Department of Environment and Science

Soil constraints mapping to inform nutrient management in the cropping industries – RP155C

Soil Constraints Framework

Queensland Government

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Disclaimer

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Introduction

The need to improve nutrient management within cropping industries, particularly sugarcane production, has been identified as a significant factor in protecting water quality of the Great Barrier Reef. Improved soil mapping and interpreted information on key soil constraints that influence production and crop nutrient management will provide a more reliable basis for cropping and land-management decisions.

Good farm management requires an understanding of environmental characteristics and soil resources. It is important for land managers to have a knowledge of soils, including the potential productivity limitations from subsoil constraints. This allows them to implement effective management responses, including mitigation and improvement measures.

This Soil Constraints mapping project addresses a number of key research priorities identified in the Reef Water Quality Protection Plan 2013 R, D & I Strategy. Specifically, it addresses Research Gaps CMP1, CMP3 and CMP4, which are associated with refining nutrient management strategies, as part of improving best management practices. The project will also provide base data for other cropping industries and contribute to Research Gap BMP24 'understanding nutrient loss pathways'. This is a multifaceted project that aims to provide examples of industry-led approaches for use of the new information products.

This project's objectives are to deliver:

- Soil maps with improved spatial detail, for key cropping areas in the Reef catchments:
    - Wet Tropics
    - Townsville
    - Burdekin
    - Mackay- Whitsunday
    - Fitzroy
    - Burnett-Mary (Wide Bay).
- A framework for the identification of soil constraints for cropping
- Information on soil constraints, spatially correlated to the enhanced soil maps
- Environmental characteristics information for the Burnett-Mary region
- A pilot assessment and method for assessing Production Unit Yield Potential for sugarcane as a key component of a Farm Nutrient Management Plan.

This report addresses the second objective above, and provides an introduction and general background to the identification and development of the key subsoil constraints to cropping industries within the Great Barrier Reef catchments. The RP155C Technical Report (in preparation) contains the general project results and full details on the methodology used, and the User Guide report (O'Brien, 2018) contains instructions on how to work with project datasets.

These constraints are limited to those factors that can be derived from intrinsic soil properties. It is not possible to estimate current condition of soil properties, such as surface soil pH and organic carbon, using digital soil mapping techniques, as these properties are too influenced by site specific land management practices. The Framework also provides critical thresholds relevant to sugarcane production. These thresholds are applicable across all of the reef catchment areas considered. The framework was developed with input from DNNRME, DES, Farmassist, Willmar and MSF Ltd.

Methods

Approach to developing the Digital Soil Mapping

Soils are identified by the characteristics of the soil profile where the horizons from soil surface to the underlying parent material are described. A 'Soil Profile Class' (SPC) groups similar soil profiles together around a defined central 'typical' concept of a particular soil type. Within each SPC group, at least one representative site is described in detail, sampled and analysed in a laboratory to identify key intrinsic characteristics.

As such, the variation of some features within an SPC is less than the variation between different SPCs. Soil morphological properties, and selected laboratory results, are typically used to define an SPC along with geology, parent material, landform/landscape position, vegetation and land use potential.

Digital soil mapping (DSM) involves mathematical techniques to develop spatial models that link a range of landscape data such as elevation, radiometric data, climate and existing land resource survey data together to more accurately map soil properties at a finer spatial scale than previously reported. This provides an improved mapping resource to land managers. These techniques also facilitate targeting of areas where available soil and land resource data warrants improvement through more conventional field survey methods.

The DSM approach for this project uses an algorithm called DSMART (Odgers et al., 2014), which essentially builds a landscape classification model from existing soil data and its spatial correlations with various environmental datasets. This model can then be used to predict soil profile class occurrence across the input map extent, but at a finer scale than published. DSM inputs for this project largely comprise 1:100,000-scale soil surveys, which allow a minimum delineated area of 40 ha. By contrast, and outputs for this project have a 30x30m pixel size, or a minimum delineated area of < 0.1 ha. The DSMART process also enables some extrapolation outside the map area, provided the landscape remains similar enough to produce a sensible result. As such, some previously unmapped gaps between survey boundaries have been filled.

The SPC analytical sites will have samples taken at different depths in the soil profile making cross-comparison and averaging data from different SPCs difficult. This problem was overcome by using a mathematical technique - a mass-preserving spline. For each SPC within each catchment the mean (average) of each soil attribute (e.g., clay content) is calculated using a mass-preserving splining process for each of the six soil depth ranges (layers):

- Layer 1: 0-5cm
- Layer 2: 5-15cm
- Layer 3: 15-30cm
- Layer 4: 30-60cm
- Layer 5: 60-100cm
- Layer 6: 100-200cm

Where appropriate, laboratory data were used for attributes. However, in some cases attributes are defined using profile description data rather than laboratory data from individual soil depths. In these cases, a greater number of sites are used to derive the attribute value used.

Once the available laboratory data for an SPC has been harmonised and average attribute values determined, the attributes can be spatialized. The disaggregated map of 'most-likely' Soil Profile Class is essentially used as a spatial index to create maps of each soil attribute, at each of the depth ranges above. Soil constraint maps are then generated by applying classification rules to one or more attribute layers.

