A PROTOCOL FOR ASSESSING SOIL CONDITION AND CAPABILITY:
A SOUTHERN DOWNS CASE STUDY

A Thesis

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Abstract

There is no established methodology to measure a change in soil condition in a way that captures the undisturbed state and compares it to the composition of soil in its current managed state. Previous attempts have relied on assessments at two or more points on the timeline of management history that do not recognise the land's initial state, mainly a pre-colonial era soil with low-intensity human interventions. Insights into the soils' natural capacity to perform given functions and deliver ecosystem services are largely missed. Recreating pre-colonial conditions is a critical challenge in the typically degraded Australian agricultural soil; thus, a proxy for the farmed land is beneficial. To test the hypothesis that management of a mixed-horticultural farming system over 70 years had a negative effect on soil condition, a protocol was developed to examine land use impacts at a farming enterprise on the Queensland Southern Downs. The landscape was surveyed, and the soil was sampled in the remnant native vegetation and the cleared area historically used for horticultural farming. Laboratory analysis of soil texture, and chemical properties of pH, electrical conductivity (EC), cation and effective cation exchange capacity (eCEC), and exchangeable sodium percentage (ESP) were conducted and formed the basis of soil attributes used to define the land use areas. The protocol identified a suitable proxy site to form the benchmark or baseline status for the farmed land by assessing comparable soil-forming factors; key environmental covariates, and soil texture. Propensity score matching techniques enabled the pairing of three proxy native vegetative soils to the suite of farmed soils. This approach progresses the Soil Security Framework (SSF) agenda, particularly the condition and capability dimensions. The landscape entity, the terron, was coupled with SSF to facilitate digital soil mapping of the regional soil attributes and environmental features. At the farm scale, ordinary kriging interpolation illustrated changes in the soil attributes. The results did not support the hypothesis, as no negative effect was observed, and divergences in the chemical properties were generally positive. However, in this demonstrative case study, the protocol was found to be an effective means of quantifying a change in soil condition, signalling where and to what degree degradation is likely to have occurred in farmed areas. The

scope of this study was restricted to a single farming enterprise on the Southern Downs and was later modified to remove the intended regional level terron analysis; nevertheless, it provided a protocol that appears promising. More testing is required to for protocol replication across different landscapes and industries. In future, landowners can identify proxies and target corrective actions for soils on-farm and provide a means to improve degraded soils as part of interconnecting landscapes. Ultimately, the developed protocol and other tools which aim to quantify soil capability, support a shift toward sustainable management practices for long-term soil security.

Certificate of Dissertation

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

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Signature of Candidate

22/04/2022

Date

ENDORSEMENT

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Signature of Supervisor

22/04/2022

Date

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Keywords:

Soil security framework; Native vegetation; Ecosystem services; Degradation; Soil capacity and condition; Digital soil mapping

Abbreviations/Glossary

ASC	Australian Soil Classification; the current and widely accepted soil classification system (Isbell 2021)
DSM	Digital soil mapping
Genosoil	Classification or mapping unit of soil in least disturbed state
LGA	Local Government Area
Phenosoil	Classification or mapping unit of soil undergone change in chemical and physical properties, to affect the function
PSMM	Propensity score matching model
R	Open-source R programming platform, noted with version of packages utilised
SDR	Southern Downs Region
SSF	Soil Security Framework
Subsoil	Soil sampled at depth 40 – 50 cm *
Terron	Pedological mapping unit comprising of soil-forming factors, in memberships of soil and environmental or landscape features
Topsoil	Top 0 – 10 cm of soil sampled *

** for the purpose of this study.*

Chapter 1

1 Introduction

Soil degradation is at the forefront of threats to sustainable land use in Australia (Metcalfe & Bui 2016; Román Dobarco et al. 2021a). Furthermore, rates of degradation are accelerating under conditions of an evolving economic landscape (Australian Goverment 2021), the uncertainty of localised climate change impacts (Kirono et al. 2020), and the need to increase productivity to satiate a growing global population (Australian Government 2020). In an agricultural setting, soil degradation can be measured by the soil's inability to perform a given function over an extended period due to poor or miscalculated land management decisions (Chapman et al. 2011). Currently, 60% of Australian arable land is classified as degraded (Metcalfe & Bui 2016).

Quantifying an acceptable level of change in soil condition that allows soil's ability to continue to support a given land use or industry function can vary greatly. However, several universal contributors to soil degradation are typically considered. Firstly, the loss of topsoil is often observed through wind and water erosion (Borrelli et al. 2020). In addition, the degradation through the removal of carbon inputs due to traditional tillage practices reduces further influences soil fertility and water holding capacity (Minasny & McBratney 2017). Soil compaction or mass movement from on-farm trafficking and system intensification is also highly degrading (Antille et al. 2016). Finally, leaching and the 'locking up' of nutrients essential to plant growth through acidity, sodicity, and interruption to chemical cycling and biological processes can also be attributed to intense system management (Schimel 2018; Neina 2019). When combined, these factors lower the resilience of the soil to external threats such as heat and water stress worsened by the ongoing global warming effect (Lal 2012).

Soils with a decline in biochemical and physical fitness may be treated with costly soil amendments (Chapman et al. 2011) for a short-term lift in output (Mandal et al. 2020). Amendments may include crop rotation, inputs of fertilisers, lime, gypsum, and organics, and mechanical soil amelioration, among others.

However, if management does not change for the soils currently being degraded, the required rates of these amendments in the future will be substantial and unlikely to be economically sound for agricultural systems long term. To avoid this situation, it is paramount to ensure currently farmed land is either maintained or improved through a shift toward sustainable management practices.

Understanding the factors contributing to degradation leads to questions about how land managers assess degradation occurring on-farm. While soil degradation is itself not a new concept, targeted action, and best practice protocols for measuring degradation are not well explored in the current literature. This is in part due to a lack of consensus on how to best deliver this information to landowners and everyday consumers of agricultural products and is further complicated by soils' naturally occurring spatial variability; how to access, assess and present soil degradation information is a critical gap.

Soils can vary massively within a region and may provide contrasting soil chemistry characterisations across farms and even within a single paddock. This may have implications. This suggests that spatial variability across landscapes can be described by the combinations of soil chemical and physical properties and the influencing factors of morphology, vegetation, terrain, and climate (Jenny 1961; Román Dobarco et al. 2021a). In other words, the spatial variability is limitless. Therefore, it is critical for effective decision making to establish a near-as-possible benchmark status of farmed soil to focus management activity and assess how soil condition has changed across management systems and timescales. A benchmark requires a theoretical reference state such as a proxy site that is determined to have reasonably equal soil-forming factors as established through well-informed site selection. The optimal proxy would also be an area of substantial native vegetative growth to indicate a robust ecosystem that has not been cleared or has no apparent evidence of anthropogenic disturbance.

Soil is formed through dynamic linkages with its environment, and soil types do not abruptly change their properties or capabilities at the farm boundary. The continuous characterisation of soils can be attained using digital soil mapping (DSM) to best capture this. A DSM representing the divergences in soil chemistry between the proxy site and the farmed areas might offer a relevant metric for changes in soil condition and thus indicate how, where and to what degree degradation has occurred onsite. The outcomes can be mapped, enhanced with layers of environmental covariates at a large scale to provide beneficial insights into soil condition. This may indicate its capacity/potential to resist anthropogenic influences and maintain performance as part of the broader ecosystem and at the landscape level. There are inherent limitations to any interpolation of unknown areas, relying on estimates based on neighbouring points and error analysis (Zhang et al. 2017; Kidd et al. 2020). The density and frequency further inform accuracy in model inputs and mapping products of points sampled, the integrity of legacy datasets such a national covariate data, and the precision of sampling equipment such as GPS. A better understanding of the relative soil condition of specific soil types in agricultural and undisturbed contexts may inform improved management decisions to maximize the function of currently used soil resources.

It is not ecologically reasonable to make more arable land available (Jackson 2016). The by-product of establishing an effective benchmark for a specific soil type and its incorporation in land use/management decision-making is the potential hinderance to further land clearing by land managers and add some remedy to the ongoing challenge of deforestation in Australia. Australia's deforestation rates have risen significantly over the last two decades (Pacheco et al. 2021). The 2020 report by the World Wildlife Fund estimates the Eastern Australian front to have cleared 101.5 MHa, citing grazing and cropping, fire and drought, and intensified logging as the leading drivers (Pacheco et al. 2021). Eucalypt and acacia-dominated forest types are specifically at risk. In the Southern Downs Region, which offers rich agricultural, horticultural, and grazing environments on typically low fertile, granitic soils (Maher 1996c), biodiversity loss is well established (Queensland Government 2021c). Widespread deforestation in slow-to-adapt industries and in regions with low acclimatization to shifts in local climate will be catastrophic to biodiversity loss and impairment of ecosystem services (Stocker et al. 2013). Land clearing for agriculture also has critical implications for the Australian carbon emissions budget and a cumulative effect on global rising temperatures (Lal 2012).

The Southern Downs is a region with ecological and economical significance and an ideal location for a case study investigating the effects of land use on soil change over time and, specifically, degradation risk if its function is found to be ill-suited. The challenge moving forward is to assess the suitability of agricultural production to soil function and the degradation risk if found to be functionally unsuitable to what it is tasked with i.e. intense cropping. This study aims to develop a protocol to establish benchmarks for soil condition and thus quantify soil capability at the farm scale. A protocol of this nature could alter the perception of remnant native vegetation often held by land managers twofold; by moving beyond valuing the vegetation for contentious land-clearing potential and secondly, removing the concept of 'wasted' land. Such a protocol would subsequently give tools and insights to growers by informing them of the unique properties of the soil and vegetation found within the whole farm boundary to secure the soil long term.

While it is valuable to articulate 'big picture' priorities of sustainable resource use to prevent deforestation and reward stewardship of agro-ecological systems, it is imperative to first refine efforts of such work by testing existing and emerging protocols of DSM. DSM forms the basis of many current approaches to quantifying soil conditions in a spatially variable area. It is also critical in translating the benefits of soil security to growers through transparency and access of soil data, optimising the soil resources currently in use, reducing management costs, and ensuring profitability and viability in future seasons. This relies heavily on investment in soil data collection today and timely follow through with applying insights results from on-site testing.

From a foundation of effective tools which are discussed throughout later chapters, valuable insights can be derived as land managers seek to answer the prevalent question, "what can I do to secure my soil?". This study aims to contribute to the development of such a toolkit with a breakdown of tasks as follows;

- Apply the Soil Security Framework to the Southern Downs Local Government Area as a case study with future regional applicability;

- Establish a protocol for quantifying changes in soil condition from pre-colonial levels to current management status;
- Interpret suitability for a given function at the farm scale and outline implications for any soil modification that may result from protocol use.

A critical review of the literature exploring the links between ecosystem services, soil security and the existing protocols to map and characterise soils is then justified. In Chapter 2, I demonstrate the broader purpose and industry applicability of an investigation into soil condition change. Chapter 3 will follow with a detailed methodology including site selection, soil sampling while the subsequent analysis and outcomes are covered in Chapter 4. This is followed with a discussion of the results and its implications to the future research of soil security, in Chapters 5 and 6 respectively.

Chapter 2

2 Literature Review

2.1 Soil function and threats

This section will review the key characteristics to be considered in this project. Sections 2.1 and 2.2, will focus on the main component of the research for this study; threats to soil and potential pathways to soil security. The following 2.3 and 2.4 sections will explore the theoretical and practical tools adapted to measure and quantify soil condition and capability, exemplified with a case study on the Southern Downs described from section 2.5.

Soil is the fertile yet fragile veneer of the Earth's surface. It is a mixture of minerals, gas, biological matter and water culminating in a complex and self-organising life support system (Singer & Munns 2002; Rabbi et al. 2020) of intrinsic value more significant than the sum of its parts. Functional soil is integral to plant growth, and the flow of nutrients, water, and energy; acting as the foundation on which other natural and human-centric systems are built (Dominati et al. 2014). Soil ecosystem services are extensive; chief among these are water filtration and air purification, nutrient transformation, ground contamination and disease control, infrastructure support, food and fibre production, fuel provisions, habitat platforms, genetic diversity and facilitating pharmaceutical advancement (Burssaard 2012). Some services may be underappreciated, such as recreational grounds for altruistic use, even spiritual, and cultural connections, as evidenced by the low publications on these themes. This is likely due to the difficulty in quantifying their expected value to society (Adhikari & Hartemink 2016). Often not realised by the end-users of soil products, the soil is a finite resource, and its products are not fully replaceable (IPBES 2019). McBratney et al. (2014) has made a case for elevating the soil agenda to the status of a global existential challenge, as secure soils are critical for food, water, and energy security to be actualised for the global community. Soils are also central to overcoming the challenge of climate change through adaptation and abatement, owing to their carbon sequestration capacity and sink-source dynamics (Stocker et al. 2013). Soils also contain the largest genetic reservoir of living organisms, including all known Phyla (Wall & Knox 2014). Increasing soil species richness is a significant advantage against the global challenge of biodiversity loss (Adhikari & Hartemink 2016). On this basis, the management of soil as a highly productive natural resource could be the panacea, limiting factor, or downfall of an ecosystems and an extension of this, society. Frameworks that integrate these existential challenges with the soil resource at all management scales, including within a farming enterprise, are vital.

Soil is a dynamic entity in a network of systems sensitive and responsive to natural and anthropogenic forcing (McBratney et al. 2019). IPBES found 75% of the global land area had undergone a degree of degradation, with agricultural practices and clearing for cropping and grazing frequently cited causes (IPBES 2019). Soil degradation or decline of its physical and biochemical properties is rooted in a weakened capacity to perform a function and is closely related to failure to deliver ecosystem services. However, quantifying soil functional decline is not a straightforward process. Computing soil degradation requires understanding the quality of soil at its point of origin or its reference state and is a product of loss of a specific attribute-based function over temporal and spatial scales (McBratney et al. 2014; Bünemann et al. 2018).

A more accessible means to view soil vulnerability to degradation is from the perspective of soil threats. Burssaard (2012) has synthesised the threats to soils (European Commission 2006) and logically linked these to soil function and their ability to deliver ecosystem services. Figure 1 describes soil functions as 'bundles' of soil processes, interdependent and deeply embedded in many services simultaneously (European Commission 2006). Though the linkages are depicted to give a universal view of what soils are capable of, this representation does not provide a weighting for any single ecosystem service to be rated as a priority over another. Here again, the question of how to value ecosystem services, and supporting soil function, is raised. Biomass production, which is reasonably the ultimate goal of agricultural land management, is interconnected to all of the fundamental soil functions, demonstrating how an enterprise dependent upon this ecosystem service must be aware of and seek to balance any threats to these functions with production targets.

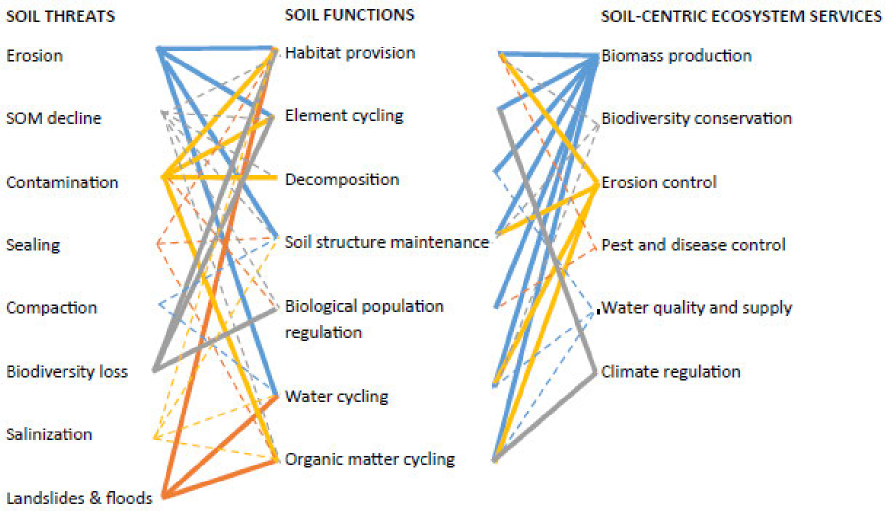


Figure 1 Soil threats, soil functions and soil-centric ecosystem services, simplified and redrawn from Burssaard (2012)

Many soil threats are associated with the accelerating effects of climate change. Australia experienced its hottest year on record in 2019, and a 1.52°C increase relative to the 1961-1990 mean annual temperatures (Bureau of Meteorology 2020a). Such events reflects what Chiew et al. (2011) identify as a 'persistent shift' to increased incidences of drought conditions. Rainfall events are expected to decrease in frequency and duration (Hennessy et al. 2015), followed by severe 'breakthrough' rain events following dry periods, risking erosional losses (Kokic et al. 2005). Hotter days are set to intensify degrading mechanisms following soil moisture scarcity and increases to evapotranspiration and atmospheric vapour (Gimbel et al. 2015). Therefore, drought poses a significant threat to soil function via interruptions to the hydrological cycle upsetting the carbon and nitrogen cycle in a deteriorating feedback loop (Pasricha 2017). Desertification processes and the loss of topsoil through water and wind erosion increase ecosystem sedimentation and escalate in a warming climate (Pasricha 2017; Hoegh-Guldberg 2018). Without intervention, existing agricultural enterprises may not be feasible in their current geographical location, as general poleward and inland-to-coast climate zone shifts are predicted across Australia (Kokic et al. 2005). Understanding the interplay between soil function and zonal climatic shift is a sensible direction for the future-proofing global food and fibre systems.

The key to increasing soil resilience to climate-change impact lies in connecting different policy stakeholders through a set of common goals and a sense of soil governance (Borrelli et al. 2020). It necessitates policy that integrates management of the soil resource as a balanced reserve for multiple functions at once. Current Australian policy - infrastructure, agriculture, environment, urban planning, and others – is enacted in isolation (Williams 2015). When lawmakers have considered soil in previous years, policy favoured a single soil function without awareness of natural system suitability across all functions. An example of this failing would be if peri-urban agricultural land is used to develop low-density housing (Bennett et al. 2019) and does not seek to maximise the opportunity to exploit the land for food production or shelter provisions. State level policy attempts to do this, however due to exclusions it is arguably ineffective. Policy terminology does not discriminate land from the soil and its explicit resource needs and constraints to function (Kokic et al. 2005). In 2021, clear progress was made with the publication of Australia's National Soil Strategy (Commonwealth of Australia 2021). The strategy recognises the soil status as a key national asset and is guided by collaboration, innovation, and indigenous governance. Adhikari and Hartemink (2016), in a global review of soil-ecosystem linkages, suggests engaging scientific bodies across a broad spectrum for a multidisciplinary approach, and output from the National Soil Strategy aims to address this with immediate action.

Within a changing climate and given the anthropogenic forcing of our soil systems, it is crucial to implement a framework that is interoperable with all levels of government and at all scales of land management. Soil security provides a potential user-centric framework to assist in futureproofing globally sustainable production. This critical review will consider how soil's capability can be established through a soil status benchmarking protocol and how current tools could be adapted to include the climate-change dynamic effect. The feasibility of an approach for initial implementation at on-farm and regional levels will be explored, and critical knowledge gaps identified.

2.2 The emerging soil security framework

Reframing soil use in terms of critical resource management has revealed the many inputs and actors required to bring their voice to the table to secure soil assets, contextualising the social, educational, political, and economic facets in a balanced fashion (Bennett et al. 2019). The emerging Soil Security Framework (SSF) suggested by McBratney et al. (2014) addresses this by prescribing a thorough multidimensional process. The processes have been developed from conventional protocols of land use assessment, aided by digital soil mapping (DSM), to be more biologically inclusive and to emphasise the interconnectedness of human and natural systems. There are five dimensions to the soil security concept contributing to the overarching goal of sustainable land use (McBratney et al. 2019). The dimensions are capability, condition, capital, connection, and codification and are defined in Table 1, though the literature review will focus on condition and capability contributions to soil security applications from this point forward.

Table 1 Expanded the definitions of the Soil Security Framework to aid in the discussions of the five dimensions, modified from Kidd et al. (2018) and Bennett et al. (2019)

Dimension	*Expanded definition*
Capability	What is the soil fit to do? This dimension targets specific functions well suited to the soil's capacity to do work and recognises the soil's biophysical constraints. This element dimension relies heavily on the current soil condition. According to Food and Agriculture Organization (1976), this is an extension of the land suitability assessments that are generally region-specific and are historically applied widely. More recently, a Tasmanian state-level study of land capability assessments (Kidd et al. 2018) harnessed parent material, climate and landscape position for a holistic view of capability.
Condition	Can the soil carry out its given tasks? This dimension is based on how the soil has been influenced over time and deviations in the soil attributes most relevant for its particular use. Does the rate or scale of the condition change indicate an improvement, maintenance, or degradation of the soil? A known or perceived target or threshold value is necessary to establish a change in condition and give context for various land-use combinations. Typically, long term monitoring is used. In some literature, soil condition is interchangeable with soil health or quality.
Capital	This dimension addresses: how can soil functions be valued in society, and is this a practical application at its core? Any derived values must be accessible for decision-making processes and recognise the economic and ecological aspects and how these contribute to society. This dimension is both ambitious and ambiguous in its scope. How ecosystem services are perceived is a critical component to the effective quantification of soil 'capital, interchangeable with natural capital. An example of economic capital is the potential earnings in a soil-landscape specific to land use or enterprise.
Codification	What regulations exist for policy and private and social contracts to protect, guide and control interactions with soil and influence sustainable land use? Furthermore, what legislative mechanisms are in place at the state and federal levels? The policy is imperfect in Australia, and the SSF overarching goal is to incentivise soil stewardship with ongoing monitoring and enforced by policy.
Connectivity	This dimension is defined by how society engages with soil, uses its products, and recognises its role in everyday provisions. Connectivity is the embodiment of 'those who know care, and those who care lobby" (McBratney et al. 2018).The level of knowledge of soil functions and sustainable soil use for the general stakeholder is difficult to quantity, though critical to continuing to grow connectivity at a community (and greater) level. Connectively is closely related to soil capital, and it intersects with how society identifies and respects soil's impact on other social institutions. For land managers, connectivity centres on upskilling with appropriate tools (such as surveys and mapping) to understand soil vulnerability, sustainable management practices, risk mitigation, climate adaptation, peer and industry training.

Soil capability gauges what the soils can do (Bennett et al. 2019) or equally how is it constrained to do work (Kidd et al. 2018). Soil capability is measured by a set of properties or attributes resistant to management (McBratney et al. 2018). Soils that bear little to no evidence of anthropogenic activity can be considered to exist in their least disturbed state, and this logically predates more intense cultivation associated with European settlement. Theoretically, some consideration must be given indirect influences, such as landscape flood and fire regimes and invasive species, and effects of loss of ecological connections (patch shape and size, edge effects etc.) (Tulloch et al. 2016). Despite being imperfect, this becomes the reference state, and its attributes are the metric the attributes of other sites may be measured against to understand their collective degree of change over time.

The reference state may also represent its natural fitness for performance for desired functions and is key to identifying the deleterious effects of agriculture (Rossiter & Bouma 2018). The definition of soil function is generally loose (Bünemann et al. 2018) as no single set of innate soil processes applies to all (McBratney et al. 2019). Optimal soil function recognises what a soil is capable of, based on the properties that define and promote the highest performance outcome. Optimal function is specific to a plot or farmed paddock. The condition measures how soil has changed and diverged from its reference with a secondary set of attributes that may be easily influenced and serve as the record of anthropogenic activity affecting the soil. An assessment of soil capability indicates if land-use practices are degrading the soil status to a point beyond which it cannot be restored. It thereby ascertains if its current condition and use are unsustainable. If soils diverge from the reference state, the function it performs is likely not well-suited to its attributes, and their capability is not being exploited to maximum effect. An example described in Zhang et al. (2007) outlines the links between mono-culture landscapes and complexity, i.e. biodiversity leading to increased insecticides, loss of non-target species and the lack of soil microbiology over time.

Conversely, a divergence may be positive if biological activity increases, for example, soil carbon metrics rising due to non-tillage practices and organic inputs. Thus, a change in chemical and physical composition is relative to its given function and the ecosystem services which benefit the most actors. It is important to note that divergence of state may not indicate unsuitability or in fact, reflect a poor soil condition. Movement from one state to the other may result in a loss of some degree of a specific function, but the trade-off may be in improvements to other functions. This is the critical challenge for future soil security research and policy implementation; to balance this demand for soil multifunctionality, such that net gains outweigh and minimises environmental losses and the landscape healthy is maintained.

2.3 Linking the terron model

The SSF is further challenged by its ability to translate large-scale application to on the ground usefulness (Bennett et al. 2019; Bennett et al. 2021). Outputs need to be mappable and to a resolution level where farms are distinguishable (McBratney et al. 2003). Without this, it is impossible to empower an individual grower to extract maximum value from the framework and leverage decision-making. It has been tested at the state level (Kidd et al. 2018), yet how to then conform the methods to the level of on-farm boundaries remains ambiguous. Carré and McBratney (2005) put forth the ‘terron’ concept for gauging soil in terms of environmental management and classifying landscapes; this may provide a practical means to address this ambiguity. The terron is a continuous pedological unit that incorporates significant factors to the respective soil’s topographical location. It provides a means to define the genosoil and phenosoil (Huang et al. 2018), extending the soil capability and condition in different states. The genoform is the site at which the soil is least disturbed. A phenoform is “a persistent divergence” from a genoform, either through misuse or purposeful management (Rossiter & Bouma 2018). The use of terron mapping units in DSM and the application statistical models (Malone et al. 2014; Huang et al. 2018) allows for breaking down the condition and capability dimensions into a common and actionable language usable by many stakeholders.

Soil capability is expressed as a function of soil capacity and soil condition (as defined in Table 1). McBratney et al. (2019) best describe this as a stepwise process for data matrices to capture the soil biophysical factors and give context to the reference soil and the secondary soil or site of interest.

Significantly, the resulting mathematical relationship depicts the soil attribute data as detailed by a matrix, thereby the soil’s ability to carry out the desired function (McBratney et al. 2019). Time may be included in the calculation in the rate of capability change to determine the speed at which degradation has occurred.

It is a broad method and may be modified to estimate the capacity of soils across a range of functions if the appropriate attributes are selected, e.g. contamination or agronomical attributes. McBratney et al. (2019) state this process conceptualises how the different dimensions interact though it has yet to be tested in-field.

For attribute selection, no one size fits all. Building a protocol for this may begin by recognising that target attributes need to be site-specific (or arguably region or industry-specific) based on which attributes have undergone the greatest degree of change in contrast to the reference state. Thus, addressing this locally does not require broad classifications for land suitability thresholds. A viable way forward is to aim for overarching judgements for land suitability, based on terron assessment, at the farm level, which may be progressively scaled to regional and national levels. Attributes would also vary depending on the given function of interest, which warrants further investigation. A next step may be to assign appropriate levels of uncertainty for on-farm decision making; what this may look like is out of scope for this review (Kidd et al. 2020).

The terron as a quantifiable and measurable unit (Carré & McBratney 2005) acts as a tool for selecting attributes for maximum effect. Its formula best relates the genosoil-phenosoil to the soil security application as a practical data capturing mechanism (Huang et al. 2018). Table 2 translates the genosoil-phenosoil dynamics to the more practical genoform-phenoform tools, illustrating key differences. This can be used as an input for a soil survey, and thus the protocol for terron mapping emerges (Huang et al. 2018). The genoform is the site at which the soil is least disturbed. A phenoform possesses a set of physical and biochemical differences affecting how the soil functions. This is true even if the productivity of the cropping system is not altered as it may be managed for performance and still be experiencing a decline in the soil condition attributes or phenosoil.

Table 2 Summary of the intra-relationships of genoform-phenoform and genosoil-phenosoil, after Huang et al. (2018)

Concept	*Definition*	*Differentiation criteria*	*Application*	*Relationship*
Genoform	Soil classes as identified by a soil classification system (such as ASC) is the starting point for detailed soil mapping in an area of interest	Soil classes (e.g., soil series)	When a detailed soil survey map (e.g., soil series map) is communicated, and land users require context for changes in soil properties/ functions relative to different soil classes	When a soil series map is developed, mapping units are the basis for identifying genosoils and phenosoils and their transition to becoming local genoforms and phenoforms
Phenoform	Persistent deviations from genoform, having sufficient physical or chemical differences to affect the capacity for soil function	Degree of change in soil physical and chemical properties that would affect soil functions, measured through soil condition		
Genosoil	Soil mapping units that were least disturbed by anthropogenic activities may be considered original or 'pre-colonial.'	Soil mapping units produced by digital soil mapping protocols	When a detailed soil survey map (e.g. soil series map) cannot be delivered, and land users need to differentiate the changes in soil properties/conditions /capacities relative to respective soil mapping units.	
Phenosoil	Soil mapping subunits with varying levels of change for soil physical and chemical properties	Degree of change in soil physical and chemical properties, which can be calculated or predicted using a reference soil database (e.g., comprehensive soil classification system or extensive legacy data)		

The terron relies on each site having a singular set of topographical and inferred climate features, thus soil-forming features (Carré & McBratney 2005). This approach also allows the soil ameliorations and associated costs to be target-based (Bennett et al. 2021) and site- and function-specific. As a result, management can strategically treat the soils for individual threats (McBratney et al. 2018) and, in turn, be more effective from a cost and resource perspective. Table 3 ties attributes to soil threats and functions in a meaningful way. The modification of this list to include soil biota directly ties into the theme of living assets of soil from the SSF (Bouma & McBratney 2013). Table 3 may be expanded upon to include other biological metrics for broad usability outside of agriculture. The list may facilitate a general discussion of what the soil is tasked with, and how it may be treated.

Table 3 Soil threats (and soil organism indicators) based on Bünemann et al. (2018) and the amended soil properties presented by Kidd et al. (2015b) and initially published by Cotching and Kidd (2010)

Condition attribute	***What threat may be acting upon the soil***	***Soil function***
Organic C (% w/w)	Erosion, SOM decline	Soil biodiversity, carbon cycling, sequestration, pest control, gene pool maintenance, climate regulation
Soil pH (in water)	Acidification, contamination	Habitat provision, food production,
Extractable phosphorous Olson or Colwell Method (P mg/kg)	Nutrient depletion, contamination	Nutrient cycling, food production
Bulk density (Mg/m3)	Compaction, sealing	Soil structure maintenance
Aggregate stability (% > 0.25 mm)	Compaction, low organic matter	Soil structure maintenance
ESP	Salinisation, contamination, flooding/breakthrough rain events following drought	Element cycling, food, and fibre production
Soil moisture content	Desertification, erosion	Water storage, purification, infiltration
Soil nutrient (N, Mg, Cu, Zn)	Nutrient depletion	Nutrient cycling, decomposition, waste containment, biological activity and community, food production
AWC via VIS-NIR	Low organic matter, drought, climate-change through an increase in temperature	Water cycling, water purification and filtration, soil structure maintenance,
Subsoil pans	Compaction	Soil structure maintenance, habitat provision, water filtration
Cation exchange capacity	Nutrient depletion, acidification	Element cycling, food and fibre production
Soil temperature	Low organic matter through biota loss, carbon sequestration	Biological population and regulation, carbon sequestration, water cycling (through evaporation control)
Soil electrical conductivity	SOM Decline, desertification	Water cycling, water purification and filtration, soil structure maintenance
Soil organisms (molecular quantification qPCR)	SOM decline, nutrient depletion	Carbon sequestration, water cycling, nutrient, and element cycling

The capacity attributes in Table 4 are included based on the understanding these are not easily affected by anthropogenic forcing. Capacity attributes may be region-specific such as the iron-rich clay and marl found in the Hunter Valley per Malone et al. (2014). This list is not limited and may be expanded upon with further in-field observations and proximal or remote sensor assessments (Kidd et al. 2015a). A reference state must ultimately provide relevance to the soil of interest, and the location/ reference site satisfactorily follows some if not all the following criteria:

- The land parcel proxy of the natural state has not been cultivated or cleared of vegetation (Malone et al. 2014)
- Two sites are in reasonable geographic proximity for climate features to be consistent for exposure to elements for soil losses. Geographical location to other topographical features may be a key determinant (Minasny et al. 2014)
- Share parent material for comparable mineralogical composition and chemical properties (Chabrillat et al. 2013)
- To be accessible at the same depths for soil observations, the depth to bedrock must be considered, i.e., cannot choose a site based on aerial data though spectroscopy data may be helpful (Kidd et al. 2015a)
- An exact or close taxonomy of soil classes, as properties may be predicted from the soil classification (McBratney et al. 2003; Hughes et al. 2017)
- On similar relief conditions for analogous water flows, drainage and erosional processes (Singer & Munns 2002)

Table 4 Capacity Attribute adapted from by Kidd et al. (2018) initially published by Cotching and Kidd (2010) and amended with inputs of Chabrillat et al. (2013)

Capacity Attribute
Spectral reflectance (spectroscopy signature)
Soil Texture (silt/clay/sand %) 0 to 10 cm
Soil Texture (silt/clay/sand %) 40 to 60 cm
Slope*
Integrated gamma radiometric, geology (radioactive nuclides: K, U, Th, total dose
NDVI Normalised Difference Vegetation Index
Depth to horizon change
Depth to bedrock
Course fragment/stone content
**Slope includes eastness index, northness index, curvatures (plan and profile), topographic wetness index (TWI), multi-resolution valley bottom flatness (MR), multi-resolution ridge top flatness (MRRTF), vertical distance to channel network (VDCN), altitude above channel network (AACN), TCI_Low (lowland exaggeration), topographic position index (TPI), mid-slope position (MSP), terrain ruggedness index (TRI), SAGA wetness index (SWI)*

The above criteria reflect the SCORPAN descriptions, mnemonically, soil (S) climate (C), organisms (O), relief (R) parent materials (P), age (A), and spatial position (N), that quantifies the soil and environmental factors of the soil formation processes (Jenny 1961; McBratney et al. 2003). By definition, SCORPAN are not influenced in reasonable human lifespans (Singer & Munns 2002; McBratney et al. 2003) though this is less feasible as extreme weather and habit destruct accelerate in the 21st century altering landscapes at unprecedented rates (IPBES 2019). Nevertheless, these factors are frequent inputs in DSM and underpin the fundamental theme of the terron model. Selecting the soil, which will be the focus of analysis and later interpolation, will be dictated by which capacity attributes are available and comparable between study sites. Degradation may be viewed as the negative outcome of soil analysis conducted to produce output for a specific industry. A more meaningful interpretation, may be one that recognises the effect of anthropogenic activity as quantified by the change or contrast in the condition attributes and which directly relates to its given function (McBratney et al. 2019). The pressing question may not be which capacity attribute is correctly selected as the baseline for soil capability analysis, but how many of the SCORPAN factors and therefore capacity attributes must be *paired* between the two sites to justify its proximal status of the native vegetation? To put it simply, it is not solely a matter of what properties the genosoil and phenosoil have in common, but how many genosoils exist in the region, where the boundary of this analysis extends, and subsequently how to standardise how soils are characterised therein. The complexity of relating the two states, and the general lack of standardisation and in this area of soil classification is a major gap within the field of DSM and forms the basis of the suggested protocol outlined later in this thesis submission.

Locating the reference site and the secondary sites of interest may be accomplished by drawing upon the techniques of Kidd et al. (2014); for stratified random sampling. In addition, government-maintained databases allow access to digital elevation models, spectroscopy, vegetation and geological and mineralogy maps, and climate grids which previous publications have employed for environmental covariate generation (Webb et al. 2014; Grundy et al. 2020; Kidd et al. 2020; Ma et al. 2021). Additionally, the algorithm-based method of McBratney et al. (2003) relates the individual covariates to a unique set of soil-forming factors, as detailed in the SCORPAN relationships, reinforcing the essential role of these factors have in soil classification and thus soil proxy status as discussed earlier.

2.4 Elevating on-farm assessment with the terron model

Kidd et al. (2018) provide a means to estimate the transformation of soil attributes in a landmark Tasmanian-wide study. Here, Kidd et al. (2018) proved the feasibility of quantifying the soil security concept by applying DSM conventions to each soil security dimension. By assigning thresholds to gauge if the current land use was sustainable, the study sought to answer the question; are soils being conserved or otherwise acted upon by industry to the degree that fits their respective capability limits? Kidd et al. (2018) recommend improvement through error propagation and decreasing uncertainties, agreeing with the expansion of prediction modelling with covariate data and greater sampling density. Furthermore, moving toward a magnitude-based attribute prediction and a target value for each soil order is advised to readily quantify soil capability across the board. This would result in a more accurate archetypal reference state for each major soil type known in the region or industry. Malone et al. (2014) subsequently defined the terron to provide quantifiable detail to various applications and offer solutions to the issues identified by Kidd et al. (2014), chiefly finer resolutions DSM, and tools to enable sub-farm scale mapping using existing data. Huang et al. (2018) progressed the study of terrons in the Hunter Valley region by dividing the landscape into genosoil and phenosoil using pre-European settlement vegetation. This study focused on the organism (O) in the SCORPAN equation to classify the soils paired with the Normalised Difference Vegetation Index (NVDI) as a condition attribute (Huang et al. 2018)

Bennett et al. (2019) discuss the lack of an agreed methodology for defining the reference state and the need for agriculture targets aligned to industry needs. By investing in soil testing and assessments, farming decisions may be informed to explicitly support the attributes in decline and facilitate short-range change in capability, increasing enterprise feasibility in the longer term. The formula developed by Bennett et al. (2021), based on McBratney et al. (2019), is proposed to allow governing bodies to calculate environmental markets and offer a mechanism to audit management systems for the long-term goal of individually motivated soil stewardship. The formula generates an annual rate of return value as a percentage of the original soil amelioration investment. It conveys the monetary value of conducting soil sampling and scientific investigations to a farming enterprise. Importantly, this return on investment (ROI) formula represents how changes in land management results in direct financial gain, through both the profit function and with the potential to develop a soil condition credit. A credit would be based upon stewardship (controlled input); this has largely failed to create the value proposition required for investment in soil management and policies to date (Bennett et al. 2019).

