queensland Water Resources Commission, 1981).

5.11. Miscellaneous Attributes

Several miscellaneous polygons were defined within the survey area. Miscellaneous polygons are to non-soil features that are not defined by a SPC. To help with consistent colouration of these features in the attribute maps, each miscellaneous unit has been assigned its own distinct number and this has been applied across all attributes. Miscellaneous units used in this survey are provided in Table 17.

Table 17: Miscellaneous attribute codes

Attribute Code	Abbreviation	Description
10	DLR	Disturbed Land – Road
11	WTR	Water
12	SWP	Swamp

6. Summary table of typical soil attributes

Median soil attribute values applied to SPCs within the study area have been summarised in Table 18 below. These are soil-based attributes determined from laboratory analysis or direct physical observations. Attributes with a significant landscape component such as Flooding, and Wetness have not been included. Soil attributes can change over time based on inputs (e.g. agricultural lime) and management practice. Whilst the results in Table 18 provide a snapshot (2020/2021) of various sugarcane growing soils in the district, this does not replace the need for regular soil testing. Median results highlight some of the soil related risks and challenges facing sugarcane growers in Wet Tropics and can be used to aid adoption of best practice land and nutrient management.

The attributes summarised in Table 18 include:

- Soil organic carbon (SOC)
- Phosphorus sorption (PS)
- Cation exchange capacity (CEC)
- Soil pH (pH)
- Aluminium saturation (AS)
- Calcium deficiency (CD)
- Surface soil texture (ST)
- Nitrogen leaching potential (NL)

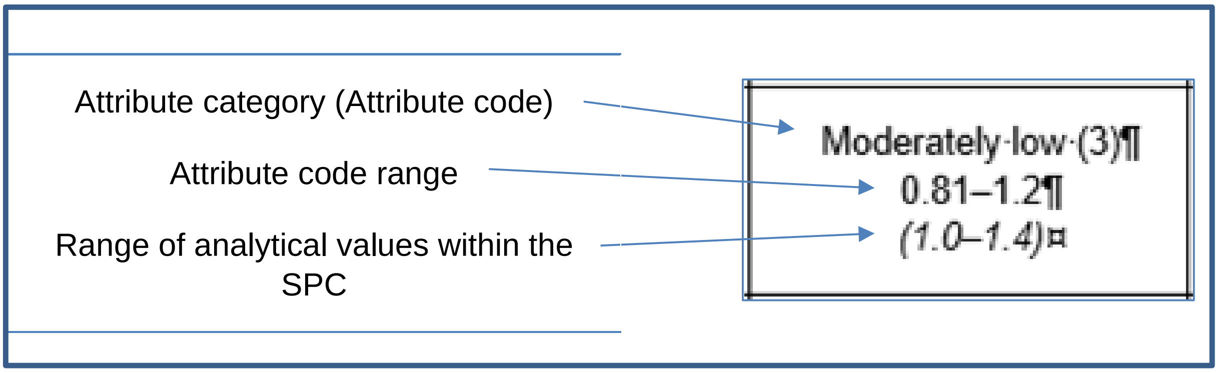


Figure 19: Key to Table 18.

Table 18: Median attribute values for soils in the Russell River catchment

Soil profile class	Australian soil classification Dominant Soil Order	Number of analytical sites	Soil organic carbon (SOC) N mineralisation index (%)	Phosphorus sorption (PS) P sorption class	Cation exchange capacity (CEC) CEC class (cmol/kg)	Soil pH (pH) pH rating	Aluminium saturation (AS) AS rating (%)	Calcium deficiency (CD) Ca rating (cmol/kg)	Surface soil texture (ST) Texture grouping of topsoil	Nitrogen leaching potential (NL) Leaching potential below 0.5 m
Soils formed from metamorphic rock										
Kimberley Ki	Dermosol	2	Moderately low (3) 0.81–1.2 *(1.1–1.2)*	Low (1) <140 *(92–135)*	Very low (1) <2 *(1.14–2.23)*	Strongly acid (2) 4.5–5.5 *(4.5–4.8)*	Severe (4) 20.01–50 *(9.9–72.1)*	Critical (1) <0.65 *(BQ–1.45)*	Loam to clay loam (3)	Moderate (3)
Well drained soils of the granitic alluvial fans (>1% slope)										
Tyson Ty	Kandosol	1	Moderately low (3) 0.81–1.2 *(1.0)*	Low (1) <140 *(78)*	Low (2) 2.01–4 *(2.32)*	Strongly acid (2) 4.5–5.5 *(4.8)*	Minor (2) 5.01–10 *(9.9)*	Deficient (2) 0.65–1.5 *(1.45)*	Sand to sandy loam (2)	High (4)
Tyson brown variant Ty(bv)	Kandosol	—	Moderately low (3) 0.81–1.2	Low (1) <140	Low (2) 2.01–4	Strongly acid (2) 4.5–5.5	Minor (2) 5.01–10	Deficient (2) 0.65–1.5	Loam to clay loam (3)	High (4)
Thorpe Th	Kandosol	8	Moderately low (3) 0.81–1.2 *(1.0–1.4)*	Moderate (2) 140–280 *(101–182)*	Low (2) 2.01–4 *(1.57–2.96)*	Strongly acid (2) 4.5–5.5 *(4.7–5.5)*	Severe (4) 20.01–50 *(10.8–51.4)*	Deficient (2) 0.65–1.5 *(0.31–1.69)*	Loam to clay loam (3)	High (4)
Thorpe sandy variant Th(sv)	Kandosol	4	Moderately low (3) 0.81–<1.2 *(0.9–1.3)*	Low (1) <140 *(100–177)*	Low (2) 2.01–4 *(1.92–3.38)*	Strongly acid (2) 4.5–5.5 *(5.0–5.2)*	Severe (4) 20.01–50 *(8.2–24.6)*	Deficient (2) 0.65–1.5 *(0.88–2.53)*	Sand to sandy loam (2)	Very high (5)
Thorpe heavy variant Th(hv)	Dermosol	1	Moderate (4) 1.21–1.6 *(1.3)*	Low (1) <140 *(121)*	Low (2) 2.01–4 *(3.11)*	Acid (3) 5.51–6.5 *(6.2)*	1 Nil or negligible (1) ≤ 5	Sufficient (4) >2.0 *(2.37)*	Silts and clays (4)	Moderate (3)
Imperfect to poorly drained soils of the alluvial fans (<1% slope)										
Prior (Pr)	Kandosol	10	Moderately low (3) 0.81–1.2 *(0.8–1.7)*	Low (1) <140 *(82–174)*	Low (2) 2.01–4 *(1.73–3.63)*	Strongly acid (2) 4.5–5.5 *(4.9–5.8)*	Moderate (3) 10.01–20 *(0–30)*	Deficient (2) 0.65–1.5 *(0.38–2.23)*	Loam to clay loam (3)	High (4)
Prior sandy variant Pr(sv)	Kandosol	3	Moderately low (3) 0.81–1.2 *(0.8–1.2)*	Low (1) <140 *(102–128)*	Low (2) 2.01–4 *(1.85–2.51)*	Strongly acid (2) 4.5–5.5 *(5.1–5.3)*	Severe (4) 20.01–50 *(19.1–26)*	Deficient (2) 0.65–1.5 *(0.66–1.44)*	Sand to sandy loam (2)	Very high (5)

Soil profile class	Australian soil classification Dominant Soil Order	Number of analytical sites	Soil organic carbon (SOC) N mineralisation index (%)	Phosphorus sorption (PS) P sorption class	Cation exchange capacity (CEC) CEC class (cmol/kg)	Soil pH (pH) pH rating	Aluminium saturation (AS) AS rating (%)	Calcium deficiency (CD) Ca rating (cmol/kg)	Surface soil texture (ST) Texture grouping of topsoil	Nitrogen leaching potential (NL) Leaching potential below 0.5 m
Bartle **Bt**	Kandosol	—	Moderately high (5) 1.61–2.0	High (3) 281–420	Low (2) 2.01–4	Strongly acid (2) 4.5–5.5	Severe (4) 20.01–50	Marginal (3) 1.51–2.0	Loam to clay loam (3)	High (4)
Malbon **Mb**	Dermosol	1	Moderately low (3) 0.81–1.2 *(1.1)*	Low (1 or 2) <140 *(132)*	Low (2) 2.01–4 *(3.28)*	Strongly acid (2) 4.5–5.5 *(5.4)*	Moderate (3) 10.01–20 *(16.2)*	Sufficient (4) >2.0 *(2.11)*	Loam to clay loam (3)	Moderate (3)
Mirriwinni **Mr**	Kandosol	3	Moderately low (3) 0.81–1.2 *(0.9–1.1)*	Low (1 or 2) <140 *(94–159)*	Low (2) 2.01–4 *(2.74–3.19)*	Strongly acid (2) 4.5–5.5 *(5.2–5.5)*	Minor (2) 5.01–10 *(0–9.9)*	Marginal (3) 1.51–2.0 *(1.79–2.52)*	Loam to clay loam (3)	High (4)
Mirriwinni sandy variant **Mr(sv)**	Kandosol	4	Moderate (4) 1.21–1.6 *(1.1–1.6)*	Moderate (1 or 2) 140–280 *(110–164)*	Low (2) 2.01–4 *(2.28–2.59)*	Acid (3) 5.51–6.5 *(5.4–5.8)*	Moderate (3) 10.01–20 *(0–25.4)*	Marginal (3) 1.51–2.0 *(1.79–2.52)*	Sand to sandy loam (2)	Very high (5)
Mirriwinni heavy variant **Mr(hv)**	Dermosol	2	Moderate (4) 1.21–1.6 *(1.2–1.6)*	Low (1 or 2) <140 *(90–185)*	Medium (3) 4.01–8 *(2.82–5.26)*	Strongly acid (2) 4.5–5.5 *(5.4–5.5)*	Minor (2) 5.01–10 *(4.2–14.5)*	Sufficient (4) >2.0 *(1.89–3.29)*	Silts and clays (4)	Low (2)
Lugger **Lu**	Kandosol or Hydrosol	3	Moderate (4) 1.21–1.6% *(1.1–1.8)*	Moderate (2) 140–280 *(137–176)*	Low (2) 2.01–4 *(2.04–14.88)*	Acid (3) 5.51–6.5 *(5.5–7.1)*	1 Nil or negligible (1) ≤ 5	Sufficient (4) >2.0 *(1.44–13.90)*	Loam to clay loam (3)	Moderate (3)
Poorly drained soils of the buried alluvial fans (<0.5% slope)										
Lugger peaty variant **Lu(pv)**	Hydrosol or Organosol	2	Very High (7) >2.4 *(2.5–3.3)*	High (3) 281–420 *(236–399)*	Medium (3) 4.01–8 *(4.21–4.45)*	Strongly acid (2) 4.5–5.5 *(4.8–5.2)*	Severe (4) 20.01–50 *(29.9–42.5)*	Marginal (3) 1.51–2.0 *(1.69–1.98)*	Dominated by peats/organic material (1)	Moderate (3)
Mirriwinni peaty variant **Mr(pv)**	Hydrosol	—	Very high (7) >2.4%	High (3) 281–420	Medium (3) 4.01–8	Strongly acid (2) 4.5–5.5	Severe (4) 20.01–50	Marginal (3) 1.51–2.0	Dominated by peats/organic material (1)	Low (2)

Soil profile class	**Australian soil classification** Dominant Soil Order	**Number of analytical sites**	**Soil organic carbon** **(SOC)** N mineralisation index (%)	**Phosphorus sorption** **(PS)** P sorption class	**Cation exchange capacity** **(CEC)** CEC class (cmol/kg)	**Soil pH** **(pH)** pH rating	**Aluminium saturation** **(AS)** AS rating (%)	**Calcium deficiency** **(CD)** Ca rating (cmol/kg)	**Surface soil texture** **(ST)** Texture grouping of topsoil	**Nitrogen leaching potential** **(NL)** Leaching potential below 0.5 m
Well drained soils of the levees, terraces and channel benches										
Russell **Rs**	Dermosol	32	Moderate (4) 1.21–1.6% *(0.8–2.6)*	Moderate (2) 140–280 *(104–358)*	Low (2) 2.01–4 *(2.08–12.56)*	Strongly acid (2) 4.5–5.5 *(4.3–8.1)*	Severe (4) 20.01–50 *(4.2–72.3)*	Deficient (2) 0.65–1.5 *(0.15–10.80)*	Silts and clays (4)	Low (2)
Russell mottled variant **Rs(mv)**	Dermosol	26	Moderate (4) 1.21–1.6% *(1.0–2.9)*	Moderate (2) 140–280 *(28–746)*	Medium (3) 4.01–8 *(3.23–12.90)*	Strongly acid (2) 4.5–5.5 *(4.4–8.0)*	Severe (4) 20.01–50 *(5.1–69.5)*	Sufficient (4) >2.0 *(0.14–12.10)*	Silts and clays (4)	Low (2)
Canoe **Cn**	Kandosols	26	Moderate (4) 1.21–1.6% *(0.6–1.7)*	Moderate (2) 140–280 *(66–329)*	Low (2) 2.01–4 *(0.58–8.99)*	Strongly acid (2) 4.5–5.5 *(4.6–6.2)*	Severe (4) 20.01–50 *(0–71.4)*	Deficient (2) 0.65–1.5 *(0.16–1.44)*	Loam to clay loam (3)	High (4)
Imperfect to poorly drained alluvial soils of the levees and backplains										
Coom **Co**	Dermosol or Hydrosol	22	Moderately high (5) 1.61–2.0% *(1.2–2.7)*	High (3) 281–420 *(198–474)*	Medium (3) 4.01–8 *(3.13–5.80)*	Strongly acid (2) 4.5–5.5 *(4.6–5.9)*	Severe (4) 20.01–50 *(11.4–51.6)*	Marginal (3) 1.51–2.0 *(0.89–4.01)*	Silts and clays (4)	Low (2)
Timara **Ti**	Hydrosols	17	Moderately high (5) 1.61–2.0% *(1.2–2.9)*	High (3) 281–420 *(126–589)*	Medium (3) 4.01–8 *(3.75–8.33)*	Strongly acid (2) 4.5–5.5 *(4.7–6.2)*	Severe (4) 20.01–50 *(0–43.6)*	Sufficient (4) >2.0 *(1.01–6.81)*	Silts and clays (4)	Low (2)
Bulgun **Bg**	Hydrosols Tenosols	5	Very high (7) >2.4% *(1.7–4.7)*	Very high (4) 421–1000 *(301–988)*	Medium (3) 4.01–8 *(3.83–6.69)*	Strongly acid (2) 4.5–5.5 *(4.8–5.9)*	Severe (4) 20.01–50 *(0–37.4)*	Sufficient (4) >2.0 (1.84–4.8)	Silts and clays (4)	Low (2)
Lee **Le**	Kandosol	1	Very high (7) >2.4% *(5.2)*	Very high (4) 421–1000 *(1000)*	Low (2) 2.01–4 *(3.02)*	Strongly acid (2) 4.5–5.5 *(4.7)*	Severe (4) 20.01–50 *(45.7)*	Deficient (2) 0.65–1.5 *(0.80)*	Sand to sandy loam (2)	High (4)
Lee heavy variant **Le(hv)**	Dermosol or Hydrosol	9	High (6) 2.01–2.4% *(1.6–6.8)*	High (3) 281–420 *(309–1000)*	Low (2) 2.01–4 *(2.85–4.96)*	Strongly acid (2) 4.5–5.5 *(4.2–5.4)*	Severe (4) 20.01–50 *(0–47.9)*	Marginal (3) 1.51–2.0 *(0.91–3.79)*	Silts and clays (4)	Low (2)
Lee grey variant **Le(gv)**	Hydrosol	6	Very high (7) >2.4% *(1.6–6.1)*	Very high (4) 421–1000 *(314–1000)*	Low (2) 2.01–4 *(2.90–4.91)*	Strongly acid (2) 4.5–5.5 *(4.5–5.7)*	Severe (4) 20.01–50 *(0–32.9)*	Marginal (3) 1.51–2.0 *(1.49–3.22)*	Silts and clays (4)	Low (2)