Soil Constraints Identification

A set of key constraints were identified from previous studies (Bloesch et al. 2006; Moody and Cong 2008) and workshopped with stakeholders. The constraints are shown in Table 1, together with their indicator attribute, the implications of each constraint, and some management options.

Table 1: Soil constraints, indicators, implications and management options.

Constraint	Indicator	Implications	Management
Acidity	pH	Probable aluminium and/or manganese toxicities. Possible acidity-induced molybdenum deficiency, and one or more deficiencies of calcium, magnesium and potassium.	Amend with appropriate ameliorant (e.g., agricultural lime or dolomite) at rates as required.
Rapid acidification	Time in years for pH of a soil layer to decrease by one pH unit. Modelled using pH, clay and organic carbon content data.	Soils with a high acidification risk have a low 'buffering capacity', or ability to absorb inputs of acidity/alkalinity without changing the pH. Acid inputs are intrinsic to cropping systems, and acidification affects the whole profile. However, amelioration below the surface 30cm is very difficult.	Monitor surface and subsoil (to the bottom of the rooting depth) pH frequently so that a regular liming program can be implemented to maintain soil pH at levels required for optimum crop growth.
Alkalinity	pH	Possible alkalinity-induced deficiencies of copper, zinc, iron and manganese.	Decrease soil pH by applying appropriate ameliorant (e.g. ammonium sulfate or elemental sulfur) at rates as required.
Low nutrient holding capacity	Cation exchange capacity (CEC/ECEC)	Soil has limited capacity to retain exchangeable cation nutrients such as calcium, magnesium and potassium. Potassium leaching possible.	Use split application of fertilisers, particularly potassium fertilisers. Add organic matter to increase CEC. Avoid over-liming and raising soil pH above pH 6.
Excessive phosphorous fixation	Phosphorus Buffer Index (PBI). Modelled using clay, organic carbon, and CEC data.	The Phosphorus Buffer Index (PBI) describes the P-'fixing' ability of a soil, or its ability to convert P into compounds that plants cannot absorb. A high PBI indicates that added P will mostly not be available to plants for long.	P fertiliser management for high P-fixing soils depends on reducing contact between water-soluble P fertilisers and soil by placing the fertiliser in bands below and to the side of the crop to facilitate early root-fertiliser contact.
Excessive phosphorus leaching	Phosphorus Buffer Index (PBI). Modelled using clay, organic carbon, and CEC data.	A low PBI indicates that a large proportion of added P will remain in the soil solution where it is susceptible to removal by leaching.	Use citrate-soluble P fertilisers (such as reactive rock phosphate) rather than water-soluble P fertilisers. Adding organic matter may increase the P-sorbing ability of a soil.
High Sodicity	Exchangeable sodium percentage (ESP). The sodium proportion of measured major cations.	Highly sodic soils can be vulnerable to dispersive erosion and/or waterlogging, and may have nutrient deficiency issues	Use gypsum as a soil ameliorant. Gypsum supplies Calcium which can displace Sodium on clay exchange sites, reducing dispersibility.

Constraint	Indicator	Implications	Management
High dispersive potential	Four potential indicators are offered for comparison: ESP (traditional approach), modified ESP including some Potassium (Exchangeable Dispersive Percentage, EDP), ratio of salinity to ESP (Electrochemical Stability Index, ESI), and ratio of salinity to exchangeable sodium (Exchangeable Sodium Concentration, ESC)	Dispersion is when soil aggregates break down into primary particles (sand/silt/clay) when saturated with water. Dispersive soils are vulnerable to physical problems like compaction, surface crusting, impeded water movement, and erosion.	Use gypsum as a soil ameliorant. Minimise exposure of soil surface. Avoid exposure of subsoil.
High salinity	Electrical conductivity (EC)	As salinity increases in the soil profile, plant roots become less able to extract water and nutrients. Plants may become water-stressed even where plant available water capacity (PAWC) appears sufficient.	Drainage is required to remove excess soluble salts, coupled with gypsum application to displace exchangeable sodium.
Insufficient Drainage	Drainage Class (field assessment)	Poor drainage results in soil waterlogging. This results in lack of oxygen supply to roots, impeded growth and vulnerability to disease.	Consider artificial drainage or laser-levelling if appropriate. Mound crop rows to improve aeration in the root zone.
Excessive Drainage	Drainage Class (field assessment) and Clay content	Excess drainage results in poor water retention after irrigation, even where PAWC may appear sufficiently high.	Consider application of organic matter and/or mill ash to improve soil water holding capacity.
Low Permeability	Permeability Class (field assessment)	Permeability issues may occur at the land surface or at depth in the soil. Either way, water movement will be affected, and plant root growth and/or seedling emergence can be impeded.	Consider application of organic matter and/or mill ash to improve soil porosity.
Low Plant Available Water Capacity (PAWC; Dryland)	Millimetres of water to a given depth of soil. Modelled using particle size, gravimetric water content at -1500 kPa, and bulk density data.	PAWC is the soil's capacity to hold moisture available to plants. It has an upper limit at full saturation, and a lower limit below which plant roots are physically unable to extract water. PAWC calculated for soil layers and added up from the surface until a depth where other soil factors that limit PAWC are encountered. These include significant rocks, sodicity, salinity, and acidity.	Soil moisture conservation by surface mulching and reduced tillage.
Low PAWC (Irrigated)			Management of irrigation method, scheduling and volume with the goal of high water use efficiency.
Shallow soil depth	Median observed depth of soil cores taken during survey fieldwork.	Plant establishment and physical support may be impeded. PAWC will be limited by a shallow soil.	Ameliorate restrictive layer where possible or adjust crop and/or management to suit soil capability
High Profile Rockiness	Amount of coarse fragments (of significant size)	Profile rockiness restricts PAWC and interferes with tillage and harvesting operations.	Shallow rocks may be mechanically removed.
High Surface Rockiness	Amount of surface coarse fragments (of significant size)	Surface rockiness impedes water infiltration and may damage equipment.	Surface rocks may be mechanically removed.