This return-on-investment approach recognises the grower’s often precarious financial position and incorporates the final three dimensions of the SSF. It would be unreasonable for landowners to relocate an enterprise following the climate zone shifts resulting from terron assessment. A positive approach would be to secure the soils currently in use, with incremental adjustments toward a best practice of attribute-based management and monetized incentives that may be reinvested for soil treatment and restoration. Also, understanding where current management practices have failed (are not secure) on the farm will go a long way to alleviating the long-term ramifications of intensive use through a “what not to do” lens (Kidd et al. 2018). Linking on-farm ROI with soil securing practices and subsequent evidence of both would incentivise growers to adopt better management practices. The terron approach and on-farm proxy references would facilitate this.

A practical toolkit which facilitates the mathematical process for proxy site selection and validation of proxy status, has not yet been developed. A suitable means forward may be borrowing established methods from medical, behavioural and economic research fields; the propensity score matching modelling (PSMM) (Granger et al. 2020). PSMM involves the exchanging of data between exposed/unexposed or treated/untreated groups in observational studies to reduce confounding bias (Austin 2011). PSMM conceptualises a ‘score’ for an observed unit in a treated group, calculated from unique set of values to characterise the unit and is derived from a universal qualitative and quantitative data series, and subsequently it matches the score to that of an independent unit in the alternate group. In the case of agricultural application, PSMM may be effective if the treatment group is expected or known, i.e. having a constraint in a farmed (treated) area and identifying an amelioration target based on a benchmark or reference state and the goal is to locate proxy site with a comparative ‘score’ to provide this information. This type of modelling can inform DSM, as data would be collected via sampling and soil analysis and used as input for interpolation. Though this is theoretically plausible it is important to note, this has not yet been attempted. The recent emergence of statistical matching for conservation (Schleicher et al. 2019) and lessons learned, may guide implementation of PSMM in the digital soil science space.

The use of a suitable protocol for locating sampling sites and designing an effective sampling regime, is as essential as developing a protocol for proxy-to-farm site pairing. An inefficient process overall could mislead management attempts to correct any poor soil conditions or worse, over-treat and lead to further degradation if the pairing is ill-informed. Overcoming this particular barrier will enable cost-effective, broader implementation and accelerate industry support for soil security concepts. Upscaling a single model, modifying or stratifying PSMM with industry specific characteristics and set variables, is a larger question posed, when one investigates wider applicability. Marrying such a tool with expertise must also be considered. A thorough previous understanding of how soil interacts with its environment is the bedrock for effectively interpreting of PSM output and counteracts causal inference. This will assist enormously in safeguarding against bias and imbalance in the model and ensure PSMM is elevated and ultimately relevant to soil management.

The issue of where to invest on-farm to inform future practices and future crop suitability when facing persistent drying conditions (Chiew et al. 2011) is also critical. In view of climate change, a landowner may look to diversify cropping systems or modify management practices to safeguard against costly relocations or industry upheavals in what may be a more competitive and climate-stressed market (Kidd et al. 2015a). Pivoting an enterprise based on well-founded soil scientific knowledge, made available through relevant and repeated testing of soil properties between the proxy reference site and the farmed areas, will help decision-makers to understand soil change and promote soil stewardship (Bennett et al. 2019).

2.5 Summary and next steps

For the SSF to be interoperable with all levels of government and at all scales of land management, it will need to evolve to become an everyday conversation between land managers and the many actors invested in its maintenance and improvement. However, implementing the framework within a dynamic climate involves considerable uncertainty, and the literature review identifies several knowledge gaps:

- The soil security framework does not consider future landscapes and climate-change impacts, but the incorporation of this should develop a prospective mitigation tool, allowing scenario testing and a climate-change awareness through its dimensions of capital, codification and connection;
- There is no agreed methodology for capability and condition assessment and no established benchmark criteria for measuring and rewarding positive stewardship. A chasm exists concerning

informing landowners on sustainable best practices for their respective soil type and land management/production systems types and incentivising a shift to sustainable soil use;

- Attribute selection remains challenging, as the selected attribute for one function might not be useful in considering other functions that the soil may perform;
- The potential for climate-zone and soil-function shift, coupled with feasibility for enterprises to transition, is an unexplored area of research.

2.6 Hypothesis

The hypothesis of this case study is the management of a mix-horticulture system over 70 years had a negative effect on soil condition.

To test the hypothesis, a series of research questions were posed:

a) Can individual sampling points across the sites be paired through a clustering effect (or propensity score matching) of the covariate data to establish the native vegetation site as a proxy reference for the farmed site?
b) Can deviations in the results of soil chemical analysis across the two sampling sites reasonably assess changes in soil condition?
c) Can DSM be employed to visually depict changes in soil condition at the farm scale?
d) How can a change in soil condition be managed for positive outcomes on-farm, and for the connecting landscape?

Once tested, it is expected that as soil condition changes, the capacity for soil to function also changes, and on-farm management decisions must be responsive to soil capability or risk (ongoing) degradation and loss of ecosystem services from the soil.

Chapter 3

3 Methods

3.1 Local Area

The Southern Downs region is economically thriving with an annual total horticultural/agricultural production of $300M (Tancred & McGrath 2013). The region favours horticulture products due to the warm to mild/temperate climate with summer dominant rainfall patterns (Maher 1996c; Bureau of Meteorology 2020b). Many of the horticultural species grown are climate-sensitive deciduous trees (e.g. apples) that rely on cold temperatures and chilling hours, illustrating the need to consider climate with soil capability in an overall view of crop suitability for the region. The region's geomorphology is characterised by igneous rock, with granite and sandstone parent materials prevalent across the region (Maher 1996c). Maher (1996c) identified 21 landscape types with distinct soils and systemic spatial variability. Local soils are often sandy and shallow. If exposed to extreme weather or on sloped land, these soils experience a more significant risk of erosion or structural change, especially hazardous for climate-sensitive species.

As detailed in the Introduction section, the study focuses on the agricultural system within the broader regional ecology and its services. The map and any subsequent suitability assessments it may inform in the future will seek to facilitate ground-up engagement in long-term soil management, along with the assisting preservation of native vegetation on individual properties and across communities. It is intended that the findings will contribute to a useful research direction with the suggested protocol being tested as a geographically larger and more comprehensive study of the region and potentially HDR topic for future research students.

While firmly a demonstrative pilot level of implementation and research, positive action such as this is critical to achieving the long-term goals of Morgan et al. (2017) to reach 50% of soils used and condition managed optimally within the limits of their respective capability by 2030. Testing and advancing the frameworks' practicability will prove valuable in futureproofing Australian agriculture. We seek to understand how soil management decisions can inoculate against the effects of the unprecedented and profound challenge of climate change.

3.2 Study design; Regional Terron Assessment

The project was designed for regional level analysis and digital soil mapping (DSM) of legacy Queensland Soil and Land Resource Survey Information (SALI) project data of the Southern Downs local government area (LGA). The study was based on the application of a series of terrons across the 7,108 km² study area. The terrons, as a mapping unit, cluster soil properties and environmental covariates as indicators of soil-forming factors to produce ‘grades’ or criteria to identify features and or soil types across large areas (Carré & McBratney 2005). Legacy soil surveys and laboratory data across the LGA provided input for the terron assessment. From a series of terrons for the region, a single terron was to be selected with sites suitable for native vegetation and farmed paddock soil sampling. Sites were then to be selected based on contrasting 60 normalised difference vegetation index (NDVI), land manuals, aerial imagery and Regional Ecosystem Reports were used to inform how two sites were located. A pilot study to establish a protocol for assessing soil security at the farm scale by investigating changes in soil condition across the two sampling sites was then to be undertaken.

For terron assessment, soil data was made available through the SALI project data streams and accessed via QGlobe (https://qldglobe.information.qld.gov.au/). The data encompassed 15 individual soil projects and 374 sites within the local government area (Queensland Government 2021b). Of these, only 88 across the 7,108 km² study area contained consistent data entries for chemical and physical properties of pH, EC, Chloride and Clay (texture content) % data. A sub dataset was produced of eligible Australian Soil Classification (ASC) records for a total of 369 sites. This classification was performed using morphological descriptions from the sites lab reports, either from existing ASC results or by applying a data conversion. The conversion was occurred through the use of the conventional Northcote (1971) principle profile forms, then updated to ASC descriptions using Isbell (2021) for consistency. A map was produced from updated dataset of the 369 total ASC sites. A validation technique was recommended due to the sparsity of the data at the regional level, which would allow some data to be used in model building and a portion removed from the dataset to test accuracy and validate results (Kidd et al. 2015b). A leave-one-out cross-validation (LOOCV) technique was attempted for a 70/30 calibration/validation effect. This reduced the eligible sites to 62 for model building for the entire Southern Downs LGA and validation technique was not applied in final results. A rapid improvement was to limit the chemistry properties as input data for interpolation models, particularly that of pH to in-field tests conducted as per Raupach and Tucker (1959). If the scope were thus reworked using the alternative pH method, 380 sites would be eligible for inclusion in the study. However, a terron model's usability based on a single chemical property was dramatically reduced and a poor model fit. The terron model was ultimately not used in this case study, due to lack of consistent, quality data. This is explored more thoroughly in Section 4.1. The time constraints of an Honours project did not allow for any modification in the data selection nor a redesign of the project scope for the regional analysis. Future terron mapping may be improved by altering the legacy sites' eligibility criteria, chiefly by including those sites using in-field methods rather than laboratory-based results, which are more frequently used across soil project types.

3.3 Study design; Farm-scale Assessment of Soil Condition and Capability

The hypothesis was tested in a case study of the Southern Downs region, which encompasses Warwick and Stanthorpe. The Thorndale area, close to Stanthorpe and in the New England Tablelands, has approximately 49.5% of its land occupied by remnant regional ecosystems and 28.35% of the total area in an endangered class (Queensland Government 2021c). Ecological surveys have found various eucalypts, cycads and the iconic *Boronia granitica* woody shrub to be of most concern (Queensland Government 2021c). The high rates of native vegetation cover and diverse horticulture and agriculture industries of the region (grapes, stone fruit etc.) attracted further investigation into the types of soil favourable for different functions.

A pilot study conducted at Thorndale addresses many of the gaps identified in the literature review and test the overall feasibility of the SSF at the farm scale. A suitable site was identified at a private property in Thorndale containing remnant native vegetative growth and mixed-horticulturally farmed land, to move the project forward. An overview of the property in the context of the Southern Downs region and its proximity to Stanthorpe is illustrated in Figure 2. The horticulture land had previously returned to either a cleared, natural state with low intensity management regimes, in recent years ensuring access throughout the project. The extensive native vegetation was spread across the property indicating what would likely capture same or comparable soil types for the two contrasting land use types. The landowner was a willing collaborator and provided multigenerational management information to advise when land clearing practices were enacted. Satellite imagery justified the initial fitness for the project, and this was later confirmed with NDVI data, as discussed in the Results section.

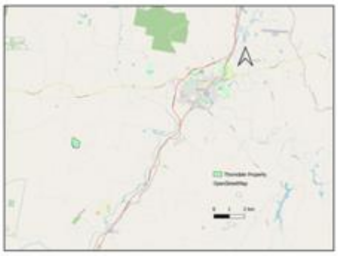
The pilot study and subsequent protocol was realised using continuous spatial descriptions of soil attributes across timescales indicative of a changing climate and terron-based DSM protocols to illustrate where farming diversification would be well-suited and drive sustainable farming. An initial attempt is expected to be imperfect, exposing the limitations in joining the SSF and the terron model yet allowing for meaningful change in soil security at the farm scale, with long term use and adaptation.

The initial survey for elevation was typically consistent across the property, with some variation in the East to West corners of the boundary. As a capacity attribute, this variation in elevation was reasonably distributed between the two land-use types and considered an acceptance of pairing of sites (through PSMM) in later analysis. The other capacity attributes, chiefly the remote-sensing data and derived terrain characteristics, support the assumption that the two sites had comparable soil-forming factors. The property was deemed appropriate for protocol implementation, and the case study proceeded to soil sampling, followed by laboratory testing of the samples in preparation for DSM and modelling.

It is important to note that the variation in covariates and terrain characteristics at the farm scale are assumed to be comparable at this stage of the case study, predominantly due to the geographical proximity of the two land-use types (that of native vegetation and farmed land sampling sites) and initial elevation analysis.

3.4 Study area; Thorndale

The total property size is 72 acres and approximately 2:3 ratio of farmed land to native vegetation land use, several of the paddocks have not been actively managed since 2016. From 2016 to mid-2021, the centre and lower paddocks grew millet for small-scale seasonal goat and cattle grazing regimes. A verbal account of land use for different crop types was taken from the multi-generational managing family (1946-2021) to complement soil sampling and provide qualitative data. The history of non-clearing in the areas of native growth was documented from 1966 using aerial photography available from 1966-2017 accessed via QImagery (https://qimagery.information.qld.gov.au/) (Queensland Government 2021a). The native vegetation was accepted as a remnant of pre-colonial levels and remains relatively undisturbed. Covariate data included 20 year, temporally stable NDVI outputs.



Insert 1: Thorndale property, in proximity to Stanthorpe (above).

Insert 2: Thorndale property boundary, over satellite imagery (below).

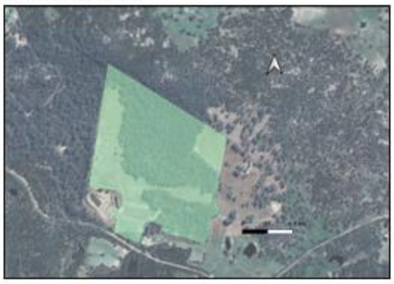


Figure 2 Thorndale Property on the Southern Downs LGA, with inserts to provide regional context

3.4.1 Structural composition and native vegetation

There are several underground springs running from the Eastern to Southern fronts of the Thorndale property. The vegetation at Thorndale was classified as dry sclerophyll forest with eucalypt and shrub-like growth (Queensland Government 2021c), as per Figure 3. Trees were evenly distributed with native grasses on the forest floor, thickest at the boundary lines. Granite rock formations were frequent and prevented access to the precise location for sampling, though consistently within +/-5 m of the GPS. The large granite rock deposits are the main factor for remnant vegetation on the property, also restricting planting and harvesting equipment in these areas.

Figure 3 Gum trees at Thorndale, representative of the Native Veg areas

Figure 4 Granite rocks on the surface and in shallow soils, Thorndale

3.4.2 Oral Management History

The Thorndale property is subdivided into five paddocks (Figure 4), with management respective of each paddock. The landowner shared limited details of the cropping and treatment history orally and informally; no official record was available. A multi-generational family managed the property, and typically, the paddocks followed the on-farm flow of early horticulture crops and diversified to small vegetable systems in the early 1980s. At this time, all stone fruit trees were removed. The following paddock-breakdown provides specific details, and is enclosed with a general treatment statement:

Paddock 1: Dedicated stone fruit grown with frequent lupin rotations 1952 to mid-1980s, shift to small vegetable capsicum, winter sprouts, and small blocks of tomatoes from mid-1980s to late-1990s. From the late 1990s to 2005, grazing was permitted, and from 2005 to 2020 the paddock returned to wild grasses with minimal grazing and slashing management.

Treatment – No inputs were used from 2005.

Paddock 2: Dedicated stone fruit grown with frequent lupin rotations 1952 to mid-1980s, shift to small vegetable capsicum, winter sprouts, and small blocks of tomatoes from mid-1980s to late-

1990s. The lower third to half is not typically sown due to rock formations limiting vehicle access and seasonal waterlogging due to proximity to damn. This area is referred to as the ‘rocky ridge’ and received periodical treatment inputs compared with the regular treatments used in the remainder of the paddock. From the late 1990s to 2005, grazing was permitted, and from 2005 to 2020, the paddock returned to wild grasses with minimal grazing and slashing management.

Treatment - No inputs were used from 2005.

Paddock 3*:* Dedicated stone fruit grown with frequent lupin rotations 1952 to mid-1980s. Snow peas, cabbages, and brussels sprouts were grown from the mid-1980s to the late-1990s when no longer actively managed agriculture/horticulture—a shift to green crop, typically millet, for grazing with minimal inputs from 2000 to 2020. Seasonal slash and mulch were used when grazing was not suitable.

Treatment – A low dose of phosphate and dolomite liming agents were used during grazing periods, minimally input.

Paddock 4: Foundational crop, stone fruit (primarily peaches and plums) from 1945 to the mid-1980s, shift to snow peas, cabbages, brussels sprouts to 2000. Capsicum was grown exclusively from 2000 to 2005. Shift to green crop, typically millet, for grazing with minimal inputs from 2005 to 2020. Seasonal slash and mulch were used when grazing was not suitable. Slash and burn techniques were applied intermittently at the far-right paddock boundary.

Minimally input, a low dose of phosphate and dolomite liming agents were used during grazing periods.

Paddock 5: The last paddock on the property to be cleared in the early-1970s. Dedicated apples and pears were grown from the date of clearing to the mid-1990s, diversified to winter sprouts until 2002. Paddock returned to wild grasses with infrequent slash and mulch management and some burning practices utilised.

The treatment details apply to all paddocks unless otherwise stated. Treatments for pH imbalances typically used lime or dolomite, with a yearly load of 300 kg/ acre or 600 to 700 kg per Ha. Fertiliser treatments were varied, with soluble, pellet or raw treatments used in recent decades. Land-specific mixers not used. Fertilizers Eco88, a blend of sulphate of ammonia and organic nitrogen, phosphorus, and sulphate of potash, was used at a rate of 300-336 lbs/acre (an outdated application rate today). Eco88 was used in bands in the planting beds at the front of the growing season. This was complemented by alternate yearly applications of organic chicken and bull manure fertilizers. Bull manure was used raw from local meat processing facilities and spread broadacre initially then in later years applied in bands at the planting bed, at a rate of 4 tonnes/ acre. Chicken manure in pellet form was applied at a 300 to 400 kg / acre rate.

Soluble fertilizers such as urea or calcium-based treatment were applied from the 1960s to 1980s, at a 25 kg/ Ha weekly rate for 16-weeks of early growth. In later years, management was advanced to use plant sap analysis to determine nutrient deficiencies and excesses and target highly concentrated soluble treatments.

Figure 5 The designated paddocks at the Thorndale property, using updated Google Satellite imagery. The dam was receded at the time of sampling and later DSM analysis.

3.4.3 Sampling regime

The two land-use types, termed Native Veg and Farmed, at Thorndale were partitioned into areas for random sampling using the PCOSA R-Package (version 0.3-8) (Walvoort et al. 2010). A total of 48 points were sampled (Table 5), 24 for each land use. The distribution of sampling points is found in Figure 5. Details regarding how sampling occurred for soil extraction at Thorndale, see section 3.6.

Table 5 Sampling points for stratification category by land-use type, and the number of sampling points with respect to property size at Thorndale.

Location	*Site classification*	*Sampling points*	*Area (acres)*
Thorndale	Native Veg	24	38.088
	Farmed	24	25.288
Total		78	63.376

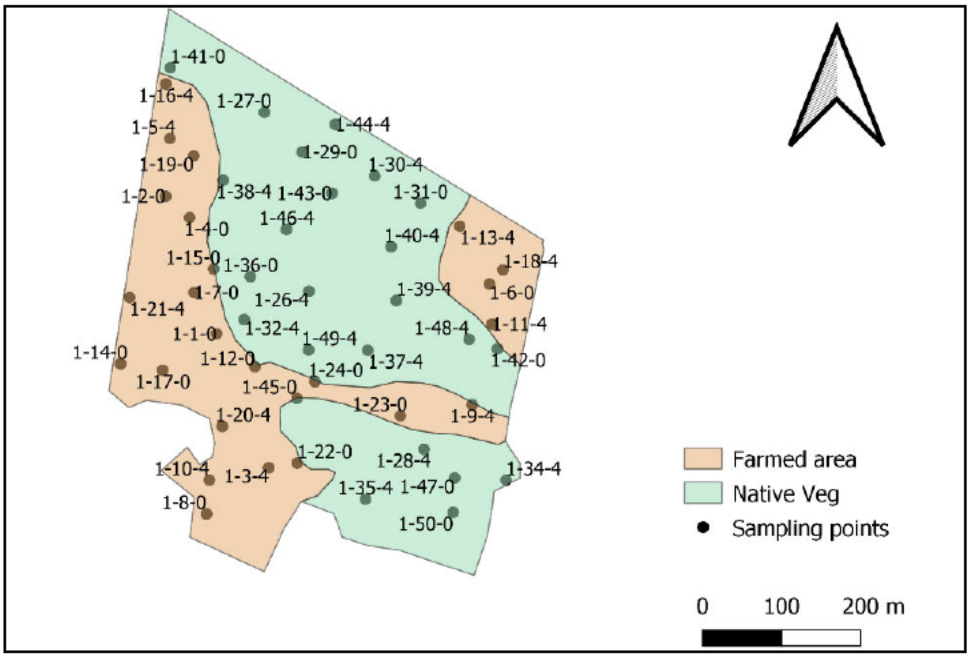


Figure 6 Thorndale property boundary and sampling design for Farmed area and Native Veg

3.5 Study area; Millmerran

A second property, at Millmerran, was selected to validate the protocol for pairing a proxy farmed sampling site with the native vegetative site; the propensity score matching technique. This property was made available due to an ongoing study by the University of Southern Queensland Centre for Sustainable Agricultural Systems soils constraints project. It qualified for inclusion in the study with its Native Veg and Cleared land boundaries and access was guaranteed for the case study, enabling soil sampling for model building and PSMM application. As the use of the collected data was limited to validation of the PSMM method, the effort to research and define the property was lessened. This property is a high-intensity farming enterprise for a variety of grains. The study area was limited to a quadrant of native vegetation with strips of cleared, unfarmed land on the Eastern and Southern boundaries. This property differs from the Thorndale property through its land-use type and motivations for retaining remnant vegetation. The cleared land was indicated to have a higher clay content than the native vegetation and believed to be the deciding factor for leaving the native vegetation undisturbed. This inherently introduces a bias in the sampling design as the 'treatment' of farmed vs. not farmed was predetermined and influenced by different factors i.e., Thorndale due to access of native vegetation owing to large deposits of granite rock; Millmerran due to sand content being ill-suited to the growing of crops. Soil texture, including Sand %, Clay % and Silt % are included as condition attributes. However, this is not the principal case study location and is included solely to apply (and validate) the PSMM protocol with separate capacity and condition attribute datasets and was therefore acceptable.

3.5.1 Structural composition and native vegetation

No surveying was conducted onsite at Millmerran, and structural composition is unavailable.

The native vegetation is predominantly open forest and is more densely populated with cacti and acacia species than Thorndale (Figure 3).

Figure 7 Cactus, acacia, and blue gum native growth at Millmerran.

3.5.2 Oral Management History

Oral management history was not included in the scope of this study for this site.

3.5.3 Sampling regime

The two land-use sites are Native Veg and Cleared for the Millmerran location (Table 5). The distribution of sampling points is illustrated in Figure 7. The Thorndale processes were transferred and applied for this second location. Notably, no issues with land saturation occurred here.

Table 6 Sampling points for stratification category by land-use type, and the number of sampling points with respect to property size at Thorndale.

Location	*Site classification*	*Sampling points*	*Area (acres)*
Millmerran	Native Veg Cleared	20 10	68.881 32.884
Total		30	101.765

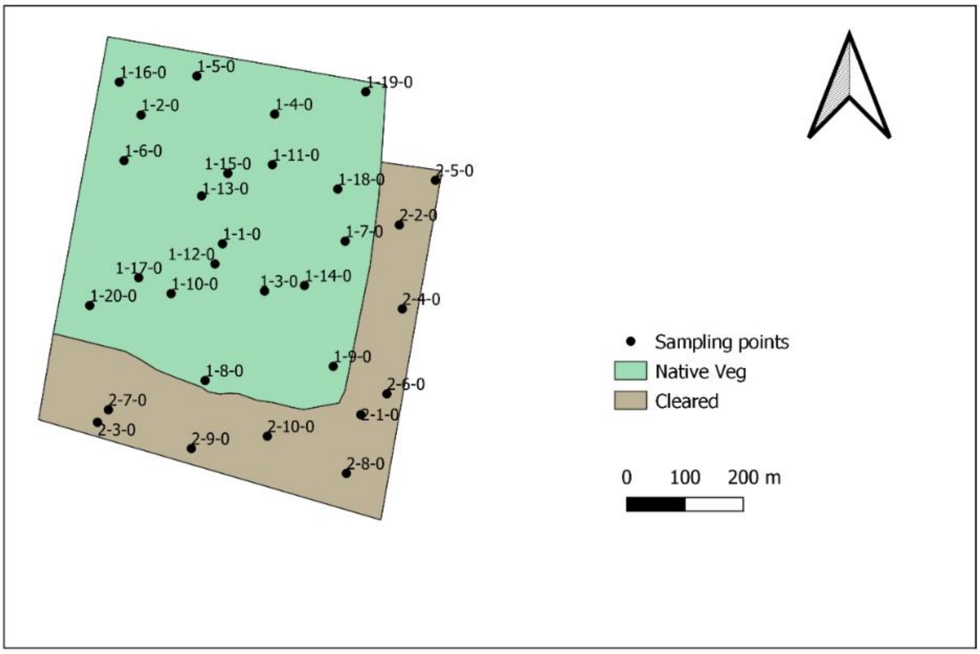


Figure 8 Millmerran property boundary and sampling design for Native Veg and Cleared areas

3.5.4 Sample extraction; Thorndale and Millmerran

Soil sampling in this study comprised using an all-terrain vehicle (ATV) equipped with a mechanical corer (or diesel operated handheld corer) which enters the ground at a near 90-degree angle and extracts a column of soil 44 mm diameter and 1200 mm length (40 mm diameter 1400 mm length). The mechanical corer was used for the Farmed areas, which were cleared at the time of sampling. The thick-growth restricted access in the Native Veg, and a hand-corer with a diameter of 40 was subsequently used. Once extracted, the soil parcel is cut and bagged into smaller samples at 10 cm depth intervals to 1 m (where saturation and soil structure allowed). The target depths were 0-10 cm for topsoil and 40-50 cm for subsoil to capture soil characteristics at the grown at Thorndale. Due to soil texture and partial saturation, the soil could not be universally sampled for depths greater than 50 cm, the subsoil target depth was selected once this was ascertained on site and sampling had commenced. The desired depth for subsoil was 40-60 cm. Due to weather events, sampling in Native Veg occurred several weeks after the Farmed points; any differences inferred from climatic influences however are a potential source of error which are not explored. Sampling for the Farmed areas occurred in early August, and the Native Veg was sampled in mid-September.

3.5.5 Surveying; Thorndale and Millmerran

Surveying of the land was conducted via overland survey technique for Digital Elevation Model (DEM), and spatial sensing conducted for Gamma-Ray Spectroscopy for radionuclides Potassium (K), Uranium (U), Thorium (Th) and Caesium (Cs) in soil, also referred to as radiometrics, and apparent electrical conductivity (ECa). Spatial sensing occurred at depths of 0.25, 0.5, 0.75, and 1.5 m as per the methods of Wong et al. (2010). For radiometric data collection the Medusa MS 2000. DEM used Lecia GS15 received equipment. ECa was collected using DUelEM1H. However, the tree density, rock and leaf litter restricted the GPS signal and corresponding locations to spatial sensing and DEM compromised and a dataset could not be retrieved from the equipment. Therefore, the sporadic survey data could not be used in the final analysis to derive from and interpolate the terrain covariate data. Government sourced DEM and radiometrics were used in lieu, as outlined in the following subsections.

3.6 Data treatment and laboratory analysis; Thorndale and Millmerran

3.6.1 Soils

The selection of in-field and laboratory protocols were informed by the existing suite of tests accessible at the University of Southern Queensland Laboratories and further constrained by scope, project funding and soil condition at the time of sampling. The focus of the data analysis is as follows:

- Soil chemical analysis; pH 1:5 water, pH calcium chloride, electrical conductivity (EC) effective cation exchange capacity (eCEC)
- Soil physical analysis; texture for respective clay %, silt % and sand %

The spring offered challenges to soil sampling from July to September due to the rapid spring recharge, high saturation in nearby soils, and slow drying rates between rainfall events. As a result, bulk density could not be accurately measured and was not included in the physical analyses. At the sampling time, the soils were determined to have high sand and very low clay content throughout the profile and were not capable of aggregate stability measurements. Logically, dispersion was also not included in the analyses.

3.6.1.1 Soil Drying

The soil samples were dried at 40 degrees for 48 hours, ground, and passed through a 2 mm sieve. Larger particles were stored for additional analysis as required.

3.6.1.2 Soil Chemical Analysis

To test for EC and pH, 8 g of soil was agitated with 40 ml of deionised (DI) water. The 1:5 soil to water suspensions were placed in an end-over-end shaker for 60 minutes at a rate of 40 RPM. The samples then settled for 10 minutes and brought to equilibrium before measurements were recorded. pH 1:5 and EC were measured consecutively in the suspension. EC was measured using an Orion Star A112 EC meter calibrated at 2.76 mS/cm, and results are reported in microSiemens per cm (µS/cm) or milliSiemens per meter (mS/m). The suspension pH 1:5 was measured using a Radiometer Analytical Titralab TIMS845 with PHC2001-8 glass body electrode. A second pH protocol (1:5 soil:0.01 M $CaCl_2$) required 2 ml of 0.21 M calcium chloride ($CaCl_2$) to be added to the suspension. This was immediately agitated for 10 seconds, then placed in an end-over-end shaker for 30 minutes at 40 RPM. After a further 10 minutes allowed for equilibration, the Radiometer Analytical Titralab TIMS845 recorded the pH ($CaCl_2$) results. The pH($CaCl_2$) readings (simplified to pH CaCl) are often preferred as it is less affected by soil electrolyte concentration (Minasny et al. 2011).

For cation analysis, 2 g of soil was prepared and added to 2 g of acid-wash sand and treated with 2 ml of 95% ethanol (C_2H_5OH) to leach soluble cations for 60 minutes. The washed soils were prepared with 40 ml of hydrochloric acid (H_3OCl), for 60-180 minutes (time varies with soil type as leaches naturally). The wash solution was collected, and 55 ml ammonium chloride solution (NH_4CL) added. The exchangeable cations. The exchanged cations in the leached extraction were tested offsite using Atomic Absorption Spectroscopy (AAS) (Rayment & Lyons 2010)

To elaborate; the soil sample was tested to find the exchangeable cations per gram soil;

Equation 1 Cation Mass Conversion

$$\mu g\ of\ Cation\ per\ g\ of\ soil = (C * V)/M$$

Where:

$C =$ ppm (mg/L) returned from ICP and corrected for dilution 1:20

$V =$ the volume of the extractant, which is 40 mL in this case

$M =$ mass of the soil sample, which is 8 g in this case

N.B. ug/g is equivalent to mg/kg

Then, the cations Calcium (Ca), Sodium (Na), Potassium (K), Magnesium (Mg) were corrected for atomic weights and valence investigated were corrected to:

Ca-44 cmol(+)/kg;

Na-23 cmol(+)/kg;

K-39 cmol(+)/kg;

Mg cmol(+)/kg.

Equation 2 Cation Atomic Weight Conversion

$$cmol(+)/kg = (Cg * v)/(Ma)$$

Where:

Cg= the gravimetric concentration

v= the valence of the cation

Ma= to the atomic mass of the cation

The effective cation exchange capacity (eCEC) was calculated as the sum of the exchangeable cations;

Equation 3 eCEC Calculation

$$eCEC\ cmol(+)/kg\ =\ Ca\ 44\ cmol(+)/kg\ +\ Na\ 23\ cmol(+)/kg\ +\ K\ 39\ cmol(+)/kg\ +\ Mg\ cmol(+)/kg$$

Exchangeable sodium percentage was calculated by:

Equation 4 ESP Calculation

$$ESP = Na\ 23\ /eCEC$$

3.6.1.3 Soil Physical Analysis

Texture studies were conducted using particle size distribution, precisely the hydrometer method with mechanical sonication (Raine & So 1994). This involved preparing samples of 40 g soil in the suspension of 300 ml DI water. The sulspension was agitated and dispersed via enclosed ultrasound sonication, QSONICA700, at the 90-amplitude program, for 5 minutes. This was poured into a 1L cylinder and DI water was added to the total capacity. A standard-issue hydrometer was inserted in the solution, stirred for 1 minute, allowed to settle for 5 minutes, then the meniscus level was read against the hydrometer scale. The hydrometer reading was repeated at 5 hours. The dispersion rates of the solution produced Clay %, Silt % and Sand % as soil texture properties, as per equation 5. A blank was prepared as DI water solution.

Equation 5 Hydrometer Reading Calculation.

$$1. Clay\ \% + Silt\ \% = Hydrometer\ Reading_{5\ minutes} - Hydrometer\ Reading\ (blank)_{5\ minutes}\ \ /Mass_{soil} x\ 100$$

$$2. Clay\ \% = Hydrometer\ Reading_{5\ hours} - Hydrometer\ Reading\ (blank)_{5\ hours}\ \ /Mass_{soil} x\ 100$$

$$3. \%\ Silt = 1. - 2.$$

$$4. \%\ Sand = 100 - 1.$$

All laboratory methodologies are summarised in Appendix 1.1, with no meaningful deviations from the standards described in the reference text.

3.7 Statistical analyses

All covariate raster maps along with DSMs of the soil chemical and physical properties, were projected to CRS UTM 32755 for Thorndale and CRS UTM 32756 for Millmerran. An important note; DSM protocols and statistical significance calculations were not conducted for the Millmerran property. A brief statistical summary of the Millmerran data was conducted to analyse clay content and allow a discussion of bias.

3.7.1 DEM

Covariate data (including radiometrics) was accessed through Geophysical Archive Data Delivery System (https://portal.ga.gov.au/persona/gadds) for the area of interest (Geoscience Australia 2021) and the reference points determined in the sampling regime (see sections 3.4.3 and 3.5.3). Government-sourced DEM at 25 m resolution was resampled to a 5 m grid using bilinear interpolation in R using the Resample R-Package (version 0.4) (Hesterberg 2015). From the DEM, terrain characteristics of the slope, aspect, terrain roughness index (TRI), topographic position index (TPI), flow direction (FlowDir) were derived using the Raster R-Package (version 3.5-2) (Hijmans 2021). The terrain characteristics were computed to 8 neighbours as in Horn (1981), and calculated in degrees. See Appendix 1.2 for full definitions of terrain characteristics. The results were coupled with Gamma-Ray Spectrometry data and NDVI to form the principal environmental covariates for Thorndale. The Gamma-Ray Spectrometry also known as radiometrics, are surface-based (0-30 cm) spectrometer readings of the natural electromagnetic radiation emitted at varying rates according to the morphology of the rock and soil (Hydon 2021). The radiometrics, characterized by the peaks in the energy spectrum, are potassium (K), thorium (Th) and uranium (U), and the number of gamma-ray counts across the whole spectrum referred to as the total count (TC). The environmental covariate data were also resampled using bilinear interpolation to 5 m grids and mapped to the property boundary.

3.7.2 DSM

For DSM, the spatial dependence of the condition attributes (except for NDVI as data was sourced in raster format) was calculated using variogram functions. An empirical variogram model was produced from the Automap R-Package (version 1.0-14) (Hiemstra 2013), and either Gaussian, spherical or exponential models were determined as fit for DSM input. The best fit was relative to the magnitude of the range and parameters of the nugget, sill, and nugget to sill ratio.

The outputs were used in ordinary kriging to create raster surfaces in DSM at the property and depth level using a series of R-packages and graphics plugins (gstat 2.0-8 R-Package; ggspatial version 1.1-5 R-Package) (Pebesma 2004; Dunnington 2021). The Shapiro-Wilke normality test informed data distribution skewness (e1071 version 1.7-9 R-Package) (Meyer et al. 2021) for transformation data via log or square root, or retained the original value. All values greater than 75th percentile value plus 1.5 inter-quartile range (IQR) or less than 25th percentile value minus 1.5 IQR are targeted as outliers and removed (outlier version 0.14 R-Package). A validation technique was not used, and all data was included in the calibration of the kriging models, primarily due to the low frequency of data sampling points.

At this point, the soil chemical and physical properties and the environmental covariates were either classified as condition attributes or capacity attributes. The Soil Security Framework guided this classification, specifically if the soil property can be easily influenced by anthropogenic activity (condition) and the properties' inferred role in soil formation (capacity). Correlations coefficient between soil properties and environmental covariates were calculated using the Pearson method (corrr version 0.4.3 R-Package) (Jackson & Cimentada 2020). Further correlations for intra-soil properties at the target depths and across both Native Veg and Farmed Land were conducted for an entire property perspective of how environmental features affect condition attributes.