Soil profile class	Australian soil classification Dominant Soil Order	Number of analytical sites	Soil organic carbon (SOC) N mineralisation index (%)	Phosphorus sorption (PS) P sorption class	Cation exchange capacity (CEC) CEC class (cmol/kg)	Soil pH (pH) pH rating	Aluminium saturation (AS) AS rating (%)	Calcium deficiency (CD) Ca rating (cmol/kg)	Surface soil texture (ST) Texture grouping of topsoil	Nitrogen leaching potential (NL) Leaching potential below 0.5 m
Soils of the prior streams										
Goolboo Go	Tenosol or Kandosol	5	Moderately low (3) 0.81–1.2 *(0.9–1.1)*	Moderate (2) 140–280 *(41–223)*	Low (2) 2.01–4 *(1.26–3.36)*	Strongly acid (2) 4.5–5.5 *(4.8–5.4)*	Severe (4) 20.01–50 *(24.5–44.0)*	Critical (1) <0.65 *(0.51–1.66)*	Sand to sandy loam (2)	Very high (5)
Derra Dr	Hydrosol or Kandosol	2	Very high (7) >2.4% *(3.0–6.0)*	Very high (4) 421–1000 *(555–1000)*	Medium (3) 4.01–8 *(4.15–5.25)*	Strongly acid (2) 4.5–5.5 *(5.1–5.3)*	Moderate (3) 10.01–20 *(8–21)*	Sufficient (4) >2.0 *(2.71–3.01)*	Dominated by peats/organic material (1)	Moderate (3)
Niringa Ni	Rudosol or Tenosol	9	Very high (7) >2.4% *(1.5–18.6)*	Very high (4) 421–1000 *(269–1000)*	Medium (3) 4.01–8 *(2.84–21.96)*	Acid (3) 5.51–6.5 *(4.6–8.1)*	Severe (4) 20.01–50 *(0–65.1)*	Sufficient (4) >2.0 *(0.34–20.50)*	Dominated by peats/organic material (1)	High (4)
Soils of the former freshwater swamps										
Hewitt He	Hydrosol	11	Very high (7) >2.4% *(3.4–10.7)*	Very high (4) 421–1000 *(461–1000)*	Medium (3) 4.01–8 *(4.25–11.29)*	Strongly acid (2) 4.5–5.5 *(4.9–6.0)*	Severe (4) 20.01–50 *(0–36.6)*	Sufficient (4) >2.0 *(1.92–8.82)*	Dominated by peats/organic material (1)	Low (2)
Wanjuru Wj	Organosol	9	Very High (7) >2.4 *(2.1–17.5)*	Very high (4) 421–1000 *(517–1000)*	Medium (3) 4.01–8 *(4.52–12.88)*	Strongly acid (2) 4.5–5.5 *(4.6–6.1)*	Severe (4) 20.01–50 *(20.5–71.3)*	Sufficient (4) >2.0 *(0.60–10.00)*	Dominated by peats/organic material (1)	Moderate (3)
Wyvuri Wv	Organosol	13	Very High (7) >2.4 *(1.7–16.6)*	Very high (4) 421–1000 *(156–1000)*	Medium (3) 4.01–8 *(3.80–7.92)*	Strongly acid (2) 4.5–5.5 *(4.5–6.0)*	Severe (4) 20.01–50 *(17.1–67.9)*	Sufficient (4) >2.0 *(0.53–6.90)*	Dominated by peats/organic material (1)	Moderate (3)
Babinda Bd	Organosol	10	Very High (7) >2.4 *(2.7–19.4)*	Very high (4) 421–1000 *(278–1000)*	Medium (3) 4.01–8 *(3.62–9.33)*	Strongly acid (2) 4.5–5.5 *(4.3–5.4)*	Severe (4) 20.01–50 *(4.9–67.9)*	Sufficient (4) >2.0 *(0.70–7.39)*	Dominated by peats/organic material (1)	Moderate (3)

Notes:

1. The attribute category rating or class applicable to the SPC is determined by the analytical results of sampled sites and physical site observations (to establish ST and NL categories).
2. Where the range of analytical results for corresponding sampled sites falls across two or more categories, the category is based on the median value of those results.
3. Where an SPC had no representative analytical sites, the attribute category has been based on results for a similar soil.
4. The CEC attribute uses both direct measurements of cation exchange capacity and the sum of the major cations (e.g. ECEC) where applicable to the associated analysed sites.
5. BQ = below quantifiable, the concentration of the analyte is too low to measure.

7. Discussion

This project created paddock and farm scale soil mapping and information important for landholders seeking to undertake soil based nutrient management and meeting obligations established by reef protection regulations. The work will also assist growers with adoption of cane industry best practice SIX EASY STEPS®. Provision of detailed soil mapping in the complex alluvial landscapes of the Wet Tropics can be very challenging on modified land under sugarcane. In these areas EMI is an important tool that can help discern underlying patterns in the soil that are not apparent at the surface.

The survey was enhanced by use of electromagnetic induction (EMI). EMI was employed to increase the efficiency of site selection and to improve soil boundary accuracy. Variability in EMI results enabled the efficient selection of soil characterisation and sampling sites used to develop the SPC's and attributes. Whilst use of the EMI resulted in efficiencies in the soil characterisation component of this work, high intensity survey remains resource intensive. This form of survey may be best suited to small catchments where measured N loads are high.

The Babinda area of the Wet Tropical Coast is one of the wettest areas in Australia. Even over the dry season period, wet conditions caused regular delays in the EMI capture program. Downtime due to inclement weather and equipment break downs had serious flow-on effects as EMI information was not always available to help guide the soil characterisation work. Collection and processing of the EMI mosaic dataset ahead of the characterisation survey should be considered in any further EMI based survey.

A new automated data EMI data processing method was developed for this project to help clean anomalous data, reduce processing times, and display the interpolated data. The final outputs were EMI mosaics that can be displayed as both a discrete depth and multiple depths as a multispectral mosaic. The normalised EMI mosaic had greater contrast and patterns in adjoining paddocks surveyed under different environmental conditions were more closely aligned. These features made the normalised EMI mosaic the most useful for delineation of soil and attribute boundaries. The absolute EMI mosaic proved to be a useful indicator of subsoil moisture, and was used in conjunction with soil site data to help define soil attributes important for nutrient management (e.g. soil wetness, nitrogen leaching potential and denitrification potential).

Soils in the Wet Tropical Coast also have typically very low electrical conductivity (EC) which can make it more difficult to separate soils and attributes using EMI sensing technology. This makes the cleaning of anomalous data much more important to the overall mosaic patterns. Data cleaning processes identified in this report are designed to assist others with removal of anomalous values and outliers to improve overall product quality.

Whilst there is significant variability across the catchment, most soils were found to be acidic with low cation exchange capacity and little capacity to adsorb applied nutrients. The potential for nutrient losses in these soils is compounded by regular intensive rainfall, flooding and soil wetness, typical across most of the Wet Tropical Coast.

Acidic to strongly acidic soils were encountered across most of study area and will be having the effect of reducing the availability of some critical plant nutrients, while increasing the availability of other toxic elements such as Aluminium (Al). Severe levels of aluminium were encountered in most parts of the project area. These levels are considered to represent a serious constraint to soil health and sugarcane productivity. It is recommended that more consideration be given to increasing the rate and regularity of agricultural lime applications, particularly on the clay and peaty textured soils.

Another key observation was the effect of landscape variability on the potential for nutrient losses. Sandy well drained, low CEC and low SOC soils of the alluvial fans were found to be the most susceptible to nutrient leaching below the effective root zone. Poorly drained clayey and peaty textured soils within the backplains and swamps were the most prone to denitrification losses.

8. Conclusion

This project has delivered much improved soil data and information across over 2000 hectares in the Russell River catchment. Thirty-two soil profile classes (including ten variants and phases) have been described across 2954 polygons. By comparison, the original medium intensity soil mapping identified 14 soil profile classes across 21 mapping polygons. Eleven additional soil and landscape attributes key to nutrient management across the area have also been identified and mapped.

The methods and outcomes described in this report provide practical information pertinent to the use of EMI to undertake high intensity area-based soil mapping. This document provides the processes and learnings gained from this study, to provide guidance for similar projects to ensure consistent and repeatable outputs. Workflows and processes described here are aimed at assisting others involved in EMI capture and soil mapping.

This work undertaken by this study has shown that EMI can be a very powerful proximal sensing tool capable of improving the efficiency and accuracy of high intensity soil survey. The project has delivered new soil mapping, along with specific and highly relevant soil attribute layers. These tailored soil attribute layers provide farmers and their agronomists with detailed information that will help inform precision paddock and farm scale nutrient management. Threshold levels within these layers align with cane industry best practice SIX EASY STEPS® and can also be used to help with production of farm nitrogen and phosphorus nutrient budgets. It is hoped that delivery of this mapping will encourage greater adoption of precision, soil attribute based nutrient management in the catchment.

9. References

Abdu, H., Robinson, D. A., & Jones, S. B. (2007). Comparing bulk soil electrical conductivity determination using the DUALEM-1S and EM38-DD electromagnetic induction instruments. *Soil Science Society of America Journal*, *71*(1), 189–196. https://doi.org/10.2136/sssaj2005.0394

Attard, S., & Shaw, M. (2010). *Paddock to Reef paddock monitoring sampling protocols.* Department of Natural Resources and Mines.

Australian Government, & Queensland Government. (2018). *Reef 2050 Water Quality Improvement Plan 2017-2022*. State of Queensland. https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0017/46115/reef-2050-water-quality-improvement-plan-2017-22.pdf

Bartley, R., Waters, D., Turner, R., Kroon, F., Wilkinson, S., Garzon-Garcia, A., Kuhnert, P., Lewis, S., Smith, R., Bainbridge, Z., Olley, J., Brooks, A., Burton, J., Brodie, J., & Waterhouse, J. (2017). Chapter 2: Sources of sediment, nutrients, pesticides and other pollutants to the Great Barrier Reef. In *Scientific Consensus Statement 2017: A synthesis of the science of land-based water quality impacts on the Great Barrier Reef*. State of Queensland.

Brodie, J. E., Waterhouse, J., Lewis, S., Basnett, A., Davis, A., Alexander, F., & Ginders, M. (2011). Comparative effectiveness of community drainage schemes and EVTAs in trapping PSII herbicides from sugarcane farms Stage 1 Report. In *Australian Centre for Tropical Freshwater Research (JCU) Report* (Issue 10/14).

Brogi, C., Huisman, J. A., Pätzold, S., von Hebel, C., Weihermüller, L., Kaufmann, M. S., van der Kruk, J., & Vereecken, H. (2019). Large-scale soil mapping using multi-configuration EMI and supervised image classification. *Geoderma*, *335*(September 2017), 133–148. https://doi.org/10.1016/j.geoderma.2018.08.001

Brown, K., & Lemon, J. (2019). *Cations and cation exchange capacity - Soil Quality Pty Ltd Fact Sheet*. Healthy Soils for Sustainable Farms Programme of the Australian Government's Natural Heritage Trust. https://www.soilquality.org.au/factsheets/cation-exchange-capacity

Bureau of Meteorology. (2021). *Climate data online*. http://www.bom.gov.au/climate/data/

Calcino, D., Schroeder, B., Panitz, J., Hurney, A., Skocaj, D., Wood, A., & Salter, B. (2018). Australian sugarcane nutrition manual. In *Sugarcane Research Australia*. Sugar Research Australia.

Cannon, M., Smith, C., & Murtha, G. (1992). *Soils of the Cardwell-Tully area, north Queensland*. Division of Soils, CSIRO.

Corwin, D., & Lesch, S. (2003). Application of soil electrical conductivity to precision agriculture: theory, principles and guidelines. *Agronomy Journal*, *95*, 455–471.

Corwin, D., & Lesch, S. (2005). Apparent soil electrical conductivity measurements in agriculture. *Computers and Electronics in Agriculture*, *46*(1-3 SPEC. ISS.), 11–43. https://doi.org/10.1016/j.compag.2004.10.005

Department of Environment and Science. (2022). *Prescribed methodology for sugarcane cultivation*. Queensland Government.

Department of Resources. (2021). *Queensland soil and land resource survey information guideline. VEG/2018/4460 Version 2.00.* Queensland Government.

Di Bella, L. P., Coventry, R. J., Sefton, M., Moody, P. W., Hanks, M., Stringer, J. K., & Kerkwyk, R. E. (2009). The use of geo-referenced soil test data in the Herbert District. *Proceedings of the Australian Society of Sugar Cane Technologists*, *31*, 296–306.