Constraint	Indicator	Implications	Management
Elevated Compaction Risk	Plastic Limit (modelled using clay and organic matter data), where it exceeds Drained Upper Limit (DUL, modelled during PAWC calculations).	Tillage and/or trafficking soil that is wetter than its plastic limit will cause compaction. Compaction restricts rooting depth and causes soil waterlogging because of impeded drainage.	Controlled traffic; permanent beds; zero/zonal tillage. Amend with deep ripping at a soil moisture content that allows the soil to fracture.

Attribute calculations for constraints

Soil constraints are either directly related to a single attribute recorded for each SPC, or rely on pedotransfer functions that combine a number of attributes. Table 2 lists the approach used for each constraint and provides details of pedotransfer functions used. Some of the more complex derivations are discussed further below the table.

Where 'expert judgement' is listed as a source for constraint definitions, this includes the opinions of experienced departmental land resource officers and sugarcane agronomists. Constraint cut-offs were workshopped during an event in February 2017.

Table 2: Constraint data sources and calculations

<table>
<tr><th>Constraint</th><th>Data source/derivation</th><th>References</th></tr>
<tr><td>Acidity</td><td>pH - Direct laboratory measurement, pH units.</td><td>Laboratory method: Rayment and Lyons, 2011, method 4A1

Interpretation: Baker and Eldershaw, 1993</td></tr>
<tr><td>Rapid acidification</td><td>pH buffering capacity

$pHBC = (0.955OC + 0.011CL) \times BD \times DI \times 2$

Where OC = Organic carbon percentage, CL = Clay percentage, BD = Bulk density (g/cm^3) DI = depth interval (cm). Units of Kmol (H^+) per hectare.

Acid accumulation curve

$ACC_{Acid} = -0.4762 + 3.751x - 0.0451x^2 + 0.0002x^3$

Where x = soil depth in centimetres. Units are Kmol (H^+) per hectare.

Time to acidify (by one pH unit)

$T_{Acid} = \frac{pHBC}{(ACC_{Acid}(LD) - ACC_{Acid}(UD)) \times 3.5}$

Where yearly acidity input for sugarcane systems Is estimated at 3.5 Kmol/yr. Units are years.</td><td>Laboratory methods: Rayment and Lyons, 2011 for OC and CL; McKenzie et al, 2002 for BD

Equations: Aitken et al, 1990; Moody and Aitken, 1997

Interpretation: Expert judgement</td></tr>
<tr><td>Alkalinity</td><td>pH - Direct laboratory measurement, pH units.</td><td>Laboratory method: Rayment and Lyons, 2011, method 4A1

Interpretation: Baker and Eldershaw, 1993</td></tr>
<tr><td>Low nutrient holding capacity</td><td>Cation Exchange Capacity - direct laboratory measurement, units of cmol$_c$/kg oven-dried soil.</td><td>Laboratory method: one of methods 15I-15K of Rayment and Lyons (2011) as appropriate

Interpretation: Baker and Eldershaw, 1993</td></tr>
<tr><td>Excessive phosphorous fixation</td><td rowspan="2">Phosphorus Buffering Index (PBI)

$PBI = -46.5 + 68.6OC - 4.5CEC + 4.1CL$

Where OC = Organic Carbon percentage, CEC = Cation Exchange Capacity in cmol$_c$/kg, and CL = Clay percentage. PBI is an index and is therefore unitless.</td><td rowspan="2">Equation: Moody, 2016 (pers. comm., based on 0-20cm soil data for representative soils of Queensland cane areas)

Interpretation: Moody, 2007; Moody and Cong, 2008</td></tr>
<tr><td>Excessive phosphorus leaching</td></tr>
<tr><td>High sodicity</td><td>Exchangeable Sodium Percentage (ESP)

$ESP = \frac{Na_{Exch.}}{CEC} \times 100$

Where $Na_{Exch.}$= exchangeable sodium, and CEC = Cation Exchange Capacity.</td><td>Laboratory method: one of methods 15I-15K of Rayment and Lyons (2011) as appropriate