3.7.3 PSMM

A propensity score matching model (PSMM) (Caliendo & Kopeinig 2008) was used to determine which single data point in Native Veg is most similar to a single Farm point, according to capacity attributes (texture, environmental covariates). The probability analysis between covariates and soil attributes were conducted in R using MatchIt (version 4.3.2 R-Package) (Ho 2011). PSMM assesses the conditional probability of the treatment (being farmed or remaining as remnant veg) given the observed covariates. As in previous statistical analysis, the covariates inputs are based on capacity attributes. These had some collinearity (John et al. 2021) and recognised the complex role of the environment in soil formation. The attributes selected are Clay %, Silt % and Sand % for soil texture. The skewness of each dataset was calculated, and outliers were removed. The decision was made to include untransformed original data rather than applying a root square mean or adding the highest positive value in the data +1, to illustrate better the direction change in the kriged DSM i.e. negative value represents a negative effect to the soil. As a result, the original dataset was used for variogram modelling irrespective of skew (though with outliers removed) and the kriging method used, as in the earlier analysis of soil attributes. The input data was rounded to 2 decimals places to reduce obscurity in the dataset and allow for better matching. Due to model limitations, no single soil-forming factor could be prioritised over other attributes; all input data was applied and weighted equally in the model. Surface radiometric concentrations of K, U and Th were included. The preference was to give a higher weighting to Th due to being the radiometric closely related to clay mineralogy, e.g. smectite and to provide insight into texture at the property however this is a limitation of the model. The covariates selected for model inclusion were elevation, slope and aspect and were also rounded to 2 decimal places. Of the terrain characteristics TRI, TPI and FlowDir were omitted due to insufficient data across the property and thus were unsuitable for the model and the model would have applied an unnecessarily high significance to these factors. The PSMM used a binary code for treated/untreated and an ‘average treatment effect in the treated’

(ATT) estimand argument, selecting control units (Native Veg) to be matched with the treated units (Farmed). A probit function was used defined by the Caliper approach, equal to 0.2 of the standard deviation of the probit of the propensity score (Austin 2011), for Thorndale, and 0.25 of the standard deviation for Millmerran.

The best-fit model was determined to be Replacement, which allowed more than one controlled unit (Native Veg point) to match multiple treated (Farmed Land) units. The alternate model facilitates a one-to-one pairing in the order of the observations/units listed in the dataset and will generally increase bias. The PSMM was replicated at Millmerran; however, all other statistical analysis was not applied to the Millmerran dataset. Its purpose for inclusion is to test and validate the pairing effect only.

Once paired, DSM of the Farmed points were produced to demonstrate differences in the condition attributes of pH 1:5, pH CaCl, EC, eCEC, ESP at these points, showing where on the property and to what degree any negative impact of management has occurred. NDVI attribute was included, as the expected outcomes were considered a control result as the vegetative index is inherently lower in cleared or farmed areas.

3.7.4 Statistical Significance

Statistical significance was calculated to a 95% confidence interval (P-value <0.05) using the R Stats package (R Core Team 2021). A two-sided Welch T-test was applied for each soil condition to compare the mean value between Native Veg and Farmed at depths 0-10 cm and 40-50 cm. The null hypothesis is described in the below equation and states there is no treatment effect. The mathematical expression of the research hypothesis statement follows this for completeness.

Equation 6 Null Hypothesis for T Test Calculations

$$H_0\text{: } \bar{x}\ Farmed = \bar{x}\ Native\ Veg$$

Where:

$\bar{x}$ = is the mean of the dataset relating to attribute and depth of interest

Equation 7 Research

$$H_1\text{: } \bar{x}Farm \neq \bar{x}Native\ Veg$$

The individual null hypothesis statements were actioned for all condition attributes and at depth 0 and 40 cm. This had an accumulative effect to the overall case study (research) hypothesis, as these soil chemical properties define and determine any negative changes in the soil condition and thus degradation. The T-Test assumed non-equal variances between the treatment groups, independent two sample sets, and confidence level at 95%. This was also replicated for the condition change datasets using the Farmed points with the paired Native Veg as the two treatment groups. Statistical summaries were calculated for soil physical and chemical properties using R-Package dplyr (version 1.0.8) (Wickham 2022).

Chapter 4

4 Results

4.1 Regional Terron Assessment

Eighty-eight sites were found to have a consistent dataset for the soil properties of pH, EC, Chloride and Clay % (Figure 9). Figure 9 illustrates a clustering of the soil sites around the townships of Stanthorpe and Warwick, with large expanses unsurveyed. Experimental variograms were applied to all soil properties in the dataset however for the purpose of this discussion, a single soil attribute that of pH 1:5, was selected for discussion, as representative of spatial variability of the dataset. The plotted experimental variogram was based on the spherical model when collated for interpolation. Figure 10 describes a nugget to sill ratio of 0.491 and a moderate spatial dependence. The range was extreme, indicating that the physical distance at which the data points (sampling sites) could not be spatially correlated was 4506.1 m. Despite the nugget to sill ratio, the range and the lack of observation sill on the experimental variogram justified the poor fit for the desired ordinary kriging output for DSM (Cambardella et al. 1994). The discontinuity of the variogram indicates the nugget effect, data sparsity and lack of autocorrelation (Kerry & Oliver 2008). Due mainly to the limited scope for model variation, and restrictive honours timeline, the decision was made to continue the intended analysis and illustrate the high nugget effect. The variogram was subsequently used to calculate ordinary kriging for the attribute of pH 1:5, for the Southern Downs LGA (Figure 11) to illustrate the nugget effect for regionalized variables. In Figure 11 attribute variability is restricted to the aforementioned clusters causing a ‘pockmarked’ visual effect and a mean value of approximately 6.6 pH units depicted for majority of the region.

A map was produced using the Australian Soil Classification data of the 369 sites (Figure 12). In Figure 12, ASC is used to describe the range of soil types across the region and is presented as point data. This demonstrates a trend of vertosol soils neighbouring the Northern LGA boundary, with tenosols and sodosol more frequent in the Southern areas near Thorndale property and the Stanthorpe township. The spatial arrangement of soil formations reflects the Southerly shift of granitic and often shallow bedrock, characteristic of the region, became more frequent. Due to insufficient data, no terrons were produced for the Southern Downs LGA.

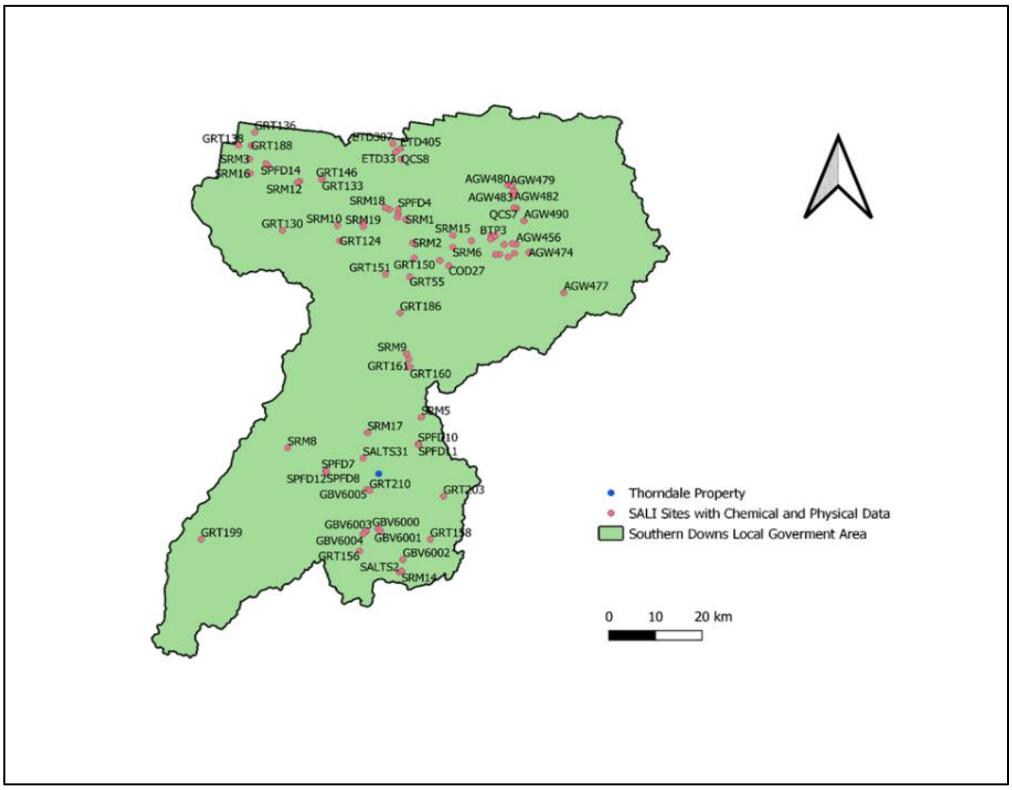


Figure 9 Suitable soil survey sites on the Southern Downs LGA with consistent soil chemical data available, represented as SALI project codes

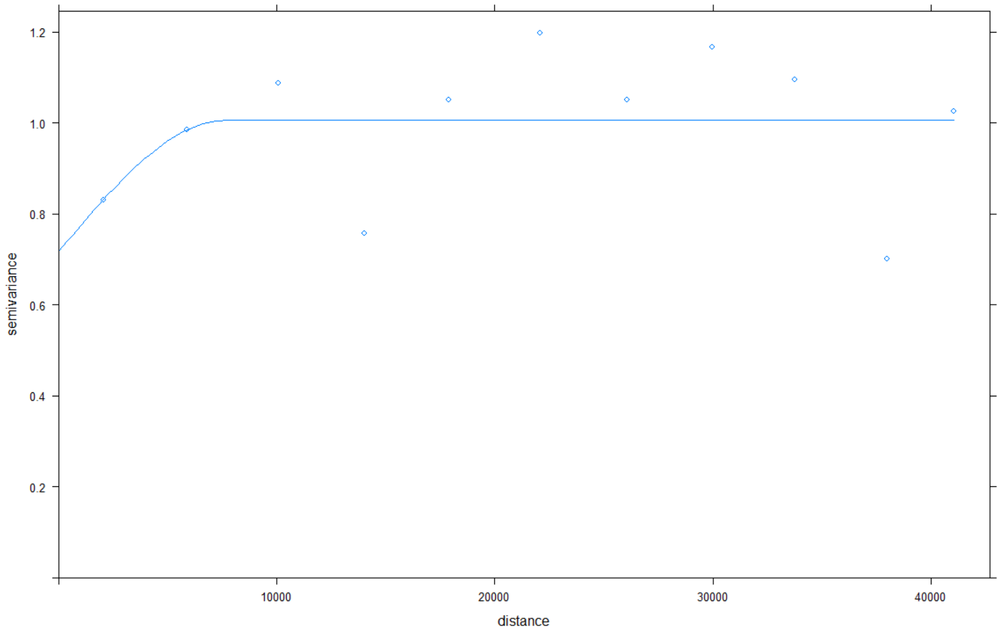


Figure 10 Experimental variogram and autofit, spherical variogram model for topsoil pH, Southern Downs LGA

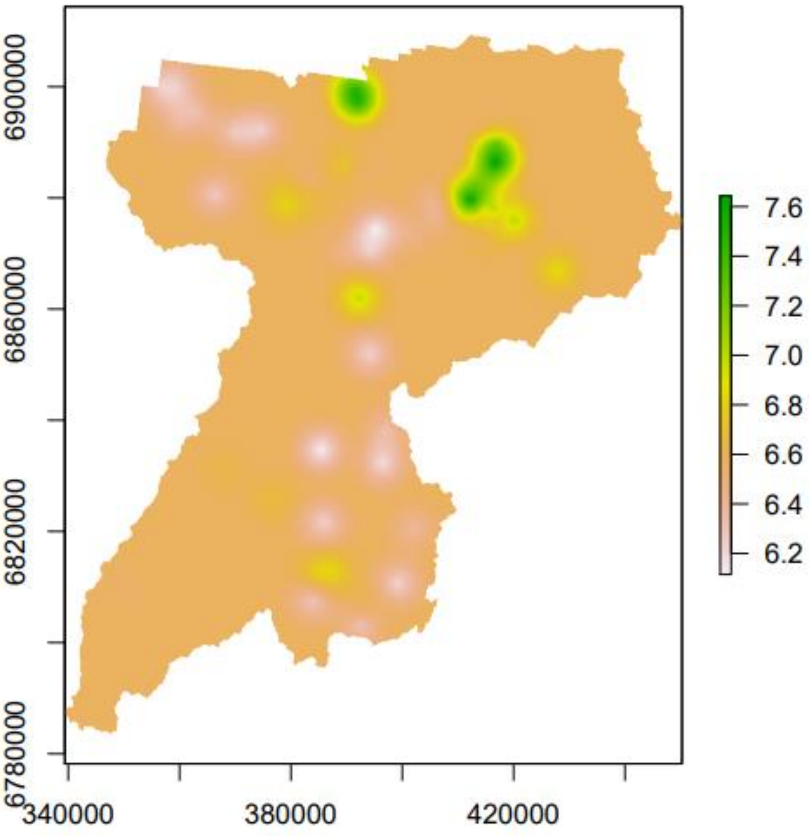


Figure 11 Kriged Map of Topsoil pH 1:5 Depth 0-10 cm, Southern Downs LGA

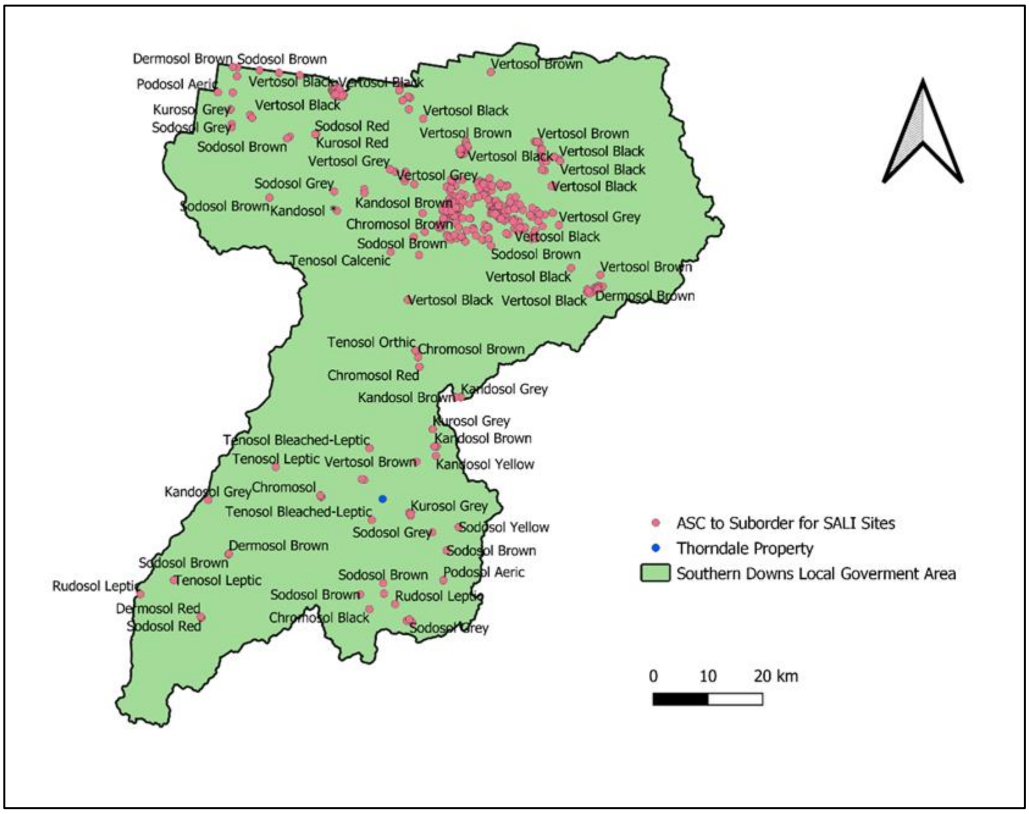


Figure 12 ASC descriptions of SALI site soils, to suborder at Southern Downs LGA

4.2 Farm Scale Assessment of Soil Condition and Capability

4.2.1 Defining the Thorndale Property: Variability in Capacity Attributes

4.2.1.1 DEM and Terrain Characteristics

The DEM of the Thorndale property (Figure 12) depicted an even elevation across the property (878 to 880 m) except for the Western quadrant where the property dam is located. The DEM appears to define the spatial trends of the other covariates, with relatively narrow ranges and variability (Figure 13). Notably, the FlowDir returned a higher flow direction value near the Eastern border and the greatest drop in elevation here. The oral history captured from the landowner described an underwater stream that collects heavily here and flows from this direction to the dam. This was highlighted in the correlation data, presented in Table 6; Clay % at depth 40 had a strong association with FlowDir (r^2=0.63) and suggested the presence of alluvial clay. This was supported by more significant levels of Mg at Farm 40 as an exchangeable cation

(r^2=0.93) and Farm 40 eCEC (r^2=0.77) when correlated against FlowDir. A strong correlation for Farm 40 pH and Aspect was also evident. Intra-soil attribute correlation analyses were not included in the scope, as relationships between soil physical and chemical properties (i.e. eCEC and Clay) are well established and did not offer unique insights into this study.

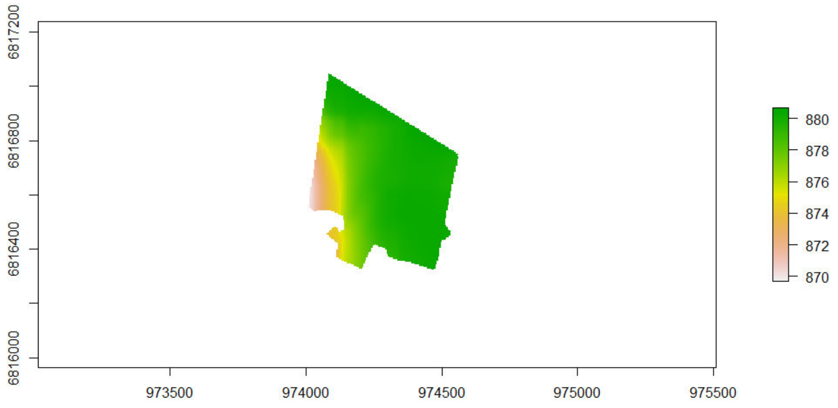


Figure 13 Digital Elevation Model Raster Map, Thorndale

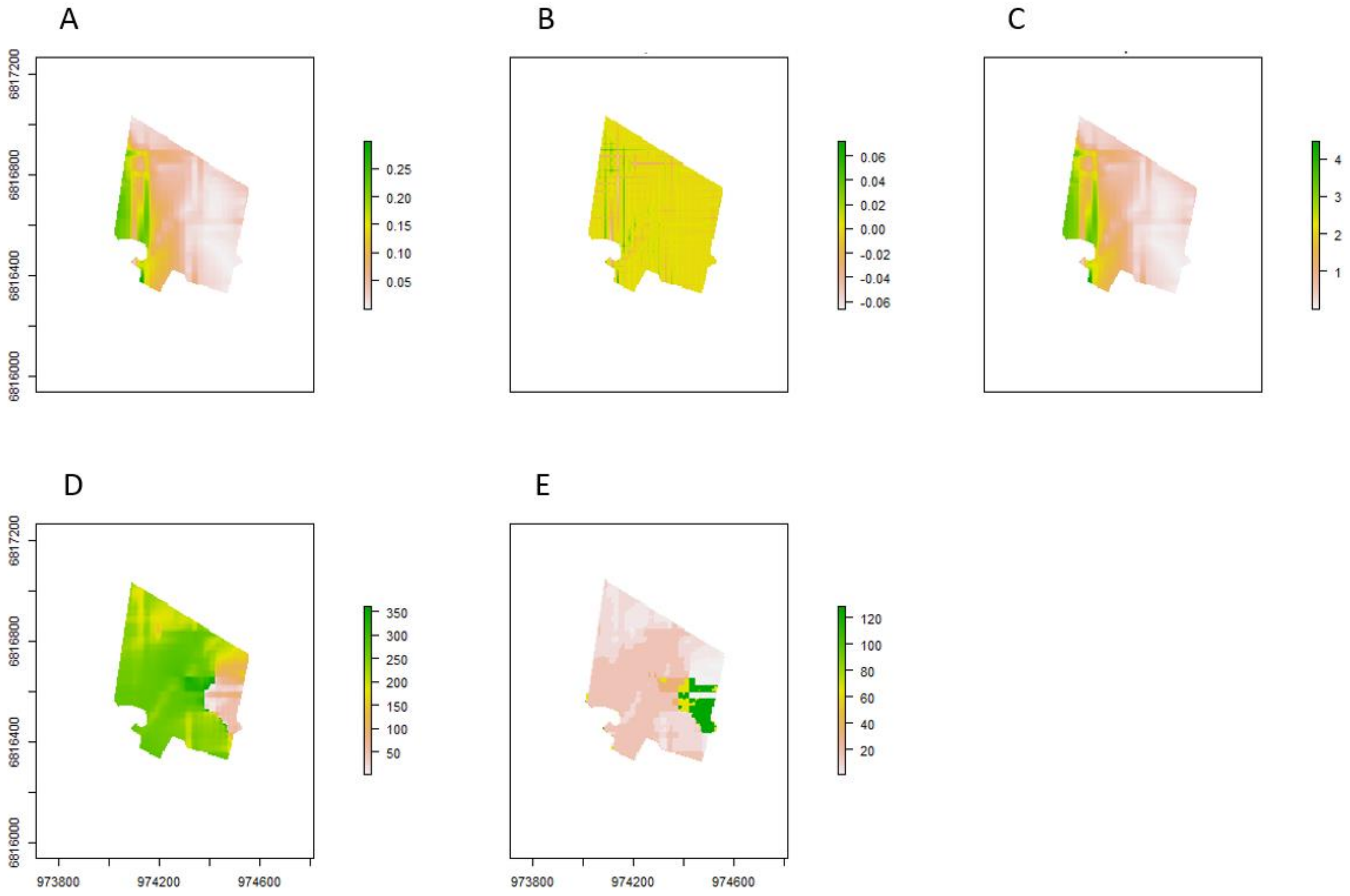


Figure 14 Terrain Characteristics Raster Maps, Thorndale A: TRI; B: TPI; C: Slope; D: Aspect; E: FlowDir

Table 7 Correlation Coefficient Table for Soil Attributes per Site and Depth, Thorndale. Values highlighted red had a weak association (+0.2 to +0.4; -0.2 to -0.4), amber had a moderate association (+0.4 to +0.6; -0.4 to -0.6), green values had a strong association (+0.6 to +0.8, -0.6 to -0.8) between variables. Very weak or no association (-0.2 to +0.2) was not highlighted (LaMorte 2021).

Property	***Environmental Covariate R^2 Values***										
Soil Attribute & Depth	*TRI*	*TPI*	*Slope*	*Aspect*	*FlowDir*	*DEM*	*TC*	*K*	*Th*	*U*	*NDVI*
Farm 0 EC	0.194	-0.044	0.197	0.092	0.439	-0.201	-0.054	-0.263	-0.065	0.091	-0.423
Farm 0 pH 1:5	0.228	-0.079	0.224	0.454	0.232	-0.088	-0.102	-0.277	-0.129	0.144	-0.196
Farm 0 pH CaCl	0.201	0.045	0.201	0.379	0.294	-0.194	-0.088	-0.285	-0.11	0.131	-0.323
Farm 0 Clay	-0.51	-0.013	-0.507	-0.268	-0.041	0.322	-0.132	0.358	-0.105	-0.329	-0.015
Farm 0 Silt	0.133	-0.051	0.123	0.178	-0.017	-0.221	-0.277	0.185	-0.283	-0.208	-0.224
Farm 0 Sand	0.082	0.051	0.09	-0.055	0.032	0.072	0.304	-0.31	0.298	0.319	0.209
Farm 40 EC	-0.477	0.028	-0.474	-0.422	0.059	0.369	0.146	0.192	0.181	-0.136	0.281
Farm 40 pH 1:5	0.442	0.218	0.434	0.746	-0.358	-0.328	-0.024	-0.25	-0.066	0.276	-0.476
Farm 40 pH CaCl	0.261	0.187	0.252	0.563	-0.295	-0.171	-0.083	-0.074	-0.115	0.131	-0.56
Farm 40 Clay	-0.449	0.036	-0.444	-0.658	0.633	0.244	-0.225	0.267	-0.187	-0.436	0.24
Farm 40 Silt	0.276	-0.099	0.28	0.27	0.019	-0.233	-0.366	0.05	-0.373	-0.228	0.018
Farm 40 Sand	0.196	0.031	0.189	0.369	-0.523	-0.056	0.404	-0.246	0.377	0.49	-0.205
Veg 0 EC	0.378	-0.304	0.362	-0.043	0	-0.259	-0.021	-0.037	-0.012	-0.053	0.176
Veg 0 pH 1:5	0.197	0.009	0.202	0.014	-0.016	-0.129	-0.331	0.14	-0.339	-0.177	-0.418
Veg 0 pH CaCl	0.328	-0.121	0.33	-0.033	0.07	-0.289	-0.397	0.129	-0.408	-0.197	-0.326
Veg 0 Clay %	0.513	0.297	0.502	0.119	-0.175	-0.36	0.166	-0.155	0.139	0.307	-0.218
Veg 0 Silt %	-0.119	-0.081	-0.122	-0.347	0.526	-0.002	-0.201	0.357	-0.193	-0.274	-0.071
Veg 0 Sand %	-0.375	-0.212	-0.365	0.064	-0.1	0.303	-0.045	-0.038	-0.026	-0.129	0.216
Veg 40 EC	-0.075	-0.153	-0.087	-0.247	0.443	0.232	-0.436	0.507	-0.417	-0.518	-0.241
Veg 40 pH 1:5	0.128	0.08	0.136	-0.024	-0.043	-0.138	-0.34	0.125	-0.363	-0.094	-0.421
Veg 40 pH CaCl	0.22	-0.005	0.224	-0.11	0.122	-0.179	-0.368	0.17	-0.386	-0.151	-0.323
Veg 40 Clay	-0.031	-0.247	-0.033	0.119	-0.021	-0.131	-0.136	0.025	-0.124	-0.157	0.01
Veg 40 Silt	-0.098	-0.059	-0.094	0.238	-0.258	0.024	-0.046	0.255	-0.04	-0.14	0.366
Veg 40 Sand	0.079	0.204	0.079	-0.223	0.168	0.075	0.121	-0.169	0.109	0.19	-0.224
Farm 0 eCEC	0.09	0.067	0.094	0.14	0.206	-0.072	-0.08	-0.007	-0.092	0.019	-0.394
Farm 40 eCEC	-0.323	-0.223	-0.32	-0.378	0.77	0.175	-0.178	0.027	-0.157	-0.249	0.345
Farm 0 ESP	-0.421	0.022	-0.425	-0.345	0.279	0.433	-0.281	0.492	-0.258	-0.452	0.005
Farm 40 ESP	-0.112	-0.216	-0.108	-0.085	0.032	0.086	0.143	-0.002	0.137	0.134	0.154
Farm 0 Ca	0.212	0.038	0.218	0.243	0.174	-0.203	-0.031	-0.153	-0.052	0.137	-0.412
Farm 40 Ca	-0.144	-0.201	-0.144	-0.037	0.391	0.016	-0.192	-0.042	-0.183	-0.176	0.284
Farm 0 Na	-0.332	0.037	-0.337	-0.266	0.395	0.357	-0.333	0.454	-0.316	-0.438	-0.122
Farm 40 Na	-0.232	-0.236	-0.227	-0.286	0.399	0.154	0.044	0.026	0.049	-0.003	0.239
Farm 0 K	0.301	-0.125	0.307	0.052	-0.043	-0.11	0.203	-0.25	0.189	0.281	-0.187
Farm 40 K	-0.063	0.017	-0.071	0.124	0.107	0.03	-0.214	0.138	-0.223	-0.141	-0.267
Farm 0 Mg	-0.251	0.156	-0.253	-0.132	0.07	0.24	-0.099	0.32	-0.085	-0.232	-0.118
Farm 40 Mg	-0.387	-0.168	-0.383	-0.578	0.926	0.257	-0.147	0.066	-0.118	-0.282	0.336
Veg 0 eCEC	-0.428	-0.416	-0.429	-0.072	0.087	0.331	-0.336	0.197	-0.3	-0.454	0.298
Veg 40 eCEC	0.232	-0.218	0.219	0.109	-0.099	-0.137	-0.278	0.092	-0.277	-0.198	0.051
Veg 0 ESP	-0.466	-0.188	-0.462	0.179	-0.127	0.363	-0.246	0.333	-0.236	-0.296	-0.187
Veg 40 ESP	-0.34	0.09	-0.338	0.124	-0.37	0.343	0.463	-0.431	0.481	0.302	0.456
Veg 0 Ca	-0.439	-0.405	-0.439	-0.073	0.095	0.324	-0.328	0.191	-0.293	-0.442	0.302
Veg 40 Ca	0.191	-0.167	0.182	0.058	-0.038	-0.093	-0.299	0.135	-0.303	-0.193	-0.094
Veg 0 Na	-0.583	-0.4	-0.583	0.168	-0.165	0.467	-0.311	0.436	-0.288	-0.439	-0.015
Veg 40 Na	-0.209	-0.039	-0.214	0.165	-0.384	0.203	0.464	-0.509	0.497	0.237	0.698
Veg 0 K	0.433	0.132	0.419	-0.048	-0.031	-0.099	-0.125	-0.072	-0.12	-0.073	-0.253

Veg 40 K	0.478	0.02	0.471	0.083	0.035	-0.348	-0.301	0.238	-0.334	-0.051	-0.26
Veg 0 Mg	-0.046	-0.383	-0.062	-0.066	-0.018	0.241	-0.235	0.123	-0.203	-0.353	0.188
Veg 40 Mg	0.204	-0.258	0.19	0.134	-0.106	-0.2	-0.161	0.04	-0.148	-0.186	0.296

4.2.1.2 Soil Texture

The high sand content was expected due to the shallow granite rock formations observed at the landscape level (Figure 4). The trends of soil texture are demonstrated in the statistical summaries of chemical and physical properties of soil attributes in Tables 7 to 10.

Clay content (represented by the Clay % of the soil sampled) was low for the entire property, ranging from a minimum of 0 to 18.75%, though typically below 11.88%, and a content of 0-2 % was recorded most frequently. Clay was higher in Native Veg than Farmed; at 2.87% and 3.20% for Native Veg 0 and 40 cm depth, respectively, compared with 1.15% and 2.86% for the Farmed counterparts. Clay % also increased with depth across both sampling sites. The dominant soil texture for the property was sand; the sand % was far greater than the clay and silt (individually and combined) at each depth and sampling site. The mean sand % for Farmed areas was 96.95% at 0 cm, and 94.84% at 40 cm depth. This corresponded with Native Veg at 94.64% at 0 cm, and 93.85% at 40 cm depth. The silt content reflected the trend of the clay content in all areas, though the clay was a focus for discussion due to its charge properties.

Table 8 Statistical Summary of Chemical and Physical Properties of Soil Attributes; Farmed Area Depth 0.

Farmed 0								
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*	*Skew Outliers Removed*	*SW Test P value*
pH 1:5	4.9	5.8	6.1	6.004	6.225	6.5	-1.127	0.024
EC µ/cm	13.900	24.890	39.310	37.860	47.420	62.670	0.124	0.227
pH CaCl	3.8	4.675	5.1	5.013	5.4	5.8	-0.3487	0.3403
Clay %	0.000	0.625	1.250	1.146	1.406	2.500	-0.066	0.036
Silt %	0.000	1.250	1.250	1.901	2.031	8.750	0.378	0.000
Sand %	90.000	96.250	97.500	96.950	98.120	98.750	-0.342	0.000
eCEC cmol(+)/kg	2.656	3.572	4.319	4.410	5.090	6.746	0.310	0.453
ESP	0.287	0.698	2.618	3.423	5.367	11.021	0.542	0.012
NDVI	0.212	0.236	0.276	0.285	0.318	0.408	0.526	0.112
Ca cmol(+)/kg	1.382	2.251	2.643	2.889	3.649	5.010	0.233	0.483
Na cmol(+)/kg	0.009	0.030	0.161	0.155	0.190	0.466	0.920	0.001
K cmol(+)/kg	0.104	0.130	0.156	0.173	0.195	0.327	1.191	0.002
Mg cmol(+)/kg	0.803	0.977	1.167	1.193	1.385	1.750	0.167	0.417

Table 9 Statistical Summary of Chemical and Physical Properties of Soil Attributes; Farmed Area Depth 40. NDVI data not included, as sensed at the surface level.

Farmed 40								
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*	*Skew Outliers Removed*	*SW Test P-Value*
pH 1:5	5.1	5.9	6.15	6.1	6.425	6.7	-0.426	0.125
EC µ/cm	6.674	12.248	14.930	16.867	18.383	53.250	0.533	0.000
pH CaCl	3.7	4.4	4.95	4.938	5.525	6.2	-0.046	0.644
Clay %	0.000	1.250	2.188	2.786	2.812	11.875	0.999	0.000
Silt %	0.000	1.250	1.875	2.370	3.750	10.000	0.329	0.000
Sand %	86.250	93.750	95.000	94.840	97.500	99.380	-0.432	0.095
eCEC cmol(+)/kg	1.430	2.027	2.259	2.486	2.575	5.785	1.101	0.000
ESP	1.430	2.721	5.600	6.317	7.969	18.022	0.958	0.009
Ca cmol(+)/kg	0.545	0.928	1.045	1.194	1.312	2.360	0.823	0.029
Na cmol(+)/kg	0.010	0.038	0.168	0.159	0.200	0.430	0.793	0.006
K cmol(+)/kg	0.058	0.078	0.102	0.110	0.124	0.262	0.858	0.002
Mg cmol(+)/kg	0.683	0.788	0.958	1.027	1.021	3.296	1.023	0.000

Table 10 Statistical Summary of Chemical and Physical Properties of Soil Attributes; Native Veg Depth 0.

Native Veg 0								
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*	*Skew Outliers Removed*	*SW Test P-Value*
pH 1:5	4.7	5.3	5.45	5.504	5.8	6.4	-0.278	0.829
EC µ/cm	14.940	23.100	25.000	27.100	29.520	49.960	0.553	0.023
pH CaCl	3.7	4.1	4.4	4.396	4.6	5.2	0.301	0.300
Clay %	0.000	1.094	2.188	2.865	3.125	18.750	0.270	0.000
Silt %	0.000	1.250	2.500	2.500	2.500	9.375	-0.295	0.000
Sand %	78.120	93.590	96.250	94.640	97.500	98.750	-0.995	0.000
eCEC cmol(+)/kg	1.380	3.536	4.495	4.837	5.530	10.148	0.791	0.044
ESP	0.731	2.009	3.375	3.789	5.139	11.394	0.929	0.004
NDVI	0.352	0.404	0.430	0.435	0.474	0.501	-0.016	0.444
Ca cmol(+)/kg	0.010	1.887	2.581	2.942	3.558	7.132	0.737	0.094
Na cmol(+)/kg	0.030	0.148	0.165	0.164	0.211	0.392	-0.491	0.031
K cmol(+)/kg	0.136	0.164	0.194	0.218	0.246	0.427	0.983	0.003
Mg cmol(+)/kg	1.040	1.300	1.478	1.514	1.596	2.423	0.561	0.064

Table 11 Statistical Summary of Chemical and Physical Properties of Soil Attributes; Native Veg Depth 40. NDVI data not included, as sensed at the surface level.

Native Veg 40								
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*	*Skew Outliers Removed*	*SW Test P-Value*
pH	4.8	5.175	5.45	5.501	5.647	7.1	0.109	0.026
EC µ/cm	9.246	14.165	16.775	16.561	19.383	23.090	0.147	0.700
pH CaCl	3.7	3.9	4	4.196	4.375	5.6	0.647	0.003
Clay %	0.000	1.719	2.812	3.203	4.062	7.500	0.512	0.416
Silt %	1.250	1.875	2.500	2.943	3.281	7.500	0.927	0.001
Sand %	86.250	92.500	93.750	93.850	95.780	97.500	-0.154	0.128
eCEC cmol(+)/kg	0.941	2.021	2.489	2.776	3.007	7.282	0.898	0.002
ESP	0.583	3.375	6.989	9.087	16.750	24.444	0.533	0.017
Ca cmol(+)/kg	0.199	0.711	0.917	1.333	1.409	5.308	1.543	0.000
Na cmol(+)/kg	0.022	0.071	0.171	0.206	0.330	0.460	0.507	0.020
K cmol(+)/kg	0.053	0.093	0.105	0.141	0.160	0.485	0.878	0.000
Mg cmol(+)/kg	0.326	0.847	1.104	1.096	1.298	2.010	-0.157	0.957

4.2.2 Defining the Thorndale Property: Soil condition as measured in chemical analysis

The chemical analysis was used in the production of DSM to demonstrate spatial variability for each attribute across Farmed areas and Native Veg. The pH 1:5 and pH CaCl at depth 40 cm (Figures 15) was markedly lower at Paddock 5, supported by the loss of basic cations down the soil profile. This trend of low cation concentrations was observed throughout the property. In Figure 16, Ca, Na, K and Mg appear at low levels, suggesting nutrient loss. The full suite of soil attribute DSMs is presented as Appendix 1.5. There was a breadth of spatial dependence across the soil attributes, and consequently, the predicted values' reliability varied. This was expected for the sampling size and geographical range. DMS was not intended as a precise diagnostic tool at this point of the analysis, rather, used to illustrate spatial trends for changes in the soil condition.

