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Putting regional digital soil mapping into practice in Tropical Northern Australia

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ABSTRACT

Tropical Northern Australia is a vast region dominated by extensive cattle grazing. Australia is seeking opportunities to intensify land use in this region through irrigation. We describe a digital soil mapping (DSM) approach for the Flinders and Gilbert catchments (combined area, 155,000 km^2) in north Queensland to supply soil property (i.e. target variable) maps for an eventual crop-specific irrigation suitability assessment.

We applied a statistically-based survey design to identify new soil sampling sites. This data was merged with legacy soil data to produce a combined dataset of 1951 soil sites used in our DSM approach to map 16 soil target variables. Our mapping relied on the RuleFit3 analytical toolset and environmental correlation employing 13 predictors from terrain analysis, mapping and remote sensing. We present prediction and evaluation for three categories of target variables, namely: numeric, binary and categorical using the examples of surface pH (H_2O) (numeric), rocky/non-rocky (binary) and permeability (categorical).

Prediction quality was evaluated using internal cross-validation, independent validation, and non-parametric bootstrapping. Under internal cross-validation the models achieved R-squared of 0.49 for surface pH (H_2O) (numerical), 76% classification accuracy for rocky/non-rocky (binary) and 56% classification accuracy for soil permeability (categorical). Under independent validation the target variables achieved a R-squared of 0.67 for surface pH (H_2O), and accuracy of 93% for rocky/non-rocky accuracy of 63% for soil permeability. Non-parametric bootstrapping conducted on the surface pH (H_2O) estimation showed the most reliable predictions to be in the pH range of 6–7.

Despite the practical pressures imposed on the project (i.e. short project duration, and study area remoteness, size and difficult access), our DSM approach delivered the soil data within required specifications for the crop-specific irrigation suitability assessment. The approach gives a working framework of other soil mapping exercises sharing similar practical (i.e. environmental, logistical, data) constraints.

1. Introduction

The region of Northern Australia occupies latitudes north of 20° S, so it takes in the tropical and sub-tropical areas of Western Australia, Northern Territory and Queensland. The region occupies an area of 1.2 M km^2 (i.e. 39% of Australia) and the population density is low (~5% of Australia) (BITRE, 2011). The sparsely developed land is characterised by poorly distributed infrastructure and services. Land use is dominated by cattle grazing, and to a lesser extent, conservation and mining. Intensification of land use in Northern Australia has been a recurrent goal of government since European settlement. This is based on the premise that Northern Australia is a vast under-utilised area with large supplies of freshwater.

The contemporary drivers for Northern intensification include the desire to grow national trade accounts, exploiting proximity to Asia-Pacific rim markets, a strategy of hedging against climate variability by reducing reliance on Australia's southern farming zone, and the desire to build resilient Northern communities. Responding to these challenges, the Office of Northern Australia commissioned a two-year integrated resource assessment study — the “Flinders and Gilbert Agricultural Resource Assessment” (FGARA) project (CSIRO, 2014). The aim of the project was to evaluate the region's opportunities for irrigated agriculture in the Flinders (109,000 km^2) and Gilbert (46,000 km^2) catchments in Queensland's north.

Successful agricultural development is underpinned by reliable land resource assessment (Dalal-Clayton and Dent, 2001; McKenzie et al., 2008; Soil Survey Staff, 1993) tailored to identify the opportunities and limitations for various land uses (FAO, 1976; Rossiter, 1996; Sanchez et al., 1982), including irrigated land practices (FAO, 1985). A crop-specific suitability assessment framework takes into account soil,

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landscape and climatic variables using thresholds that define parameters for successful crop production. Usually assessments produce a ranking of suitability classes (e.g. highly suitable to unsuitable) accompanied by information on limiting factors like slope, physical and chemical soil constraints (FAO, 1976, 1985). These inform management decisions and provide estimates of the scale of the agricultural opportunity. Coupling crop-need thresholds with soil, landscape, climate and other information at appropriate scales in a geographic information system (GIS) allows implementation of site-specific crop suitability evaluations.

Traditional land resource assessment frameworks facilitate systematic collection of soil and landscape information so that the environmental factors governing soil formation and distribution (Jenny, 1941) can be integrated and conceptualised before the start of soil mapping (Hudson, 1992). Traditional soil maps show sharp cartographic boundaries — *polygons* in GIS data terminology — between taxonomic units and characteristic sets of soil properties, and are interpreted using mapping legends and supporting information (McKenzie et al., 2008; Soil Survey Staff, 1993). Digital soil mapping (DSM) described more fully elsewhere (e.g. Grunwald, 2006; Hengl and MacMillan, 2009; McBratney et al., 2003; McKenzie et al., 2008) is an alternative soil mapping approach to the traditional method. Most DSM involves single soil variable estimations (e.g. pH, carbon content) and relies on building statistical models — or rulesets — from relationships at the spatial intersection of soil data and environmental covariates. Environmental covariates are spatially extensive, continuous data themes — *rasters* in GIS terminology — that bear functional relationship to soil properties (McKenzie and Ryan, 1999; Minasny et al., 2008), either by correlating to soil forming factors (e.g. topography, relating to soil depth) or expressing a soil property (e.g. reflected surface wavelength, relating to mineralogy).

DSM is a credible alternative to traditional soil mapping (Carré et al., 2007). Outputs differ from traditional soil mapping in a number of attractive ways, amongst these: rulesets are quantitatively-based and their execution is rapid and repeatable during map generation, reducing human-induced inconsistencies. Also, estimates of uncertainty can be routinely mapped to guide users in the weight of confidence they should place in the maps they are using to make planning decisions (Grunwald, 2006; Hengl and MacMillan, 2009; McBratney et al., 2003). However, like traditional mapping, quality hinges on input data quality (i.e. laboratory analyses, field description) and robust soil survey design.