Interpretation: Baker and Eldershaw, 1993</td></tr>
</table>

Constraint	Data source/derivation	References
High dispersive potential	In addition to ESP, *Exchangeable Dispersive Potential (EDP)* $EDP = \frac{Na_{Exch.} + 0.556K_{Exch.}}{CEC} \times 100$ Where $Na_{Exch.}$= exchangeable sodium, $K_{Exch.}$= exchangeable potassium, and CEC = Cation Exchange Capacity. *Electrochemical Stability Index (ESI)* $ESI = \frac{EC}{ESP}$ Where EC = salinity by direct laboratory measurement (method 3A1, Rayment and Lyons, 2011) and ESP = Exchangeable Sodium Percentage. ESI is an index and therefore unitless. Source: Blackwell et al, 1991 *Exchangeable Sodium Concentration (ESC)* $ESC = \frac{EC}{Na_{Exch.}}$ Where EC = salinity by direct laboratory measurement (method 3A1, Rayment and Lyons, 2011) and $Na_{Exch.}$= exchangeable sodium.	Laboratory method: one of methods 15I-15K of Rayment and Lyons (2011) as appropriate for CEC and cations; method 3A1 for EC. Equations: EDP - Bennett et al, 2016; ESI - Blackwell et al, 1991; ESC - Hulugalle et al, 2012.
High salinity	Electrical conductivity (EC) of a saturated soil paste (EC_{SE}), estimated from direct laboratory measurements of EC of a 1:5 soil-water suspension (method 3A1, Rayment and Lyons, 2011)	Laboratory method: Rayment and Lyons, 2011, method 3A1 Interpretation: Baker and Eldershaw, 1993
Insufficient Drainage Excessive Drainage	Modal field drainage rating assigned to soil profile class. Where this data is unavailable, the modal field drainage rating of available soil profiles is used.	Category definitions: Australian Soil and Land Survey Field Handbook, 3rd ed. (NCST, 2008) Interpretation: Expert judgement
Low Permeability	Modal field Permeability rating assigned to soil profile class. Where this data is unavailable, the modal field permeability rating of available soil profiles is used.	Category definitions: Australian Soil and Land Survey Field Handbook, 3rd ed. (NCST, 2008) Interpretation: Expert judgement
Low Plant Available Water Capacity (PAWC; Dryland) Low PAWC (Irrigated)	*Drained Upper Limit (DUL)* $DUL = \left(\frac{GWC_{FC} \times BD}{100}\right) \times ((LD - UD) \times 1000)$ Where GWC_{FC}= gravimetric water content at field capacity, BD = Bulk Density, LD = lower depth of soil in meters, and UD = upper depth of soil in meters. Output is in units of millimetres. *Drained Lower Limit (DLL)* $DLL = \left(\frac{GWC_{WP} \times BD}{100}\right) \times ((LD - UD) \times 1000)$ Where GWC_{WP}= gravimetric water content at wilting point, BD = Bulk Density, LD = lower depth of soil in meters, UD = Upper depth of soil in meters. Output is in units of millimetres. *PAWC* $PAWC = DUL - DLL$ PAWC values are calculated for each soil layer, summed and adjusted to effective rooting depth (ERD).	Equations: Littleboy, 1997 Interpretation: Expert judgement

Constraint	Data source/derivation	References
Shallow soil depth	Median depth of observed soil profiles in meters.	Observation procedure: Australian Soil and Land Survey Field Handbook, 3rd ed. (NCST, 2008) Interpretation: Expert judgement
High Profile Rockiness	Profile Coarse Fragment abundance and size rating classes (NCST, 2008). Maximum (worst-case) from available sites. Only coarse fragments above 60mm in size are considered. Segregations of pedogenic origin are included.	Category definitions: Australian Soil and Land Survey Field Handbook, 3rd ed. (NCST, 2008). Interpretation: RPI Act Statutory Guideline 08/14, State of Queensland, 2017
High Surface Rockiness	Surface Coarse Fragment abundance and size rating classes (NCST, 2008). Maximum (worst-case) from available sites. Only coarse fragments above 60mm in size are considered.	Category definitions: Australian Soil and Land Survey Field Handbook, 3rd ed. (NCST, 2008). Interpretation: RPI Act Statutory Guideline 08/14, State of Queensland, 2017
Elevated Compaction Risk	*Plastic Limit* $PL = 14.22 + (0.005 \times CL^2) + (3.63 \times OC) - 0.048 \times CL \times (OC \times 1.724)$ Where CL= Clay percentage and OC = Organic Carbon Percentage. Not applicable where CL < 11% or CL > 74%. Compaction risk is considered present where PL < DUL.	Laboratory methods: Rayment and Lyons, 2011 Equation and interpretation: Keller and Dexter, 2012

Notes on estimation of time to acidify

Acidification risk is the estimated time over which a soil will decrease in pH by one unit without intervention due to agricultural management practices. Acidity additions in Queensland sugarcane systems are estimated to be ~3.5 Kmol H^+ per year (Moody and Aitken, 1997). Limited data is available about how this acidity moves through the soil profile, but it is generally considered to be more concentrated near the surface. Data from the previous reference can be used to construct an appropriate acid accumulation curve (Moody, pers. comm. 2017), describing the distribution of the added acidity by depth:

$$ACC_{Acid} = -0.4762 + 3.751x - 0.0451x^2 + 0.002x^3$$

Where x = soil depth in centimetres and units are Kmol H^+. Acid inputs to a given depth range can thus be calculated as $ACC_{Acid}(LD) - ACC_{Acid}(UD)$. A total input of ~3.5 Kmol H+ per year is apportioned to Layers 1-4 as per Table 3.