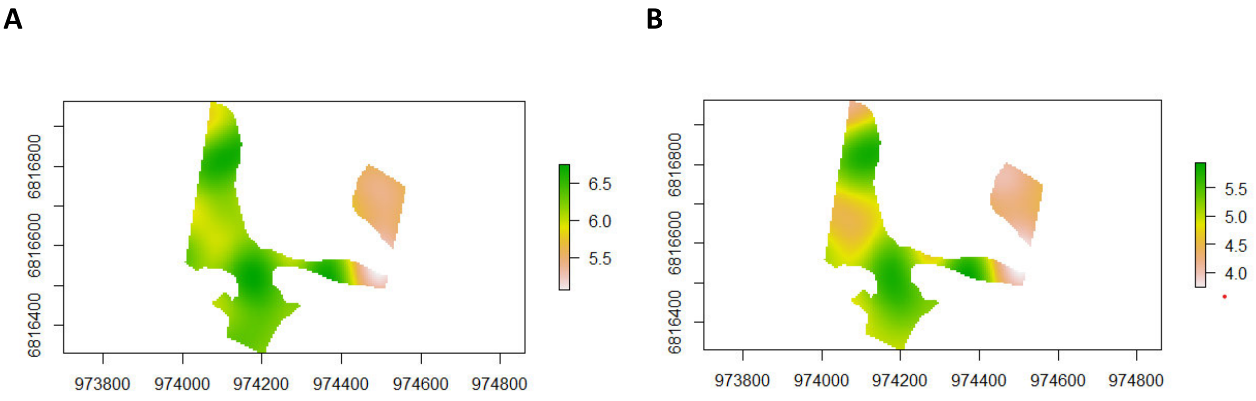


Figure 15 Spatial Variability of pH at Depth 40 cm, for Farmed areas. A: pH 1:5, B: pH CaCl

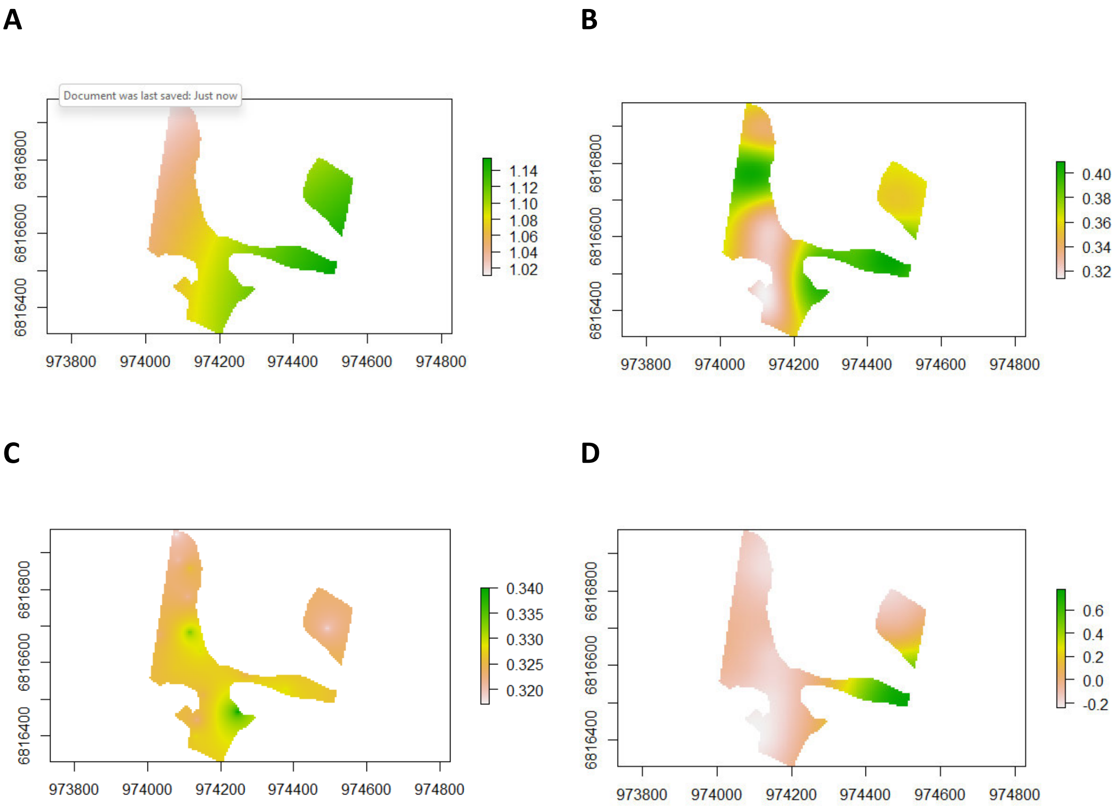


Figure 16 Series of Cation DSM for Spatial Variability at Depth 40 cm, for Farmed areas at Thorndale.

A: Sqrt Ca, B: Sqrt Na, C: Sqrt K, D: Log Mg

There were statistically significant differences for many of the soil condition attributes between the Native Veg soils and Farmed area soils. The attributes which had significantly different means were determined to have experienced a change in condition; the direction of the change (i.e., more or less positive) varied with the particular chemical property. This was best articulated by P-Values presented in Table 11, with other supporting statistical data summarised in Tables 7 to 10. Firstly, a mean pH at depth 0 for Farmed areas at 6.00 vs. the mean of Native Veg of 5.50 was statistically significant at $P < 0.001$. At depth 40, the P value for difference of pH was statistically significant at $P < 0.001$ This trend was evident in the alternate pH measurement; pH CaCl had $P < 0.001$ at each depth. Overall, the Farmed soils were less acidic than the Native Veg soils. A few results of interest were the consistently higher cation concentrations in the Native Veg, as per the mean values of Ca, Na, K and Mg at each depth. However, this was a relatively narrow difference and unlikely to have practical implications. The target levels of cations vary with soil type and function, however in a general horticultural context the cation levels were low for all, exception Mg approaches a moderate level. This was an interesting result given EC at depth 0; the Farmed area mean of 37.86 indicated a higher salt concentration than the Native Veg at 27.1, with statistical significance at P=0.0024. EC is the soils' ability to conduct electrical currents through the negatively charged particles (clay, silt etc) and attract positively charged cations. It is typically reflective of soils salinity and nutrient levels and when coupled with eCEC (theoretically equal to CEC) is indicative of soils' fertility capacity. The eCEC across the property is low, the sandy soil was expected to produce a CEC <10 cmol(+)/kg , mean of the Native Veg and the Farmed area did not exceed 5 cmol(+)/kg. The difference between the Farmed and Native Veg soils was statistically significant only at the 40 cm depth. Considering the Clay % was greater for Native Veg at depth 0 (see section 4.2.1.2; Tables 7 and 9), this is counterintuitive of the typical result for CEC being an indicator of clay content (Singer & Munns 2002), and requires further on-site investigation.

As expected, the NDVI results were higher in the Native Veg, with a mean value of 0.45 vs the Farmed area mean value of 0.29, and the P<0.001 differentiating the two sampling sites supports this. Furthermore, there was also a strong correlation between Native Veg Na at 40 cm and NDVI, which was supported by a moderate correlation of ESP and NDVI for the same soils (Table 6). This result suggests the vegetation had an influential role in determining where and how this cation accumulated at the subsurface level. Significantly, the ESP was higher in the Native Vegetation soils at this level. The range of the ESP across the property was vast. Any interpretation of the mean ESP results for topsoils as non-sodic across the property would be an oversimplification of a complex soil mechanism. Soils in the Farmed area ranged from 0.28 to 11.02, and 1.43 to 18.02 (though Q3 is 7.70, revealing high outliers) for 0 and 40 cm depths. For Native Veg, the respective ranges were 0.73 to 11.39, and 0.58 to 24.44 (Q3 is 16.75).

Table 12 The Effects of PSMM Pairing Compared to General Site Data. Highlighted values indicate a significant value. Null hypothesis $H_0\colon \bar{x}\ Farmed = \bar{x}\ Native\ Veg$ (x is the attribute and depth of interest).

Conditional Attribute & Depth	*Farmed Mean*	*Native Veg Mean*	*Mean difference before PSMM pairing*	*Welch T Test P Value*	*Mean difference after PSMM pairing*	*Welch T Test P Value*
pH 1:5 0	6.00	5.50	0.50	<0.001	-0.16	0.210
pH 1:5 40	6.10	5.50	0.60	<0.001	0.09	0.436
pH CaCl 0	5.01	4.40	0.62	<0.001	0.02	0.891
pH CaCl 40	4.94	4.20	0.74	<0.001	0.22	0.171
EC 0	37.86	27.10	10.76	0.002	12.59	<0.001
EC 40	17.52	16.56	0.96	0.883	-1.29	0.295
ESP 0	3.42	3.79	-0.37	0.671	0.53	0.438
ESP 40	6.32	9.09	-2.77	0.095	3.77	0.012
ECEC 0	4.41	4.84	-0.43	0.765	-0.47	0.086
ECEC 40	2.49	2.78	-0.29	0.437	-1.13	<0.001
NDVI	0.28	0.43	-0.15	<0.001	-0.09	<0.001
Ca 0	2.89	2.94	-0.05	0.501	0.23	0.362
Ca 40	1.19	1.33	-0.14	0.594	-1.01	<0.001
Na 0	0.16	0.16	-0.01	0.689	0.01	0.639
Na 40	0.16	0.21	-0.05	0.254	0.10	0.016
K 0	0.17	0.22	-0.05	0.043	-0.16	<0.001
K 40	0.11	0.14	-0.03	0.212	-0.11	<0.001
Mg 0	1.39	1.51	-0.13	<0.001	-0.56	<0.001
Mg 40	1.03	1.10	-0.07	0.692	-0.11	0.382

4.2.3 Establishing Soil Condition Change through Proxy Site Pairing (application of PSMM)

The PSMM produced pairs for 21 Farmed area sites and 3 Native Veg proxy sites (Figure 18). The most frequent Native Veg pairing was for 1-45-0 at 17 pairs, followed by 1-36-0 at three pairs, and a single pair for 1-40-0. The Native Veg sites detailed in Table 12 were the only three out of the possible 21 sites mathematically justified for pairing to a Farmed site. A weak geospatial pattern was evident in the model site selection, as the paired sites suggested clusters or zones for points 1-36-0 and 1-40-0 (Figure 18). The '0 difference' in capacity attributes indicated optimal pairings. The first, 1-21-0 in the Farmed area paired with 1-45-0 in the Native Veg with seven equal (within a margin of +/-0.1) attributes based on each soil texture, and one for K Gamma. The second optimal pairing was between 1-03-0 Farmed site and 1-45-0 Native Veg site, with Clay %, subsurface Silt % and subsurface Sand %, K Gamma and U Gamma for a total of six equal attributes. Most paired sited shared had two equal attributes. The site pairings of 1-19-0 and 1-45-0; 1-17-0 and 1-45-0 were least optimal, with 1 equal attribute. All pairs had equal K Gamma values.

Once paired, the mean was recalculated for the Native Veg and the Farmed area sites, for each condition attribute and the means contrasted to establish if a significant change in condition occurred (Table 11). This required the Native Veg dataset to be reset for 21 entries based on the 3-paired site metrics and their pairing frequency; 17 Farmed sites paired 1-45-0, 3 sites paired 1-36-0, and a single site paired 1-40-0. The pairing process effects (PSMM) were evaluated by contrasting the difference in the means pre- and post-pairing processes (Table 11). In several instances, the difference of the mean between the sites was no longer statistically significant though this implied ramifications to the management of the property and outputs of the agricultural/horticultural system. The pH 1:5 and pH CaCl values were no longer statistically significant. The mean difference of ESP, eCEC, Ca, Na, and K at depth 40 and K at depth 0 was statistically significant post-pairing. The breakdown of attribute divergences, based on chemical changes from the proxy status to the current management status, were presented in Table 13. The most persistent attributes to depict a change in condition were pH 1:5, eCEC, K and Mg at depth 0, and eCEC, Ca, K and Mg at depth 40 and is implications for agricultural management moving forward. A change in soil condition is demonstrated in Figure 17 for pH 1:5, here the negative depicts a more acidic result. The full suite of DSM illustrating a change in condition can be perused in Appendices 1.3. Importantly, several of the DSM for soil condition change. The contributing factors for these divergences are probed further in the Discussion section.

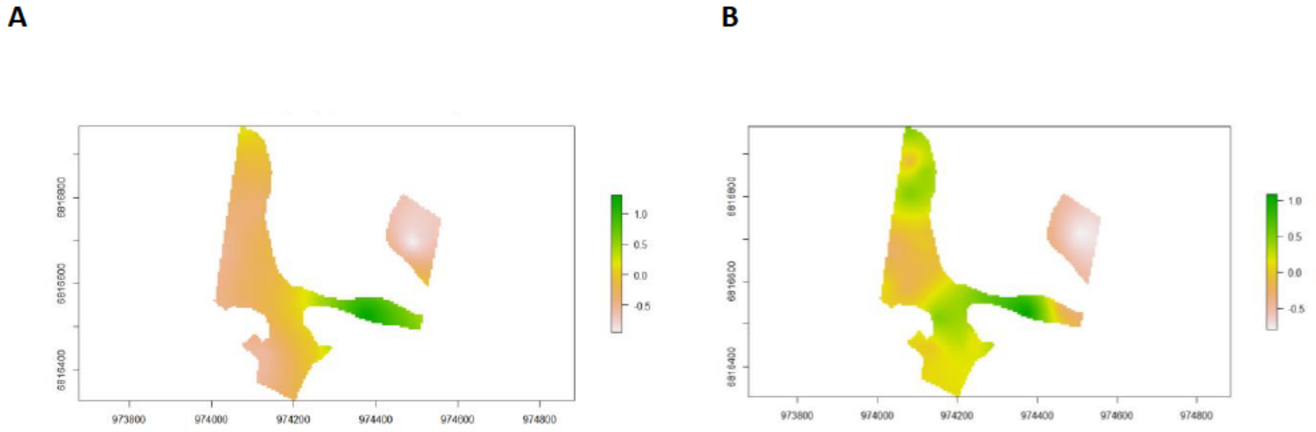


Figure 17 Predicted Values for Change in pH 1:5, at Farmed Points. A: Depth 0, B: Depth 40.

The PSMM of the Millmerran property capacity attributes resulted in 10 pairings of the Cleared area to 2 of the Native Veg points. Native Veg site 1-14-0 resulted in 9 pairs, and 1-19-0 resulted in a single pair. There were fewer matches with equal capacity attributes; there were less frequent results based on soil texture matches than the Thorndale property. Bias was introduced by the advised higher clay % in the cleared areas, as the primary reason for clearing this land. The most frequent changes in condition attributes were eCEC and ESP at each depth. This also supports the probit modelling (PSMM input) requirements, a 0.25 factor of standard deviation criteria for the matching process, in contrast to the 0.2 factor for the Thorndale property of standard deviation. This has implications for the role of bias in the PSMM overall and is discussed in later sections.

The inclusion of the pH CaCl measurement did not produce any contextual differences to the pH 1:5 measurement in any of the soil chemical analyses to date. Consequently, it was not included in the condition change investigations. [i]

[1] *Please note, raw data is not included in this Thesis document due to grower privacy and intellectual property restrictions. Raw data may be made available upon request, with the permission of the landowner.*

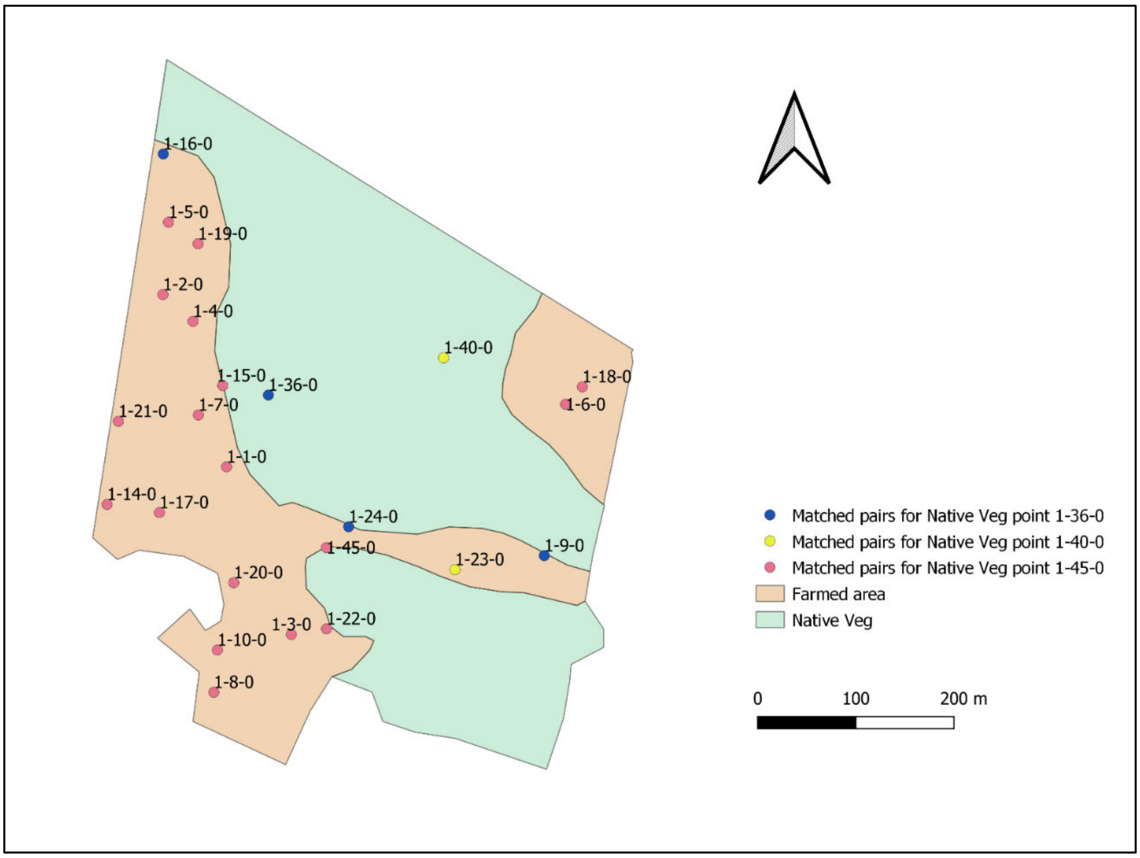


Figure 18 Geospatial Pairing based on Matched Pairs of Farm and Native Veg Capacity Attributes, Thorndale

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Table 13 Difference in Capacity Attributes for Paired Points, Thorndale. Highlighted cells (0 values) indicate where no difference exists between capacity attributes, and is an optimal pairing for the attribute.

Paired Points			***Difference in Capacity Attributes***											
Paired Series	*Farmed Point*	*Veg Point*	*Clay% 0*	*Clay% 40*	*Silt% 0*	*Silt% 40*	*Sand% 0*	*Sand% 40*	*DEM*	*Aspect*	*Slope*	*K Gamma*	*Th Gamma*	*U Gamma*
1	1-1-0	1-45-0	0	-1.25	0	6.25	0	-5	-2.91	-0.93	2.04	-0.07	1.69	0.36
1	1-2-0	1-45-0	0	-1.875	1.25	-3.125	-1.25	5	-2.81	-32.53	1.29	-0.09	10.51	0.91
1	1-3-0	1-45-0	0	0	2.5	0	-2.5	0	-1.28	-9.83	0.31	0	-0.63	-0.01
1	1-4-0	1-45-0	-0.625	0	1.25	-2.5	-0.625	2.5	-2.77	-54.89	0.40	-0.08	10.37	0.89
1	1-5-0	1-45-0	-0.625	-1.875	0.625	-1.875	0	3.75	-1.02	-51.28	1.77	-0.10	13.75	0.95
1	1-6-0	1-45-0	0.625	1.25	-0.625	-2.5	0	1.25	0.85	-145.85	-1.23	0.01	5.41	0.07
1	1-7-0	1-45-0	0	0	1.25	-2.5	-1.25	2.5	-4.00	-14.26	0.52	-0.09	5.79	0.68
1	1-8-0	1-45-0	0.625	1.25	0.625	-1.25	-1.25	0	-4.06	2.6	1.82	0	-1.15	-0.09
2	1-9-0	1-36-0	0	6.875	-1.25	-0.625	1.25	-6.25	2.17	-216.6	-1.14	0.02	-2.37	-0.57
1	1-10-0	1-45-0	0.625	-0.625	8.125	0.625	-8.75	0	-3.96	-14.91	0.94	-0.01	-1.16	-0.08
1	1-14-0	1-45-0	0	-1.25	2.5	0	-2.5	1.25	-8.72	1.25	1.99	-0.09	1.13	0.31
1	1-15-0	1-45-0	0	-2.5	0.625	-3.125	-0.625	5.625	-2.91	-6.8	1.66	-0.08	5.42	0.60
2	1-16-0	1-36-0	0	-3.75	-0.625	-1.25	0.625	5	1.72	-37.92	0.09	-0.05	9.2	0.53
1	1-17-0	1-45-0	1.875	3.125	1.875	-1.875	-3.75	-1.25	-5.89	0.76	1.63	-0.08	1.08	0.34
1	1-18-0	1-45-0	1.875	-1.25	0.625	-2.5	-2.5	3.75	0.81	-139.52	-1.14	0.01	5.58	0.08
1	1-19-0	1-45-0	1.875	-1.875	0.625	-3.125	-2.5	5	-0.83	-63.95	-0.23	-0.09	12.92	0.93
1	1-20-0	1-45-0	-0.625	-1.25	0.625	-3.75	0	5	-2.41	-13.8	1.19	-0.04	-0.62	0.13
1	1-21-0	1-45-0	0	0	0	0	0	0	-7.72	-7.21	2.10	-0.1	4.76	0.59
1	1-22-0	1-45-0	1.25	-1.25	1.25	-1.25	-2.5	2.5	-0.21	-14.95	-0.07	0.01	-0.38	-0.03
3	1-23-0	1-40-0	1.875	1.25	-1.875	-1.875	0	0.625	0.26	15.69	-0.33	0	-4.62	-0.2
2	1-24-0	1-36-0	0	-3.75	1.25	-1.875	-1.25	5.625	1.53	1.17	-0.15	0.05	-4.29	-0.43
		Mean	0.42	-0.42	0.98	-1.34	-1.40	1.76	-2.10	-38.27	0.64	-0.04	3.45	0.28
		Range	2.5	10.625	10	10	10	11.875	10.89	232.29	3.33	0.15	18.37	1.52

Table 14 Changes in Condition Attributes per Farmed Points, Thorndale. Highlighted cells indicate a negative effect, or a more alkaline effect for pH values. NDVI is included as an expected outcome.

Paired Points			***Changes in Condition Attributes***																
Paired Series	*Farmed Points*	*Veg Points*	*pH 1:5 0*	*pH 1:5 40*	*EC 0*	*EC 40*	*ESP 0*	*ESP 40*	*eCEC 0*	*eCEC 40*	*NDVI*	*Ca 0*	*Ca 40*	*Na 0*	*Na 40*	*K 0*	*K 40*	*Mg 0*	*Mg 40*
1	1-1-0	1-45-0	-0.3	-0.1	10.38	-10.43	-2.65	0.98	-1.12	-1.53	-0.05	0.05	-0.94	-0.14	0.01	-0.05	-0.12	-0.99	-0.48
1	1-2-0	1-45-0	-0.3	0.5	25.18	1.23	-0.61	14.01	1.63	-1.45	-0.08	1.86	-1.42	0.01	0.32	-0.14	-0.15	-0.11	-0.20
1	1-3-0	1-45-0	0	0.3	18.99	-1.79	4.78	5.56	-0.09	-1.29	-0.13	0.62	-1.10	0.23	0.13	-0.22	-0.13	-0.71	-0.20
1	1-4-0	1-45-0	-0.5	0.3	11.39	4.60	-0.48	17.44	1.17	-1.38	-0.10	1.73	-1.28	0.01	0.41	-0.17	-0.17	-0.40	-0.34
1	1-5-0	1-45-0	-0.2	-0.1	27.97	-3.32	-2.68	2.14	0.56	-2.12	-0.07	1.56	-1.64	-0.13	0.02	-0.06	-0.17	-0.82	-0.33
1	1-6-0	1-45-0	-1.5	-0.7	-2.08	-0.95	2.34	2.16	-1.45	-2.24	-0.09	-0.70	-1.62	0.03	0.02	-0.23	-0.19	-0.55	-0.45
1	1-7-0	1-45-0	-0.1	0	28.11	-4.76	-2.60	0.99	0.11	-1.54	-0.12	1.15	-1.21	-0.13	0.01	-0.12	-0.05	-0.79	-0.30
1	1-8-0	1-45-0	-0.6	0.1	0.61	-1.88	0.29	0.85	-0.46	-1.95	-0.12	0.21	-1.39	0.00	0.00	-0.24	-0.12	-0.43	-0.45
2	1-9-0	1-36-0	0.7	-0.3	38.62	15.39	5.81	1.85	-0.74	2.60	-0.09	-0.94	0.10	0.30	0.25	-0.02	0.02	-0.07	2.24
1	1-10-0	1-45-0	-0.7	0	15.07	-5.68	-2.10	1.87	-0.74	-2.34	-0.14	0.12	-1.80	-0.11	0.01	-0.14	-0.18	-0.61	-0.37
1	1-14-0	1-45-0	-0.5	0.1	15.00	-5.45	-2.54	5.02	-0.04	-0.77	-0.05	1.23	-0.62	-0.12	0.15	-0.22	-0.14	-0.93	-0.16
1	1-15-0	1-45-0	-0.2	-0.1	-2.97	-5.13	-2.87	4.39	-1.73	-0.35	-0.02	-0.32	-0.36	-0.15	0.15	-0.25	-0.14	-1.02	-0.01
2	1-16-0	1-36-0	0.3	0.5	-2.92	-0.96	3.24	4.12	-2.50	-1.02	-0.03	-2.21	-0.93	0.07	0.03	-0.08	-0.04	-0.28	-0.09
1	1-17-0	1-45-0	-0.2	-0.2	34.9	1.44	0.15	3.22	-0.04	-1.74	-0.13	0.71	-1.53	0.01	0.06	-0.21	-0.13	-0.55	-0.13
1	1-18-0	1-45-0	-0.6	-0.8	-13.11	-2.20	1.51	7.39	-0.42	-1.51	-0.09	0.07	-1.33	0.05	0.16	-0.24	-0.15	-0.30	-0.19
1	1-19-0	1-45-0	-0.1	0.4	16.79	7.27	-2.44	-4.41	-1.55	-1.73	-0.11	-0.21	-1.10	-0.13	-0.01	-0.21	-0.09	-1.01	-0.44
1	1-20-0	1-45-0	-0.1	0.5	20.35	-1.50	4.02	1.51	1.09	-1.96	-0.14	1.20	-1.39	0.27	0.02	-0.20	-0.16	-0.19	-0.43
1	1-21-0	1-45-0	-0.6	-0.3	-4.62	-8.56	-1.58	6.43	-2.21	-1.17	-0.03	-0.83	-1.03	-0.11	0.16	-0.26	-0.17	-1.02	-0.14
1	1-22-0	1-45-0	-0.2	0.1	13.22	-4.54	7.86	14.25	-0.64	-1.19	-0.1	-0.10	-1.30	0.31	0.36	-0.23	0.02	-0.63	-0.27
3	1-23-0	1-40-0	1.8	1.1	9.01	-3.31	-1.02	-13.73	1.65	1.87	-0.19	1.70	1.57	-0.01	-0.23	0.01	0.05	-0.05	0.47
2	1-24-0	1-36-0	0.5	0.6	4.46	3.38	2.64	3.19	-2.33	-0.84	-0.07	-2.04	-0.82	0.05	0.03	-0.06	-0.03	-0.28	-0.02
		Mean	-0.16	0.09	12.59	-1.29	0.53	3.77	-0.47	-1.13	-0.09	0.23	-1.01	0.01	0.10	-0.16	-0.11	-0.56	-0.11
		Range	3.3	1.9	51.73	25.82	10.73	31.17	4.15	4.94	0.17	4.08	3.37	0.46	0.64	0.27	0.24	0.97	2.72

Chapter 5

5 Discussion

5.1 Applying the soil security framework to the Southern Downs Local Government Area as a case study with future regional applicability.

Attempts to krige the regional chemical characteristics were made and the terron analysis for the Southern Downs was not feasible with the data available. A DSM using terron-mapping units necessitates a wide range of soil properties and environmental covariates to form the memberships of unique value-set for each unit (Carré & McBratney 2005). Any terron based on the kriged properties of the poorly fit variogram model (Figure 10) would be highly degraded, as evident by the map of predicted pH values (Figure 11). A very low variability was represented by a mean value of a soil property pH 1:5 to 'smooth' areas between sites and near the boundaries of the DSM. This was further depicted in the lack of intersection with any spatial points or the sill line on the plotted empirical variogram model; the extensive range effectively negated these parameters (Figure 10). The result created an unusually high nugget effect and a misleading spatial dependence (Kerry & Oliver 2008).

Furthermore, an attempt at the LOOCV method reduced the dataset to 62 sites and degraded the variogram output further and thus found to be far too low for model building and geospatial prediction for the Southern Downs LGA. The small pool of the qualified SALI dataset rendered the model incapable of any validation technique. As a result, the DSM was deemed unreliable and produced extremely low accuracy for predicting the spatial variability of soils. This was further confirmed when the ASC data-point series produced from SALI dataset was mapped and then contrasted against the land type units (and inferred soil types) represented in the legacy map of the region (Maher 1996b) and found to be an inferior indicator of soil variability.

With respect to the Australian Soil Classification data series, its qualitative nature restricted its usability for the case study. ASC offers a special characterisation of categorical data from the soil sites and provides insights into the range of soil classes in the region from the point data alone (Figure 12). However, the data cannot be extrapolated to represent continuous soil classes as no discrete values exist between sites. It thus cannot fully predict the extent of the soil types in the region. An accurate extent of the soil classes cannot be achieved without the out-of-scope inputs described to build covariate layers in a DSM. The inputs may not be limited to extensive soil chemical and physical properties; beneficial qualitative data can be garnered from regional landscape assessments, land manuals, and corresponding legacy soil class maps (Maher 1996c, 1996b, 1996a). These assessments are typically available through local or state-level governing bodies. Ultimately the DSMART method was not employed for this case study for regional assessment. It was prudent to move forward with the available resources to address the core aims more directly at the farm-scale. Without landscape or regional contexts, such as derived from LGA terron-based DSM or DSMART or additional qualitative resources, the narrow range of covariates presented at the Thorndale property cannot offer insight into the region's variability. Further to this, the extent to which soils characterised in the case study, cover the region cannot be achieved solely with an upscaling of the protocol as it does not support a way to quantitatively, spatially scale it. Finally, linking microclimates will not be possible without quantitative spatial analysis, diminishing the desired protocol usability in the future-proofing the region. The SALI dataset, including the ASC data series, was insufficient and not fit for purpose without supplementary information.

In the scope of future analysis, regional extrapolation can be made with the land use data offered by Maher (1996a). A qualitative approach can be justified and does give usable commentary at local and regional levels, yet it remains limited in its transferability, and sustained effort in this space is needed to refine the protocol further. Regardless of the terron assessment status, the case study progressed to the site selection of the Thorndale property. The covariate analyses were initiated by harnessing an acute DEM and the proximity of the two land use sites to infer comparability. On-farm sampling and soil testing proceeded and ultimately added value to the SSF endeavours. Through the demonstrative DSM and PSMM protocol, the study characterised the soil and concluded with actionable recommendations for the management of the farming enterprise for positive flow-on effects for broader landscape and ecosystem.

5.2 Examination of the quantified changes in soil condition and understanding divergences in soil chemical properties between land use sites

The hypothesis of this study states management of a mixed-horticulture system over 70 years had a negative effect on soil condition. Minimal divergences were observed in several soil condition attributes. However, the range of soil condition change was reasonable for the Thorndale soils characterised as poorly buffered and derived from granitic sand. Overall, the divergences were positive, with indications the management was effective and well suited to the previously given functions. The case study was compelled to reject the null hypothesis by this measure. Yet, the study design presented limitations that likely did not fully capture all attributes that may define soil degradation at the farming enterprise. Therefore, the following sections will discuss the on-farm outcomes directly.

5.2.1 Understanding divergences in the pre-colonial levels to current management status

The study assessed how the soil attributes diverged from the pre-colonial era to the current management status however, not all changes have practical implications on-farm. The results indicated a change in EC at depth 0 despite being approximately 40% higher in the Farmed areas. Farmed soil EC did not approach rates at which salinity, driven by an abundance of salts at the soil surface, affected soil quality (Northcote & Skene 1972). Importantly, neither EC levels in the Farmed areas nor the Native Veg were in a range preferred for plant growth; at 110 - 570 milliSiemens per meter (mS /m) (Cook & Walker 1992). The range of EC values at the farming enterprise indicated low fertility (the availability of cations as plant nutrients). This decreased down the soil profile, indicating leaching occurred between depths 0 and 40 cm. EC at the scale of microSiemens per centimetre (µS/cm) did not necessitate a shift in management on-farm, however any change in local salt levels can have implications for off-site discharge points. It is imperative that landowners be aware of and actively seek to reduce run-off and leaching risk across the landscape. The highly permeable, sandy soils of Thorndale are at risk of losing salts to underground spring flows, especially following rainfall events when the spring is rapidly recharged. Leaching, or the loss of soluble cations via soil water, is often hugely detrimental to downstream ecosystems with unintended growth effects (Singer & Munns 2002).

Leaching is prevalent in sandy soils due the porosity allowing fast infiltration of water into the soil profile. In addition to soil texture, the generally low nutrient absorption and retention capacity due to sands' inert quality, plays a role in the loss of fertilizers and other inputs to the system (Matichenkov et al. 2020). This was supported by the analysis of cations at depth 40 across the property; Ca, K and Mg were recorded at lower levels in the subsoil than topsoil. The lack of trees/ crops to extract nutrients at the root zone, and the observation of free-flowing water at depth 30 to 50 cm following heavy rainfall, provide physical evidence of the leaching effect at depth 40 cm. Na increased at this depth for the Farmed areas, driving the significant difference to the Na and ESP levels at this depth for the Native Veg. ESP at depth 40, as above 6% is typically classified as marginally sodic (Northcote & Skene 1972). Despite an ESP result signifying sodicity, the soil did not disperse, which is potentially a function of the higher salinity associated with the increased ESP (Quirk & Scholfielde 1955). Importantly, Bennett et al. (accepted 2022) have demonstrated that not all sodic soils should be expected to disperse, and the chief measurement to direct treatment decisions is that of aggregate stability. The cost of acting on misleading ESP values is up to 600 times greater than the cost to directly determine soil stability, per hectare. Therefore, for this Thorndale soil, structural stability issues were not considered in need of any ameliorative action and use of fertilizers is cautioned for the cation deficiencies.

Interestingly, ESP was higher in the Native Veg and not a constraint to growth. The ESP result and inferences of soils aggregate stability coupled productivity of the NDVI results, despite the low eCEC results, describe a well-balanced system with sustained output. Many *Eucalyptus* species are well-adapted for wet or dry conditions and prefer slightly acidic, drained soils with a poor nutrient profile (Harper et al. 2008). In this regard, the Native Veg was well-suited to its given function and speaks to a greater capacity for resilience than what is suggested by the status of the soils in the Farmed areas. This raises the issues of a return to native growth possibly being financially advantageous to the farming enterprise and the entire landscape capability. For this to be fairly ascertained, further assessment for the suitability of the Farmed areas for a continued horticultural function must be given. This will be covered in the forthcoming subsections.

The differences between Farmed areas and Native Veg ESP may be credited to the historical use of liming agents. The application of lime or dolomite likely had the effect of Ca offsetting the increased Na levels in previous seasons (Quirk & Scholfielde 1955). However, this clear-cut approach does not consider changes to the landscape as contributing factors to the soil chemical divergences. A more prudent assessment views ESP as an indirect measure of landscape degradation. Clearing the land for farming has likely increased the flow of the underground spring through the rising water table and compounded the leaching effect. Thus, the change in ESP and landscape water movement can be linked to management.

Moreover, the presence and influence of underwater springs on the condition attribute illustrated the unique form of degradation not explicitly captured in the protocol proposed by the case study. Clearing remnant native vegetation for farm use reduced the number of trees providing ecosystem services via water filtration and retention (Harper et al. 2008). A weakened 'pump' effect from too few trees appears to have raised the recharge rate of the underground water flow, as observed when sampling depth 30-50 cm and indications of increased leaching. Effectively, the management of farming enterprise modified the landscape above and below ground. How to quantify this modification and classify it as degradation through the loss of function and ecosystem services, is less clear. Physical changes to the landscape may be more directly measured with a reworked set of physical and chemical soil property tests through heightened awareness of the adjoining soils and local systems (Maher 1996c, 1996a). A strategic start would include further sampling to establish a change in condition across several points in time. A time-series dataset would be useful to management with respect to short-term shifts in soil chemical properties to monitor input loss rates and the influences of climate and weather events, especially the wet season for poorly buffered soils.