Enderlin, N. (2020). *Soil characterisation of sugarcane farms in the Johnstone River Basin – Wet Tropics Major Integrated Project.* Department of Natural Resources, Mines and Energy.

Esri Australia Pty. Ltd. (2021a). *Cluster and outlier analysis (Anselin Local Moran's I) (spatial statistics)—ArcGIS Pro* | *Documentation*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/cluster-and-outlier-analysis-anselin-local-moran-s.htm

Esri Australia Pty. Ltd. (2021b). *Comparing interpolation methods—ArcGIS Pro | Documentation*. https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/comparing-interpolation-methods.htm

Esri Australia Pty. Ltd. (2021c). *How cluster and outlier analysis (Anselin Local Moran's I) works—ArcGIS Pro | Documentation*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-statistics/h-how-cluster-and-outlier-analysis-anselin-local-m.htm

Esri Australia Pty. Ltd. (2021d). *Natural neighbor (spatial analyst)—ArcGIS Pro | Documentation*. https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/natural-neighbor.htm

Esri Australia Pty. Ltd. (2021e). *Understanding interpolation analysis.* https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/understanding-interpolation-analysis.htm

Furnas, M. J. (2003). *Catchments and corals: terrestrial runoff to the Great Barrier Reef*. Australian Institute of Marine Science.

Gazey, C., & Azam, G. (2018). *Causes of soil acidity*. Department of Primary Industries and Regional Development. https://www.agric.wa.gov.au/soil-acidity/causes-soil-acidity?page=0%2C0

Hall, R. (2008). *Soil essentials: Managing your farm's primary asset.* Land Links - CSIRO Publishing.

Hazelton, P. A., & Murphy, B. W. (2007). *Interpreting soil test results: What do the numbers mean?* CSIRO Publishing.

Jacobsen, C., Keith, K., & Kamel, T. (1992). *Understanding soil ecosystem relationships.* Department of Primary Industries.

Jaragun Ecoservices. (2021). *Jaragun ecoservices*. https://www.jaragun.com.au/

Larsen, P. L., & Dougall, A. J. (2017). Sugar productivity - Time to make an omelette. *39th Conference of the Australian Society of Sugar Cane Technologists, ASSCT 2017*, *39*(2015), 38–48.

Leksono, E., Adamchuk, V., Wenjun, J., & Leclerc, M. (2018). Development of a soil ECa inversion algorithm for topsoil depth characterization. *Proceedings of the 14th International Conference on Precision Agriculture*, 1–11.

Leslie, J. K., & Wilson, G. L. (1996). *Productivity trends in sugarcane in the wet tropics.* Sugar Research and Development Corporation and Cooperative Research Centre for Sustainable Sugar Production.

Lewis, S. E., Bartley, R., Wilkinson, S. N., Bainbridge, Z. T., Henderson, A. E., James, C. S., Irvine, S. A., & Brodie, J. E. (2021). Land use change in the river basins of the Great Barrier Reef, 1860 to 2019: A foundation for understanding environmental history across the catchment to reef continuum. *Marine Pollution Bulletin*, *166*, 112193. https://doi.org/10.1016/j.marpolbul.2021.112193

Mantovanini, L. J., Silva, R. G. da, Silva, J. de O. L., dos Santos, T. M. R., dos Santos, D. M. M., & Zingaretti, S. M. (2019). Root system development and proline accumulation in sugarcane leaves under aluminum (Al 3+) stress. *Australian Journal of Crop Science*, *13*(2), 208–213. https://doi.org/10.21475/ajcs.19.13.02.p1198

Masters, B., Tahir, N., Fries, J., Mortimore, C., Enderlin, N., & Armour, J. (2017). *Paddock-scale water quality monitoring of nitrogen fertiliser management practices in sugarcane cropping: 2014-2016 Paddock to Reef Integrated Monitoring, Modelling and Reporting Program Technical Report, Wet Tropics region.*

McKenzie, N. J., Grundy, M. J., Webster, R., & Ingrose-Voase, A. J. (Eds.). (2008). *Guidelines for surveying soil and land resources.* CSIRO Publishing.

Minsley, B. J., Smith, B. D., Hammack, R., Sams, J. I., & Veloski, G. (2012). Calibration and filtering strategies for frequency domain electromagnetic data. *Journal of Applied Geophysics*, *80*, 56–66.

Moody, P., & Aitken, R. (1997). Soil acidification under some tropical agricultural systems. 1. Rates of acidification and contributing factors. *Soil Research*, *35*, 163–174.

https://doi.org/10.1071/S96069%0A%0A

Murtha, G. (1986). *Soils of the Tully-Innisfail area, north Queensland*. CSIRO.

Murtha, G., Cannon, M., & Smith, C. (1996). *Soils of the Babinda - Cairns Area, North Queensland* (CSIRO (Ed.)). CSIRO Division of Soils. https://doi.org/10.25919/5cd5ca3c55bb0

National Committee on Soil and Terrain. (2009). *Australian soil and land survey field handbook* (3rd ed.). CSIRO Publishing.

Oliveira, M. de S., Rocha, S. V., Schneider, V. K., Henrique-Silva, F., Soares, M. R., & Soares-Costa, A. (2021). Physiological, nutritional, and molecular responses of Brazilian sugarcane cultivars under stress by aluminum. *PeerJ*. https://doi.org/10.7717/peerj.11461

Pimenta, L. S., Mariano, E. D., Gazaffi, R., & Carneiro, M. S. (2020). Root growth and antioxidant enzyme responses to aluminium stress in sugarcane. *Semina:Ciencias Agrarias*, *41*(6), 3449–3456. https://doi.org/10.5433/1679-0359.2020v41n6Supl2p3449

Powell, B. (2008). 19. Classifying soil and land. In N. McKenzie, M. Grundy, R. Webster, & A. Ringroase-Voase (Eds.), *Guidelines for surveying soil and land resources* (pp. 307–315). CSIRO Publishing.

Queensland Economic Advocacy Solutions. (2019). *The economic contribution of the sugarcane industry to Queensland and its regional communities. A report analysing the economic importance of the sugarcane value chain to communities across Queensland prepared for: Canegrowers* (Issue July). http://www.canegrowers.com.au/icms_docs/310175_economic-contribution-of-the-sugarcane-industry-to-queensland.pdf

Queensland Government. (2022). *Agricultural ERA standard for sugarcane cultivation – version 2* (Version 2., Issue ESR/2022/5958). State of Queensland. https://www.qld.gov.au/__data/assets/pdf_file/0017/113147/sugarcane-era-standard.pdf#:~:text=agricultural ERA standard for sugarcane cultivation provides the,criteria Activity general The activity is sugarcane cultivation

Queensland Water Resources Commission. (1981). *Report on flooding of canelands in the Babinda swamp area*.

Rayment, G., & Lyons, D. (2011). *Soil chemical methods – Australasia*. CSIRO Publishing.

Rengasamy, P., & Churchman, G. (1999). Cation exchange, exchangeable cations and sodicity. In K. Peverill, L. Sparrow, & D. Reuter (Eds.), *Soil analysis and interpretation manual*. CSIRO Publishing.

Ridge, R., & Reghenzani, J. (2000). Drainage. In M. Hogarth & P. Allsop (Eds.), *Manual of cane growing* (pp. 227–239). Bureau of Sugar Experiment Stations.

Ringrose-Voase, A. J., Geeves, G. W., Merry, R. H., & Wood, J. T. (1997). Soil indicators of changing land quality and capital value. *CSIRO (Australia) Land and Water Technical Report*, *17/97*.

Rudd, A. V., & Chardon, C. W. (1977). The effects of drainage on cane yields as measured by water-table heights in the Macknade mill area. *Proceedings of the 44th Conference of the Queensland Society of Sugar Cane Technology, Australia.*

Salter, B., Park, G., & Kok, E. (2018). A field experiment to evaluate the response of sugarcane varieties to waterlogging. *40th Annual Conference Australian Society of Sugar Cane Technologists, ASSCT 2018*, *40*, 138–150.

Schoknecht, N., Wilson, P. R., & Heiner, I. (2008). Survey specification and planning. In N. J. McKenzie, M. J. Grundy, R. Webster, & A. J. Ringroase-Voase (Eds.), *Guidelines for surveying soil and land resources* (2nd ed.). CSIRO Publishing.

Schroeder, B., Salter, B., Moody, P., Skocaj, D., & Thorburn, P. (2014). Evolving nature of nitrogen management in the Australian sugar industry. In *A review of nitrogen use efficiency in sugarcane*. Sugar Research Australia Limited. elibrary.sugarresearch.com.au/bitstream/handle/11079/14733/A review of nitrogen use efficiency in sugarcane.pdf;jsessionid=833D2D451BBE695D8BE14633CC95304B?sequence=1%0Ahttp://hdl.handle.net/11079/14735%0Ahttp://elibrary.sugarresearch.com.au/

Schroeder, B., Wood, A., Moody, P., Stewart, B., Panitz, J., & Benn, J. (2007). *Soil-specific nutrient management guidelines for sugarcane production in the Johnstone catchment*.

Smith, D. M., Inman-Bamber, N. G., & Thorburn, P. J. (2005). Growth and function of the sugarcane root system. *Field Crops Research*, *92*(2-3 SPEC. ISS.), 169–183. https://doi.org/10.1016/j.fcr.2005.01.017

Sugar Research Australia. (2022). *Nutrient management guidelines for sugarcane in the Wet Tropics* (Issue January). https://sugarresearch.com.au/sugar_files/2022/02/Nutrient-Guidelines-for-Wet-Tropics.pdf

Terrain NRM, Queensland Government, & Australian Governemnt. (2021). *Russell catchment profile story map*. Wet Tropics Plan for People and Country. https://terrainnrm.maps.arcgis.com/apps/MapSeries/index.html?appid=85b6f348f55643e78240ce1a16c91062

Vilas, M. P., Shaw, M., Rohde, K., Power, B., Donaldson, S., Foley, J., & Silburn, M. (2022). Ten years of monitoring dissolved inorganic nitrogen in runoff from sugarcane informs development of a modelling algorithm to prioritise organic and inorganic nutrient management. *Science of the Total Environment*, *803*, 150019. https://doi.org/10.1016/j.scitotenv.2021.150019

von Hebel, C., Rudolph, S., Mester, A., Huisman, J., Kumbhar, P., Vereecken, H., & van der Kruk, J. (2014). Three-dimensional imaging of subsurface structural patterns using quantitative large-scale multiconfiguration electromagnetic induction data. *Water Resources Research*, *50*, 2732–2748. https://doi.org/10.1002/ 2013WR014864.

Wallace, J., & Waltham, N. J. (2021). On the potential for improving water quality entering the Great Barrier Reef lagoon using constructed wetlands. *Marine Pollution Bulletin*, *170*(June), 112627. https://doi.org/10.1016/j.marpolbul.2021.112627

Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J., Star, M., Thorburn, P. J., Rolfe, J., Ronan, M., Taylor, B., & Kroon, F. (2017). *2017 scientific consensus statement: Land use impacts on Great Barrier Reef water quality and ecosystem condition*. https://www.reefplan.qld.gov.au/about/assets/2017-scientific-consensus-statement-summary.pdf

Appendix A. Using the DualEM 21s in the field

The following tools were used to conduct the electromagnetic induction (EMI) survey in the Russell River catchment.

- EMI instrument (DualEM) with a 10 m data/power cable.
- Motorcycle battery for 12V power supply.
- Rugged field computer with RS232 serial port.
- Software applications (QGIS) to log EMI data.
- A suitable vehicle to tow the EMI trailer (RTV).
- Non-conductive trailer (no metal components) to carry the EMI instrument.
- Non-conductive Personal Protective Equipment and safety gear (PPE).

1. About the EMI meter

The DualEM 21s EMI meter is a 2.4 m long tubular instrument comprising a signal transmitter and four sensors—referred to as PRP1, PRP2, HCP1 and HCP2—arrayed along its length to measure apparent electrical conductivity (ECa). The instrument includes a built-in GPS receiver to record the location of each ECa reading. Each sensor measures ECa to nominal depths of 0.5, 1.0, 1.6 and 3.2 m of soil respectively, however the effective depth of readings is reduced by the instrument's height above the ground surface. Refer to DUALEM Inc, 2018 for further information about this instrument.

The DualEM comes with factory-programmed default settings, which can be adjusted by the operator to suit different applications. For this project, recordings were set to a frequency of one per second and ECa was displayed in milliSiemens per meter (mS/m). There are other pre-programmed default settings that can be changed to suit user preferences, such as data output type, date and time settings and GPS configuration. Refer to the instrument's manual for further information.

The DualEM 21s comes with a combined power and data cable for connection to a 12V power supply and a data logger. The instrument doesn't contain a stand-alone internal or back-up battery although it does save a limited amount of data on the internal storage.

In addition to the cable, the DualEM has Bluetooth capability for wireless logging and data transfer. The Bluetooth connection was found to be less reliable, prone to interruption from metal barriers and dropping out during intermittent showers of rain. Use of the power/data cable connected to a laptop computer with a serial RS232 port was found to provide the most reliable data capture.

The instrument provides text output 'sentences' in either NMEA0183-standard or 4-line by 20-character format (see DUALEM Inc, 2018 for further information). As NMEA0183 is the standard for GPS communication, a variety of GPS enabled loggers and associated software can record ECa measurements and integrate them with GPS positions.

2. EMI logging equipment

The DualEM 21s can be used with a range of hardware and software components. Refer to the manufacturer's website for links for recommended proprietary software and logging devices, (https://dualem.com/links/). The following describes the hardware used in the Russell catchment project.

3. Hardware

The DualEM 21s was originally supplied with small hand-held (phone style) Bluetooth enabled logging devices for wireless transfer of data. Significant limitations were encountered when using this type of logging equipment on earlier projects. Issues included intermittent drop-out of Bluetooth connectivity during rainfall events, or due to external electronic interference. Physical separation distance and barriers also affected connectivity (e.g. a steel mesh cargo barrier on the towing vehicle formed a physical barrier to the signal between the instrument and the logger). These small logging devices were also particularly prone to the effects of overheating which resulted in data loss. Real-time viewing of logged data was not possible, and it was not clear if data capture was successful until post-field processing had been undertaken.