Table 3: Distribution of added acidity in Layers 1-4

Layer	Depth Range (cm)	Percent of total acid input	Acid input per soil layer, per year (Kmol H^+ / ha)
1	0 - 5 cm	17.18	0.601
2	5 - 15 cm	29.14	1.020
3	15 - 30 cm	30.55	1.069
4	30 - 60 cm	23.19	0.812

Per Table 2, time to acidify can be calculated by dividing pHBC for each layer by its estimated acid input per year.

Soil profile classes considered likely to be acid sulfate soils are always rated Severe for acidification hazard due to their particular chemistry. By region, these are:

- Burnett-Mary: Fairymead, Fairydale, Jaro and Walker.
- Mackay-Whitsunday: Mangrove Soils, Dundula, Goorganga, Hillsborough and Wilmington.
- Townsville: Brolga and Doughboy.
- Wet Tropics: Bulguru, Hewitt, Inlet, Mangrove Soils, Needep, Sumalee, and Timara. Note that Babinda and Nind, as peat soils, are also highly prone to acidification under agriculture, but the pHBC pedotransfer function in use does not adequately capture the dynamics of those soils.

Acidification risk may be underestimated as most of the organic carbon (OC) data available was measured pre-cultivation, and it is well-known that OC levels can decrease sharply when sugarcane cultivation commences (Moody and Aitken, 1997). Coarse channel sediments are especially vulnerable to OC loss. In cases where a soil class has pH > 5.2, Clay < 15%, and a drainage class > 4, measured OC has been divided by 3 to simulate this loss on cultivation.

Notes on estimation of effective rooting depth and Plant Available Water

As indicated in Table 3, Plant Available Water Capacity (PAWC) constraint ratings are dependent on defining the effective rooting depth (ERD). ERD is commonly estimated during field survey based on the surveyor's observations of a particular soil class, and expressed as a range. An attempt is made in this project to model the surveyor's decision process programmatically. To that end, several soil constraints known to impact root growth (see Table 4) are calculated centimetre-by-centimetre down the soil profile, and ERD is set as the shallowest depth where any one of those constraints occurs. A minimum ERD of either the soil depth or 30cm is also set, as the constraints in use are considered ameliorable near the soil surface.

Table 4 Threshold indicator values for restriction of root growth.

Constraint	Threshold
Acidity	pH < 5.2
Sodicity	ESP > 15%
Salinity	EC_{SE} > 4
Rockiness	Coarse fragments > 60mm in size occupying more than 50% of the soil volume
Soil Depth	Median of available field observations

The soil hydraulic properties relevant to calculating PAWC are the upper and lower soil moisture limits for each soil layer (gravimetric water content at field capacity, and at wilting point). These are calculated using pedotransfer functions developed for the PAWCER model (Littleboy, 1997). Water content at field capacity at a given depth is given by

$$GWC_{FC} = (0.995 + 0.0011S) \times 13.2e^{-2.845}d + (1.0054 + 0.0041C) \times m_{15bar}$$

Where S = Sand percentage, d = depth in metres, C = Clay percentage, and m_{15bar} is moisture content at −1500 kPa (Cresswell, 2002). Water content at wilting point is given by

$$GWC_{WP} = 100 \times (-2.41 + 0.05665C) \times (-0.0176 + 0.022d) + 1.0054m_{15bar}$$

Units are percent of soil mass occupied by water. These figures must be converted into a volumetric measure using the soil's bulk density. Where direct measurements of soil bulk density are unavailable, this parameter is estimated using the following pedotransfer function:

$$BD_{est} = \frac{85.82 + 0.12C}{GWC_{FC} + 37.74}$$

Units are g/cm^3. The outputs of this estimator are programmatically constrained to a range of 0.97-1.70. Per the above equations, direct measurements of soil particle size fractions and of 15 bar moisture content are required before PAWC can be estimated.

Constraint severity thresholds

Soil constraints are constructed from soil attributes using the rules defined in Table 5. Each constraint has four levels - None, Mild, Moderate, Severe - and these levels reflect both an increase in constraint severity and an increase in amelioration difficulty.

Table 5: Soil constraint threshold definitions. Refer to the Methods section for definitions of soil layers.