Conversely, select changes in soil condition attributes are directly tied to soils' capability to support plant growth (Chapman et al. 2011). pH of the soil can restrict nutrient accessibility and absorption rates by crops and require ongoing treatments to improve soil condition. The pH 1:5 values preceding the PSM pairing describe a significant difference between the Farmed areas and Native Veg, indicating the Farmed soil values to be less acidic and an improved condition (Table 11). However, following PSMM the mean shifted to become a significantly more acidic result despite the reality of the on-farm soil conditions and DSM spatial predictions (Figure 17). Therefore, it is essential to caveat the PSMM protocol use; when conflicting information is given, further sampling is recommended to determine the direction of the soil condition in response to recent management in consultant with soil scientists to leverage expert knowledge. By being selective with the information generated by the PSMM, management will prevent an overcorrection and excessive treatment regime and avoid the environmental and financial costs associated with an overload to the system. The principal component mapping is a more powerful tool for instances where soil condition information is conflicting. Regarding the pH of 6 at depth 0 and 6.1 at depth 40 are suitable for a range of horticulture and agriculture crops at the current condition, no increased rates are required. Historical use of lime and dolomite effectively increased the alkalinity for horticulture function.

A common theme of the chemical properties of the soils in the Farmed areas is for an improvement as compared to the Native Veg. However, this raises a critical question; is this the result of a conscious effort by the landowner or the soils' intrinsic properties? The low eCEC results and the high sand content characterized the Thorndale soils as poorly buffeted and low resistance to change. It is reasonable then that the soil would be highly responsive, at least in short term management, as slight changes in the soil can rapidly affect the function of the system. As attempts to quantify the SSF at the farm scale is ongoing with this and other emerging protocols, are these growers and landowners of sandy soils better positioned to receive a theoretical soil condition credit? Or does the influence of soil type in such assessments provide an unfair advantage compared to other landowners actively investing resources in managing soil constraints? If the protocol is to aid in the implementation of a SSF payment, it will require comprehensive guidelines that account for the complexity of how soil condition credits can be assigned for different soil types.

Despite largely rejecting the hypothesis, the means to quantify soil condition change was established. The PSMM paired Farmed soils and Native Veg soils on key environmental features as input to qualify the proxy status and define the property. The effective pairings based on the most relevant soil-forming factors can be inferred by joining the correlation data (Table 6) with the outcomes of the evaluation of paired capacity attribute (those with 0 differences recorded) (Table 12). The PSMM justified three Native Vegs soils for the proxy status for the entire Farmed areas. This is preferred to a one-to-one pairing system as it is reasonable for the size of the sampling space (approx. 35 acres) to cross over covariates and reflect the natural variability of the landscape. Generally, reducing size reduces variability in the sampling pool. A single paired point for each Native Veg soil would suggest unique covariates for any given position, and this is not a true representation of the variability observed at Thorndale. Furthermore, single pairings, is not reflected in the clear lack of multiple phenosoils on-farm, nor does it recognise the regional paedogenesis (trends in the soil-forming processes and classes) (Román Dobarco et al. 2021b). Given the variability of randomly placed (PCOSA method) sampling points, bias was actively reduced in the PSMM though other forms of bias based which designate land use are entrenched in agriculture and were recognised in this case study. This reinforces the fitness of the replacement model type of the PSM used in this case study and offers real-world applicability for landowners. How the model can reduce risk from bias overall and how the study validated the success of the PSMM is explored further in the following subsection.

5.2.2 Evaluating the PSMM

Propensity score matching models (PSMM) provide insights into which covariates influence the treatment effect and, therefore, predict receiving the treatment and which covariates are neutral to the process (Rosenbaum & Rubin 1983). This was shown to be directly applicable to the Thorndale case study, albeit with a rethinking of how to apply the methodology. At the Thorndale property, the driver for leaving Native Veg undisturbed over 70 years of management, and what determined the treatment, was the shallow rock formation restricting vehicle navigation. The case study reversed the standard PSMM process by knowing the treatment outcome and elucidating near and optimal matches by analysing the pre-treatment variables; environmental covariates of interest. The environmental covariates (also presented throughout this thesis as the capacity attributes) are theoretically not affected by which units are selected for farming treatments, as all land is equally accessible to the landowner. This is straightforward in the reality of the agricultural context. It is reasonable that landowners will have retained the remnant vegetation at their farming enterprise for a myriad of reasons, such as land clearing restrictions, conservation, or agro-forestry. However, it is more likely, that the land possesses undesirable environmental or soil attributes inherently ill-suited for high-intensity use. Often untreated land (Native Veg) that has returned to native growth status experienced degradation through intense use or ill-suited function. The predetermination described here directly introduces bias to the PSMM model. Conversely, at Millmerran, the determining factor for clearing the land was desirable clay content with high mean clay % in these areas (Appendix 1.17) with the intention to expand cropping to this sampling location in the future. There was likely bias in the respective sample pool, given fewer sampling sites. This poses the question; is the PSMM in its current form, useful for on-farm application?

The intended benefit of the PSMM is to reduce confounding bias and thereby “spurious associations or correlations” (Austin 2011) between covariates in the Farmed areas. However, improvements to the mathematical process would further reduce the bias ensure it is suitable for real-world application. By applying a weighting or stratified value to each of the covariates for input in the model, the pairing process can recognise and devalue predetermining covariates in favour of the neutral covariates. In doing so, any biased covariates, such as clay content for the Millmerran property, will be less influential. This gives way to a richer selection of covariates to define the landscape features. For example, the covariates of depth to bedrock, parent material, and soil horizon change would offer associations to soil forming factors comparable to those of covariates assessed and discussed in this study. By building a value-based stratification into the PSMM model, these covariates would be captured but not lead the pairing process. Bedrock formation etc. was not included for study due to equipment use and access for data collection, and not due to their lack of usefulness. Arguably, all covariates add value and strengthen the PSMM. Given the relatively simply landscape at Thorndale, in terms of the range of capacity attributes observed (Table 11), the PSMM enabled pairs to be selected from a biased sampling pool and yet found acceptable natural proxies in the Farmed area. With minimal refinement, the model is ready for replication in future case studies

The Geospatial pairing map generated by the PSMM (Figure 18) cannot predict values nor offer diagnostic tools as point-based or zone-based comparisons, and subsequent decision making is primitive. There is still a requirement to link useful proxies to understand the level of uncertainty, i.e. the fluctuations in the individual values of a proxy, given what we know about the area, to then be able to map the values in the form of a spatial continuum. The benefit of coupling the PSMM and DSM techniques into a single protocol is the broader predictions of the soil chemical characterisations on-farm. A richly layered DSM can illustrate soil and environment constraints and facilitate discussions with growers as to where the investment of resources is best suited given locations of any divergences from the proxy status soils. The following Discussion subsection outlines an interpretation of the DSMs for the soil condition attributes and offers some suitability statements for future cropping at Thorndale.

5.2.3 Implications for on-farm soil modification that may result from protocol use

In reviewing all information and data available, the Thorndale soils are characterised as having a high buffering capacity and low fertility. It is not clear if the management of the horticulture system exceeded the capability of the Native Veg proxies, and more qualitative analysis is required. Based on the Land Manuals (Maher 1996a), Thorndale is best represented by the Granite Hills landscape with a tenosol soil. The typical soil is described being as non-sodic and slightly acid, possessing poor fertility and low concentrations of nitrogen (N), phosphorous (P), copper (Cu), zinc (Zn) and K. It is expected the Farmed soils are readily changed and responsive to treatments. However, changes to the soil chemistry cannot be maintained due to the soils capacity to store nutrients and require ongoing input. This is supported by the narrow ranges of the soil condition change of the Thorndale case study (Table 13) and would be compounded if harvesting were to resume and effectively remove further nutrients from the system. This landscape type's relief and geological association and the bordering Flat Granite Plains landscape and clay loam sodosol influence the soil on-farm and off-farm flows of natural resources (Maher 1996a). The regional climate and terrain-based features of interest are seasonal dry streams, water storage and access in drought, lower aquafers and rock-trapping of water, shifts from sandy soils (high leaching) to clay loams (high nutrient retention capacity), the flow of soil resources between landscape, frequent heavy rainfall, and frost (Maher 1996c). When coupled with the on-farm covariate data, known regional environmental constraints allow us to make reasonable arguments for and against managing soils for a persistent condition change or otherwise modifying the Thorndale Farmed soil to such an extent that a new genosoil emerges. Applying this knowledge to Thorndale property, the flows beyond the property boundaries through the underground springs pose a credible threat of degradation to the landscape caused by the leaching of nutrients through the sandy soil.

Managing soils to exceed the capability of Native Veg proxy status may require intense modifications and with adverse effects on-and off-farm. This begins with determining a suitable land-use at Thorndale given its change in soil condition and if treatments are required to fulfil this function. The Thorndale soils are suited to horticulture (apples, pears, stone fruits) mainly due to the well-draining soil texture (Maher 1996a). The soil texture also determines the risk of erosion, though positively, very few areas on-site have exposed topsoil due to a return of native grasses between growing seasons. Here, depleted soil may be advantageous as the accumulation of nutrients leading to toxicity is far less likely to occur. As indicated in the oral histories (see subsection 3.4.2), the use of broad-spectrum fertilizer treatment aims to address the low nutrient levels. As the low levels are universal, targeting an individual deficiency was viewed as less productive. However, the leaching rates inferred by the cation analysis outcomes (Table 11) strongly suggests this is not continued. Any cropping system will need a layout that considers erosion controls and the need for drainage (Maher 1996a). If the landowner is determined to retain all cleared land for agricultural use, raised beds for vegetables cropping over springs and erosion controls may be the most appropriate future direction. Furthermore, the terrain features and current soil condition at Thorndale Paddock 5 indicate its previous function of winter vegetable cropping is ill-suited to continue. A select few ameliorative actions are identified to demonstrate how treatments may improve the soil condition on-farm yet have detrimental effects to the interconnecting systems.

Claying is the process of applying large clay deposits to the surface and delving the soil to alter the subsoil texture. Improving soil texture addresses the root issues of leaching inputs and low fertility. The benefits of claying may be demonstrated in the immediate improvement of the subsoil chemistry. eCEC and EC, would have relative improvements and lead to greater nutrient and water hold capacities (Davenport et al. 2011). Plant available water plant nutrient uptake would also increase and is likely to result in a boost to crop productivity and yield (Verberg et al. 2018). The landowner is then in a better position to future-proof the enterprise as management is expected to become more cost-effective long term with fewer inputs required and subsequently wasted. Such a significant divergence of soil chemistry and texture would lead to an emergence of a new genosoil in the Farmed soils and open the enterprise to other cropping options suitable to the genosoil. The use of the claying program is demonstrative of the final three dimensions of the SSF; capital, codification, connectivity and their role in applying the developed protocol. All users having the right to benefit from soils is a central belief of the SSF and should be considered in the decision-making process for any intensive soil modification (Koch et al. 2013). The following impacts are intended to caution any application of the protocols that may inform land modification by outlining the significance of its use beyond clinical practicality and replicability.

For the implementation of a claying program, the potential for negative impacts must be considered for on-farm and off-farm flows (Davenport et al. 2011). On-farm the major impact of a claying is the cost and labour. Locating, removing, and applying the clay deposits is expensive and lengthy. The soil chemical profile is complex, and claying program must be well informed to generate a positive effect; thereby, repeat soil chemical and texture analyses are required. Any off-farm impacts are more difficult to predict, contain and mitigate. For claying, the deposits that do not aggregate move downstream (Almajmaie et al. 2017). Fertilizers are more likely to be held in soil with higher clay %, and growers may purposefully overload the soil to capitalise on this new soil condition. Nitrogen applied in excess of the soil's capacity to retain it would also be transported to stream.

The commodity of the desired crop will largely direct if it is economically viable to continue a high rate of inputs (including clay) considering the rate of input loss. These factors can shift the landowner's perception of a productive landscape. A viable alternative land-use at Thorndale would be to reclaim the land for native growth and habit conservation, requiring little to no ongoing management. Landowners need to reognise the myriad of ways ecosystem services have practical value on-farm, these include; theoretical soil condition credit (Bennett et al. 2019), habitat restoration or protection for endangered species, the benefit of agro-forestry for improved on-farm nutrient and water cycling (Harper et al. 2008), Biodiversity Offset Scheme credits (Department of Planning Industry and Environment 2021) cultural heritage value and its associated tourism. Land used for conservation can provide passive revenue to the farming enterprise, encourage a positive value association for the landowners, and then conceptualise the total social benefit of soils.

An alternative issue may be the continued use of nitrogen and phosphorous based fertilizers. When discussing the mechanisms and dynamics of soil salinity on-farm and for the landscape, trends are generally applicable to nitrogen in reference to the EC results (Zeng et al. 2013). Nitrogen is the basis for most fertilizers, and being anion will not be attracted to soil particles and easily applied in excess and flow out of the profile (Northcote 1971). Phosphorous, another heavily used fertilizer in horticulture, also acts as a cation and will typically flow and stop with any clay sediments though it presents a concern for off-farm flows and eutrophication in sandy soils (Bista et al. 2018). For fertilizer use to continue at Thorndale, ongoing testing and analysis are recommended to inform application rates on an 'as needed' basis. Further to this, growing crops with greater nitrogen use efficiency and reducing irrigation is beneficial (Ullah et al. 2019). When discussing the mechanisms and dynamics of soil salinity on-farm and for the landscape, trends are generally applicable to nitrogen in reference to the EC results (Northcote 1971). Nitrogen is the basis for most fertilizers and being an anion would not be attracted to soil particles and easily applied in excess and flow out of the profile. The Land Manual may guide opportunities for further management shifts (Maher 1996a).

Increasing clay content at the subsoil through claying or delving the surface would highly likely modify the internal hydrology structures. The clay aggregates would retain water inputs (typically through rainfall) and divert water from the springs to reduced recharge rates (Davenport et al. 2011). Any discharge sites external to the property would experience some level of impact. Suppose large communities of landowners all sought to change the internal hydrological structures on-farm. In that case, the effect is compound and likely cripple landscape-level ecosystem services by altering modes of access to critical water points and water quality for the landscape (Foufoula-Georgiou et al. 2015). Examples of social implications may be a reduced supply of the nearest township during drought or eutrophication driving water stress in the plants (Kübert et al. 2019) necessary for converting habitat of vulnerable species. Landowners must, therefore, consider the broader costs and benefits of soil modification.

A suitable function for Paddock 5 is the return to native vegetation growth. Replanting native species would increase carbon inputs, over time replicating the effect of clay deposits on the soil structure naturally (Devi

2021). It would also anchor the cations with deep tree roots to absorb water resources while reducing the flow. In the case of Paddock 5, the conservation-based function may prove beneficial to the entire farming enterprise if the soils are not actively managed yet remain productive in their given function and cycle nutrients and water on-farm. If a return to the natural state is economically sound to the landowner, the transition will serve as an experiment to measure ecosystem services' flow-on effects through soil condition changes assessments. An argument can be made for returning Paddock 5 to native vegetation. Treating the recharge point benefits the nutrient uptake in this area (Peck & Hatton 2003). Trees improve salinity and soil structure; however, the water uptake is not guaranteed throughout the season, and some underground flow would be sustained. A return to native vegetative at the corridors and discharge point of flow would be advantageous for agro-forestry (Harper et al. 2008). Therefore, leveraging trees' ‘pump’ effect would reduce the flow (Peck & Hatton 2003). Concentrating native vegetation at the property boundary is expected to minimise off-flow, specifically preventing overloading the soils at neighbouring properties (Peck & Hatton 2003).

The benefit of using the soil proxy protocol is the empowerment of landowners to look at the Farmed soils objectively. If one or few soils represent on-farm capability, then it is reasonable to accept those select soils are likely to also represent the landscape. However, landowners must be aware any inputs to the system intended to change soil conditions have on-farm and off-farm implications, often compounding at the landscape level leading to degradation (Dominati et al. 2014). An increase in soil capability by way of altering internal hydrology structure in a landscape that relies on underground stream systems is highly detrimental, even hazardous, to society. Bennett et al. (2021) describes circumstances when a theoretical soil condition credit designed for positive on-farm change, is at odds with the total social benefit of land modification. A theoretical soil condition credit is a core tool in the realisation of the SSF and in encouraging landowners’ participation however it is clear the application of such a payment scheme is complex and many more mechanisms are needed to address landscape specific issues. To prevent malpractice at any scale, metrics for incentivising positive soil condition change and increases in soil capability are needed (Bennett et al.

2019). Realistically, no government structures or policies offer a fair reward for increases in soil capability, and the soil condition credit remains a theoretical concept of the SSF This gap in the science and policy structures of SSF can be bridged if protocols such as the one developed in the Thorndale case study, are replicated, refined, and informed by a myriad of environmental and social resources across industries. A fitting protocol is one that is guided by social consciences and an awareness of the interconnected environment (McBratney et al. 2014). Given the recent National Soil Strategy, land modification will become regulated (Commonwealth of Australia 2021), and a degree of landowner accountability will also come into effect. Though beyond the scope of the study, the effects would need to broadly consider; how is the total social benefit best quantified, how can any actionable payment scheme recognises the multitude of factors which influence soil stewardships; and finally, how can truly sustainable soil management balance the financial security of the individual grower and of the wider industry, with the need for soil security, and as an extension of this, food security? Further to this, allowing farmers to pivot management and future-proof their income stream is critical to adopting any soil condition protocol. Governing bodies have no recourse currently for poor management practices. While soil users lack a practical framework for decision-making and a lessons-learned approach (see the Murray Darling Basin current state) (Murray Darling Basin Authority 2021), few mechanisms prevent soil-lead landscape decline today. Thus, the way forward must be sustainable *and* profitable action based on a total social benefit in which agricultural products are correctly valued. In these concluding statements, it is essential to underscore education's role in increasing soil capability. Educating landowners through soil testing and information, useable and accessible regional land assessments, and conferences with soil scientists are vital steps in cultivating a sense of soil stewardship in the grower community and creating momentum for SSF aims (McBratney et al. 2018). It is therefore imperative landowners exploit all available resources to inform management of soils, elevate the total social benefit of current and future changes in soil condition, and ultimately recognise they form part of a community which benefits from fully functional landscapes.

5.3 Limitations

5.3.1 Limitations of this Study

The study design could not facilitate the application of the Soil Security framework for the Southern Downs region. The lack of a universal suite of soil chemical analysis prescribed to all SALI projects and inconsistent soil chemistry data contained therein severely limited which of the 368 accessible SALI sites located within the LGA qualified for inclusion in the study. Dataset parameters were ill-suited for ordinary, universal or regression kriging interpolation at this scale. Given spatial statistics fundamentals, the poor data density for the expansive region and low variability of the soil property data could not be remedied for this case study. A useable DSM would require further surveying and sampling in the area or a supplementary spatial dataset to address the imbalance of the SALI dataset. A polygon-based qualitative method (Odgers et al. 2014) based on the legacy map of regional land types (Maher 1996b) would produce such a dataset. It is helpful to explore this retrospectively for future improved implementation of the SSF at the regional scale. This method involves resampling the individual soil classes/ land type units of the legacy map to realise the potential extent of the soil class in raster form, unlimited by the fixed boundaries or proportions of the legacy units. This process is termed “Disaggregation and Harmonisation of Soil Maps Units Through Resampled Classification Trees” or simply, DSMART and offers an opportunity to resume the terron analysis and generate richer data output.

In particular, exchanging the pH 1:5 laboratory method for the in-field tests per Raupach and Tucker (1959) method and is used far more frequently across SALI projects. In addition, a thorough review of the Maher (1996c, 1996a) polygon-based qualitative assessment statements would also improve the input selection for interpolation, creating a more continuous map with a universal set of attributes over large areas

5.3.2 Limitations of the Protocol

A degree of error is expected in using polygon-based legacy maps, such as the Stanthorpe-Rosenthal Region Land Types Map (Maher 1996a), as it requires the transfer of soil-specific information to a finer resolution for farm-scale interpretation. This applies to the case study as the Thorndale property is spread across two land types.

There is a lack of time-series data to establish the rate of change for the soil condition; whether it has improved or declined in recent years cannot be determined. The effect of any recent change in management cannot be stated.

PSMM is limited to selecting proxies and does not have built-in spatialisation features. Therefore, the next step in protocol use requires the outputs to be married with the DSM techniques. The Thorndale case study is limited to using the ordinary kriging interpolation technique. As such, no statements can be made about the suitability of this protocol using one interpolating technique over others; universal kriging or inverse distance weighting may be found to be a better fit if tested.

Furthermore, the narrow range of soil-forming factors and subsequent low variability for the soil chemical characterisation farm-scale supports the conclusion there is a single genosoil at the Thorndale property. However, this statement is a qualitative outcome and not quantifiable or replicable currently. Furthermore phenosoil-genosoil model may not be sufficiently sensitive to identify this scale, at which point in the soil chemical characterisation of a genosoil does a phenosoil emerge as a new classification of soil. The threshold for determining individual phenosoils would be difficult to ascertain at Thorndale, owing to the narrow range of changes in soil chemical properties and the role of the underground spring. The phenosoil-genosoil model for determining the difference in soil condition was not explored and is a limitation or weakness of the case study.

5.4 Improvements and Recommendations

An improvement to the PSMM would include setting a standard Caliper width. The two properties apply two different factors of the standard deviation for building the Caliper function. This will effectively lower the gatekeeper that allows matches to be found and further reduce risk. More investigations are needed to determine a maximum acceptable value for the Caliper width.

The case study outcomes focus on how readily soils are changed and the effects of any modification made in response to understanding changes in soil condition. It is recommended the study be replicated in other land uses and soil types to understand how soil condition metrics are influenced. More data are needed to strengthen the arguments for soil modification and allow specific soil/industry recommendations to be determined. Using the approach of Maher (1996b) to locate alternative soil types and aid site selection is further recommended in place of regional terron analysis.

Site selection may then be improved to include farming enterprises covering a larger area. Ordinary kriging models are sensitive to data pool sizes, as demonstrated with the disparity of DSM quality for the final soil condition maps (Appendix 1.6). A property larger than the 72 Acres at Thorndale, will increase sampling frequency and, logically, offer greater soil and environmental covariates variability. Additionally, applying the protocol to soils with known constraints will provide insights into the usability of the soil condition metrics for a growing already motivated to treat soil quality, and offer alternative tools to do so. The protocol may then be adapted on-site for immediate improvement in a targeted area. Soil constraints are thereby recommended to be considered in future site selection.

Determining the optimal frequently for testing to be carried out in farmed areas to establish directional change and effects of recent management through a time-series model would be beneficial. However, costs are associated with repeat testing and may influence how landowner's uptake the protocol and its general usefulness. This study adds to the current discussion regarding how to fund soil surveys that have private benefits at the farm scale though it contributes to a broader landscape capability assessment. Further work is needed to address this, as the options to offer public funding for paddock-farm scale high-density surveys and how this translates to landscape/region/catchment applicability is contested (Biggs 2021). For example, is consistency using extensive soil chemical testing the key to enabling terron-based analysis? Or, as Biggs (2021) suggested, by targeting specific soil attributes in testing and establishing a state-level framework for surveying, soil research can collectively maximize knowledge extraction and work towards better-informed soil chemical characterisation.

Chapter 6

6 Conclusion

The results produced by the case study did not support the hypothesis that the management of a mixed-horticulture system over 70 years negatively affected soil conditions. However, the primary investigation was found to be successful in developing a protocol for identifying a proxy for farmed areas in the nearby undisturbed native vegetation as the pairs were formed on key criteria of environmental covariates and soil texture. The study applied the Soil Security Framework (SSF) at the farm scale with a case study at Thorndale. It informed statements about the suitability of future functions on-site to alleviate detrimental flow-on effects to the connecting landscape. While apparently effective, this pilot protocol necessitates further refinement for PSMM, specifically a weighting element to differentiate how covariate inputs and soil information influence the pairing processes. Soil texture would be given priority as this is the ideal indicator for soil capability, given its correlation to soil chemistry and ability to supply plant nutrients. Despite the model usability on-farm, it was incapable of upscaling the SSF application to the Southern Downs Local Government Area, as it could not infer soil class variability at this spatial scale. For terron-based DSM and other regional analysis techniques, the inclusion of qualitative land assessments moving forward is critical for sustainable practices to be applied on-farm and in respect of the landscape as a continuous entity. The aims of the SSF are soon to be realised, and the inevitable shift has implications for on-farm, regional, and broader management of environmental resources, beneficial to all users and procurers of soil products.

6.1 Future Direction

The inclusion of carbon as a soil attribute would be an excellent indicator of soil condition change. Measuring the carbon input and the soils' ability to maintain a labile carbon pool under native vegetation vs. cleared or farmed paddocks would indicate the capacity of the soil to sequester carbon and further define suitability assessments. It also offers opportunities for correlation studies between native vegetation type and total carbon stocks to promote agro-forestry on farms and across industries. This is an exciting direction for the protocol and would provide insights into future regional-level climate change mitigation strategies. Further investigations are recommended to determine which soil types are an ideal pairing for specific native species and the optimal distribution of each, specific to farm or industry type. Again, a sophisticated restricting of the PSMM is recommended to prioritise the covariates.

Following this, the logical next step is to implement treatments and ameliorative actions tailored to the soils benchmark status and study how effective this is in increasing the soil (and landscape) resilience to climate change impacts. Here, climate change is an external threat to the management of farming systems and the longevity of their current functions. A solid starting point is a richer analysis of the data available at the Millmerran site. Followed by a study of the neighbouring soils here and at Thorndale to investigate long-range soil water flow and the risk to soil and hydrological structures as atmospheric warming persists. Quantifying soil resilience poses a major challenge in a study of this design. Microclimate maps would offer insights into the acute impacts of climate change on soil and landscape types on the Southern Downs. Though labour intensive, this type of investigation would provide climate-sensitive and industry-specific suitability statements (Webb et al. 2014; Kidd et al. 2015a) and guide regional decision making. The outcomes would aid in future-proofing the horticulture and agriculture grower communities.

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Appendices

Appendix 1. 1 Laboratory Methods Summary

Methods used to Analyse Samples				
Analyte	ALHS Reference	Unit	Name	Method Description
pH (H_2O)	4A1		pH in water	1:5 water extr., pH meter
pH (Ca_2Cl)	4B3		pH in 0.01M Ca_2Cl	1:5 CaCl extr., pH meter
EC	3A1	µS/m	Electrical conductivity	1:5 water extr., EC meter
eCEC			Cation Exchange Capacity	Sum of exch. (NA, K, Ca, Mg)
ESP, eCEC	15N1	%	Exchangeable Na%, cation exchange capacity	(Exchangeable Na/sum of exch. cations) %
Sand		%	Particle size, sand	Hydrometer, gravimetric
Silt		%	Particle size, silt	Hydrometer, gravimetric
Clay		%	Particle size, clay	Hydrometer, gravimetric
ALHS is Australian Laboratory Handbook of Soil and Water Chemical Methods (Rayment & Lyons 2010)				

Appendix 1. 2 Definitions for Terrain Characteristics, as Environmental Covariates

Terrain Characteristic	***Definition***
TRI	Topographic Roughness Index is calculated using the mean of the elevation differences of its 8 neighbouring cells (squared and then square rooted to transform to positive values, referred to as the root-mean-square) (Riley et al. 1999)
TPI	Topographic Position Index is calculated as difference between the value of a cell and the mean value of its 8 neighbouring cells (Wilson et al. 2007)
Slope	Slope is the steepness of a cell, calculated from the cell's tangent, using 8 neighbouring cells (Horn 1981).
Aspect	Aspect is the orientation of the slope, calculated in clockwise direction from 0 to 360 degrees. If slope is 0, aspect is set to 90 degrees (Horn 1981)
FlowDir	The flow direction (of rainfall), as influenced by the greatest decline in elevation or smallest incline if all 8 neighbours are at a higher elevation (Horn 1981)

Appendix 1. 3 Statistical Summaries Chemical and Physical Properties of the Soils of Southern Downs LGA

Subset Data Depth 0-10 cm

	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*	*Skew*	*Shapiro-Wilke Test P value*
pH	4.962	5.879	6.492	6.696	7.363	10.518	0.174	0.004
EC dS/m	0.008	0.028	0.056	0.079	0.109	0.550	0.322	<0.001
Cl mg/kg	8.078	18.000	21.114	32.068	38.390	287.743	0.695	<0.001
Clay %	2.076	13.446	26.857	30.316	48.258	69.465	0.115	<0.001

Subset Data Depth 40-50 cm

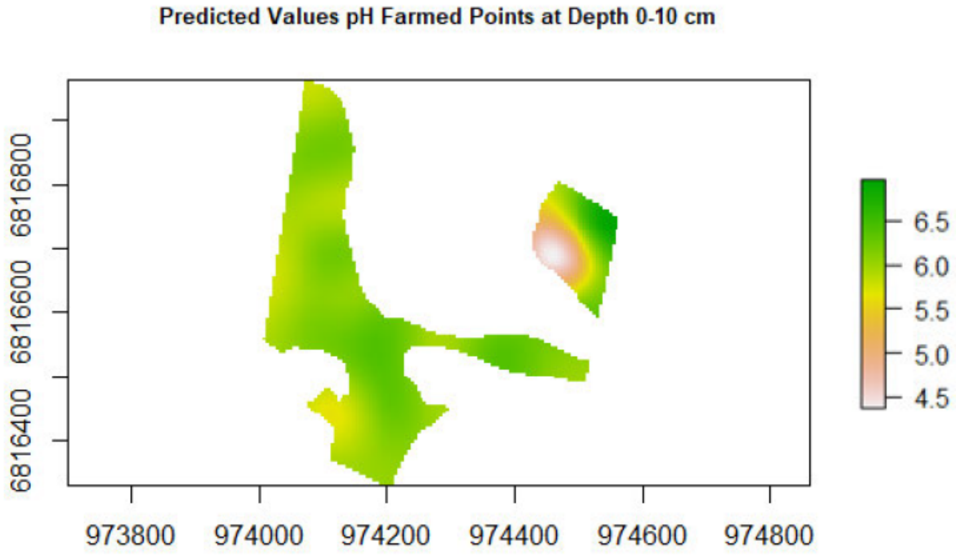
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*	*Skew*	*Shapiro-Wilke Test P value*
pH	4.84	6.20	6.76	7.07	8.15	9.30	0.43	<0.001
EC dS/m	0.09	11.34	25.30	29.81	48.26	69.47	0.41	<0.001
Cl mg/kg	8.97	20.63	39.70	130.92	118.44	787.01	0.61	<0.001
Clay %	0.09	26.04	43.66	40.39	55.58	75.00	-0.19	<0.001

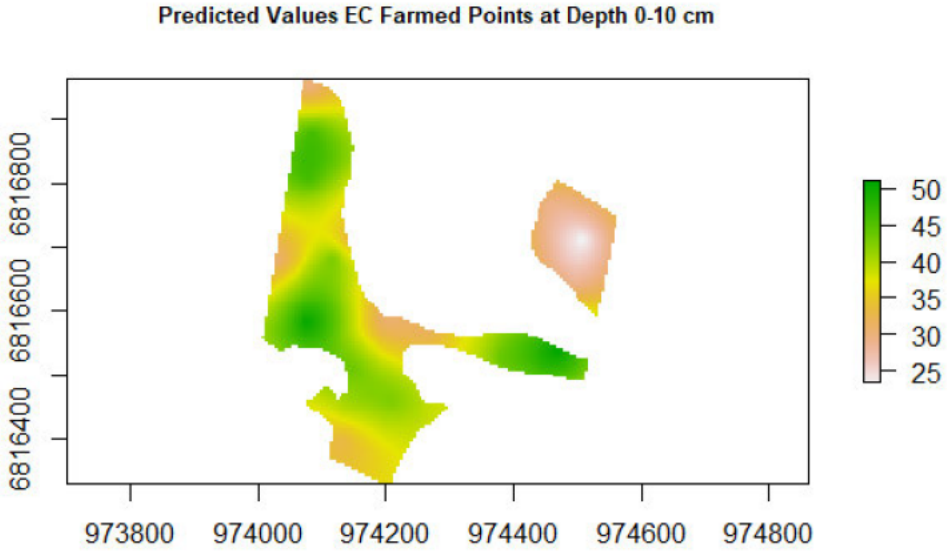
Appendix 1. 4 Summary of Transformed Data for Variogram Modelling, for Thorndale Sites

Farmed	***0-10 cm Depth***	***40-50 cm Depth***
pH 1:5	Original	Original
EC µ/cm	Original	Sqrt
pH CaCl	Original	Original
Clay %	Original	Sqrt
Silt %	Original	Original
Sand %	Original	Original
eCEC cmol(+)/kg	Original	Log
ESP	Sqrt	Sqrt
Ca cmol(+)/kg	Original	Sqrt
Na cmol(+)/kg	Sqrt	Sqrt
K cmol(+)/kg	Original	Sqrt
Mg cmol(+)/kg	Original	Log

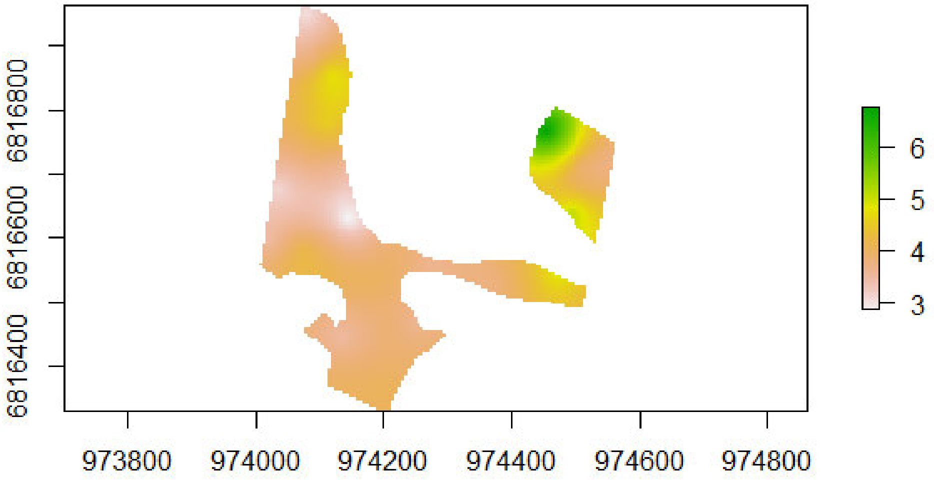
Native Veg	**0-10 cm Depth**	**40-50 cm Depth**
pH	Original	Original
EC µ/cm	Sqrt	Original
pH CaCl	Original	Sqrt
Clay %	Original	Sqrt
Silt %	Original	Sqrt
Sand %	Sqrt	Original
eCEC cmol(+)/kg	Sqrt	Sqrt
ESP	Sqrt	Sqrt
Ca cmol(+)/kg	Sqrt	Original
Na cmol(+)/kg	Original	Sqrt
K cmol(+)/kg	Sqrt	Sqrt
Mg cmol(+)/kg	Sqrt	Original

Appendix 1. 5 Series of Digital Soil Maps of Soil Attributes per Depth for Farmed Areas, using Ordinary Kriging Interpolation

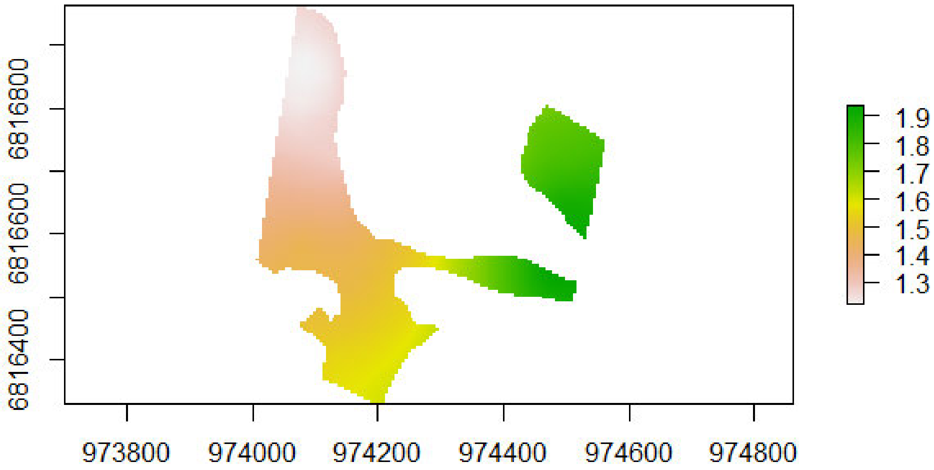




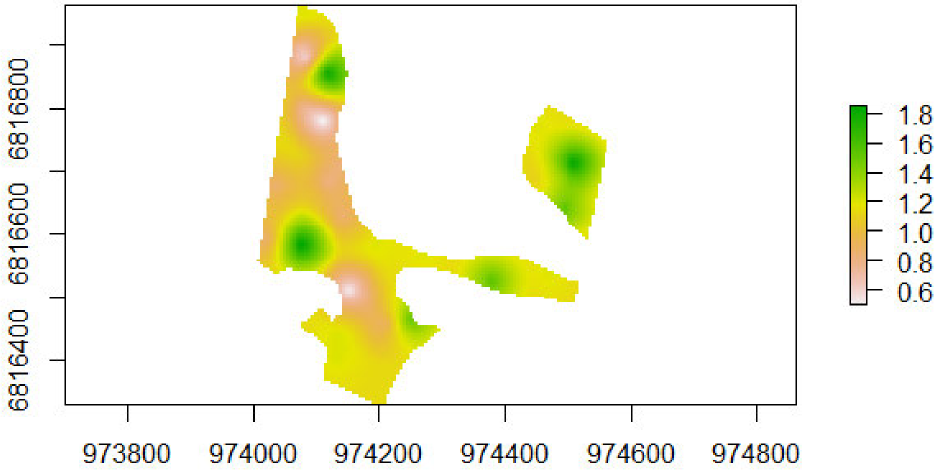
Predicted Values Sqrt EC Farmed Points at Depth 40-50 cm