Reliable data capture was achieved using a rugged, weather, dust and shock-proof field laptop computer, connected to the DualEM via the supplied data cable and serial RS232 port. Use of the rugged laptop for the EM survey fieldwork provided additional benefits including:

- Enabled viewing and tracking of the instruments position on aerial imagery in real-time.
- Ease of operator handling during surveying (e.g. it could be placed on the lap of the operator, or the passenger seat beside the driver, or mounted on the dash of the towing vehicle).
- The device's ability to withstand regular exposure to wet, humid, dusty, precipitous and/or rough terrain conditions.
- Greater internal memory storage capacity and capability for immediate and quick download of data via the USB port to an external back-up storage device.
- Additional functionality for immediate and post-field data processing and EMI map production.

To avoid damage to the data cable and connectors, the cable was encased in protective HDPE tubing (25 mm low density irrigation pipe) and secured to the vehicle and EMI trailer to prevent dragging, shearing, twisting, or straining.

4. Software

The survey employed QGIS (http://download.qgis.org), a free open-source cross-platform GIS software application, for logging EMI data to the field laptop. This application also allowed location tracking (traverses) and real-time determination of EMI position on aerial imagery, based on the DualEM's inbuilt GPS.

5. DualEM trailer

Due to the length and weight of the DualEM 21s, a fit-for-purpose conveyance was needed to undertake this survey. As the project sought to capture EMI data from around 2000 ha of land, a purpose-built trailer was constructed for towing behind a 4WD rough terrain vehicle (RTV). RTVs or ‘quad-bikes’ are commonly used for in-paddock work to limit soil compaction.

EMI instruments typically require a minimum set-back distance from any conductive materials (e.g. towing vehicle) as metal interferes with the instrument’s apparent conductivity readings. The recommended minimum setback from metal components on the tow hitch and vehicle is equivalent to the length of the instrument (2.4 m).

The trailer used for this survey was constructed of timber and plyboard, with nylon fastenings and rubber pneumatic tyres on plastic rims (Figure 20). Other non-conductive materials such as fibreglass or polyvinyl chloride (PVC) plastic may also be used for construction.

Figure 20: EMI trailer, showing instrument housing, cabling and out-rigger wheel assembly

6. Trailer design considerations

A fundamental design consideration for the non-conductive trailer was the necessity for distancing the DualEM from the metal in the tow hitch and towing vehicle. A trailer with a draw bar that is too short, can result in data interference ‘hot spots’ from the towing vehicle when turning at the end of each row. Alternately, long draw bars make the trailer unwieldy in the field, causing difficulties when turning on narrow headlands or tight corners.

A drawbar length with 2.5 m between the tow-hitch and the instrument front-end was used on the trailer. This was considered optimal for minimising interference from the towing vehicle when working in cultivated sugarcane blocks. The draw bar was also detachable from the body of the trailer for ease of transport to site and for storage. A greater separation distance will be necessary for EMI instruments that are longer than the DualEM 21s.

The trailer also incorporated adjustable wheel height, to increase or decrease ground clearance to suit crop row height (or furrow depth). The trailer was designed to straddle the plant row, with either wheel in the furrow. An adjustable tow hitch can be used to ensures the instrument remains horizontal when being towed by different vehicles.

The DualEM is an expensive scientific instrument with sophisticated and sensitive internal electronic components. When towed in the paddock, the DualEM was housed in 150 mm diameter PVC pipe (see Figure 20) to protect it from dust, rain and direct sunlight. Inside the PVC housing, the instrument was wrapped in low density foam held in place by plastic cable ties to both protect the instrument and centre it within the housing. The end spaces within the housing were also packed with foam to prevent the instrument from moving horizontally.

During earlier projects, the DualEM instrument was found to rotate on its axis within the housing, particularly when traversing rough terrain. This rotation was an ever-present issue and did result in some data being discarded due to excessive rotation within the housing. To help ensure the instrument remained correctly oriented in the housing, the cushioning foam was also wrapped with a non-slip rubberised matting. To check for any rotation, an inspection port was cut into the top of the housing, and the instrument was marked to ensure correct orientation was maintained. This inspection port was covered with silver tape to minimise dust or water ingress into the housing.

Trailer wheel spacing should be at least equivalent to the track width of the towing vehicle, though wider is preferable as there is reduced risk of rolling over cane in the row or trailer wheels falling into plant cane beds. The trailer track width should be as consistent as possible with prevailing furrow/track separation for the district being surveyed. In this case the width between trailer wheels was 1.65 m, consistent with single row cane spacing. Interrow spacing can vary between single and double-row plantings on farms in the same district.

7. Towing vehicle considerations

A side-by-side all-terrain or rough-terrain vehicle (ATV/RTV) was utilised for towing the EMI trailer during this project. Lightweight vehicles such as utilities or small 4WD vehicles with high-flotation tyres may also be suitable for towing purposes and offer greater operator comfort. A 12-volt supply such as a cigarette lighter socket, should be available to supply external power to the field computer. This can also act as a back-up source of power to run the EMI provided connections are reliable. Be aware that power supply interruptions from vehicle lighter sockets can interrupt instrument recording. The DualEM does not have an internal back-up battery and will cease collecting measurements and transmitting data when power is disconnected.

Just as for the trailer, the wheelbase of the towing vehicle is an important consideration. The horizontal distance between wheel centres should align as closely as possible with the furrow widths to avoid damage to the row and plant. We suggest selecting a vehicle with very high ground clearance (>0.3m) to avoid damaging young cane, and to extend the data capture window before cane becomes too tall and woody.

Appendix B. Planning and survey considerations

The following section identifies some of the steps and considerations for appropriate field planning and preparation with the aim of identifying hazards and risks to be mitigated or avoided. This includes situations affecting personal safety and accurate, efficient data collection, or causing damage to equipment, infrastructure, property, or crops.

1. Planning for safe and successful field operations

The following are general considerations recommended for persons undertaking this type of field work.

1. Be sure to obtain landholder consent for property access prior to commencing any field survey work. A copy of completed and signed grower consent forms should be maintained for record keeping purposes.
2. Check for infrastructure on the land to be surveyed including underground services, overhead power lines and hazards such as drains. Surveyors should complete a dial-before-you-dig (DBYD)[9] search of any properties to be visited. The landholder/farmer should be consulted to locate any privately installed on-farm infrastructure, buried material or other hazards such as unsafe causeways or drain crossings between blocks.

   Avoid operating under or near powerlines when digging to sample and describe soils when using equipment such as a soil sampling rig or backhoe. The safe separation distance will increase with the size and voltage of the powerlines. Also be aware of the slope limits that your vehicles will have, as well as locations prone to waterlogging that may cause vehicles to become bogged.
3. Undertake pre-operational checks of all vehicles being used in the field to ensure safe working conditions. Check the vehicle is fit for purpose, safe to operate, and is equipped with suitable communication devices, a first aid kit and fire extinguisher. Appropriate tools and spares should also be included for any running repairs to the EMI trailer or other portable equipment used in the field.
4. Be vigilant when in the paddock, particularly at the ends of rows, and when moving between cane blocks as these access tracks and headlands are shared with tractors, harvesters, haul-outs, and cane trains during the harvest. Any vehicles being driven in and around cane paddocks should have an amber flashing warning light to ensure other vehicles can see you. We recommend surveyors avoid operating near active harvest areas and the associated haul out roads.
5. For cane-based projects, block maps from landholders (**Error! Reference source not found.**) can aid communications with the grower about which blocks are ok to traverse and which blocks to avoid. Block identifiers can also be useful for labelling and identifying files

9 https://www.infrastructure.gov.au/department/media/publications/dial-you-dig

captured during the EMI capture process (e.g. Grower_BlockID). Recent aerial imagery will also identify where drains, roadways, and other features are located.

Figure 21: Example cane block map with soil mapping as a base

6. Be aware of deep drains, narrow culverts, and washouts. Sugarcane blocks can be bounded and bisected by deep, steeply sided drains. In many instances, there may be no headland between outside rows and the drain. Headlands bounding drains are often narrow and can be oriented at acute angles, creating difficulties when turning the long towing vehicle and trailer.
7. Personnel undertaking the EMI survey should ensure they are not wearing or carrying any conductive materials and objects. Composite cap boots can be worn in place of steel caps to ensure that EMI results are not compromised.
8. Personnel undertaking the EMI survey should wear appropriate PPE, full length protective clothing, sunscreen, wide-brimmed hat and eye protection. High-vis clothing is strongly recommended when operating in the field during the harvest season. Dust can be an issue in open vehicles, so having access to a well-fitting dust mask is recommended. Sufficient, cool drinking water should be carried at all times.
9. For safety reasons, we chose to avoid active harvest areas and their associated haul routes. We also maintained a flashing yellow beacon on the roof the towing vehicle to increase our visibility amongst larger harvest vehicles. An extinguisher was carried in the tray to quell any fires and mobile phones were used to maintain communications. Seat belts and protective

sunglasses were required when operating of the RTV. Our vehicle was conditionally registered, so we were could legally drive for short distances on the roads between farms

2. Survey timing and traversing sugarcane

Fieldwork was timed to follow the harvest across two dry seasons (July to November in 2020 and 2021). There is a limited window to undertake ground-based EMI data collection in the survey area. This extends roughly six weeks from the date of harvest and until the base of the cane stalk becomes woodier and less flexible. This window of operation varies depending on vehicle clearance, plant mound height and prevailing growing conditions. Traversing more mature cane with the towing vehicle and EMI trailer can result in the cane snapping at the base, setting back plant development. Insufficient ground clearance proved to be a significant limitation to our data collection activities.

The harvest schedule can involve somewhere between 3–5 separate passes per farm over the full season. This schedule is designed to accommodate access restrictions on some land (e.g. bogging risks), plants at different stages of maturity, and to ensure each farm has an equitable chance to get cane off in case of inclement weather/flooding etc. This harvesting process necessitates repeated visits to farms and increased downtime for weed and pathogen washdowns. It also meant that most of the farms had at least one paddock of standing cane when EMI operations ceased for the year in early December. This resulted in EMI data gaps within the mosaic, that appear like missing pieces of a puzzle. To capture entire farms, it would be necessary to continue data capture into late December or early January. At this time of year in the Wet Tropics, there is an increased likelihood of wet conditions unsuitable for EMI capture.

It is easiest to undertake EMI data capture and soil surveying immediately following the harvest. Working in paddocks immediately following the harvest avoids difficulties arising from ratoon cane getting too tall and woody. Recently harvested, late ratoon (4th or 5th) blocks are the easiest to traverse as the cane is leafy and the plant mounds have settled. In early ratoon blocks, the plant mounds are typically higher and low clearance vehicles can scrape the mound, moving trash and damaging the cane. Fallow blocks are relatively easy to traverse, though they are typically very weedy.

3. Other land management considerations

Permission should first be sought from the grower before commencing operations involving traversing recently cultivated plant cane blocks. Cultivated soil prepared for planting is soft, loose and prone to compaction, and survey vehicle use risks severely damaging the plant bed.

Growers can also be sensitive about traversing paddocks that have recently been sprayed with pre-emergent herbicides as disturbance from vehicles can reduce the effectiveness of sprays. It is important to regularly check restrictions with the grower prior entering any paddock.

Coulter-ripping or ‘centre-busting’ the furrow is often used to improve surface drainage following harvest, however it can cause considerable ride roughness. Silty and clay textured soils are particularly prone to quite large hard clods being created in the interrow. Traversing such rough furrows can cause discomfort or strain to the driver and result in extra wear and survey equipment damage.

4. Reducing downtime

The EMI survey team had experienced at times significant delays associated with inclement weather and occasional equipment failures. In terms of the equipment, the RTV used was found to be at risk of overheating due to its low clearance and an associated accumulation of cane trash about the radiator and undercarriage. Regular checking and clearing of cane trash was required to avoid overheating and risk of fire. Access to a vehicle with a much higher ground clearance would have reduced some of this downtime.

The non-conductive EMI sensor trailer was also found to be prone to breakages when traversing rough ground due to the light nature of its construction. A trailer constructed from using high pressure PVC water pipe was originally used for this survey but was particularly delicate, requiring regular running repairs and major rebuilds. In response, the team constructed a more sturdier timber trailer (see Figure 20) which resulted in significantly reduced downtime from trailer repairs. A spare wheel for the trailer is also strongly recommended.

Any significant downtime when collecting EMI data can have a serious flow-on effect for other aspects of the survey. Significant impacts can occur on the efficiency and effectiveness of the soil survey component as a result. There is usually some form of a time lag between the collection of EMI data and the delivery of useable information that will guide the soil survey due to data processing. Downtime can increase this lag and severely reduce the amount of data that would normally be available for the soil survey. Opportunities to survey blocks at the ideal time could be missed due to the lack of EMI data, or the soil characterisation and sampling of blocks could not effectively be guided by it.

5. Surveying in wet weather

Regular communication with the grower about access is essential to maintain good relationships. Field data collection should only be undertaken during dry conditions to avoid damaging headlands and compacting soil. We also found that EMI patterns in wet soils weren’t as clear or sharp when compared with soils surveyed under dryer conditions. Data collected during protracted showery conditions (wet subsoils) was found to be less useful for the delineating soil boundaries. Showers of rain were also found to limit Bluetooth data transmission, resulting in some data collection failures. Be sure to check the forecast and plan fieldwork during dry periods. In the Wet Tropics, its best to plan fieldwork during the driest periods (July-Nov).

6. Farm biosecurity and washdown

Prior to the commencement of fieldwork in the Russell Catchment project, farmers were consulted for their farm biosecurity requirements. Growers raised concerns over the risk of spreading weeds and ratoon stunting disease (RSD) and requested that vehicles be washed down between farms. Growers were typically happy for our team to use their existing farm washdown bays and pressure washing equipment for this purpose. Washdowns were undertaken upon exiting a farm and prior to accessing a new farm.

Our washdown procedure included:

- Inspection, removal and disposal of debris (e.g., cane stalks) from the underside of vehicles and trailers upon exiting a farm.
- Application of a detergent and pressure washing mud and weed seed from vehicles and trailers upon exiting the farm and upon entry (if requested).
- Application of a broad-spectrum biocide spray commonly used in the control of the spread of RSD in sugarcane to the vehicles and trailers. We ensured spray was applied to all parts of vehicles that will have been in contact with plant and soil material. (**Error! Reference source not found.** and **Error! Reference source not found.**).
- Recording each wash-down event with photographic evidence, including location and time stamps to show the work was undertaken.