Constraint	Severity			
	None	**Mild**	**Moderate**	**Severe**
Acidity	pH > 5.2 in top four layers	pH < 5.2 in top two layers only	pH < 5.2 in layers 3 and/or 4	pH < 5.2 in majority of top four layers
Rapid acidification	None of the first four layers are predicted to acidify by one pH unit in less than 30 years	At least one of the first four layers is predicted to acidify by one pH unit in less than 30 years	At least one of the first four layers is predicted to acidify by one pH unit in less than 20 years	At least one of the first four layers is predicted to acidify by one pH unit in less than 10 years
Alkalinity	pH < 8.2 in top four layers	pH > 8.2 in top two layers only	pH > 8.2 in layers 3 and/or 4	pH > 8.2 in majority of top four layers
Low nutrient holding capacity	CEC > 15 in top four layers	4 < CEC < 15 in top two layers only	CEC < 4 in any of layers 2 to 4	CEC < 4 in majority of top four layers
Excessive phosphorous fixation	PBI < 280 in top two layers	PBI > 280 in top two layers	*Undefined (lack of input data)*	*Undefined (lack of input data)*
Excessive phosphorus leaching	PBI < 36 in top two layers	PBI > 36 in top two layers	*Undefined (lack of input data)*	*Undefined (lack of input data)*
High Sodicity	ESP < 6% in top four layers	ESP between 6% and 15% in at least one layer	ESP between 6% and 15% in at least two layers	ESP >15% in majority of top four layers
High dispersive potential	EDP < 6% in top four layers	EDP between 6% and 15% in at least one layer	EDP between 6% and 15% in at least two layers	EDP >15% in majority of top four layers
	ESI > 0.15 in top four layers	ESI < 0.15 in top two layers only	ESI < 0.15 in layers 3 and/or 4	ESI < 0.15 in majority of top four layers
	ESC > 0.30 in top four layers	ESC < 0.30 in top two layers only	ESC < 0.30 in layers 3 and/or 4	ESC < 0.30 in majority of top four layers
High salinity	EC_{SE} < 2 in top four layers	EC_{SE} between 2 and 4 in top four layers	EC_{SE} > 4 in any of layers 2 to 4	EC_{SE} > 4 in majority of top four layers
Insufficient Drainage	Drainage rating ≥ 4	Drainage rating 3	Drainage rating 2	Drainage rating 1
Excessive Drainage	Drainage rating ≤ 4, or 5 where clay > 35%	Drainage rating 5, where clay between 20% and 35%	Drainage rating 5, where clay ≤ 20%	Drainage rating 6
Low Permeability	Permeability rating 4	Permeability rating 3 and not hardsetting	Permeability rating 3 and hardsetting	Permeability rating 1 or 2
Low Plant Available Water Capacity (PAWC; Dryland)	PAWC to effective rooting depth (ERD) ≥ 95 mm	PAWC to ERD 80-95 mm	PAWC to ERD 65-80 mm	PAWC to ERD < 65 mm
Low PAWC (Irrigated)	PAWC to effective rooting depth (ERD) ≥ 75 mm	PAWC to ERD 50-75 mm	PAWC to ERD 25-50 mm	PAWC to ERD < 25 mm

Constraint	Severity			
	None	**Mild**	**Moderate**	**Severe**
Shallow soil depth	> 0.60 m	0.45-0.60 m	0.30-0.45 m	< 0.30 m
High Profile Rockiness	By Layer: No coarse fragments over 60 mm Whole profile: Layers 1-4 unaffected by rockiness	By Layer: Up to 20% coarse fragments > 60 mm Whole Profile: One of Layers 1-4 with moderate to severe rockiness	By Layer: 20-50% coarse fragments > 60 mm Whole Profile: More than one of Layers 1-4 with moderate to severe rockiness	By Layer: >50% coarse fragments > 60 mm. Whole More than two of Layers 1-4 with moderate to severe rockiness
High Surface Rockiness	No surface coarse fragments over 60 mm	Up to 20% surface coarse fragments > 60 mm	20-50% surface coarse fragments > 60 mm	>50% surface coarse fragments > 60 mm.
Elevated Compaction Risk	PL > DUL in top three layers	PL < DUL in one of top three layers	PL < DUL in two of top three layers	PL < DUL in top three layers

Application of constraint thresholds

Constraint thresholds differ in complexity, depending on the parameter in question. Some simply involve classifying a single measurement, like soil depth, or recoding an existing classification scheme, like permeability or drainage. Others use a presence/absence system on each soil layer, and the constraint rating becomes more severe as more soil layers are affected. There is also a weighting applied - deeper layers are harder to ameliorate, so when they have a constraint present, the severity is boosted. The acidity constraint is an example of this. Some constraints have a three-level system, which reflects a progressive worsening of constraint severity. This is more appropriate than a single cut-off for parameters like CEC and ESP. Decision rules for constraints are shown in Appendix 1.

Constraint levels are usually defined using the first four layers of soil attributes (0-60 cm). However, some parameters only use the first two or three layers, as necessary lab data is not available to make calculations further down the profile.

References

Aitken, R. L., Moody, P. W., & McKinley, P. G. (1990). Lime requirement of acidic Queensland soils. I. Relationships between soil properties and pH buffer capacity. Australian Journal of Soil Research, 28(5), 695–701. https://doi.org/10.1071/SR9900695

Baker, D. E., & Eldershaw, V. (1993). Interpreting soil analysis for agricultural land use in Queensland (QO03014). Indooroopilly, Queensland, Australia: Queensland Department of Primary Industries.

Bennett, J. M., Marchuk, A., & Marchuk, S. (2016). An alternative index to the exchangeable sodium percentage for an explanation of dispersion occurring in soils. Soil Research, 54(8), 949–957.

Blackwell, P., Jayawardane, N., Green, T., Wood, J., Blackwell, J., & Beatty, H. (1991). Subsoil macropore space of a transitional red-brown earth after either deep tillage, gypsum or both II. Chemical effects and long term changes. Soil Research, 29(2), 141–154.

Bloesch, P. M., Le Grand, J., Moody, P. W., Moss, J., & Searle, R. (2006). Soil erosion and soil condition hazard maps for Great Barrier Reef Catchments of Queensland (QNRM06214). Brisbane, Queensland: Queensland Department of Natural Resources, Mines and Water.

