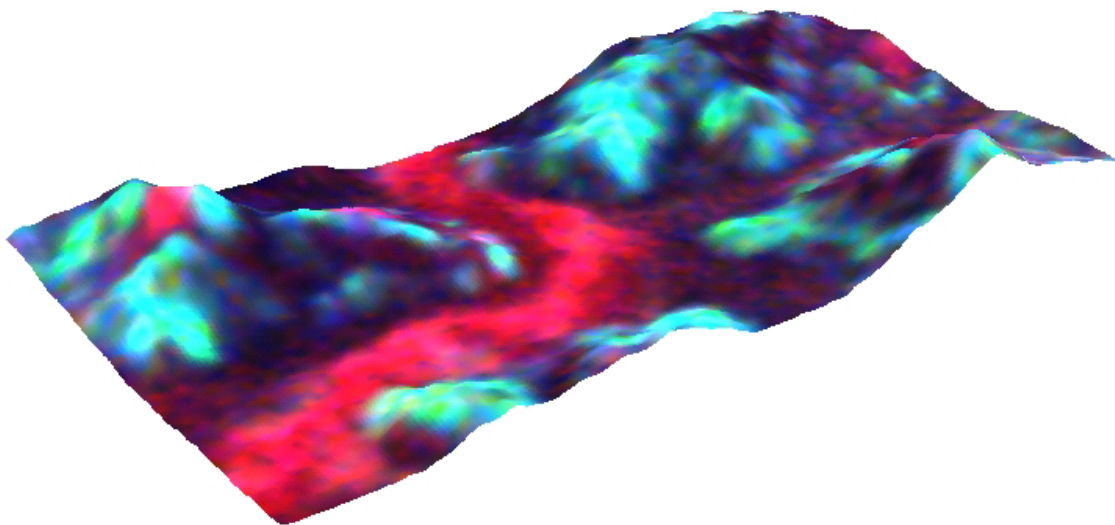

A Farm Scale Site Selection Method for Dryland Forestry

Maia Williams

October 2006



Supervisor:
Associate Professor Keith Smettem



Abstract

Forestry is expanding into new regions of the south-west of Western Australia. Plantations are being developed in lower rainfall areas for timber harvesting, salinity control and carbon sequestration purposes. There is an urgent need for location specific, efficient site selection methods to ensure that plantations are optimally located from both economic and environmental perspectives. Traditional site selection methods are based on soil surveys which require costly, intensive sampling regimes and often do not characterise the factors effecting tree growth. This study uses a Forest Products Commission plantation near Kojonup, 'Sandawindy', as a study site for assessing a new site selection method. The tree performance observations were made on two year old *E. cladocalyx* trees. The carbon sequestration and groundwater recharge rates associated with the plantation have been calculated and the potential effects of salinity assessed.

The method of site selection uses gamma radiometric, electromagnetic (EM) and Digital Elevation Model (DEM) data available for the area. Previously determined relationships between soil types and radiometric data have been implemented, together with well defined limitations to tree growth. Spatial analysis and interpretation of the data has been performed using a Geographic Information System (GIS), leading to a classification of the study area in terms of predicted plantation performance. This classification consists of five different growth categories.

Field observations of tree performance and major soil or topographic features were used to determine the success of the landscape assessment. The results indicate that the available data can be used to accurately identify variations in plantation performance. These variations are in response to areas of salinity, shallow soil, waterlogging, sand, surface laterite and ironstone gravel content. The assessment has been based on the current performance of the trees, although it is recognised that their response to the landscape will change as they mature.

The current rate of carbon sequestration of the *E. cladocalyx* species present at the site is 2 t CO₂-e/ha.yr. This is low, as expected, due to the ages of the trees. The reduction in recharge to groundwater associated with the plantation is between 78 and 132 mm/yr across the site. The plantation is likely to suffer severe growth limitations across 42% of the planted area due to the effects of salinity detected at 1-4m below the surface.

Acknowledgments

I would hereby like to offer my thanks to the people who have helped in defining, designing, doing and dealing with this project!

Firstly, thankyou very much to my supervisor, Keith Smettem, for offering me a project so finely suited to what I requested. And thankyou for assuring me I was thinking straight and renewing my enthusiasm when needed.

Thankyou to Gabriella Pracilio for much help with the data processing and GIS aspects of the project. Thankyou for the pre processing you did of most of the data and for helping with my little questions whenever you could.

For help in developing the project, providing data and accompanying us on the field trip, thankyou to Richard Harper from the Forest Products Commission. Thankyou also to Kim Allen for providing information on the study site.

Thankyou to my mother, Miranda, for long distance proof reading!

Lastly, thankyou to friends long finished and graduated who offered their post-thesis wisdom.

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1.0 Introduction

1.1 Rationale

The changing purposes, viability and location of forestry plantations results in the need for an improvement of site selection methods. Site selection is the key step to ensuring that plantation goals are met, and provides a basis for successful plantation and land use management.