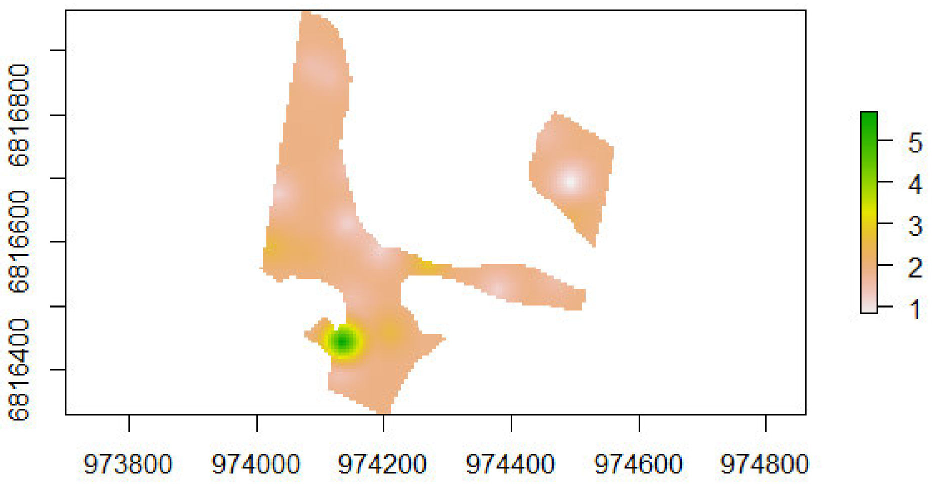


Predicted Values Sqrt Clay % Farmed Points at Depth 40-50 cm

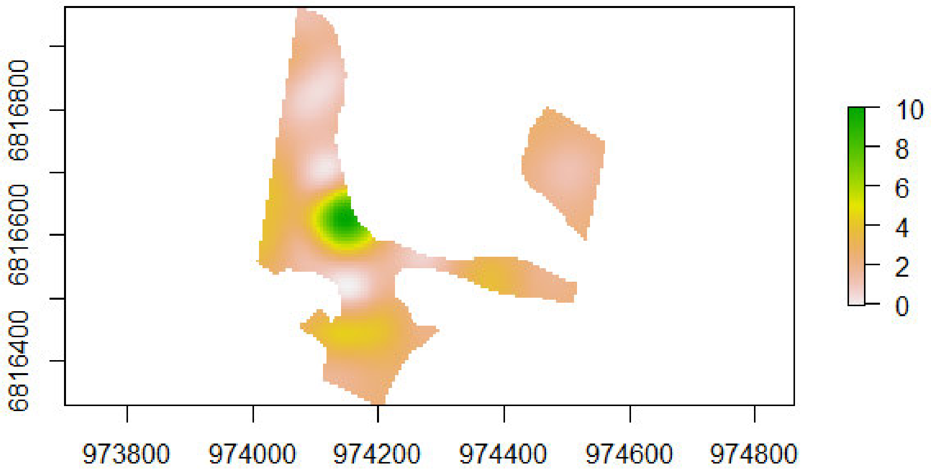


Predicted Values Clay % Farmed Points at Depth 0-10 cm

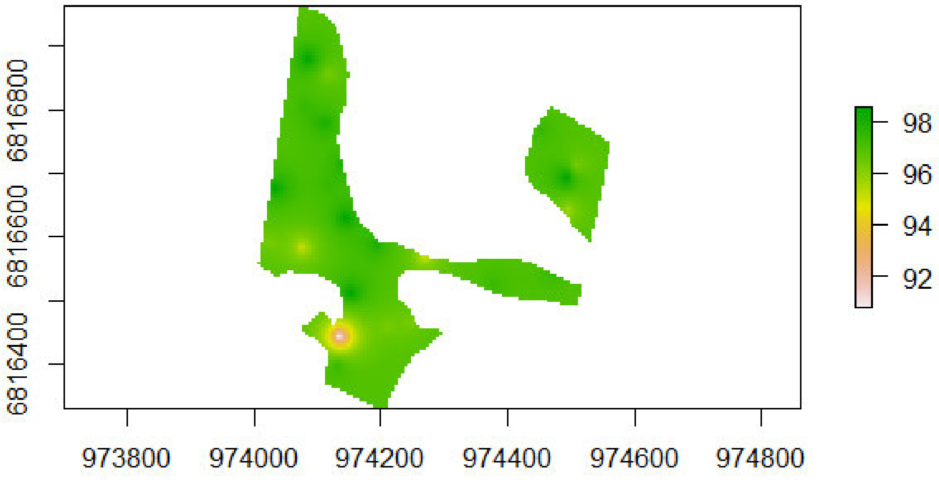




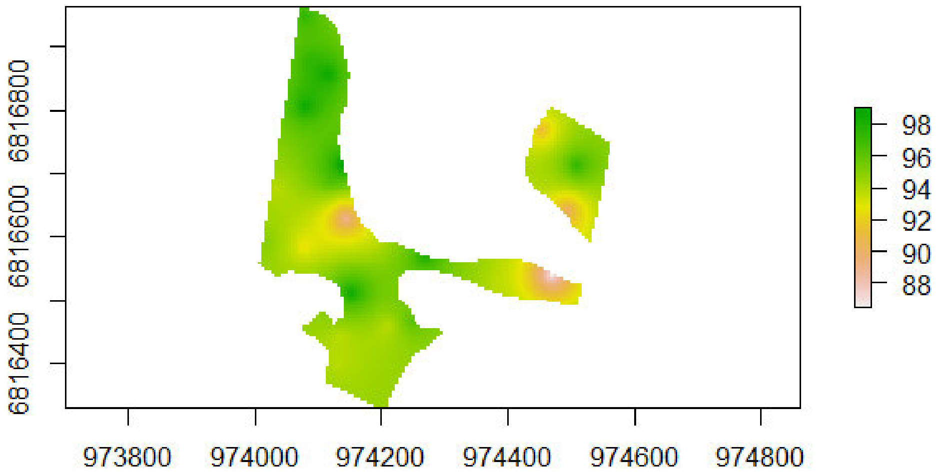
Predicted Values Silt % Farmed Points at Depth 0-10 cm

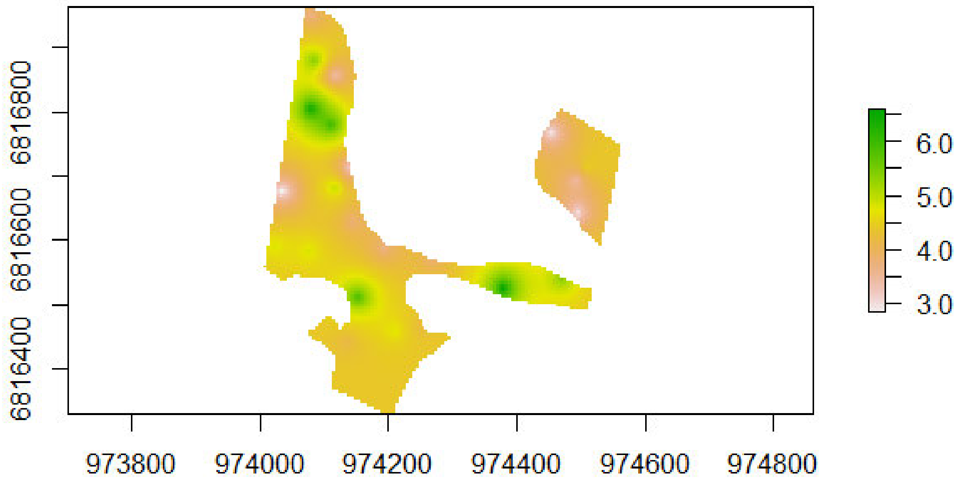


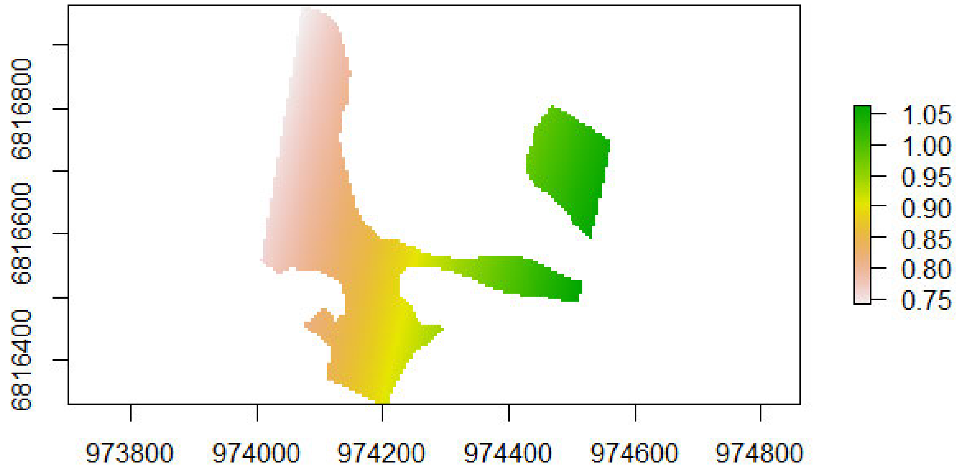
Predicted Values Silt % Farmed Points at Depth 40-50 cm



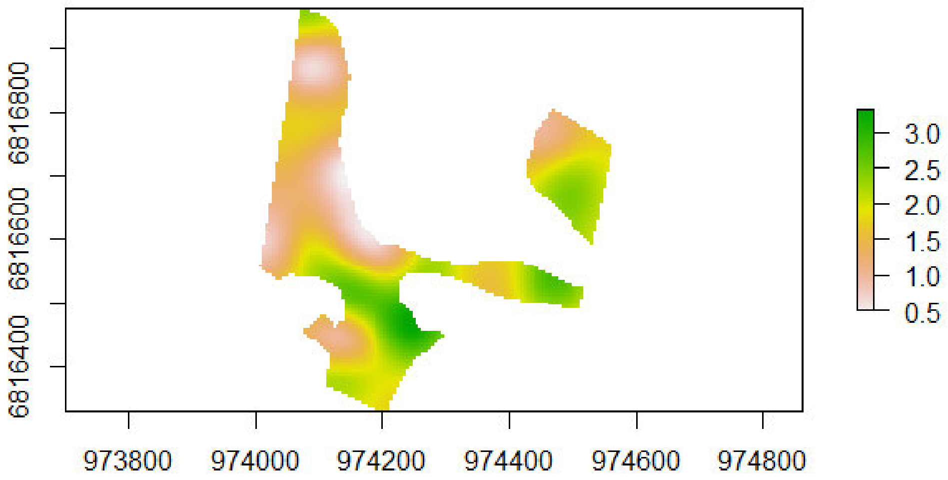
Predicted Values Sand % Farmed Points at Depth 0-10 cm


Predicted Values Sand % Farmed Points at Depth 40-50 cm

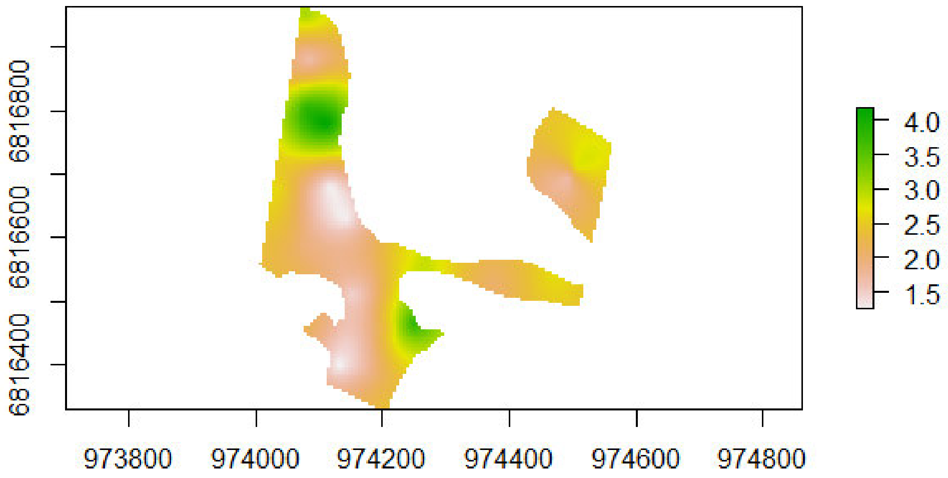

Predicted Values CEC Farmed Points at Depth 0-10 cm


Predicted Values Log CEC Farmed Points at Depth 40-50 cm

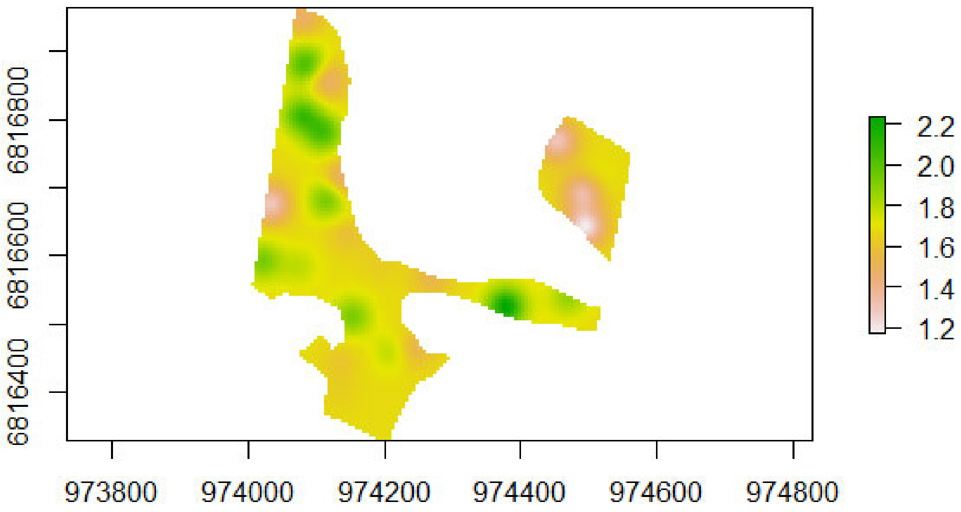
Predicted Values Sqrt ESP Farmed Points at Depth 0-10 cm

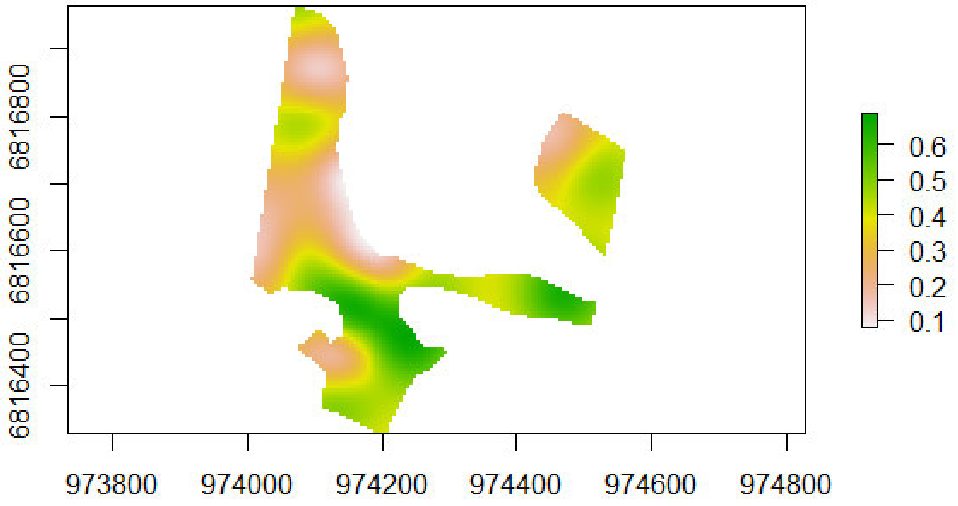


Predicted Values Sqrt ESP Farmed Points at Depth 40-50 cm

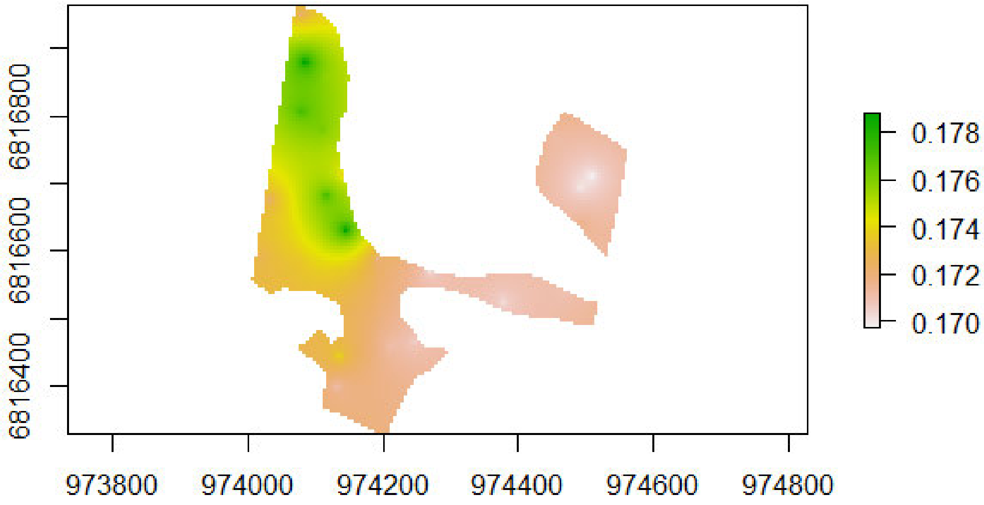


Predicted Values Ca Cations Farmed Points at Depth 0-10 cm

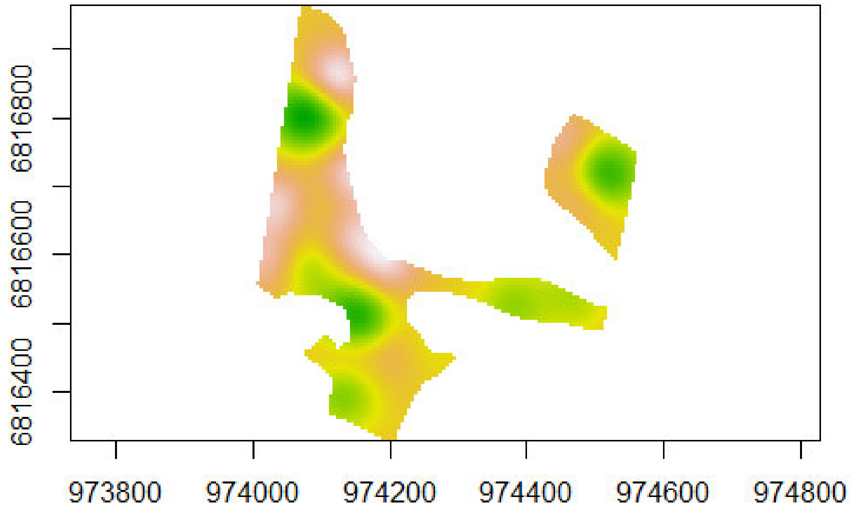




Predicted Values Sqrt Na Cations Farmed Points at Depth 0-10 cm

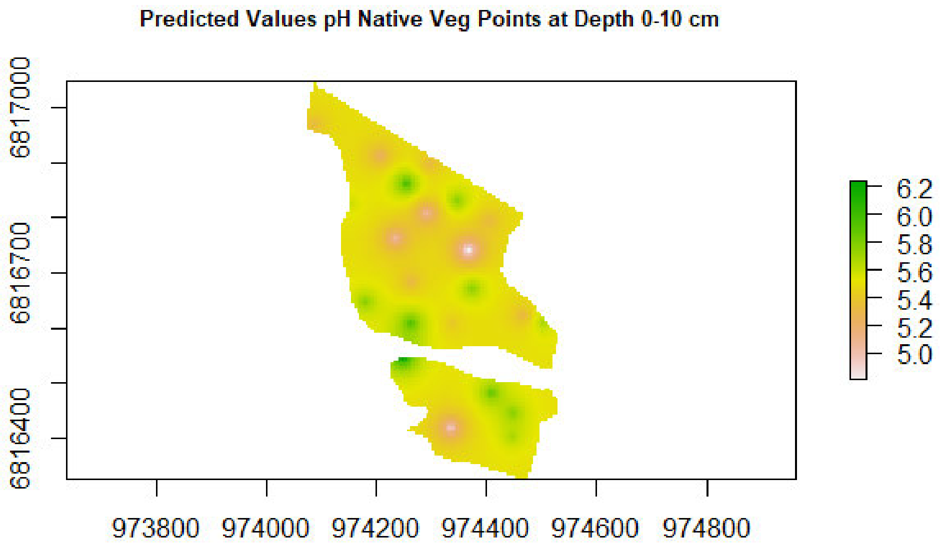


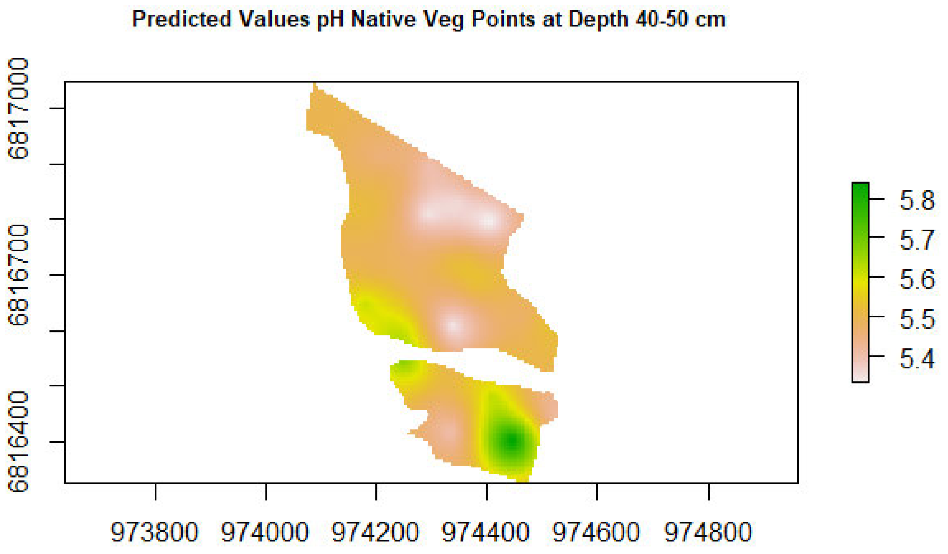
Predicted Values K Cations Farmed Points at Depth 0-10 cm

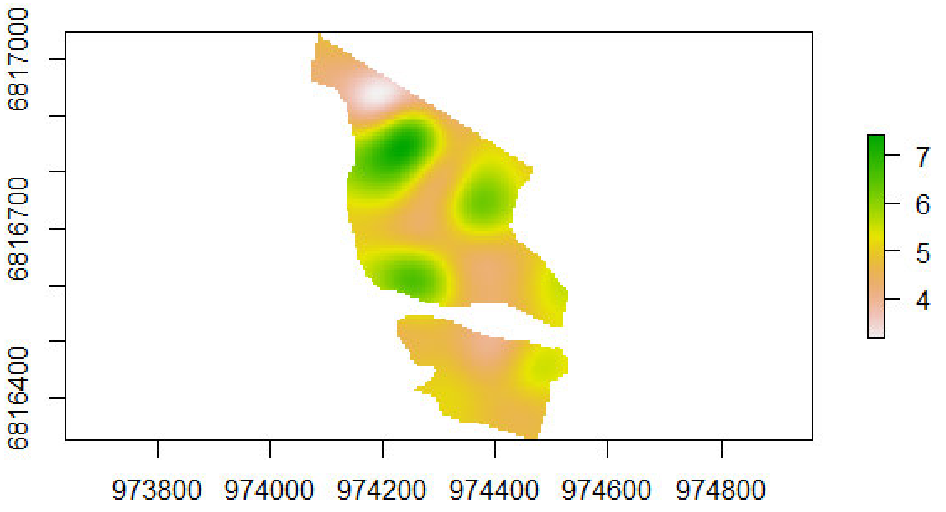


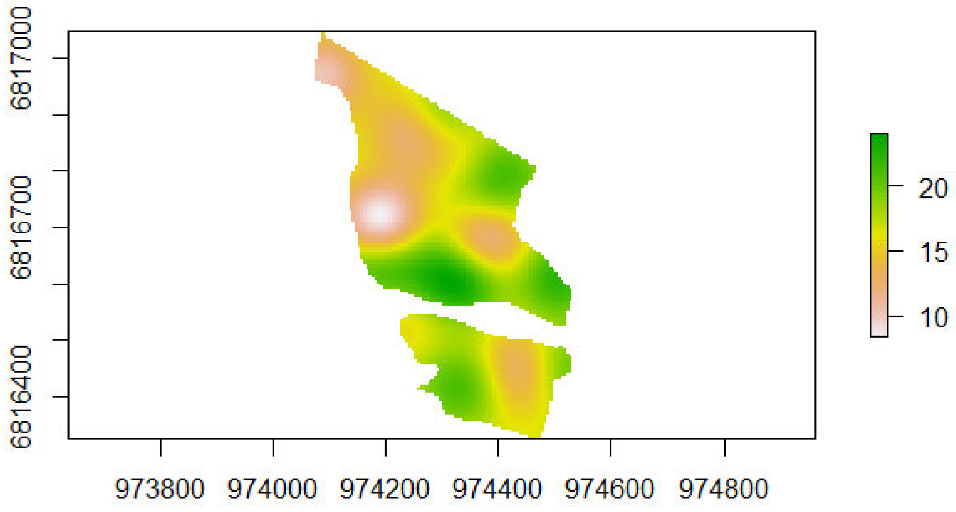
Predicted Values Mg Cations Farmed Points at Depth 0-10 cm

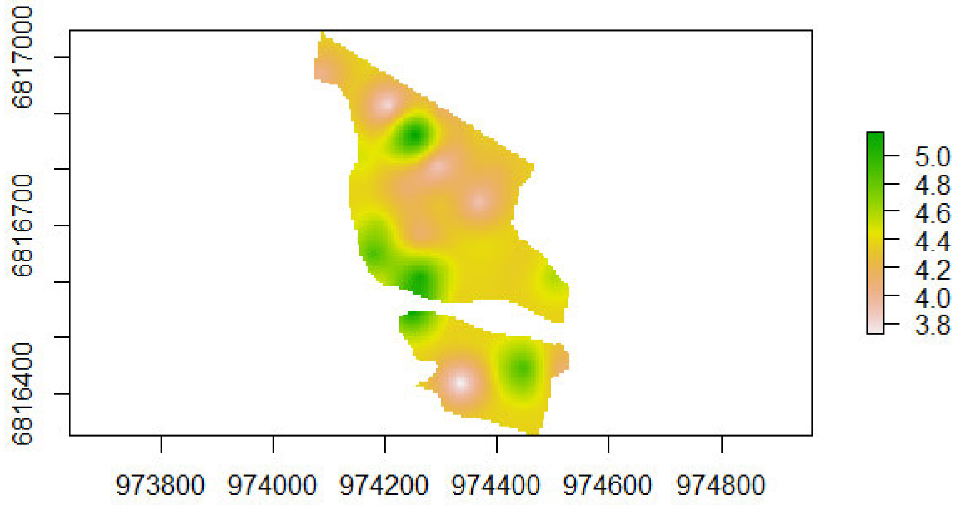
Appendix 1. 6 Series of Digital Soil Maps of Soil Attributes per Depth for Native Veg Areas, using Ordinary Kriging Interpolation

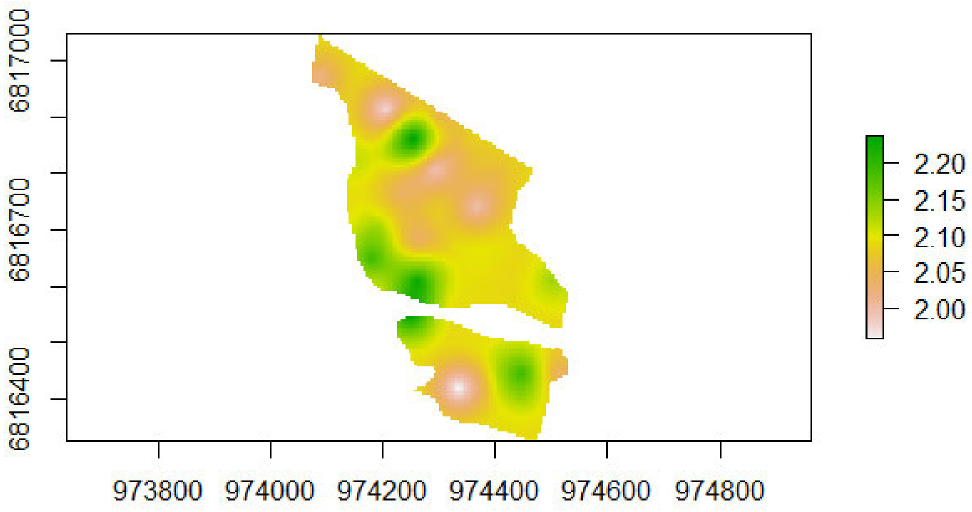

Predicted Values pH Native Veg Points at Depth 0-10 cm


Predicted Values pH Native Veg Points at Depth 40-50 cm

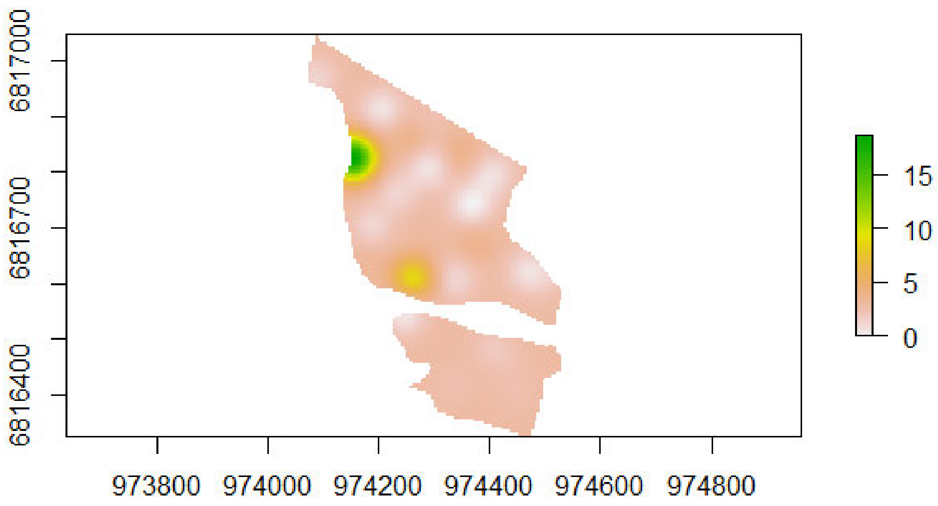

Predicted Values Sqrt EC Native Veg Points at Depth 0-10 cm


Predicted Values EC Native Veg Points at Depth 40-50 cm

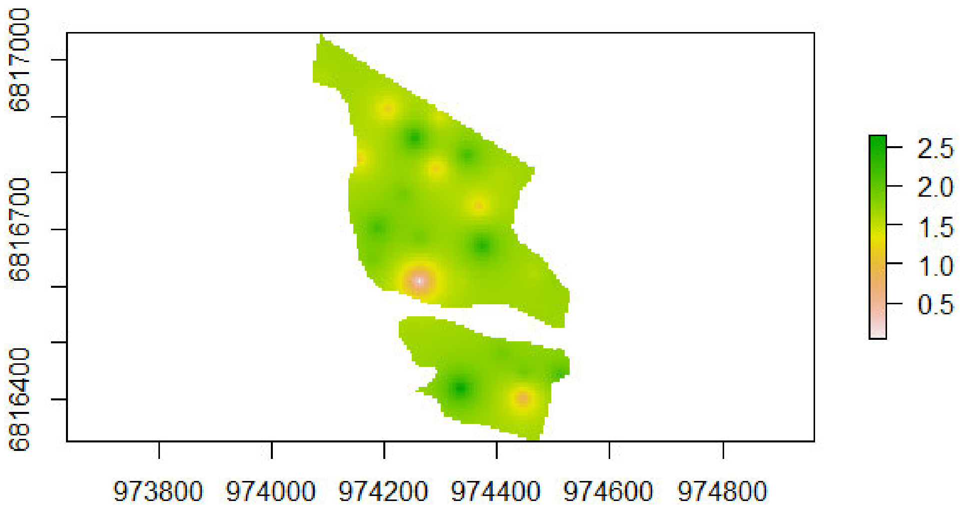

Predicted Values pH CaCl Native Veg Points at Depth 0-10 cm



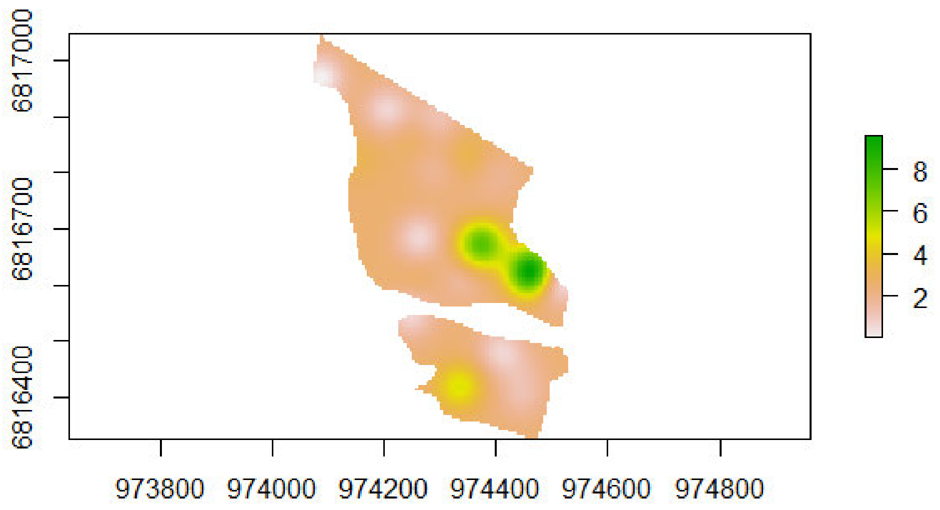
Predicted Values pH CaCl Native Veg Points at Depth 40-50 cm

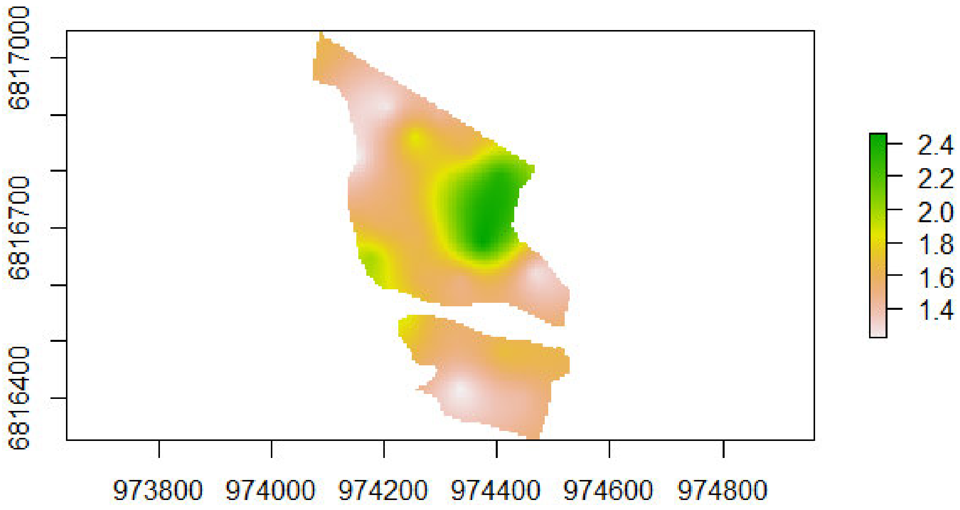


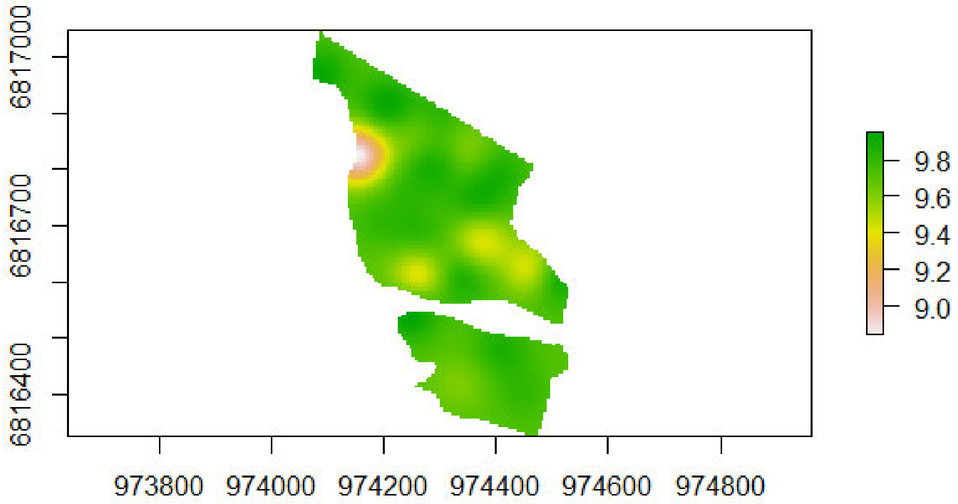
Predicted Values Clay % Native Veg Points at Depth 0-10 cm