Cresswell, H. (2002). The Soil Water Characteristic. In Soil Physical Measurement and Interpretation for Land Evaluation (pp. 59–84). Collingwood, Victoria: CSIRO Publishing.

Hulugalle, N. R., Weaver, T. B., Finlay, L. A., & Lonergan, P. (2012). Soil properties, black root-rot incidence, yield, and greenhouse gas emissions in irrigated cotton cropping systems sown in a Vertosol with subsoil sodicity. Soil Research, 50(4), 278–292. https://doi.org/10.1071/SR12088

Keller, T., & Dexter, A. R. (2012). Plastic limits of agricultural soils as functions of soil texture and organic matter content. Soil Research, 50(1), 7–17.

Littleboy, M. (1997). Spatial generalisation of biophysical simulation models for quantitative land evaluation : a case study for dryland wheat growing areas of Queensland (Ph.D.). University of Queensland, School of Geography, Planning and Architecture, St. Lucia, Qld.

McKenzie, N. J., Coughlan, K. J., & Cresswell, H. P. (2002). Soil physical measurement and interpretation for land evaluation. Collingwood, Victoria: CSIRO Publishing.

Moody, P. W. (2007). Interpretation of a single-point P buffering index for adjusting critical levels of the Colwell soil P test. Australian Journal of Soil Research, 45(1), 55–62. https://doi.org/10.1071/SR06056

Moody, P. W., & Aitken, R. L. (1997). Soil acidification under some tropical agricultural systems. 1. Rates of acidification and contributing factors. Australian Journal of Soil Research, 35(1), 163–173.

Moody, P. W., & Cong, P. T. (2008). Soil Constraints and Management Package (SCAMP): guidelines for sustainable management of tropical upland soils (ACIAR Monograph Series No. 130) (p. 90). Canberra, ACT: Australian Centre for International Agricultural Research. Retrieved from http://aciar.gov.au/files/node/8946/MN130%20full%20text.pdf

National Committee on Soil and Terrain (Australia). (2009). Australian soil and land survey field handbook (3rd ed.). Collingwood, Victoria: CSIRO Publishing.

O'Brien, L. E. (in prep). Soil constraints mapping to inform nutrient management in the cropping industries – RP155C: Technical Report. Brisbane: Queensland Department of Environment and Science.

O'Brien, L. E. 2018. Soil constraints mapping to inform nutrient management in the cropping industries – RP155C: Dataset User Guide. Brisbane: Department of Environment and Science, Queensland Government.

Odgers, N. P., Sun, W., McBratney, A. B., Minasny, B., & Clifford, D. (2014). Disaggregating and harmonising soil map units through resampled classification trees. Geoderma, 214–215, 91–100. https://doi.org/10.1016/j.geoderma.2013.09.024

Rayment, G. E., & Lyons, D. J. (2011). Soil chemical methods : Australasia. Collingwood, Victoria: CSIRO Publishing.

Reef Water Quality Unit. (2014). Reef Water Quality Research, Development and Innovation Strategy, 2014-15-2018-19. Queensland Department of Environment and Heritage Protection.

State of Queensland. (2017). How to demonstrate that land in the strategic cropping area does not meet the criteria for strategic cropping land (RPI Act Statutory Guideline 08/14). Department of Infrastructure, Local Government and Planning.

Appendix 1 - Soil constraint coding rules

Simple recoding

Attributes that apply to a whole soil profile are simply recoded to the constraint rating system in use. Soil constraints treated in this way are: rapid acidification, insufficient drainage, excessive drainage, low permeability, shallow soil depth, low PAWC (Dryland), low PAWC (Irrigated), and high surface rockiness.

Low plastic limit is handled by recoding the number of layers affected to a severity rating. No attempt is made to boost severity at depth, as only the top 30 cm of soil is assessed. This is due to lack of organic carbon data at depth, which is required for the plastic limit pedotransfer function.

Presence/absence ruleset

The presence/absence ruleset determines whether a criteria is met for each of layers 1-4 or not (TRUE/FALSE) and then assigns a severity rating based on the number of TRUE values. Severity ratings are boosted where TRUE occurs at >30 cm depth. Table A1 shows the severity ratings for each possible combination of TRUE/FALSE values.

Table A1: Two-stage ruleset for soil constraints

Presence				**Rating**
Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	
TRUE	TRUE	TRUE	TRUE	Severe
FALSE	TRUE	TRUE	TRUE	Severe
TRUE	FALSE	TRUE	TRUE	Severe
FALSE	FALSE	TRUE	TRUE	Severe
TRUE	TRUE	FALSE	TRUE	Severe
FALSE	TRUE	FALSE	TRUE	Moderate
TRUE	FALSE	FALSE	TRUE	Moderate
FALSE	FALSE	FALSE	TRUE	Mild
TRUE	TRUE	TRUE	FALSE	Severe
FALSE	TRUE	TRUE	FALSE	Moderate
TRUE	FALSE	TRUE	FALSE	Moderate
FALSE	FALSE	TRUE	FALSE	Mild
TRUE	TRUE	FALSE	FALSE	Mild
FALSE	TRUE	FALSE	FALSE	Mild
TRUE	FALSE	FALSE	FALSE	Mild
FALSE	FALSE	FALSE	FALSE	None

Constraints that use the presence/absence ruleset are: acidity, alkalinity, excessive phosphorous fixation, excessive phosphorus leaching, high dispersive potential by ESI, and high dispersive potential by ESC.