Figure 22: Pressure washing survey equipment

Figure 23: Disinfecting survey equipment

7. Example grower consent form

Electromagnetic Induction Soil Mapping in the Russell River Catchment

Date: ________________

Jaragun Pty Ltd
PO Box 219
Babinda QLD 4861

Department of Resources
PO Box 156
Mareeba QLD 4880

RE: Consent for property access to undertake soils mapping

Jaragun Ecoservices and the Department of Resources (DRES) are partnering to develop detailed soil maps for improved farm productivity and water quality to the Reef. The project will combine state-of-the-art electromagnetic induction (EMI) technology and conventional soil survey across 1,500-2,000 ha of cane area in the Russell River catchment. This innovative survey approach will produce detailed sub-block scale soil mapping information covering all or part of your property.

We appreciate your participation in this innovative project and request acknowledgement and consent of the following.

I/we acknowledge and consent to:

1. Providing access to land parcels listed on Page 2 for the purposes of soil surveying and mapping from August 2020 to July 2022. The work will entail use of an EMI sensor, soil coring rig, and in some instances a drone operated by the Department of Agriculture and Fisheries (DAF). I understand that project team members will contact me directly by phone to arrange proposed visits, and will advise when entering and exiting the property. I understand that if I have concerns regarding property access, I can contact Jaragun Ecoservices or DRES.

2. Project-generated soil boundary and site information being stored and made publicly available on Queensland Government platforms (e.g. Queensland Globe).

Name: ____________________ Signature: ______________________________

Name: ____________________ Signature: ______________________________

Name: ____________________ Signature: ______________________________

If you have property access information or other matters for consideration, please include below (e.g. Specific biosecurity requirements / location of wash-down facilities):

Page | 1

Electromagnetic Induction Soil Mapping in the Russell River Catchment

Map displaying area of interest:

Land parcels for inclusion in the survey are depicted in yellow outline above and include Lotplans:

Lot on plan/s: ____________________

____

____

Page | 2

Appendix C. EMI data considerations

EMI sensors are commonly used to provide rapid information about soil variability over large areas (Abdu *et al*., 2007; Leksono *et al*., 2018), however there are limitations to using EMI to map soils (Corwin & Lesch, 2003, 2005). The interpretation of the data requires a clear understanding of the multiple physico-chemical soil properties that will influence EMI readings.

EMI instruments measure apparent electrical conductivity (ECa) which is influenced by properties such as soluble salts, moisture, clay content and mineralogy, bulk density, organic matter and soil temperature (Corwin & Lesch, 2005). The usefulness of EMI data depends upon establishment of correlations between ECa values and observed soil properties, as well as consideration of the influence of dynamic vs fixed soil properties (e.g the effect of water content vs clay content on the EMI signal).

Smaller studies in cultivated paddocks (<100 ha) have demonstrated the feasibility of mapping soil variability using EMI (for example Brogi *et al*., 2019; Enderlin, 2020). However, the use of EMI capture for soil characterisation in larger areas can be difficult. Challenges arise from wide-ranging temporal variations in dynamic soil characteristics (e.g. soil water content) occurring when working across multiple fields accessed at different times over a long period (Brogi *et al*., 2019). Prior to conducting an extensive EMI survey, the potential for transient environmental variables such as soil moisture and soil temperature to affect EMI sensor readings should be considered, along with the consistency of outputs and interpretation. Mitigation strategies such as correction factors or normalisation of the sensor values should be considered to minimise the effect of these environmental variables.

1. Soil temperature variation

Soil temperature variations can affect EMI readings. A review of locally available soil temperature variation found that, apart from the shallowest PRP1 sensor (refer Table 1), temperatures within the crucial capture depths (0.5 m PRP2 sensor and 1.1 m HCP1 sensor) were relatively consistent about the nominal standardisation temperature of 25°C. As there was no substantial seasonal variation in mean subsoil temperatures during the survey periods, a temperature correction factor was not applied during interpolation. It is noted that soil temperature can also be affected by the presence of groundwater, though presence of the groundwater has a much greater bearing on the apparent ECa response than temperature. Due to the inherent complexity of the area-based survey, and variables including time of year, sensor depth, and presence/absence of groundwater, applying any correction factors ran the risk of introducing new errors into the dataset.

2. Results from the shallowest PRP1 sensor

Soil temperatures did vary appreciably throughout the day and season. These upper parts of the profile, represented by the PRP1 sensor, were also more prone to EMI spikes from showers of rain and salty applied fertilisers. There was considerably more anthropogenic disturbance (cut/fill) present at this depth and in some areas we had to traverse/straddle recently cultivated plant cane furrows, as opposed to a plant mound in the ratoon blocks. These factors, both by themselves and in combination, had an appreciable effect on data collected by the PRP1 sensor. While this depth has been provided for completeness, the PRP1 sensor depth should only be used with due consideration of these multiple limitations.

3. Results from deeper sensors

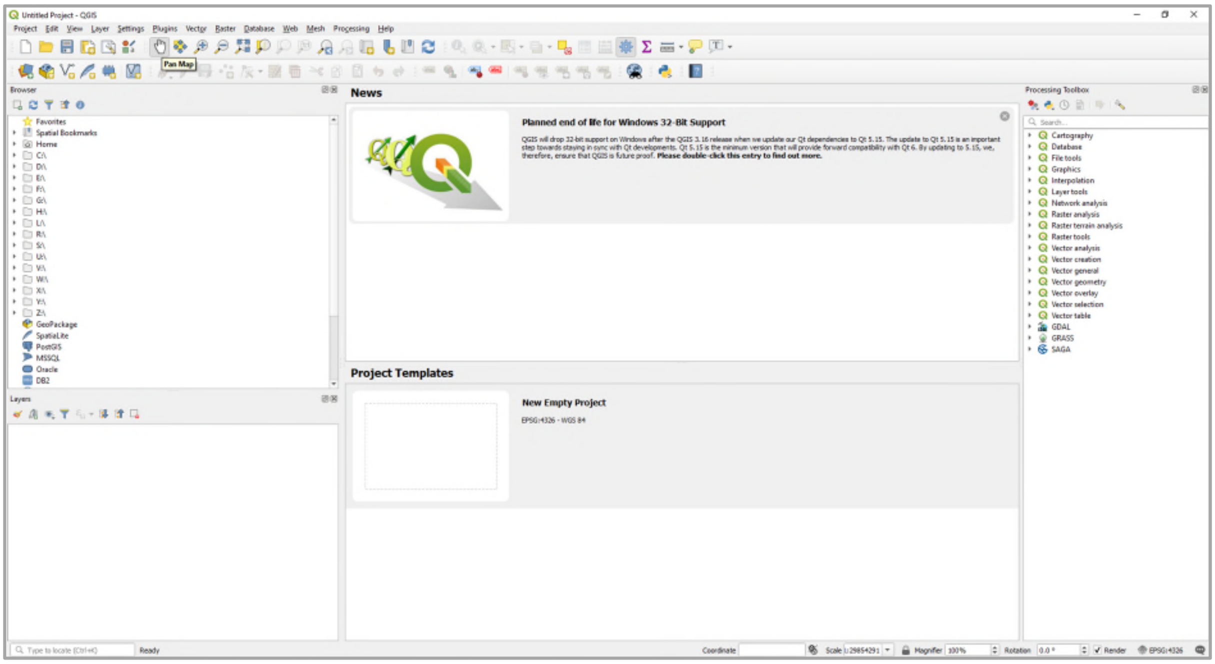
In terms of the deeper subsoils (>0.5 m), we found that most of the seasonal and temporal variation in EMI results could be attributed to changes in soil moisture across the dry season capture period. This variation was significant, though normalisation of the dataset helped to reduce variations caused by environmental conditions. Normalisation of the EMI dataset enabled improved edge matching of EMI patterns taken at different times and soil moisture conditions. This process enabled development of a continuous and relatively seamless EMI mosaic product. A full description of the normalisation process is included in Appendix E along with other data cleansing and corrective measures used to remove outliers and interpolate the dataset.

Appendix D. Logging the EMI data with QGIS

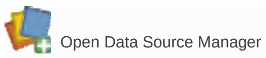
EMI data was logged onto the rugged field computer using QGIS. This program also allowed real time positioning and tracking in the landscape. It proved relatively easy to use and stable (rarely freezes or crashes under hot field conditions). Based on experience with this project, a description of how QGIS can be set up and used in the field is provided below.

1. Create a Project

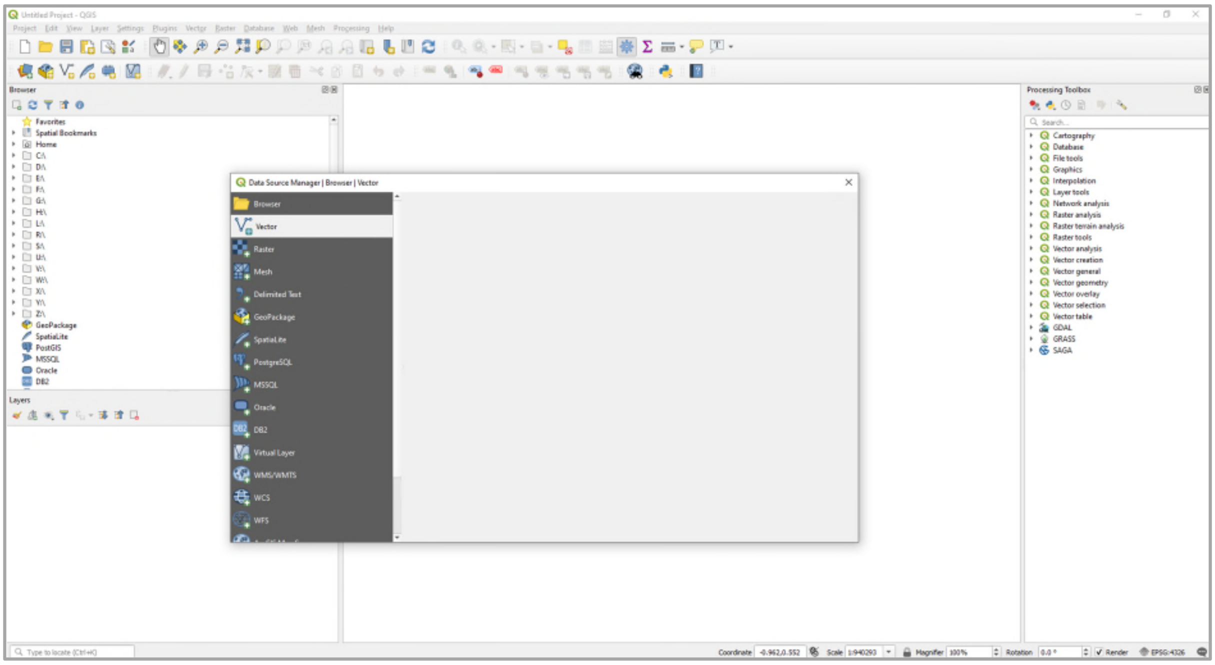
Download QGIS to your field computer then open the program.

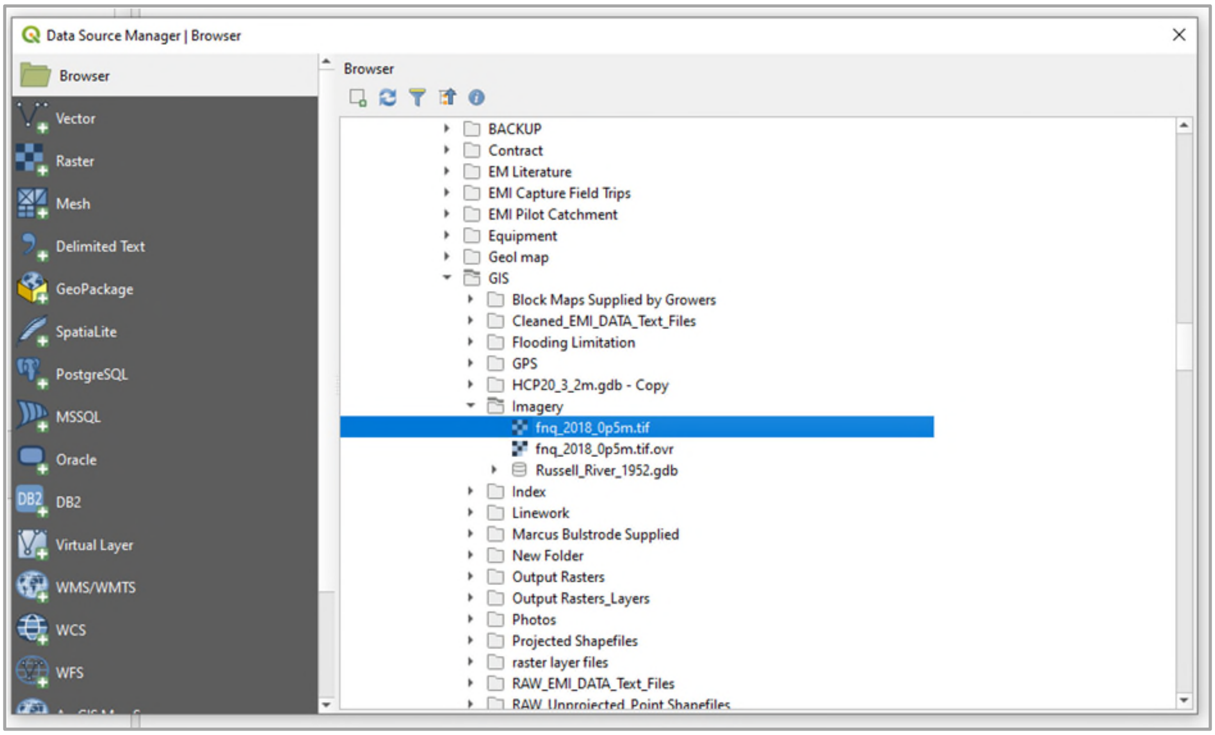


Select ‘Project’ tab then ‘New’ to create a project file for data collection during a field survey. Save the project using an appropriate name e.g. RUSS_project_field_2020. Now add the layers required.

Add a base imagery layer by clicking on the 

icon. The Data Source Manager should open in Browser mode.