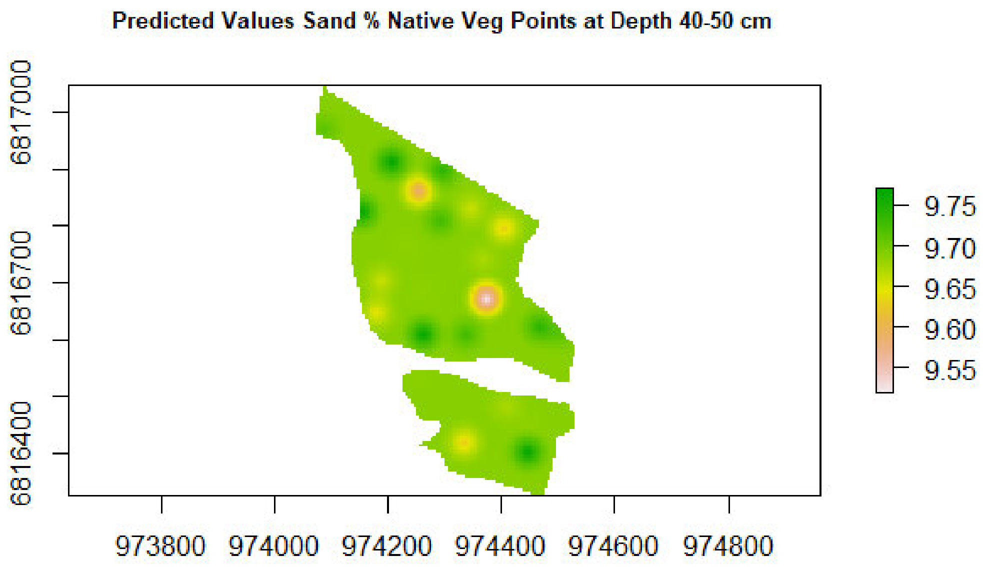


Predicted Values Sqrt Clay % Native Veg Points at Depth 40-50 cm

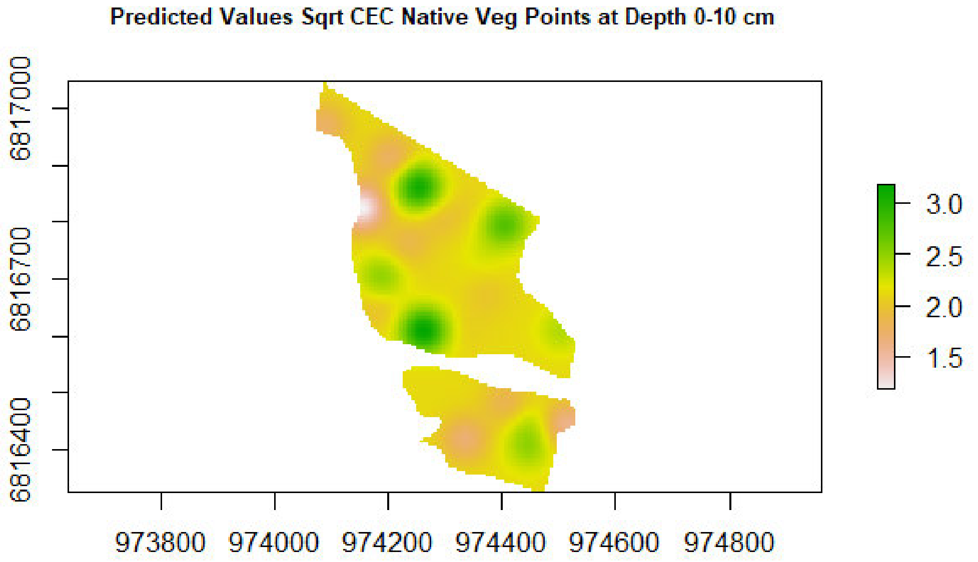

Predicted Values Silt % Native Veg Points at Depth 0-10 cm


Predicted Values Sqrt Silt % Native Veg Points at Depth 40-50 cm

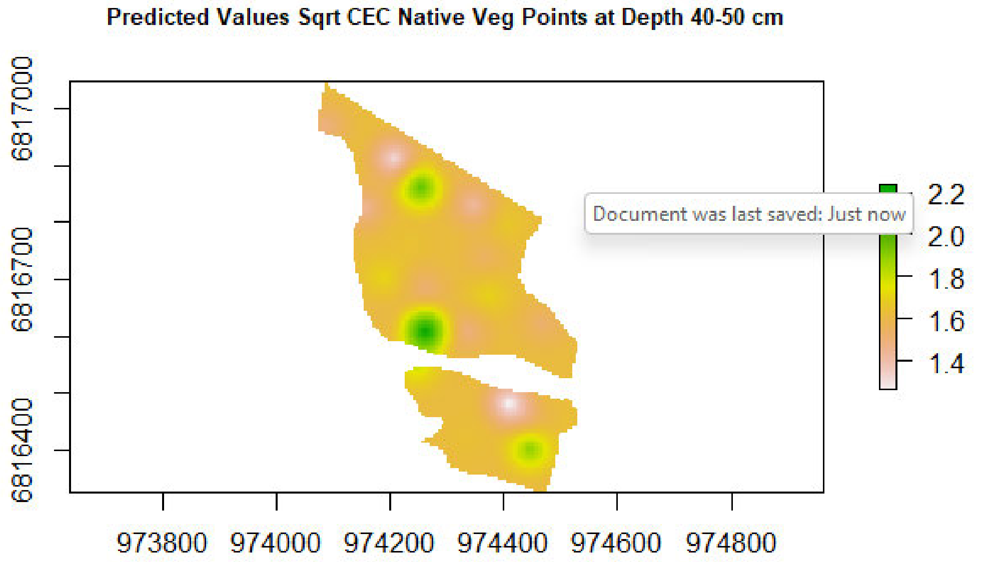

Predicted Values Sqrt Sand % Native Veg Points at Depth 0-10 cm



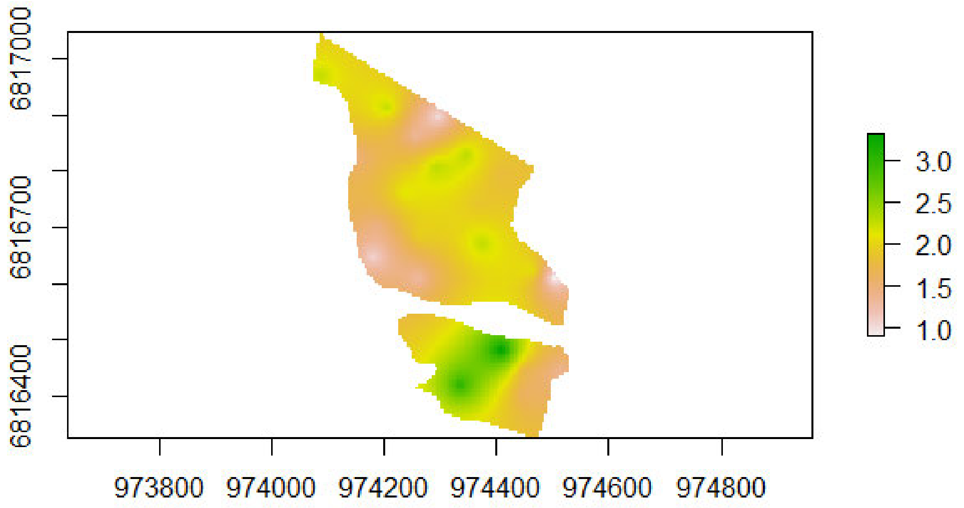
Predicted Values Sand % Native Veg Points at Depth 40-50 cm



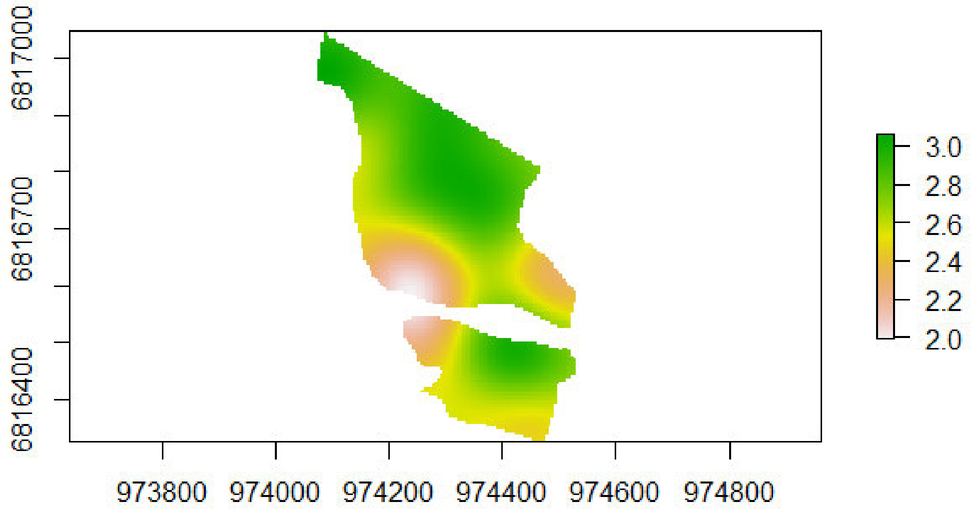
Predicted Values Sqrt CEC Native Veg Points at Depth 0-10 cm



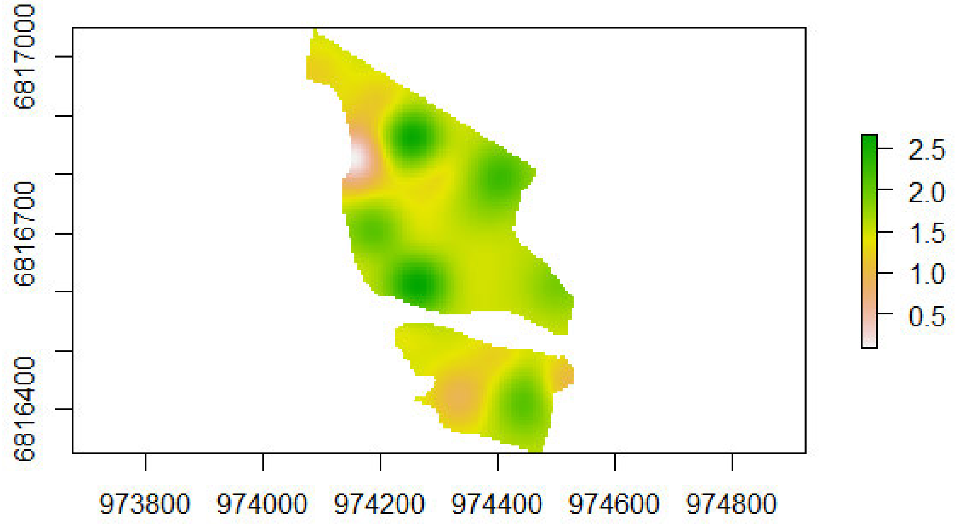
Predicted Values Sqrt CEC Native Veg Points at Depth 40-50 cm



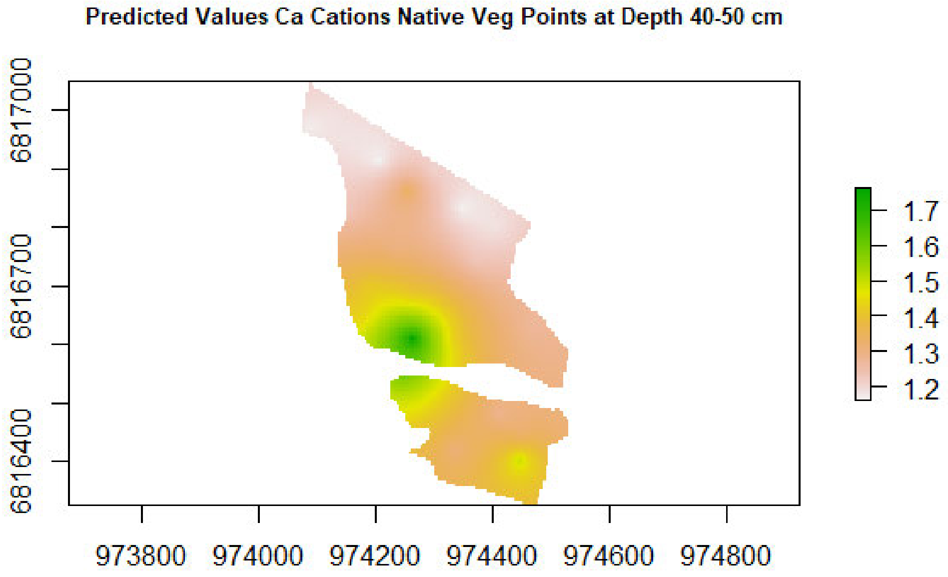
Predicted Values Sqrt ESP Native Veg Points at Depth 0-10 cm



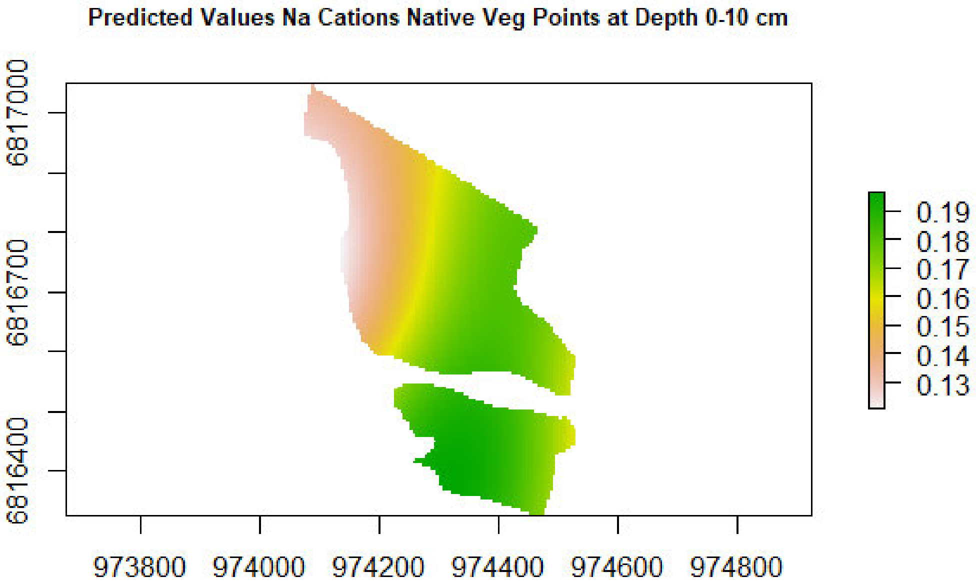
Predicted Values Sqrt ESP Native Veg Points at Depth 40-50 cm



Predicted Values Sqrt Ca Cations Native Veg Points at Depth 0-10 cm

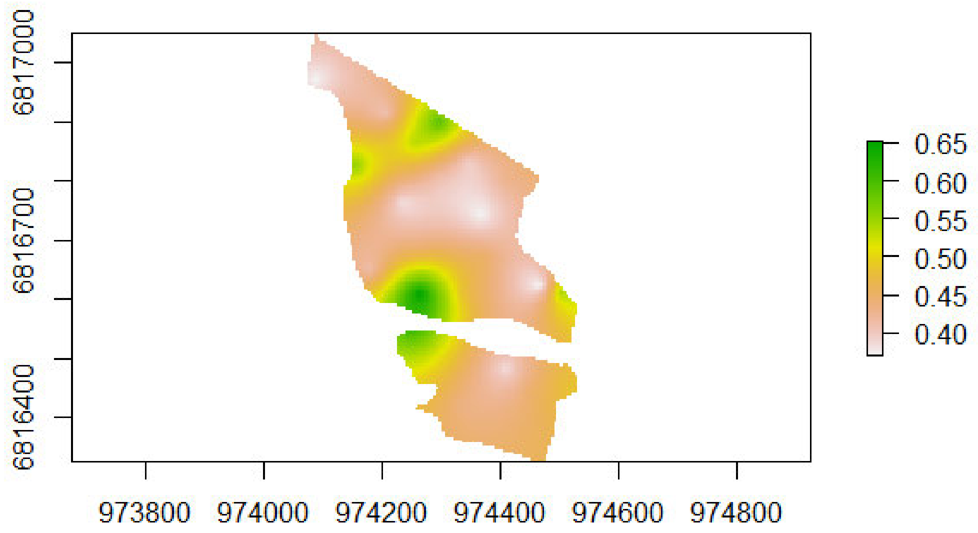


Predicted Values Ca Cations Native Veg Points at Depth 40-50 cm

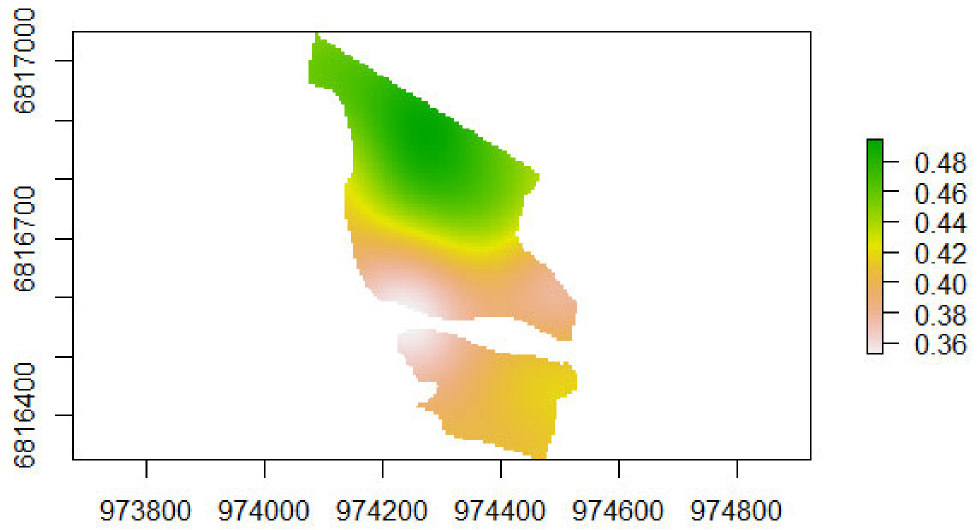


Predicted Values Na Cations Native Veg Points at Depth 0-10 cm

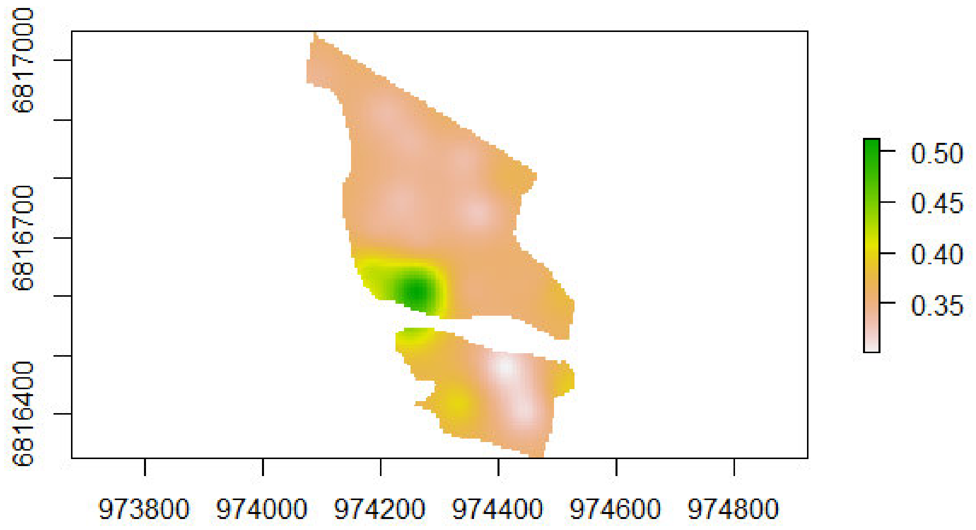
Predicted Values Sqrt K Cations Native Veg Points at Depth 0-10 cm

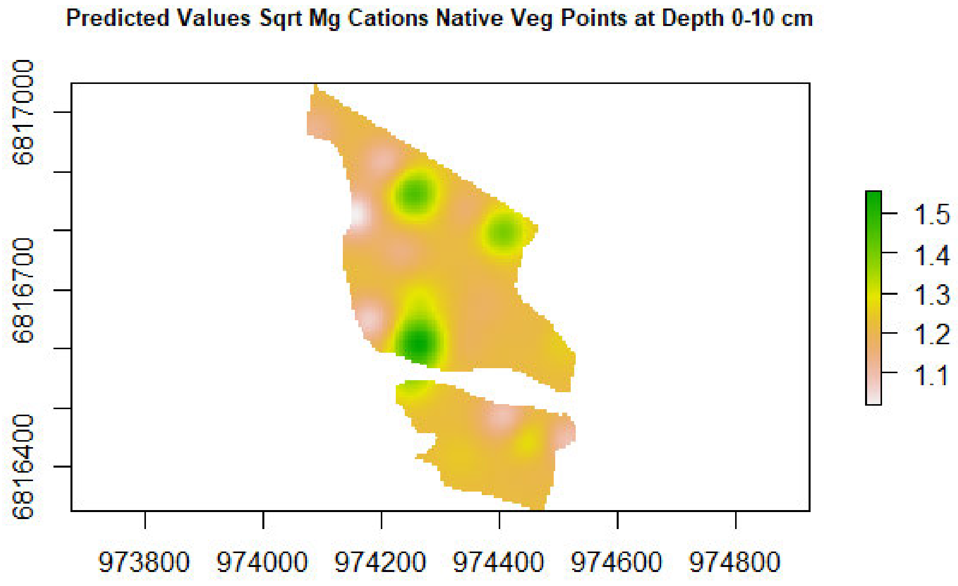


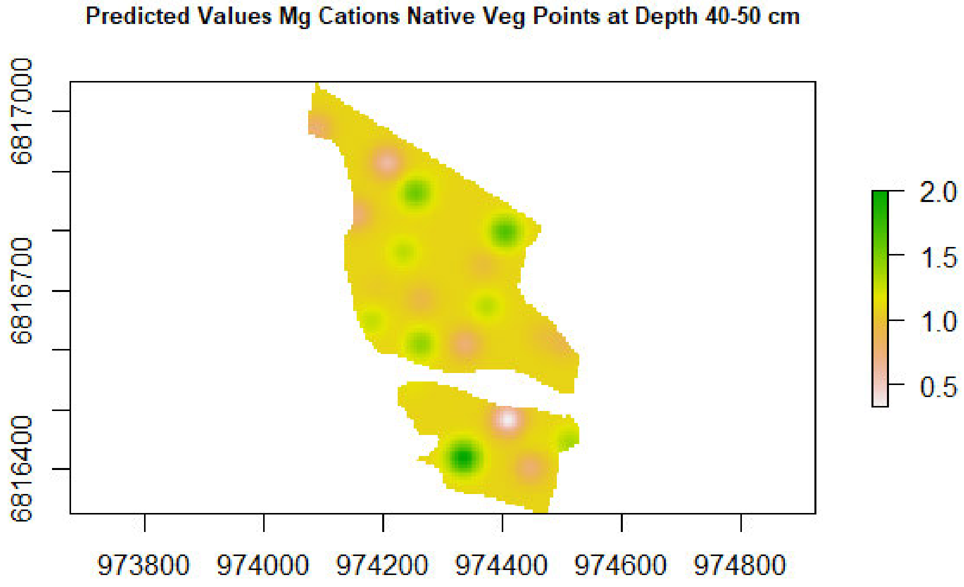
Predicted Values Sqrt Na Cations Native Veg Points at Depth 40-50 cm



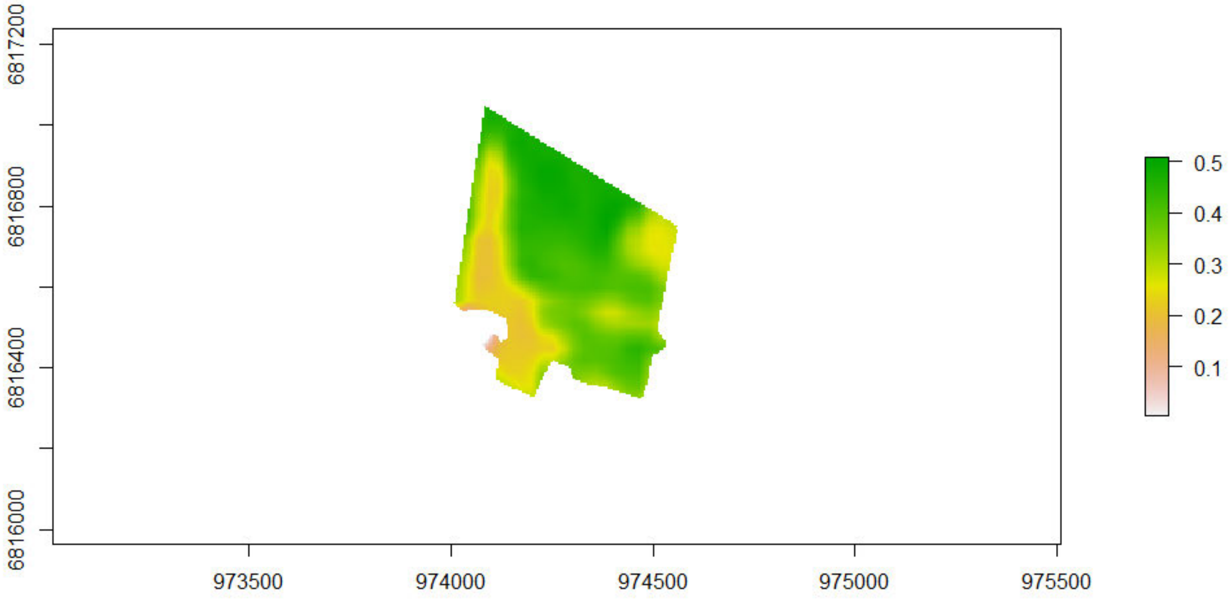
Predicted Values Sqrt K Cations Native Veg Points at Depth 40-50 cm



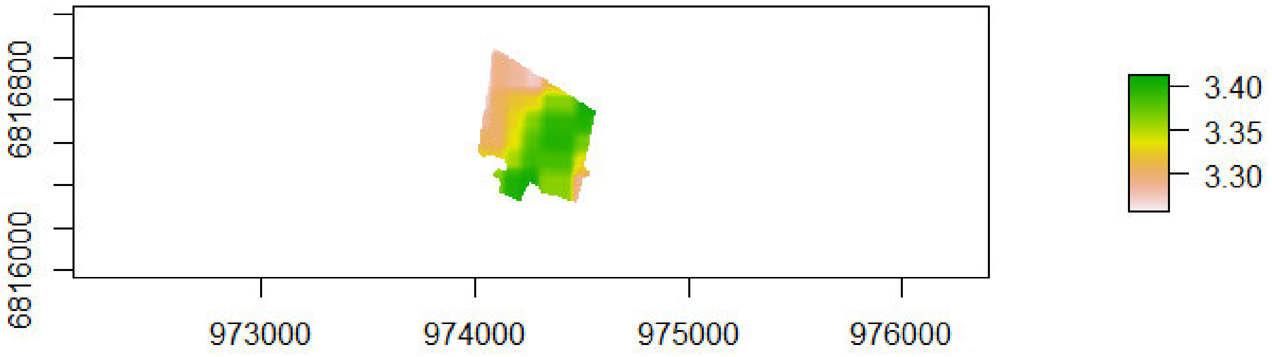




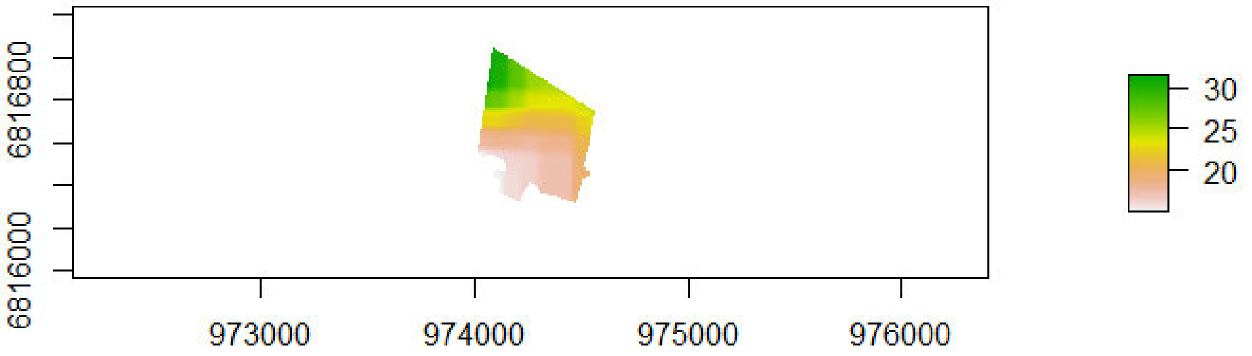
Appendix 1. 7 NDVI 20 Year Long Term Average Raster, Thorndale


6817200
6816800
6816400
6816000
973500
974000
974500
975000
975500
0.5
0.4
0.3
0.2
0.1

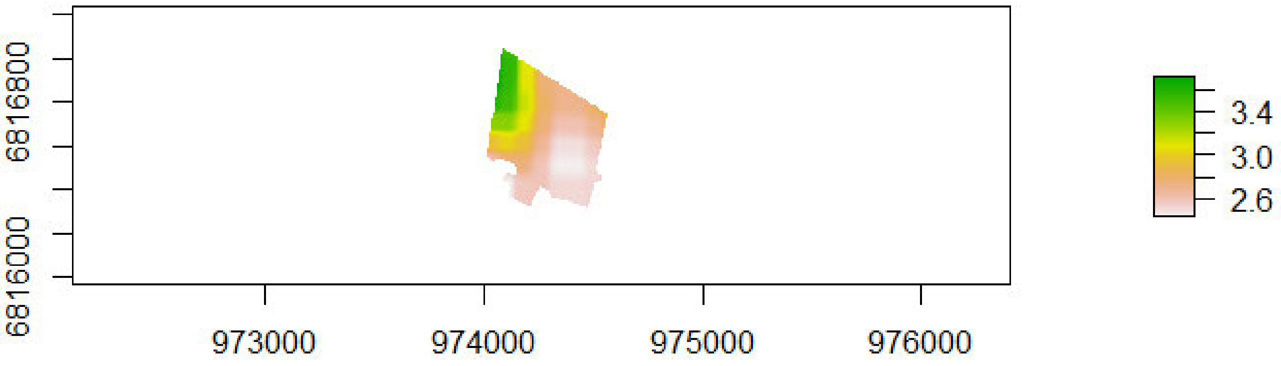
Appendix 1. 8 National Covariate Raster Potassium, Thorndale



Appendix 1. 9 National Covariate Raster Thorium, Thorndale



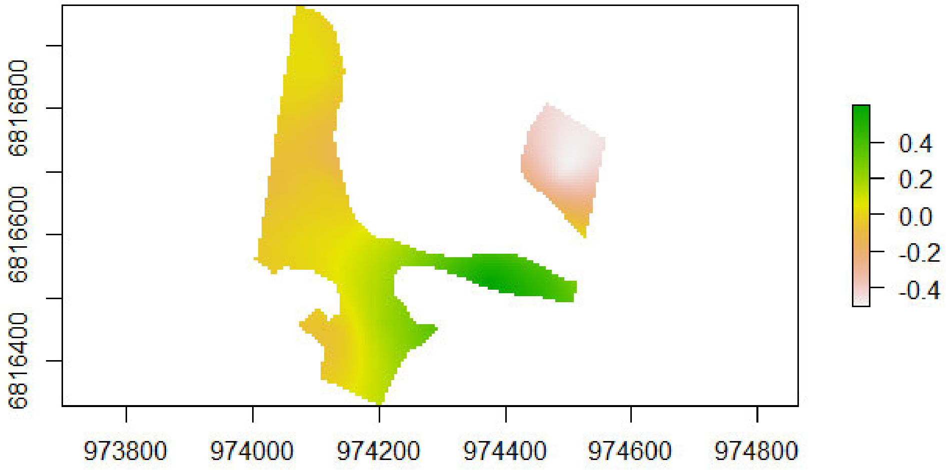
Appendix 1. 10 National Covariate Raster Uranium, Thorndale

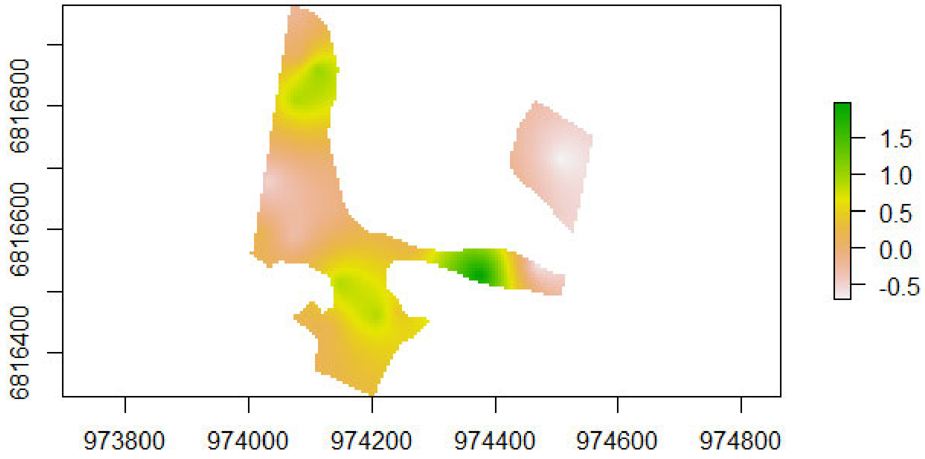


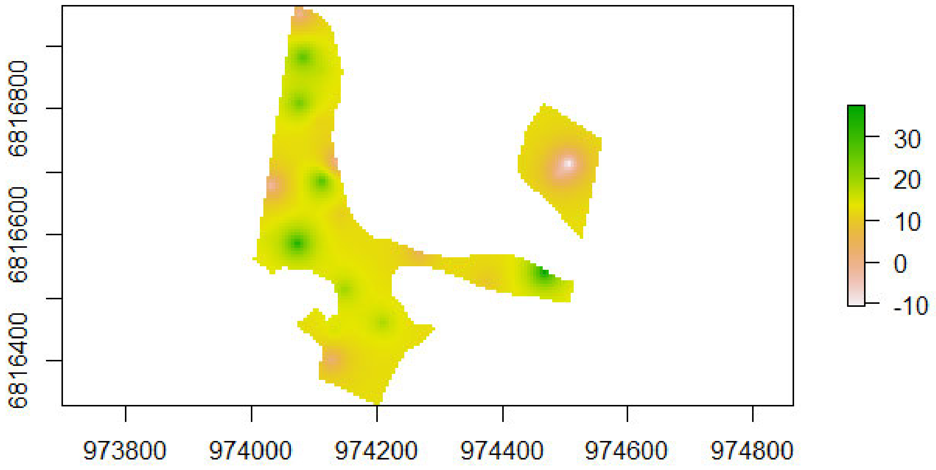
Appendix 1. 11 Correlation Table for Soil Attributes per Depth at Property Level, Thorndale. Values highlighted amber have a moderate association (+0.4 to +0.6; -0.4 to -0.6) between variables. Red values have a week association (+0.2 to +0.4; -0.2 to -0.4). No values have a strong to very strong association (+0.6 to +1, -0.6 to -1). Very weak or no association (-0.2 to +0.2) was not highlighted (LaMorte 2021).