There is much research being done in related fields such as landscape mapping, salinity control, carbon sequestration and dryland forestry. This study sources information from each of these areas, and through an integrated assessment, addresses the need for effective landscape assessment at a farm scale.

1.2 Context

In Western Australia dryland salinity is a major threat to agricultural regions. A potential method of control and mitigation is to implement large scale revegetation with deep rooted perennial species. This is best achieved through the inclusion of forestry, lucerne or forage shrubs amongst annual crops and grazing. It has been found, however, that these land use options are currently unviable across most affected areas and hence not being readily implemented (Lefroy et al. 2005).

There is, however, an increase in the variety and magnitude of the economic inputs associated with forestry. Carbon sequestration and emissions offsetting schemes are leading to the formation of investment plantations funded largely by the private sector. There is also an increase in the demand for plantation eucalyptus timber, associated with stricter controls on native forest harvesting. If implemented in conjunction with salinity abatement schemes, forestry projects will become increasingly viable (Petersen 2003). This is of particular significance to dryland regions where forestry is traditionally an unfeasible land use.

Plantation site selection involves a landscape assessment of the proposed area. Current advances in assessment techniques, for all applications, involve the use of airborne geophysical data and geomorphological approaches to soil mapping. Airborne radiometric data interpretation within a Geographic Information System (GIS) analysis environment has been identified as a useful technique for farm scale site assessment.

1.3 Aims and Objectives

The central aim of this study is to develop an efficient farm scale site selection method which ensures that forestry plantations are optimally located from both environmental and economic perspectives. The specific objectives used to achieve this aim are as follows:

1. To identify relevant soil types and landscape features and classify the study site according to these characteristics.
2. To apply a growth rating index and predict the performance of trees across the study site. Then assess this prediction using current plantation performance observations.
3. Calculate current carbon sequestration and groundwater recharge rates, and assess the effects of salinity on the plantation.

Chapter 2 of this dissertation contains a literature review of material related to the context and purpose of the study, as well as the methodology used. The review covers the changing purposes of forestry, current site selection methods and an assessment of the use of airborne radiometric data.

Chapter 3 gives a detailed outline of the methodology used to achieve the aims of the study, followed by the presentation of the results in Chapter 4. The implications of these results are discussed in Chapter 5 followed by the conclusions of the study and recommendations for future work in Chapters 6 and 7, respectively.

2.0 Literature Review

Small scale farm forestry is being introduced into the agricultural regions of Western Australia. This is due to the creation of economically viable forestry markets, the need to manage dryland salinity and the potential for increased economic input from the development of greenhouse gas abatement schemes (Petersen 2003; Herbohn & Harrison 2004). In order to maximise the productivity and environmental benefits associated with these plantations, there is the need to develop accurate and efficient methods of site selection. This literature review examines the driving forces behind dryland farm forestry, current and developing methods for site selection and the inclusion of airborne radiometric data in landscape assessment applications.

2.1 Carbon Sequestration

2.1.1 Kyoto Protocol

In response to the threat of global climate change the United Nations Framework Convention for Climate Change (UNFCCC) was developed. The framework forms the basis upon which international efforts can be made to address climate change through the reduction and monitoring of greenhouse gas emissions (UNFCCC 2006). The Convention initially met in 1992 and has been followed by the Montreal Treaty of 1994 and the Kyoto Protocol in 1997 (Specht & West 2003). Under the Kyoto protocol all countries have been given specific emissions reduction targets relative to their 1990 levels. These must be reached by 2008 – 2012 should the country agree to ratify. The protocol came into force in 2005 and the commitment made by the 164 ratifying countries is now legally binding (UNFCCC 2006). Australia has not agreed to ratify the Protocol.

The mechanisms by which targets can be met are split into three groups: the Clean Development Mechanism - emission reduction or development of carbon sinks; Joint Implementation – one country investing in emissions reduction or carbon sink development in another country and obtaining credits for itself; and Emissions Trading – countries can trade carbon credits obtained through any mechanism (UNFCCC 2006).

As the treaty progresses, the focus is moving away from direct greenhouse gas emission reduction to carbon sequestration, carbon offsetting and carbon trading options. A major component of each Kyoto mechanism is the Land use, Land use Change and Forestry (LULUCF) sector which covers vegetation and soil carbon sink options. These methods are the most debated components of the protocol, as the prediction, measurement, verification,

certification and management of natural systems is highly complex. Only in the Marrakech Accords of 2001 were the final details of Sections 3.3 (Plantations and Farm Forestry) and 3.4 (Rangeland Management, Cropland Management and Revegetation) agreed upon (Petersen 2003; UNFCCC 2006). There is, however, an upper limit placed on the contribution of emissions offsetting mechanisms; sequestered carbon can only account for up to 80% of the international 2008-2012 target (Gower 2003).