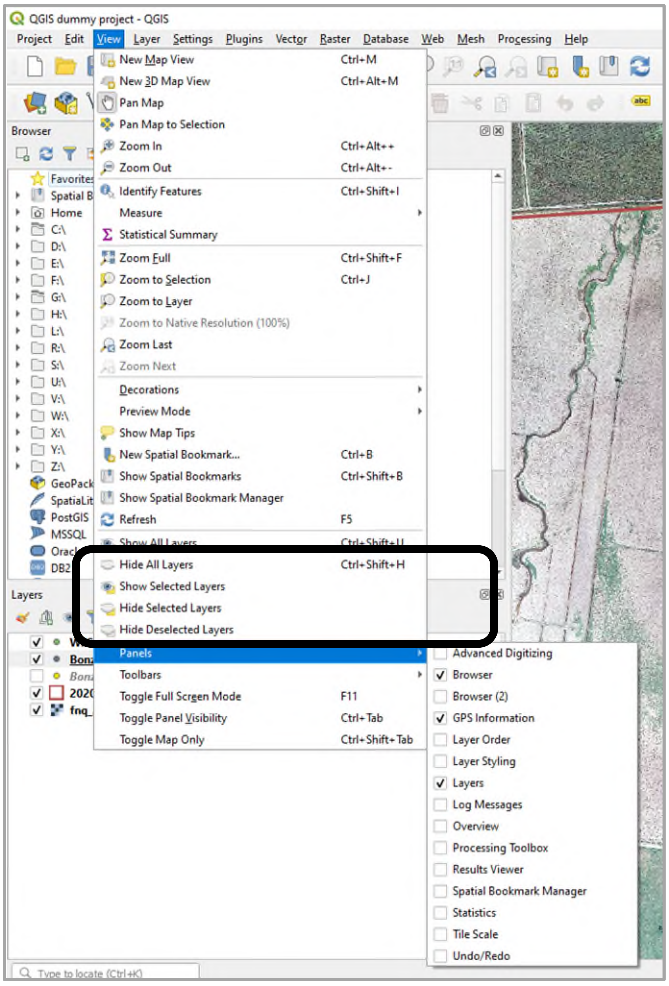


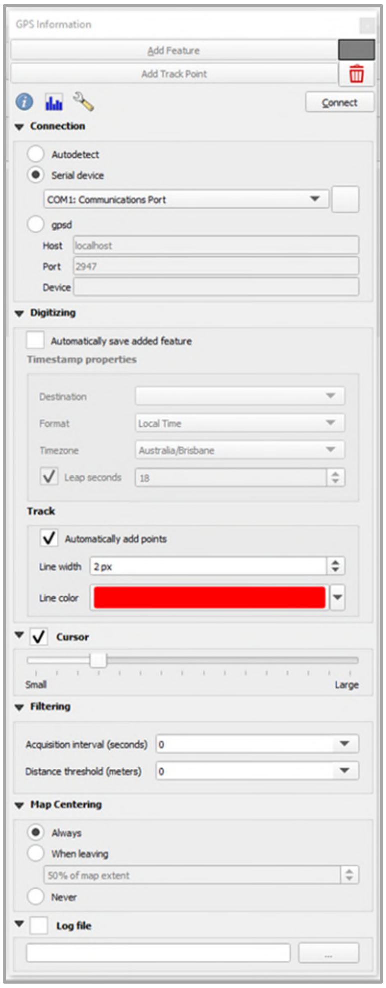


Add imagery and any additional layers of interest, for example, land parcels, roads. An imagery TIF file is recommended.

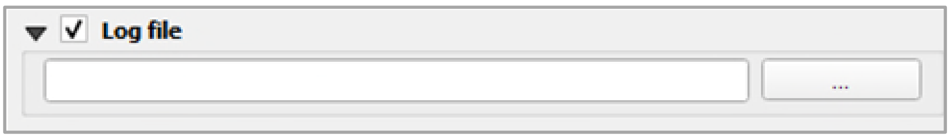
2. Logging data in QGIS

To log point data in QGIS, the GPS information panel view is required. In an open session of QGIS select the ‘View’ tab, navigate to ‘Panels’ and check the ‘GPS Information’ box. It will automatically appear on the bottom left side of the screen view. For ease of viewing, hold and drag it to the right of the screen and when a block colour panel appears release it. It should then be ‘pinned’ to the right side of the screen view.



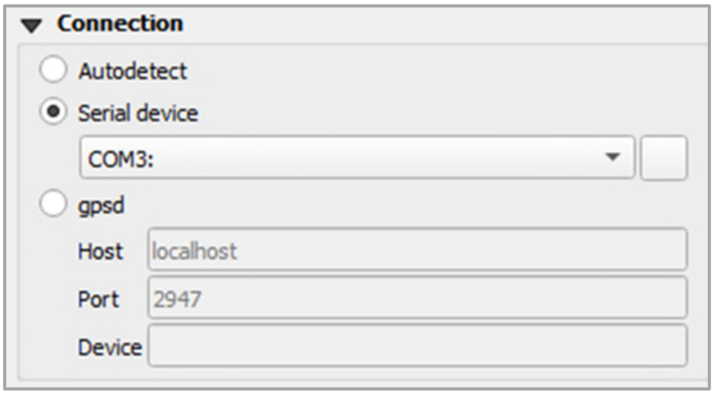


Navigate to the bottom of the GPS Information panel to ‘Log file’ and check the box. Select the box with three dots and navigate to the location where the NMEA file is to be saved. Good naming convention allows the file to be readily identifiable and spatially located (e.g. block name and capture date).

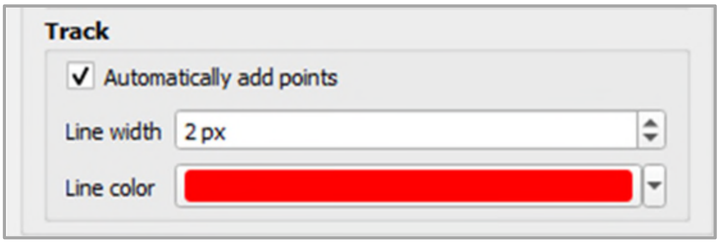


Set features of the GPS Information panel:

Under ‘Connection’, the COM ports of the computer in use will be populated in the drop-down selection list under ‘Serial device’. Choose the appropriate COM port.

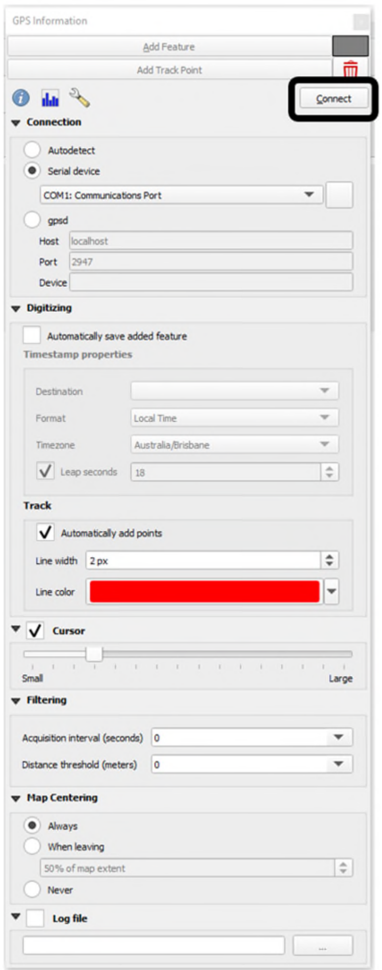


- Under ‘Track’ check the ‘Automatically add points’ box. Specify line width and colour.

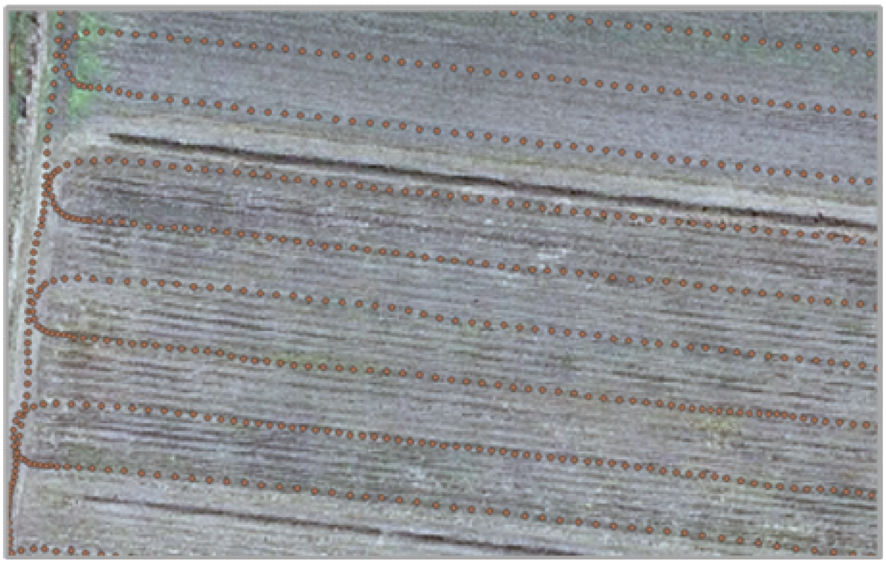


- Adjust other ‘Map Centering’, ‘Filtering’, and ‘Cursor’ settings to suit.

To commence surveying, select ‘Connect’ in the top right-hand side of the GPS Information panel (once selected this button will automatically appear as ‘Disconnect’).



As plant rows are traversed, data points will appear (refer below).



Map scale can be adjusted to optimise the real-time viewing of data points as they are captured. Once the survey is complete, select ‘Disconnect’ in the top right-hand side of the GPS Information panel. The file created at the commencement of the survey will automatically be saved.

Review the data. The completed survey data will appear as a block of data points (refer below). Where possible, save the point dataset to a second location as back up (i.e. on an external USB drive).

3. Data management and processing

At the end of each day, the raw data was sent back to the office for processing. This involved conversion of the raw '.nmea' format data to a feature class format, using an internally developed ArcGIS® add-in tool called DualEM to feature class. These feature class datasets were then cleaned and processed in ArcGIS Pro® (refer Appendix E). Data cleaning involves the removal of outliers and extraneous points, such as non-essential measurements taken outside the survey area. To minimise skewing the interpolated mosaics, extraneous, atypical, high readings (attributed to conductive infrastructure such as pipes and reinforced culverts) were also removed.

Appendix E. Automated EMI data processing

To allow analysis and final map development, the raw EMI data required processing by interpolation to transform point data from each EMI sensor into area-wide GIS raster layers. Interpolation creates a continuous layer of data across an area by predicting or extrapolating values into locations with no data from known data sample point values. Interpolation is based on the assumption that the point values are spatially correlated, that is, points that are closer together are more likely to share similar values than those further apart (Esri Australia Pty. Ltd., 2021e).

During the project, the raw EMI data underwent a series of data correction, cleaning and interpolation techniques aimed at developing a comprehensive, systematic, and repeatable process for data management and analysis. An automated process was developed to provide a structured and standardized approach to processing the raw EMI data. This process came in the form of a 'script' developed for ArcGIS Pro (version 2.7, Copyright © 1995–2021 Esri). It allows for rapid processing of large data sets, reduces human bias and/or error, and is designed to be easily replicated across similar EMI surveys.

The DualEM instrument exports data into a '.nmea' format. The Resources Spatial Services team developed an Add-In for ArcMap that converted the '.nmea' data to a feature class format. The feature class datasets were then able to be imported as point data into Esri software (e.g., ArcMap, ArcGIS Pro).

ArcGIS Pro spatial software was used to develop a python script to facilitate and automate the standardised approach from initial raw data points through to data preparation, interpolation, and storage. It provides the following functions:

- Data correction and cleaning, including the removal of outlying data and normalising of EMI data in readiness for interpolation and analysis.
- Interpolation of the data using the 'natural neighbours' method on original data values and normalised data values for each of the four sensor depths.
- Interpolated surfaces are then combined to provide a multispectral image incorporating all four sensor depths, and mosaiced as a single surface.

1. Data cleaning

Data was initially cleaned by removing spatial, numerical and statistical outliers. To achieve this, the data needed to be cleaned of extraneous points or outliers, such as non-essential measurements taken outside the survey area or random negative readings, to minimise skewing the interpolation of the readings. Extraneous, atypical, high readings, attributed to buried metal, concrete culverts or other infrastructure such as pipes, were also removed.

2. Removal of outliers

Block boundaries

Points located outside the area of interest were removed using a pre-defined survey area boundary (e.g. cane block/paddock boundaries). Points can be removed manually by deleting from the data set once identified or may be clipped out by creating a boundary polygon in ArcGIS.

The use of an automated block boundary polygon is an optional input to the processing script and used to eliminate points outside this area. Where a pre-defined boundary polygon was not supplied, the script creates a polygon based on the supplied data points using a maximum distance parameter between points. Post processing review of the created boundary was necessary on occasion to adjust the distance parameter to ensure the boundary was correctly identified.

Binning/histogram filtering

Large-scale EMI data are rarely normally distributed (Minsley *et al*., 2012), so the removal of outliers using traditional statistical methods is often not appropriate. To overcome this constraint, von Hebel *et al*. (2014) derived a histogram filtering technique to effectively identify and remove outliers of such data. Using this technique, the project EMI data was placed into 15 equally spaced bars (bins) within the histogram and the percentage of data within each bin calculated. Where a bin contained less than 0.5% of data, the bin was considered to contain outlier data, and as such, all data within the bin was removed (Brogi *et al*., 2019; von Hebel *et al*., 2014).

Figure 24 and Figure 25 below show an example of the distribution of ECa values prior to and post binning, clearly identifying the effectiveness of the binning process in removing outlier and anomalous data. The resulting data, as shown in Figure 25 more closely represents a standard distribution and was used in additional cleaning processes and analysis.