The large area and remoteness of the Flinders and Gilbert catchments, and the short project timeframe made DSM the only practical option to providing the required data. Here we describe the design of the DSM methodology to generate 16 soil variable estimation maps (with uncertainty maps) to support the data needs of an irrigation suitability assessment to follow for the Flinders and Gilbert catchments (see Bartley et al., 2013). Central to the DSM approach was a design that balanced the dual practical needs of (i) suitable soil variable estimation quality within (ii) the demanding operating constraints of the project. We describe estimation approaches for three types of soil variables: numeric, binary and categorical. These are illustrated using the examples of surface pH (H_20) (numeric), absence or presence of rocks (binary) and soil permeability class (categorical).

2. Methods and materials

2.1. Study area

The Flinders and Gilbert catchments are sparsely populated (Flinders, ~6000; Gilbert, ~1200). Population centres are few and far between, with the Flinders containing the towns Cloncurry, Julia Creek, Richmond and Hughenden, and the Gilbert, Georgetown and Einasleigh. All towns service surrounding cattle stations, while Cloncurry is also a significant mining town (Fig. 1).

Perry et al. (1964) present a physiographic description of much of the Flinders and Gilbert Agricultural Resource Assessment (FGARA) study area. Both catchments drain northwest to the Gulf of Carpentaria and share a common watershed in the Great Dividing Range; at 1,050 m their maximum elevation lies along this common boundary. The Flinders catchment is dominated by extensive lowlands in the centre and north, with highlands to the east and west. The Gilbert catchment is dominated by southern uplands containing the Gilbert River headwaters (draining the southern and western tracts), and the Einasleigh River (draining the northern and eastern tracts); their confluence is at the upland/lowland transition. Uplands dominate the Gilbert catchment, whereas lowlands dominate the Flinders catchment.

Climatically, the FGARA area ranges from semi-arid tropical in the south-west to humid tropical in the north-east. The rainfall is unimodal, with rainfall strongly coinciding with summer months (October–April), and generally peaking in January–February. Annual rainfall in the south of the area is ~380 mm, and the north, ~1020 mm. Much of the rainfall is intense and associated with cyclonic weather systems stemming from the Indian Ocean to the west, or the Coral Sea to the east. These systems cause extensive floods that can persist for months, particularly in the flat lowlands. Maximum daily temperatures exceed 40 °C in summer months and reach 24 °C in winter (Perry et al., 1964).

The following discussion relies on orders of Australian Soil Classification (ASC) (Isbell and CSIRO, 2002) to describe soil classes. The soils of the Flinders catchment are dominated by clay-rich soils (ASC: Vertosols) with shrink-swell properties (i.e. cracking clays, National Committee on Soil and Terrain, 2009) in the lowlands from in situ weathering of Cretaceous mudstones. The Flinders River mouth area is dominated by seasonally or permanently wet soils low in the local landscape (ASC: Hydrosols) while loamy soils are found higher up in the local landscape (ASC: Rudosols and Tenosols). In the eastern uplands loams are common especially where Quaternary alluvium and Tertiary colluvium slopes are found, and cracking and non-cracking clays (ASC: Vertosols and Ferrosols) have formed on basalts. The eastern uplands also have shallow sandy and stony soils (ASC: Rudosols and Tenosols) that have formed on coarse grained grandiorites and gneisses. The western uplands feature shallow sandy and stony soils (ASC: Rudosols and Tenosols) formed on weathered quartzites, sandstones, granites and grandiorites. These uplands also have cracking clays (ASC: Vertosols) formed on metabasalts and schists. Clay loams and non-cracking clays (ASC: Dermosols and Kandosols) dominate alluvial and channel floodplain areas of these uplands (Perry et al., 1964).

The Gilbert catchment shows a diversity of soils. In the lowlands towards the river mouth permanently and seasonally wet loamy and clayey soils (ASC: Hydrosols and Vertosols) dominate, whereas upstream, sodic clayey soils (ASC: Sodosols & Vertosols) are more common in low-relief areas. In the uplands shallow coarse sandy soils (ASC: Rudosols and Tenosols) are commonly formed on siliceous rhyolites, granites and grandiorites. Finer sandy soils are formed on sandstones and siltstones (ASC: Dermosols and Tenosols), and clay loams (ASC: Kandosols) and non-cracking clay soils (ASC: Demosols and Ferrosols) are on basalt. Sands or loams over friable clays, and uniform textured loams (ASC: Kurosols, Chromosols and Kandosols) are formed on grandiorites, on high grade metasedimentary rocks, in Quaternary channel flood areas and deeply weathered (Tertiary) sediments. In the east of these uplands, cracking clays (ASC: Vertosols) are associated with basalt and alluvial deposits. Quaternary and Tertiary alluvial deposits in the central upland catchment contain a diversity of soil types ranging in textural and chemical composition (ACS: Kandosols, Dermosols, Chromosols, Sodosols and Vertosols) relating to depositional energy and age. Finally, localised areas of sand or loam over sodic clays (ASC: Sodosols) have formed on sedimentary, felsic volcanic and granitic parent materials or the outwash areas located down-slope.

2.2. Soil data and soil survey

We followed a pragmatic approach to meet the soil data needs of the project. This approach used two sources of soil data: firstly, pre-existing legacy soil data intersected with a zone surrounding the FGARA study