Exceedance ruleset

The exceedance ruleset looks at how badly a criteria is exceeded for each of layers 1-4 and then assigns a severity rating based on both the degree of exceedance (none/minor/major) and the number of exceedances. Severity ratings are boosted where exceedances occur at depth. Table A2 shows the severity ratings for each possible combination of exceedance value and layer.

Table A2: Exceedance ruleset for soil constraints

Exceedance				**Rating**
Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	
None	None	None	None	None
Minor	None	None	None	None
Major	None	None	None	None
None	Minor	None	None	None
Minor	Minor	None	None	Mild
Major	Minor	None	None	Mild
None	Major	None	None	Mild
Minor	Major	None	None	Mild
Major	Major	None	None	Moderate
None	None	Minor	None	Mild
Minor	None	Minor	None	Mild
Major	None	Minor	None	Mild
None	Minor	Minor	None	Mild
Minor	Minor	Minor	None	Moderate
Major	Minor	Minor	None	Moderate
None	Major	Minor	None	Moderate
Minor	Major	Minor	None	Moderate
Major	Major	Minor	None	Severe
None	None	Major	None	Moderate
Minor	None	Major	None	Moderate
Major	None	Major	None	Moderate
None	Minor	Major	None	Severe
Minor	Minor	Major	None	Severe
Major	Minor	Major	None	Severe

Exceedance				Rating
Layer 1	Layer 2	Layer 3	Layer 4	
None	Major	Major	None	Severe
Minor	Major	Major	None	Severe
Major	Major	Major	None	Severe
None	None	None	Minor	Mild
Minor	None	None	Minor	Mild
Major	None	None	Minor	Mild
None	Minor	None	Minor	Mild
Minor	Minor	None	Minor	Moderate
Major	Minor	None	Minor	Severe
None	Major	None	Minor	Moderate
Minor	Major	None	Minor	Severe
Major	Major	None	Minor	Severe
None	None	Minor	Minor	Moderate
Minor	None	Minor	Minor	Moderate
Major	None	Minor	Minor	Severe
None	Minor	Minor	Minor	Moderate
Minor	Minor	Minor	Minor	Moderate
Major	Minor	Minor	Minor	Severe
None	Major	Minor	Minor	Severe
Minor	Major	Minor	Minor	Severe
Major	Major	Minor	Minor	Severe
None	None	Major	Minor	Moderate
Minor	None	Major	Minor	Severe
Major	None	Major	Minor	Severe
None	Minor	Major	Minor	Severe
Minor	Minor	Major	Minor	Severe
Major	Minor	Major	Minor	Severe
None	Major	Major	Minor	Severe

Exceedance				Rating
Layer 1	Layer 2	Layer 3	Layer 4	
Minor	Major	Major	Minor	Severe
Major	Major	Major	Minor	Severe
None	None	None	Major	Moderate
Minor	None	None	Major	Moderate
Major	None	None	Major	Moderate
None	Minor	None	Major	Moderate
Minor	Minor	None	Major	Severe
Major	Minor	None	Major	Severe
None	Major	None	Major	Moderate
Minor	Major	None	Major	Severe
Major	Major	None	Major	Severe
None	None	Minor	Major	Moderate
Minor	None	Minor	Major	Severe
Major	None	Minor	Major	Severe
None	Minor	Minor	Major	Severe
Minor	Minor	Minor	Major	Severe
Major	Minor	Minor	Major	Severe
None	Major	Minor	Major	Severe
Minor	Major	Minor	Major	Severe
Major	Major	Minor	Major	Severe
None	None	Major	Major	Moderate
Minor	None	Major	Major	Severe
Major	None	Major	Major	Severe
None	Minor	Major	Major	Severe
Minor	Minor	Major	Major	Severe
Major	Minor	Major	Major	Severe
None	Major	Major	Major	Severe
Minor	Major	Major	Major	Severe

Exceedance				Rating
Layer 1	Layer 2	Layer 3	Layer 4	
Major	Major	Major	Major	Severe

Constraints that use the exceedance severity ruleset are: low nutrient holding capacity, high sodicity, high dispersive potential by EDP, and high salinity.

Excessive Profile Rockiness

Profile Rockiness is described by a paired set of categorical attributes (rock size and abundance) and so a nested set of if/else statements is used to assess these for each soil layer and finally the profile as a whole. The decision tree is diagrammed in Table A3.

Table A3: Decision rules for profile rockiness

By-layer criteria and rating			By-soil criteria and rating	
Size > 3 AND Abundance > 4	Severe	**Summarise by counting number of Moderately and Severely affected layers**	> 2 layers affected	Severe
Size > 3 AND Abundance > 3	Moderate		> 1 layer affected	Moderate
Size > 3 AND Abundance > 0	Mild		> 0 layers affected	Mild
Size ≤ 3	None		0 layers affected	None

Abundance ratings are as follows:

- 'Mild' (categories < 4): 0-20% by volume
- 'Moderate' (category 4): 20-50% by volume
- Severe (categories > 4): >50% by volume

Size > 3 equates to an average rock size of > 60 mm.