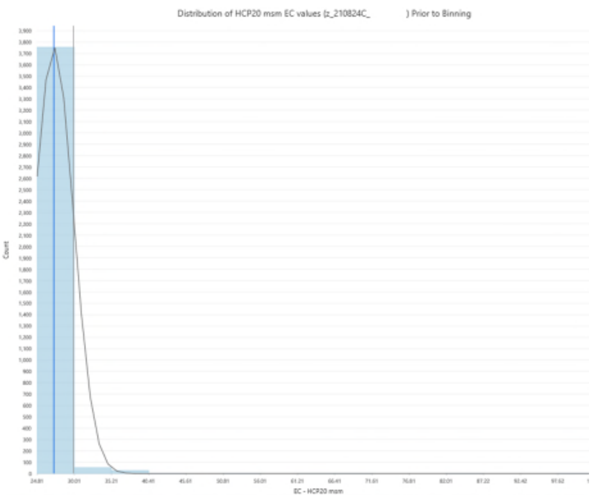


Figure 24: Distribution of ECa values 15 bins prior to removal of outliers

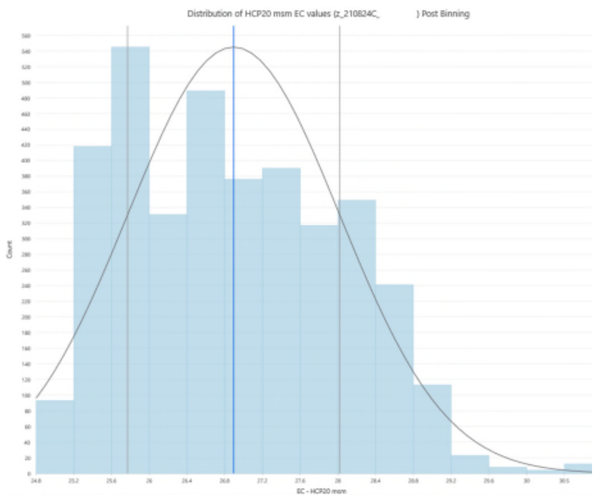


Figure 25: Distribution of ECa values in 15 bins following binning process to remove outliers

Spatial outlier analysis

Following the histogram filtering process, spatial outliers were identified and removed using the spatial statistic tool; Cluster and Outlier Analysis in ArcGIS (Anselin Local Moran's I) (Esri Australia Pty. Ltd., 2021a). The inverse distance parameter was chosen for the conceptualisation of spatial relationship parameter, using a Euclidean distance band, or threshold distance, of 20 m.

Spatial outlier analysis evaluates the value at each point compared to neighbouring values. The Cluster and Outlier Analysis geoprocessing tool specifically identifies spatial clusters of features with high or low values. That is, a low value surrounded by high values, or a high value surrounded by low values. The analysis uses the Anselin Local Moran's I Index to identify outliers, where a negative value indicates that the feature has neighbouring features with dissimilar values (Esri Australia Pty. Ltd., 2021c). Local Moran's I Index is a relative measure and is interpreted in the context of its computed z-score and p-value. A high z-score indicates the surrounding features have similar values, and a low negative z-score indicates a statistically significant spatial data outlier.

Using the Cluster and Outlier Analysis geoprocessing tool, an outlier was removed from the project's dataset where:

- Cluster and Outlier Analysis has identified the point as an outlier (either HL – a high value surrounded by low values, or LH – a low value surrounded by high values). A HL or LH occurs where an outlier is statistically significant, at the 95% confidence level), and
- z-score is less than -1.96 (where z-score relates to standard deviations, and -1.96 correlates to the 95% confidence level), and
- p-value is less than 0.05 – also correlating with a 95% confidence level. Where the p-value is very small, there is a small probability that the pattern is the result of a random process (i.e. clustering).

The resulting distribution of z-score and p-value are shown in Figure 26 where points located outside the limits set (lower left of Figure 26) were removed.

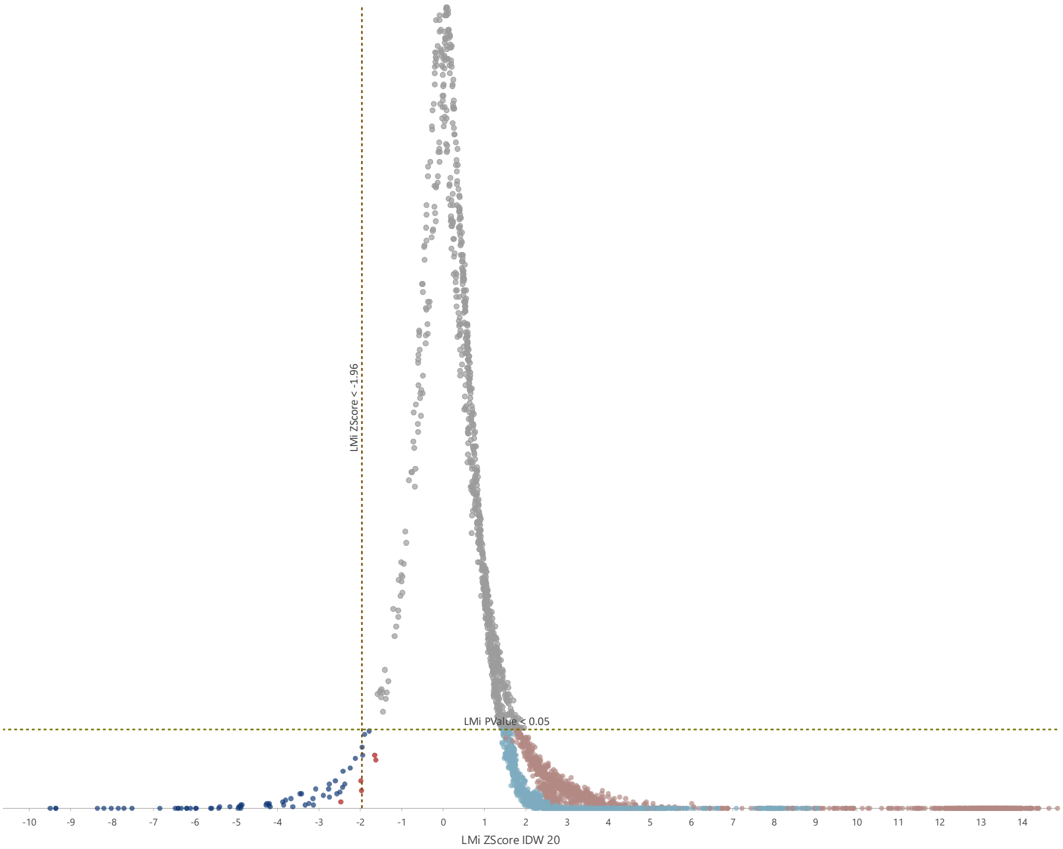


Figure 26: Visual representation of cluster and outlier analysis identifying spatial outliers removed in the lower left

Standard deviation removal

Following binning and spatial outlier processes, the EMI data distribution identified additional outlying data to be removed based on the standard deviation. Statistics were calculated to identify a standard distribution, and EMI values more than 2.5 standard deviations either side of the mean were removed.

3. Normalising data

The final stage in preparing the data for interpolation involved normalisation of the EMI data by rescaling the values between 0 and 1. The aim of normalising the data was to enable larger scale analysis of the data across multiple paddocks (datasets) captured under differing environmental conditions at different times. Normalisation was completed using the formula:

$$z_i = \frac{x_i - \min(x)}{\max(x) - \min(x)}$$

Where $x = (x1, ... xn)$ for each EMI value and z_i is the normalised value.

Interpolated surfaces of normalised data were found to provide greater visual continuity of patterns between datasets across the survey area, which assisted soil boundary interpretation. Although the EMI values for normalised (between 0 and 1) and original values differ, the spread and distribution of data is not changed as shown in **Error! Reference source not found.** and **Error! Reference source not found.** below.

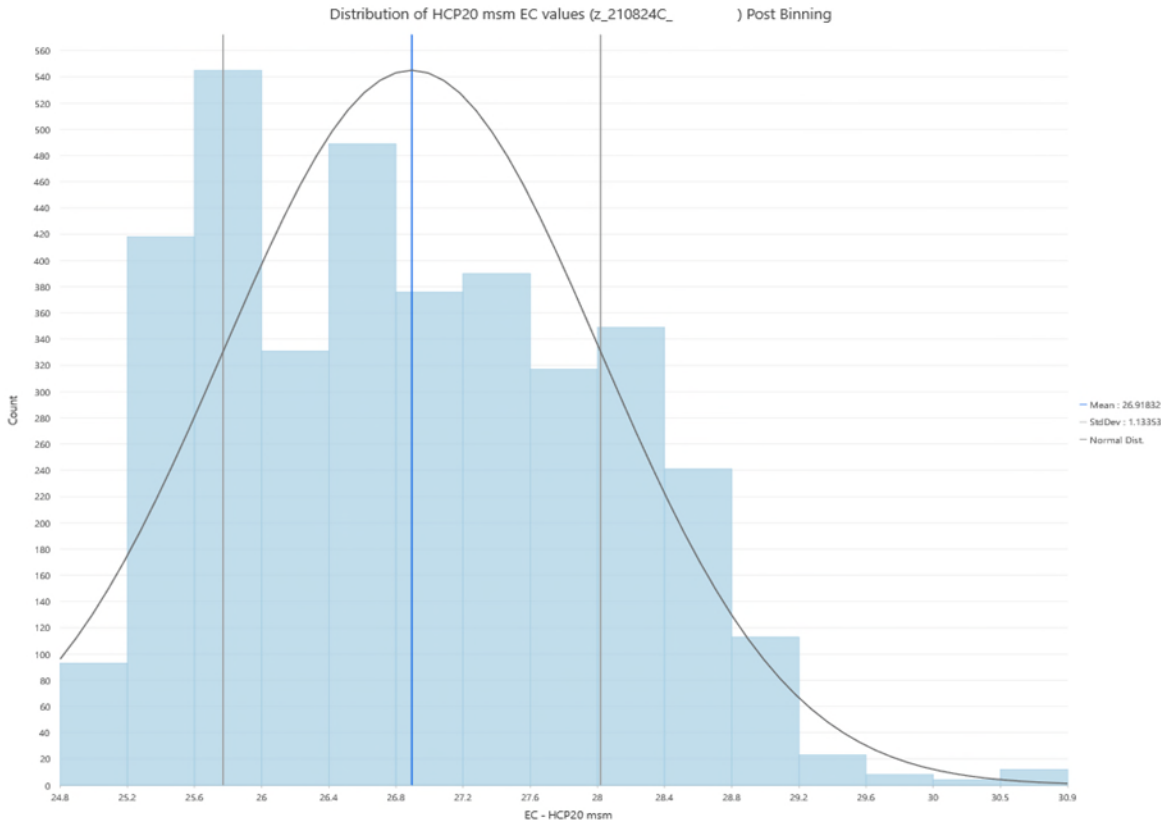


Figure 27: Distribution of EC values post binning

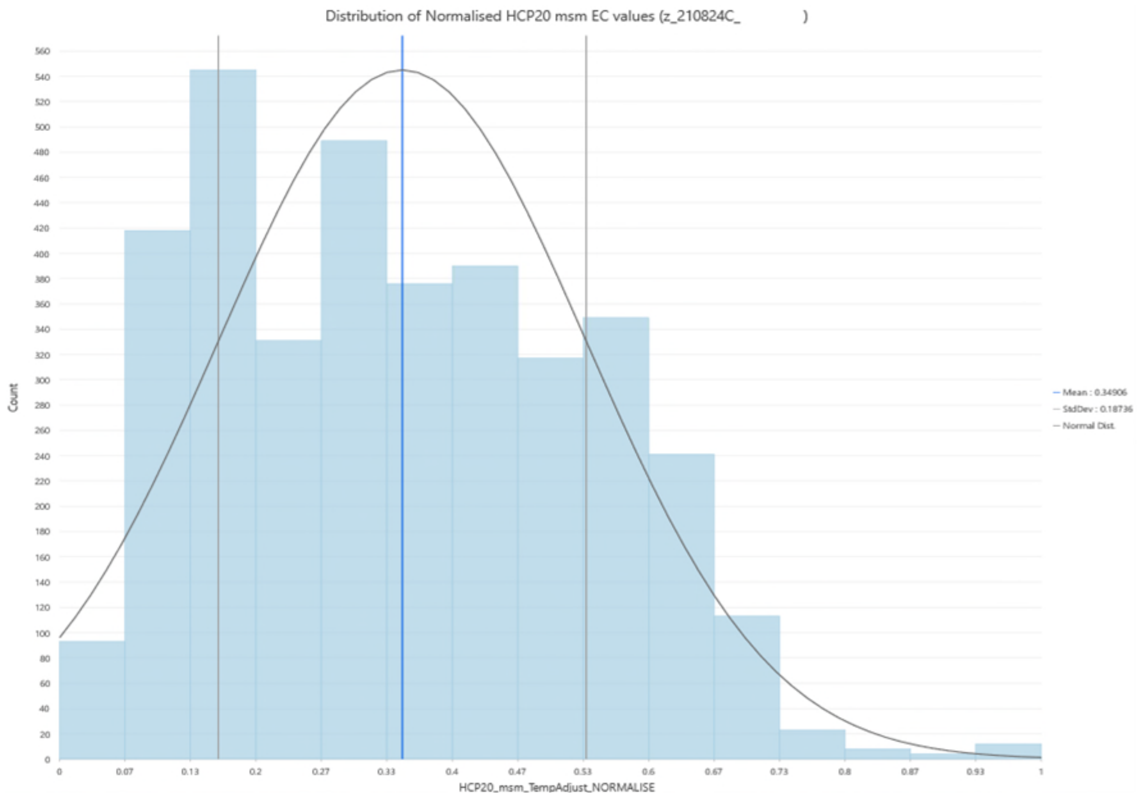


Figure 28: Distribution of EC values following normalisation

4. Interpolation

A number of interpolation methods are available for use in ArcGIS Pro (Esri Australia Pty. Ltd., 2021b). Interpolation of EMI data was completed using the ‘natural neighbours’ method following testing and review of several other methods. Natural neighbour is considered a good general purpose interpolation technique (Esri Australia Pty. Ltd., 2021d). The method finds the closest sample of input points, and applies weights based on proportionate areas to interpolate a value (Esri Australia Pty. Ltd., 2021d).

Surfaces were interpolated individually for each sensor depth (PRP1, PRP2, HCP1, and HCP2) using both the EMI value (following cleaning and outlier removal) and the normalised value. A cell size of 1 m (1 m x 1 m grid) was used for all interpolated surfaces. The figures below (Figure 31 show examples of single band rasters in greyscale representing the interpolated surface(s) at each depth.