Property	***Environmental Covariate R^2 Values***										
Soil Attribute & Depth	*TRI*	*TPI*	*Slope*	*Aspect*	*FlowDir*	*DEM*	*TC*	*K*	*Th*	*U*	*NDVI*
EC 0	0.398	-0.005	0.397	0.013	0.157	-0.369	-0.045	-0.186	-0.069	0.151	-0.469
EC 40	-0.339	0.015	-0.339	-0.333	0.162	0.289	0.012	0.257	0.037	-0.199	0.061
pH 0	0.432	0.042	0.43	0.148	0.007	-0.336	-0.175	-0.084	-0.217	0.145	-0.593
pH 40	0.506	0.211	0.503	0.25	-0.202	-0.443	-0.144	-0.081	-0.199	0.229	-0.648
pH CaCl 0	0.444	0.092	0.443	0.129	0.085	-0.409	-0.178	-0.122	-0.219	0.149	-0.595
pH CaCl 40	0.46	0.206	0.454	0.207	-0.139	-0.386	-0.154	-0.012	-0.203	0.172	-0.666
Clay % 0	-0.082	0.021	-0.082	0.064	-0.102	0.131	0.077	-0.031	0.081	0.033	0.183
Clay % 40	-0.333	-0.017	-0.33	-0.311	0.306	0.189	-0.194	0.178	-0.16	-0.352	0.15
Silt % 0	-0.048	-0.068	-0.053	-0.116	0.335	-0.036	-0.228	0.273	-0.22	-0.258	0.049
Silt % 40	0.062	-0.106	0.066	0.256	-0.1	-0.067	-0.242	0.139	-0.235	-0.228	0.214
Sand % 0	0.09	0.02	0.093	0.012	-0.099	-0.084	0.061	-0.121	0.054	0.112	-0.17
Sand % 40	0.214	0.077	0.21	0.08	-0.171	-0.102	0.292	-0.218	0.262	0.403	-0.242
eCEC 0	-0.097	-0.08	-0.098	-0.027	0.09	0.035	-0.195	0.109	-0.182	-0.22	0.012
eCEC40	-0.152	-0.182	-0.153	-0.075	0.199	0.131	-0.215	0.071	-0.2	-0.236	0.213
ESP % 0	-0.376	-0.018	-0.379	-0.104	0.065	0.351	-0.267	0.431	-0.247	-0.388	-0.009
ESP % 40	-0.301	-0.14	-0.299	0.025	-0.191	0.251	0.278	-0.198	0.302	0.098	0.401
Ca 0	-0.058	-0.078	-0.058	-0.016	0.081	-0.011	-0.18	0.08	-0.171	-0.183	-0.023
Ca 40	-0.029	-0.116	-0.031	0.028	0.058	0.034	-0.219	0.078	-0.217	-0.17	0.084
Na 0	-0.353	-0.023	-0.359	-0.108	0.15	0.343	-0.327	0.447	-0.306	-0.436	-0.023
Na 40	-0.288	-0.189	-0.287	-0.047	-0.041	0.229	0.22	-0.208	0.251	0.026	0.417
K 0	0.099	-0.081	0.101	-0.005	0.008	0.068	0.038	-0.129	0.044	0.021	0.105
K 40	-0.016	-0.02	-0.019	0.077	0.075	0.075	-0.232	0.199	-0.243	-0.139	0.051
Mg 0	-0.363	-0.027	-0.366	-0.086	0.08	0.375	-0.142	0.231	-0.105	-0.356	0.355
Mg 40	-0.246	-0.179	-0.246	-0.25	0.404	0.192	-0.151	0.061	-0.124	-0.262	0.247

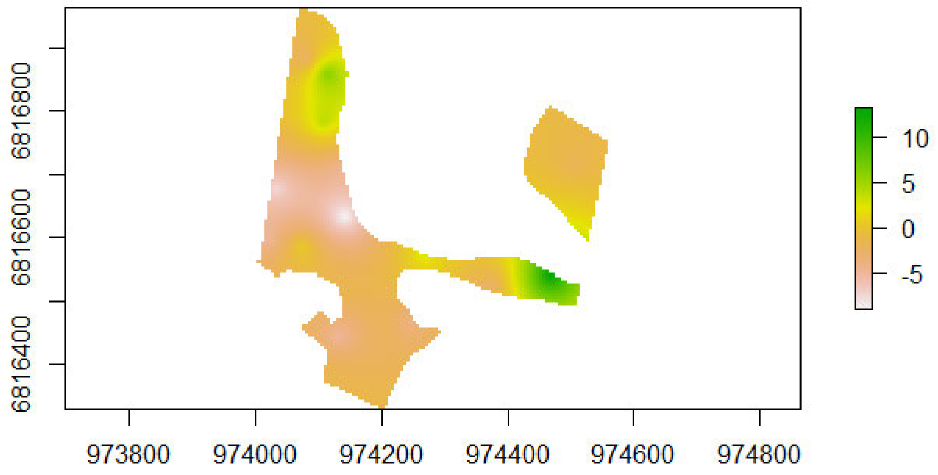
Appendix 1. 12 Series of Digital Soil Maps of Changes in Condition Attributes including NDVI per Depth for Farmed Areas, using Ordinary Kriging Interpolation


Predicted Values for Change in pH CaCl, Farmed Points at Depth 0-10 cm

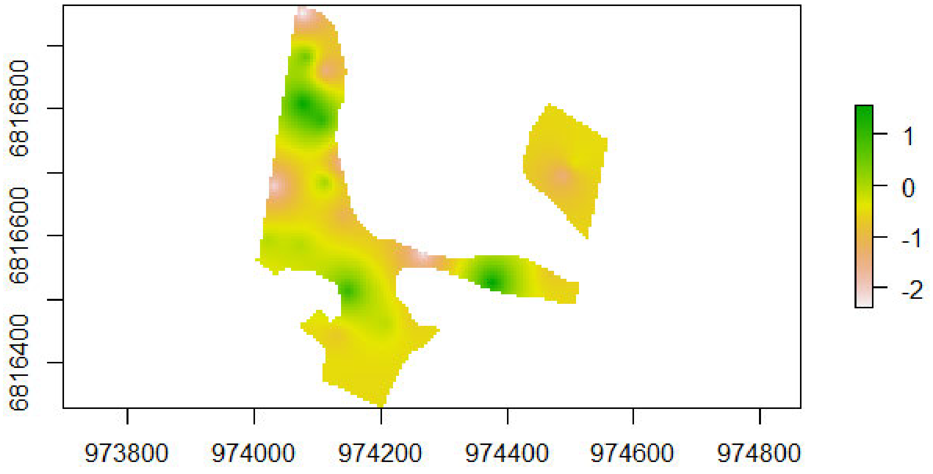

Predicted Values for Change in pH CaCl, Farmed Points at Depth 40-50 cm


Predicted Values for Change in EC, Farmed Points at Depth 0-10 cm

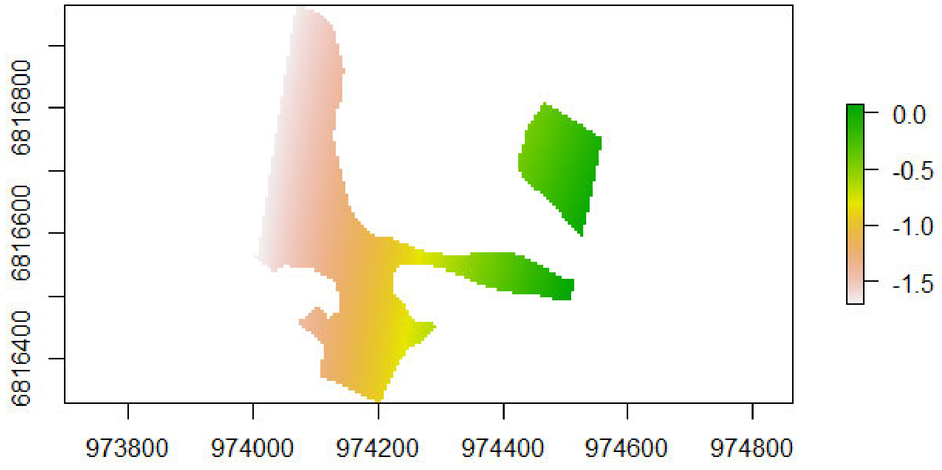
Predicted Values for Change in EC, Farmed Points at Depth 40-50 cm

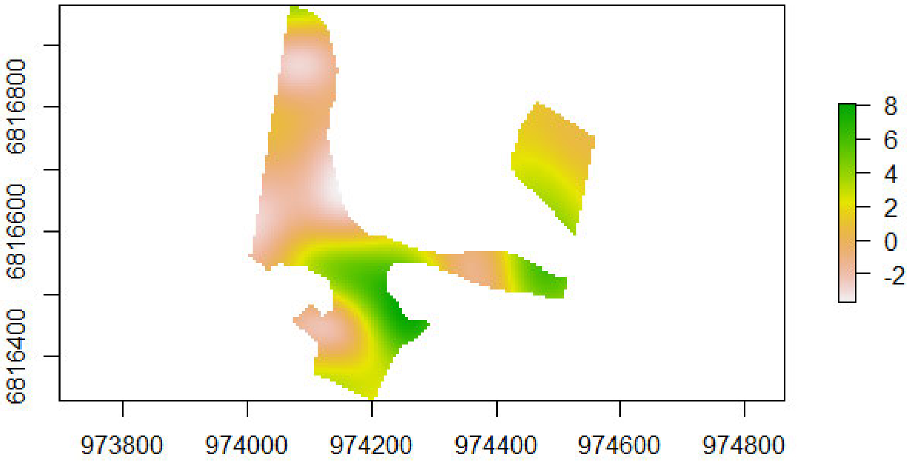


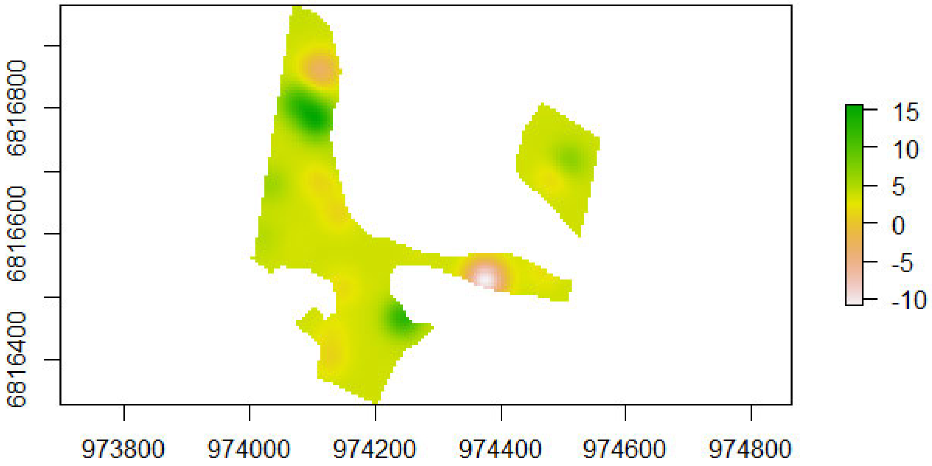
Predicted Values for Change in CEC, Farmed Points at Depth 0-10 cm

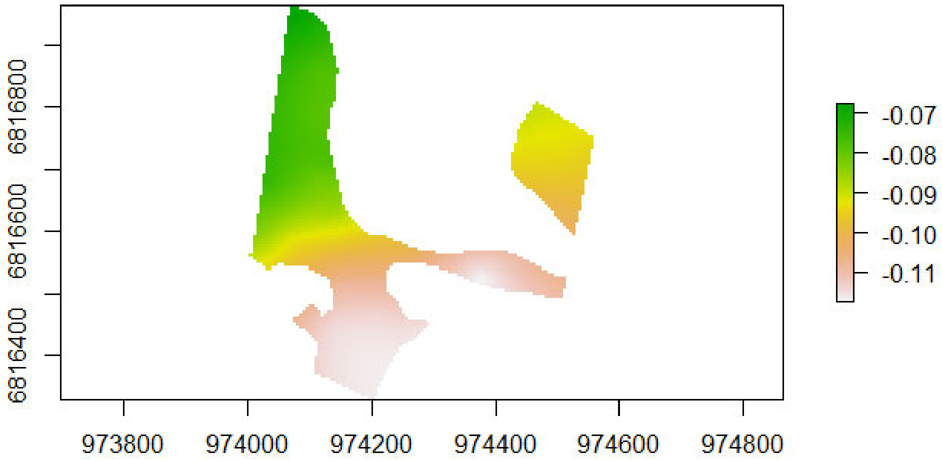


Predicted Values for Change in CEC, Farmed Points at Depth 40-50 cm

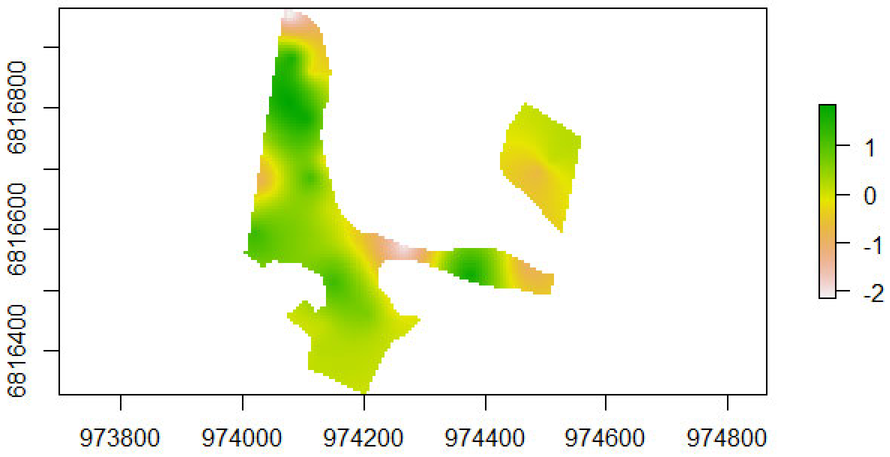



Predicted Values for Change in ESP, Farmed Points at Depth 0-10 cm

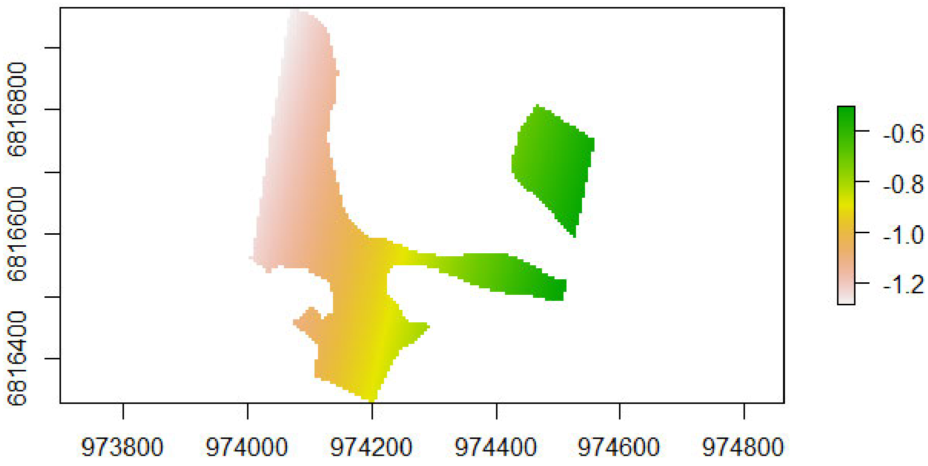

Predicted Values for Change in ESP, Farmed Points at Depth 40-50 cm


Predicted Values for Change in NDVI, Farmed Points

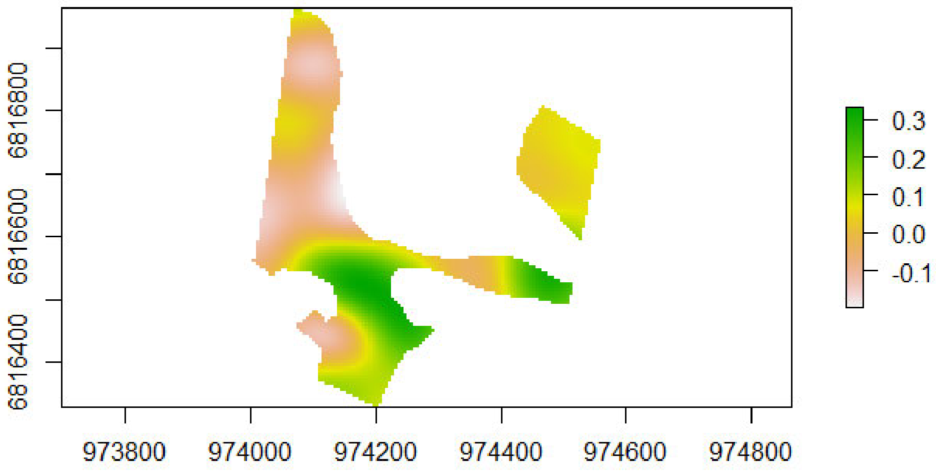
Predicted Values for Change in Ca Cations, Farmed Points at Depth 0-10 cm

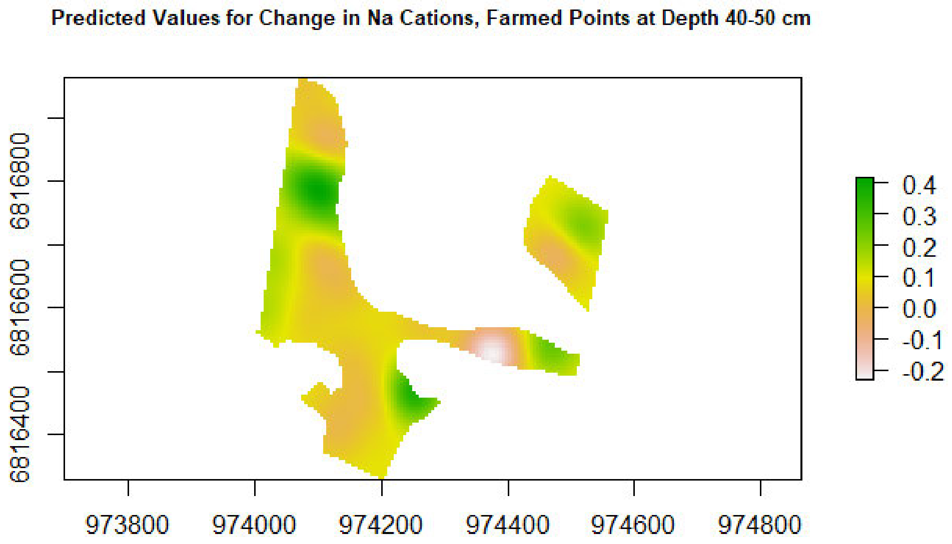


Predicted Values for Change in Ca Cations, Farmed Points at Depth 40-50 cm



Predicted Values for Change in Na Cations, Farmed Points at Depth 0-10 cm




Predicted Values for Change in Na Cations, Farmed Points at Depth 40-50 cm
6816400
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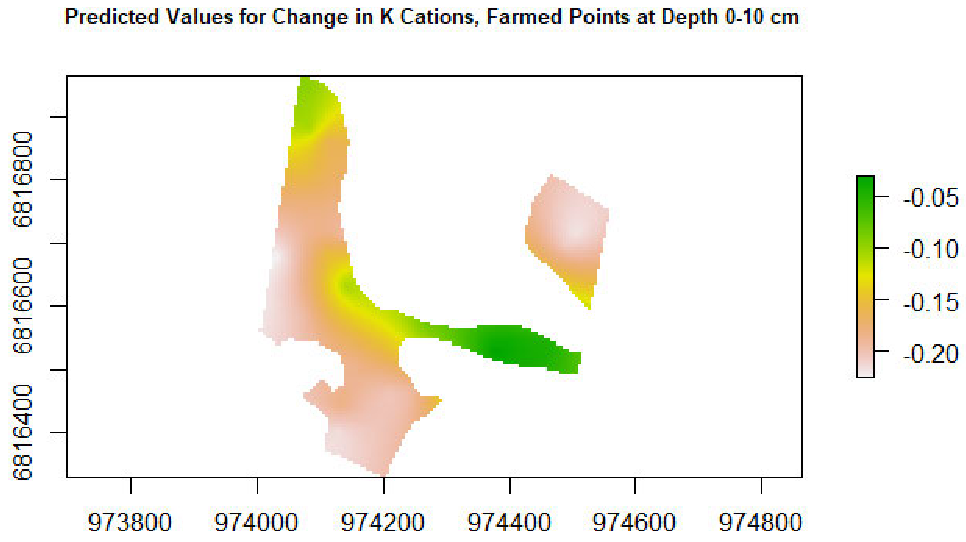
6816800
973800
974000
974200
974400
974600
974800
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2


Predicted Values for Change in K Cations, Farmed Points at Depth 0-10 cm
6816400
6816600
6816800
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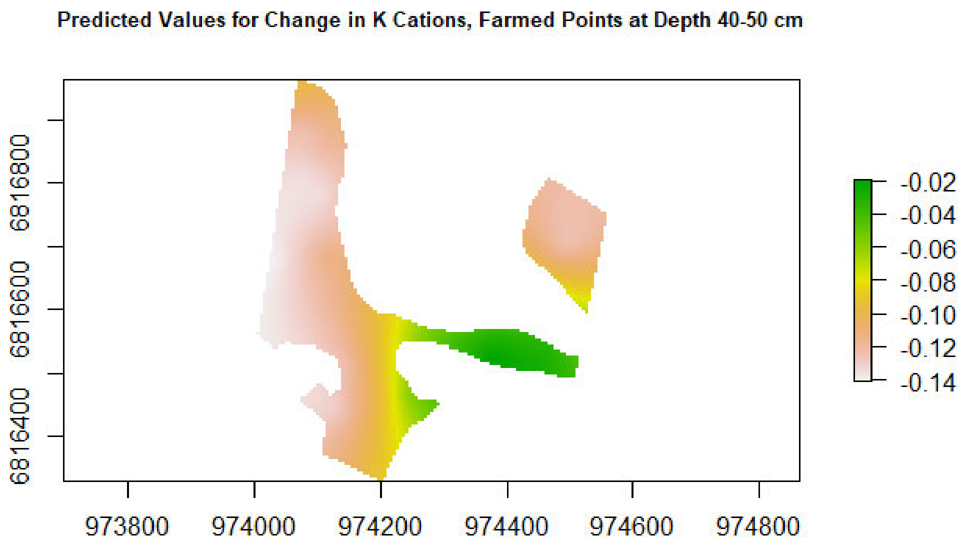
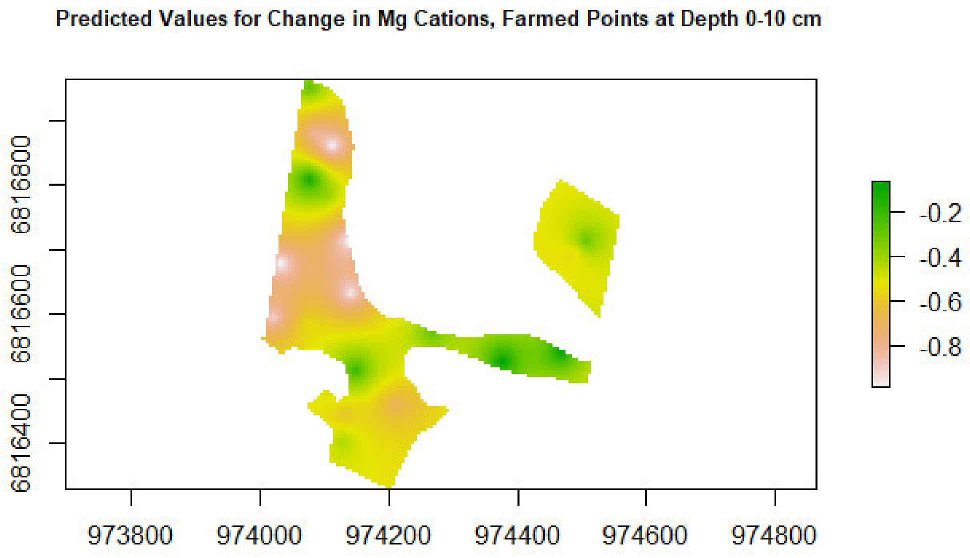
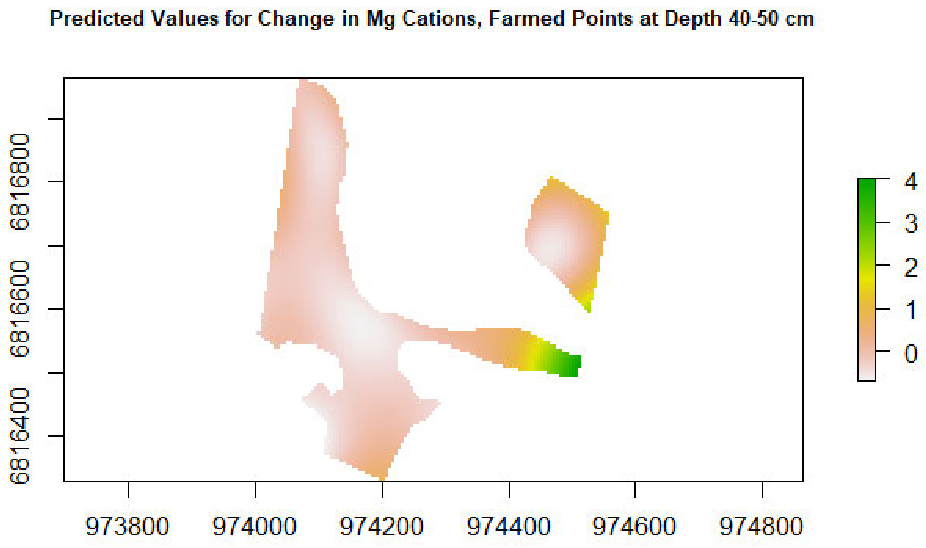
974000
974200
974400
974600
974800
-0.05
-0.10
-0.15
-0.20



Predicted Values for Change in K Cations, Farmed Points at Depth 40-50 cm

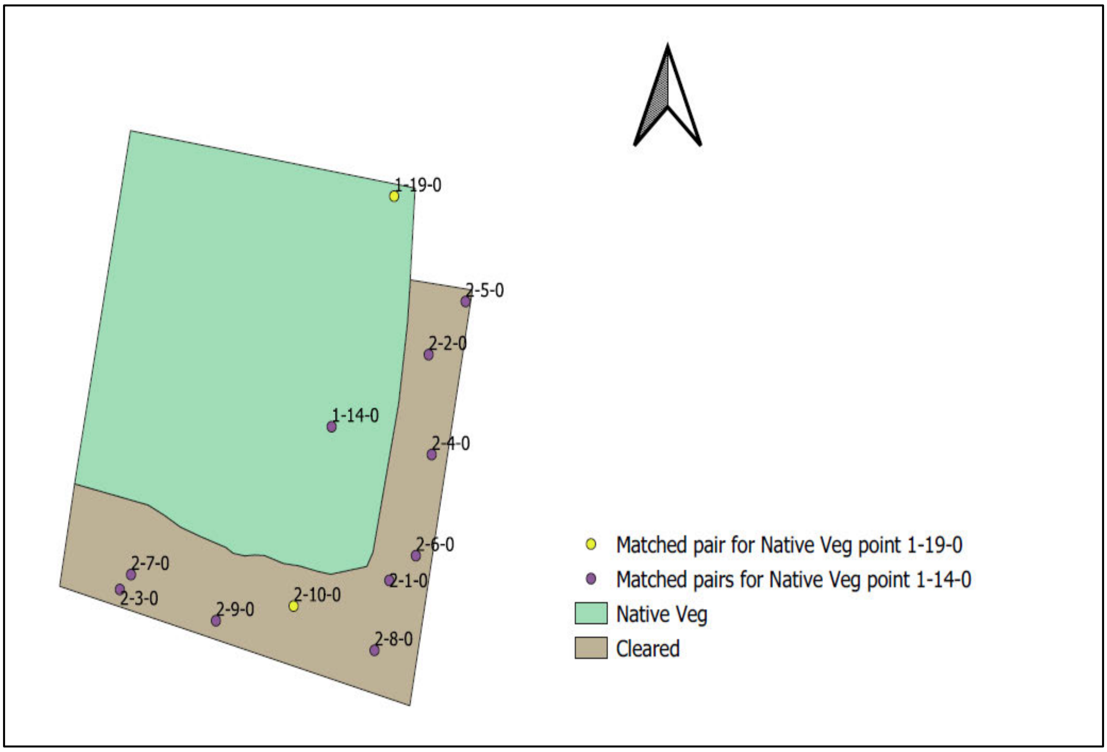


Predicted Values for Change in Mg Cations, Farmed Points at Depth 0-10 cm



Predicted Values for Change in Mg Cations, Farmed Points at Depth 40-50 cm

Appendix 1. 13 Geospatial Pairing based on Matched Pairs of Farm and Native Veg Capacity Attributes, Millmerran



Appendix 1. 14 Brief Statistical Summary of Chemical and Physical Properties of Soil Attributes; Cleared Area Depth 0 at Millmerran

	Cleared 0					
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*
pH 1:5	5.20	5.85	6.15	6.29	6.90	7.10
EC µ/cm	19.12	25.48	43.05	57.30	59.87	164.60
pH CaCl	4.20	4.50	4.70	4.77	5.08	5.60
Clay %	0.00	0.00	2.19	4.88	5.78	23.75
Silt %	0.00	1.41	2.50	2.94	3.59	6.88
Sand %	69.38	88.91	95.00	92.19	98.59	100.00
eCEC cmol(+)/kg	3.18	3.80	6.04	8.84	11.50	27.62
ESP	1.73	6.61	9.39	9.92	10.83	20.40
NDVI	0.28	0.31	0.32	0.32	0.32	0.36
Ca cmol(+)/kg	1.41	1.79	2.64	3.59	4.29	8.59
Na cmol(+)/kg	0.00	0.16	0.63	0.87	1.34	2.94
K cmol(+)/kg	0.22	0.31	0.34	0.41	0.53	0.79
Mg cmol(+)/kg	1.02	1.42	2.23	3.92	4.17	15.30

Appendix 1. 15 Brief Statistical Summary of Chemical and Physical Properties of Soil Attributes; Cleared Area Depth 40 at Millmerran

	Cleared 40					
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*
pH 1:5	5.70	6.33	7.60	7.76	9.38	9.70
EC µ/cm	12.28	23.24	146.45	156.75	222.00	450.90
pH CaCl	4.40	4.88	6.30	6.18	7.40	7.70
Clay %	0.00	1.25	5.00	5.81	9.06	13.75
Silt %	0.00	1.41	2.50	2.31	2.97	5.00
Sand %	81.25	88.12	92.81	92.12	98.44	99.30
eCEC cmol(+)/kg	1.34	2.68	7.47	7.53	9.75	20.75
ESP	2.75	19.06	26.79	23.74	31.16	34.32
Ca cmol(+)/kg	0.34	0.93	1.05	1.15	1.22	2.86
Na cmol(+)/kg	0.04	0.49	2.40	2.09	2.76	5.50
K cmol(+)/kg	0.05	0.11	0.13	0.15	0.16	0.33
Mg cmol(+)/kg	0.64	1.08	4.06	4.15	5.84	12.06

Appendix 1. 16 Brief Statistical Summary of Chemical and Physical Properties of Soil Attributes; Native Veg Area Depth 0 at Millmerran

	Native Veg 0					
	Min.	*1st Quart*	*Median*	*Mean*	*3rd Quart*	*Max.*
pH 1:5	4.70	5.08	5.30	5.36	5.63	6.20
EC µ/cm	9.25	18.46	23.46	32.26	33.47	114.90
pH CaCl	3.20	3.80	3.85	3.98	4.08	5.30
Clay %	0.00	0.00	0.31	1.05	0.70	8.75
Silt %	0.00	0.63	0.94	1.08	1.88	2.50
Sand %	89.38	97.97	98.75	97.97	98.91	99.38
eCEC cmol(+)/kg	1.02	2.49	3.64	4.36	5.24	12.05
ESP	0.41	2.07	6.28	6.58	9.61	19.14
NDVI	0.47	0.54	0.55	0.54	0.56	0.59
Ca cmol(+)/kg	0.35	1.21	2.03	2.24	2.79	5.60
Na cmol(+)/kg	0.02	0.07	0.21	0.33	0.39	2.31
K cmol(+)/kg	0.08	0.11	0.17	0.19	0.21	0.70
Mg cmol(+)/kg	0.50	0.86	1.18	1.60	1.58	6.82

Appendix 1. 17 Brief Statistical Summary of Chemical and Physical Properties of Soil Attributes; Native Veg Area Depth 40 at Millmerran

	Native Veg 40					
	Min.	1st Quart	Median	Mean	3rd Quart	Max.
pH 1:5	4.10	5.43	5.65	5.65	5.83	7.60
EC µ/cm	4.87	8.05	8.79	36.63	13.48	293.40
pH CaCl	3.80	3.88	4.00	4.16	4.25	6.10
Clay %	0.00	0.63	0.94	2.22	2.50	16.25
Silt %	0.00	0.00	0.63	0.81	1.25	3.75
Sand %	80.62	97.50	98.75	97.00	98.75	100.00
eCEC cmol(+)/kg	0.85	1.62	1.96	3.34	2.38	21.82
ESP	2.28	6.36	17.53	14.75	21.20	28.91
Ca cmol(+)/kg	0.12	0.49	0.60	0.65	0.83	1.22
Na cmol(+)/kg	0.03	0.15	0.37	0.69	0.38	5.63
K cmol(+)/kg	0.05	0.08	0.09	0.11	0.13	0.31
Mg cmol(+)/kg	0.63	0.75	0.85	1.89	1.08	14.66

Appendix 1. 18 Difference in Capacity Attributes for Paired Points, Millmerran. Highlighted green text (0 values) indicate where no difference exists, and optimal pairing for the attribute. Thorium (Th) gamma data was not available for this site.

Paired Points			***Difference in Capacity Attributes***										
Paired Number	Cleared Points	Native Veg Points	Clay % 0	Clay % 40	Silt % 0	Silt % 40	Sand % 0	Sand % 40	DEM	Aspect	Slope	K Gamma	U Gamma
1	2-1-0	1-14-0	5.00	8.75	1.25	1.25	-6.25	-10.00	0.29	-2.21	-0.03	-0.04	-0.25
1	2-2-0	1-14-0	1.25	0.63	-1.88	1.25	0.63	-1.88	-4.26	69.41	0.09	0.02	1.70
1	2-3-0	1-14-0	25.00	1.88	5.00	-2.50	-30.00	0.63	6.77	240.57	-0.06	0.19	0.90
1	2-4-0	1-14-0	1.25	-1.88	-0.63	0.63	-0.63	1.25	-2.64	251.11	0.09	-0.03	0.88
1	2-5-0	1-14-0	1.88	0	0.63	-0.63	-2.50	0.63	-5.52	161.12	0.07	0.14	3.31
1	2-6-0	1-14-0	1.25	6.88	0	1.88	-1.25	-8.75	-1.02	175.34	0	-0.01	0.89
1	2-7-0	1-14-0	7.50	13.13	4.38	1.25	-11.88	-14.38	6.42	-1.38	0.19	0.19	0.90
1	2-8-0	1-14-0	5.63	7.50	0.63	2.50	-6.25	-10.00	1.39	295.59	-0.03	-0.04	0.42
2	2-9-0	1-14-0	11.25	13.13	1.88	3.75	-13.13	-16.88	4.95	2.80	0.12	0	0.63
1	2-10-0	1-19-0	00	1.25	0.63	0	-0.63	-1.25	9.34	12.80	-0.16	0.06	-1.32
		Mean	6.00	5.13	1.19	0.94	-7.19	-6.06	1.57	120.52	0.03	0.05	0.81
		Range	25.00	15.00	6.88	6.25	30.63	18.13	14.86	297.80	0.35	0.23	4.63

Appendix 1. 19 Difference in Condition Attributes for Paired Points, Millmerran. Highlighted red text indicates a negative effect, or more alkaline effect for pH values. NDVI is included as an expected outcome.

Paired points			***Changes in Condition Attributes***								
Pair Number	Cleared Points	Native Veg Points	pH 0	pH 40	EC 0	EC 40	eCEC 0	eCEC 40	ESP % 0	ESP % 40	NDVI
1	2-1-0	1-14-0	1.90	3.60	14.78	139.15	3.14	4.92	10.23	27.39	-0.25
1	2-2-0	1-14-0	1.10	0.50	-0.64	10.84	-0.24	0.34	0.78	4.58	-0.23
1	2-3-0	1-14-0	0.00	-0.20	98.10	300.75	23.82	18.27	0.55	19.60	-0.27
1	2-4-0	1-14-0	0.60	0.20	-1.08	1.03	-0.32	-1.14	0.02	-4.18	-0.19
1	2-5-0	1-14-0	0.80	0.40	5.54	15.45	1.34	0	-2.34	16.23	-0.23
1	2-6-0	1-14-0	0.50	3.40	5.19	196.05	-0.62	5.11	-7.69	24.33	-0.24
1	2-7-0	1-14-0	0.80	2.40	42.43	439.65	9.12	7.99	-1.47	20.13	-0.22
1	2-8-0	1-14-0	1.70	3.50	30.93	131.25	3.43	5.07	10.29	25.35	-0.24
1	2-9-0	1-14-0	1.80	3.80	31.37	215.65	10.03	9.83	-3.89	23.94	-0.23
2	2-10-0	1-19-0	0.90	0.80	120.97	2.99	-2.58	0.53	-4.84	-3.480	-0.15
		Mean	1.01	1.84	34.76	145.28	4.67	5.09	-1.08	15.39	-0.23
		Range	1.90	4.00	122.05	438.62	26.40	19.41	22.66	31.57	0.12

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[i] The inclusion of the pH CaCl measurement did not produce any contextual differences to the pH 1:5 measurement in any of the soil chemical analyses to date.

Consequently, it was not included in the final condition change demonstrative results.