Multispectral image

Each individual interpolated surface was combined to provide a multispectral image where each depth of measurement is recorded as a separate band, where:

Band 1 (PRP1)	approx. soil surface
Band 2 (PRP2)	approx. 0.5 m below soil surface
Band 3 (HCP1)	approx. 1.1 m below soil surface
Band 4 (HCP2)	approx. 2.7 m below soil surface

A multispectral image allows easy viewing of the EMI data at each individual soil depth using a coloured stretch symbology (Figure 33), or a combination of bands representing multiple depths using a RGB (reg, green, blue) symbology (Figure 34).

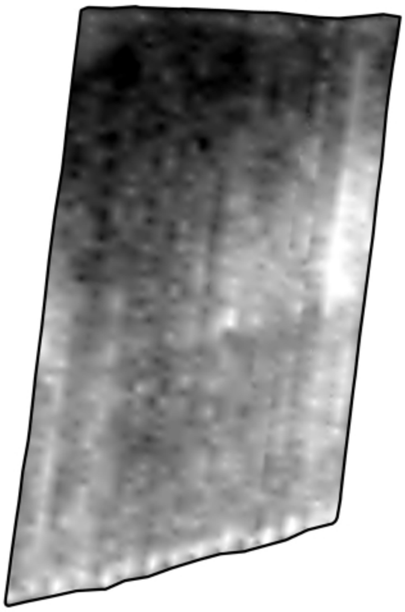


Figure 29: PRP1 (surface) interpolation using natural neighbours

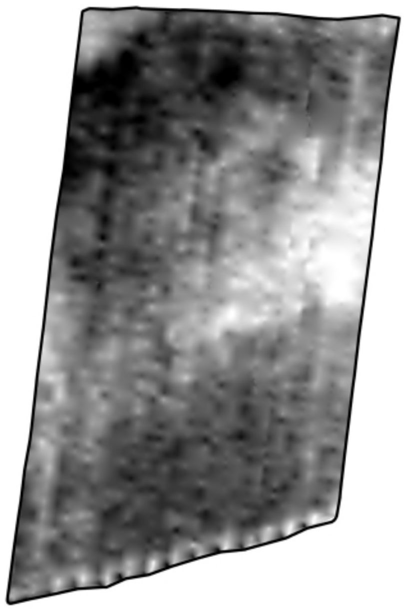


Figure 30: PRP2 (0.5 m) interpolation using natural neighbours

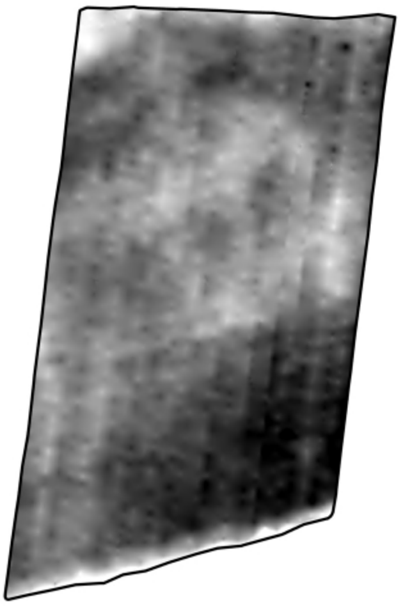


Figure 31: HCP1 (1.1 m) interpolation using natural neighbours

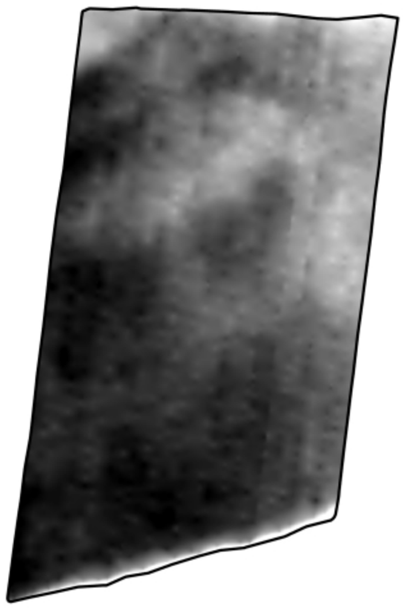


Figure 32: HCP2 (2.7 m) interpolation using natural neighbours

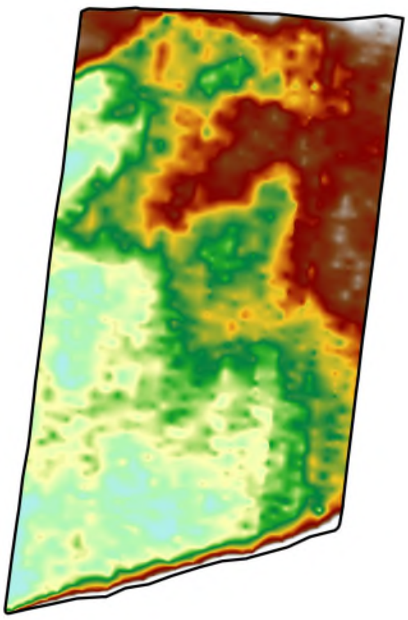


Figure 33: Band 4 (HCP2) displayed using a stretch symbology in colour

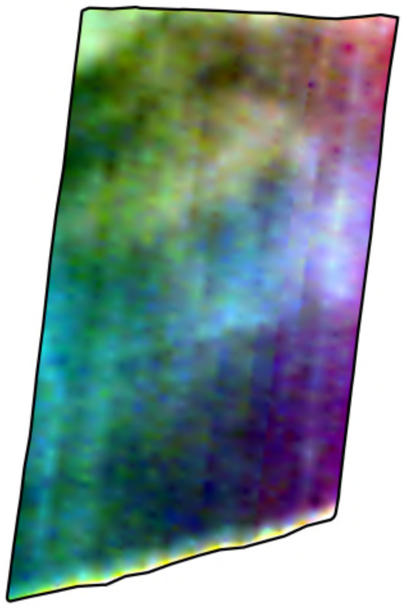


Figure 34: Bands 4, 3 and 2 (HCP2) represented as red, green and blue respectively

Mosaic Image

Multispectral images from each dataset are then combined to form a single multispectral mosaic raster across the entire study area (Figure 35). This allows a single image to be loaded and interrogated while providing access to data from each component dataset and at each depth.

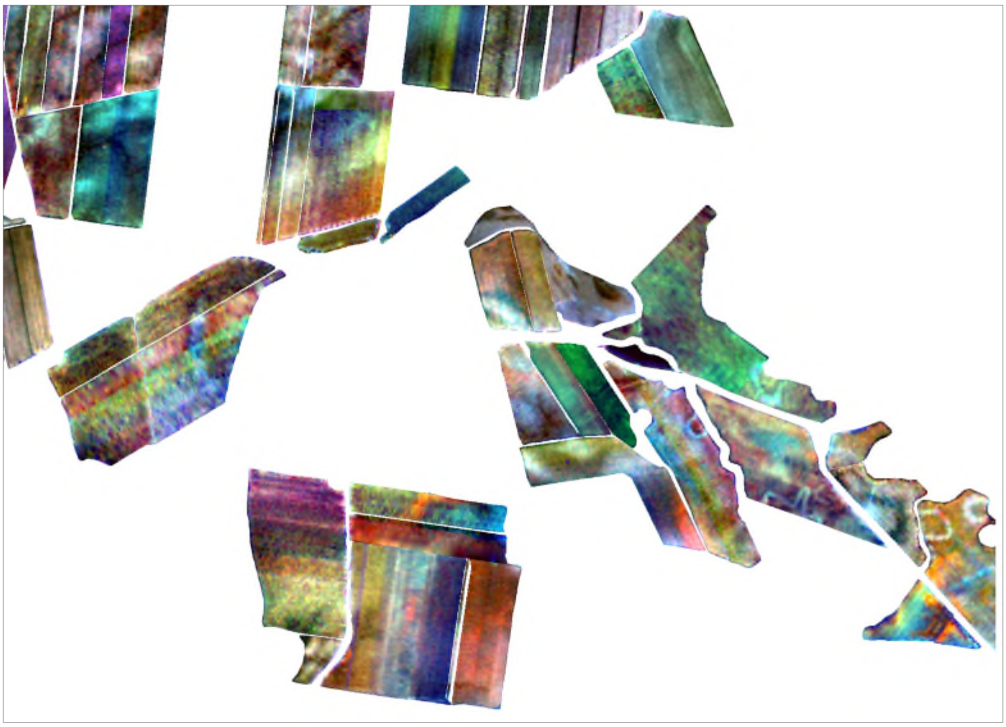


Figure 35: Sample of mosaic image across multiple datasets displaying multispectral bands 4, 3 and 2 as red, green and blue respectively

5. Output storage

A parent folder is initially selected as an input parameter in the script, with subfolders created as part of the script process (as required). The data created is structured into four subfolders (Figure 36), including:

- Log Files - a copy of the log file created while running the script.
- Natural Neighbours - interpolated surfaces using adjusted EM values.
- Normalised Natural Neighbours - interpolated surfaces using normalised EM values.
- Process Statistics (used for Intermediate Outputs).

As the script is run with different EMI datasets (i.e., different paddocks), the same output folder is specified to ensure intermediate data, final data outputs, and log files are recorded to the same project folder, including the mosaicking of interpolated surfaces.

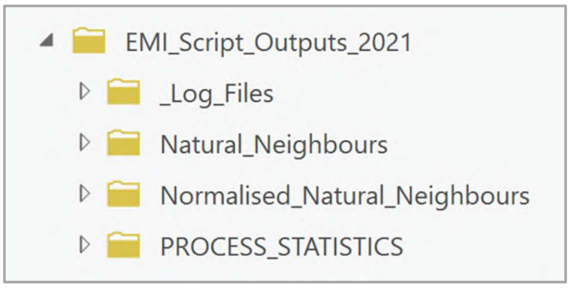


Figure 36: Example of outputs folder and geodatabase structure created by the script.

The initial folder (in this example. EMI_Script_Outputs_2021) is supplied as a script parameter. Other folders and geodatabases are created as required by the script.

Intermediate outputs

Intermediatory outputs are stored in a geodatabase created by the script within the current ArcGIS project (Figure 37). Intermediatory data can be used for verification and validation purposes, and to view statistics used in calculations. Intermediatory outputs include:

- Copy of original data, projected, and with adjusted temperature values for each EMI depth.
- Copy of data for each EMI depth, including bin field (created during Histogram Filtering), and normalised value. This is the final point data used for interpolation.
- Statistical table of bin data (created during Histogram Filtering), including each bin, the number of data values and percentage of data within each bin.
- Statistical table of EMI data values identifying number of points and points removed at each stage of pre-processing and cleaning.
- Cluster and outlier analysis point data for each EMI depth.
- External boundary created using supplied points.

Final outputs

Several final outputs are created for each dataset, including:

- Interpolated surface using adjusted data values.
- Multispectral surface incorporating the individual interpolated surfaces for each dataset using raw values.
- Mosaic incorporating each multispectral image for raw data values.
- Interpolated surface using normalised data values.
- Multispectral surface incorporating the individual interpolated surfaces for each dataset using normalised values.
- Mosaic incorporating each multispectral image for normalised data values.

Each of the folders of interpolated surfaces include multiple geodatabases (Figure 38): one containing results for each individual dataset at each depth (HCP1, HCP2, PRP1, and PRP2); and one containing the multispectral interpolated surfaces (including mosaic).

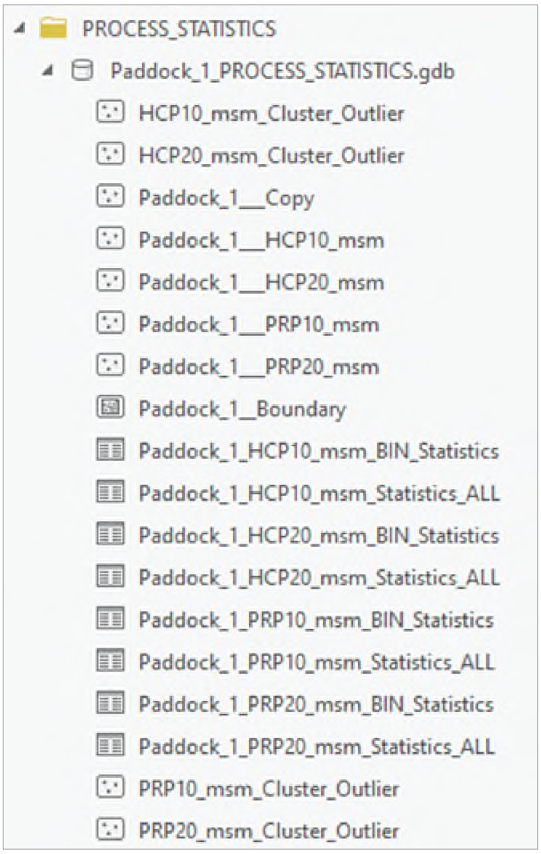


Figure 37: Example of geodatabase created and intermediatory data created by the script

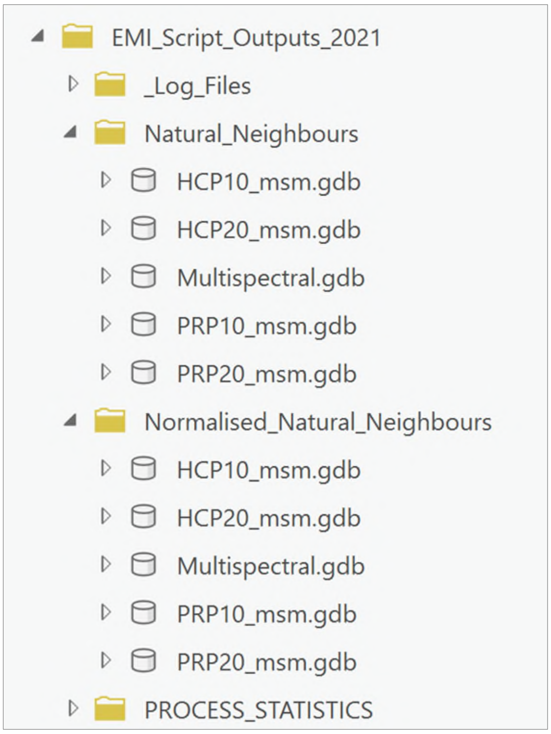


Figure 38: Structure of geodatabases created for interpolated surfaces; Natural Neighbours and Normalised Natural Neighbours folders