Under the Kyoto Protocol, international emission trading markets can exist between ratifying, developed, industrialised countries known as Annex 1 countries. The units can be obtained from any of the sequestration mechanisms but are converted into 1 tonne equivalent Carbon Dioxide units ($\text{CO}_2 - \text{e}$) to be compared and traded. The emissions trading under the Protocol is designed to work alongside national and regional domestic markets (UNFCCC 2006). The first major cross-industry trading market started in the United Kingdom in 2002 and has been followed by the establishment of similar schemes in Europe, Canada, Denmark, Japan and some states in the United States of America (IETA 2006).

2.1.2 Australia - International

As a party of the UNFCCC, Australia's commitment to the convention requires the implementation of national emission reduction programs, the support of research into relevant technologies, the maintenance of a National Greenhouse Gas Inventory and the promotion of public awareness regarding climate change issues. It participates in the convention meetings, submits climate change reports, and aims to meet the 2008-2012 emissions target of 108% (relative to 1990 levels). It is not, however, legally bound to do so. (Australian Greenhouse Office 2006).

Australia has entered into a number of bilateral climate change partnerships with the United States, New Zealand and China, and is working in collaboration with the European Union and Japan on a number of climate, energy, carbon accounting and technology projects. None of these partnerships have extended to emissions trading, although there is work being done with the European Union to standardise emissions accounting methods (Australian Greenhouse Office 2006). Groups such as the Australasian Emissions Trading Forum (2006) state that although Australia is not eligible to take part in international trading under Kyoto, it is still important to consider Australia's interaction with such markets .

2.1.3 Australia – Domestic

Domestic emissions trading is a definite possibility for Australia, with serious consideration being given to the expansion of existing state emissions trading schemes. The Electricity Benchmarks Carbon Trading Scheme has been functioning in New South Wales since 2003 and lead to the initiation of a similar greenhouse gas abatement scheme which was due to start in the ACT in 2005. These schemes are currently only functioning within the electricity generation and distribution industries (ICRC 2006; CRC for Greenhouse Accounting 2006).

A National Emissions Trading Task Force has been established in order to investigate the viability of extending these existing markets to other states and national scale trading. Each state is conducting their own investigations and a report of the current situation is expected in 2006 (Australasian Emissions Trading Forum 2006).

Rising alongside emissions trading schemes, are other governmental and private initiatives whereby landowners are paid to establish carbon sinks on their properties. In Victoria the government has established Carbon Tender – a scheme which offers five years of funding from the government, and the possibility of future carbon trading as an added incentive to farmers. Two other major carbon sequestration schemes are run by CO2 Australia, which buys land and land rights from farmers to establish long term mallee plantations on their properties, as a part of the NSW abatement scheme. Greenfleet is a non profit organisation which uses money from individuals and transport providers to plant sufficient trees to offset the investors' emissions (CRC for Greenhouse Accounting 2006).

Other, non-governmental, schemes have been developed by large companies such as BP, Shell, DuPont and Toyota whereby their investment into forestry projects allows them to offset their carbon emissions with carbon sequestration credits (RIRDC 2000).

2.1.4 Western Australia's position

The existence and formation of carbon sequestration programs within Western Australia is of particular relevance to the viability of forestry across the state.

Carbon sequestration projects in Western Australia are currently associated with private carbon offsetting schemes, rather than government driven abatement schemes or carbon trading markets. In 2004 the Cooperative Research Centre for Greenhouse Accounting, a federal organisation specialising in carbon accounting within Australia, found that there where no national or state markets available to Western Australia and thus carbon trading

potential in the region is limited. There exists the possibility of government driven markets to be further developed in the future, although current schemes are being driven largely by the private sector (CRC for Greenhouse Accounting 2004).

The Infinitree plantation brand, initiated by the Forest Products Commission, is the only government-run commercial plantation program in the country (Forest Products Commission 2006b). Two other major greenhouse gas emission offsetting programs running in Western Australia were established by the BP Kwinana refinery and the Water Corporation. The BP refinery, has been involved in carbon sequestration and emissions offset programs since 1998. It has worked with the Forest Products Commission (FPC) to establish sequestration plantations in the south-west of Western Australia (BP 2006). The Water Corporation joined the Australian Greenhouse Challenge program in 2001 and in 2005 committed to establishing sufficient plantations to offset the emissions of their transport fleet. They have introduced an internal carbon tax on all vehicles, proportional to their emission levels, and use the money to fund plantations developed by the Men of the Trees Carbon Neutral program (Water Corporation 2006).

The potential for viable carbon sequestration forestry has been assessed across the agricultural regions of Western Australia (CRC for Greenhouse Accounting 2004). It was found that feasibility assessments were highly dependant on the location of the plantation and hence its performance, as well as economic variables such as the price of land and value of carbon units.

2.2 Dryland Forestry

2.2.1 Multipurpose Forestry

The dryland regions of Western Australia are defined as the areas which receive less than 600mm annual rainfall. They have not traditionally been used for plantation purposes, although the demand for timber, the need for salinity and waterlogging control and the establishment of emissions offsetting schemes is driving the expansion of forestry into these areas. The regions receiving 400-600mm annual rainfall are shown in Figure 1, below.

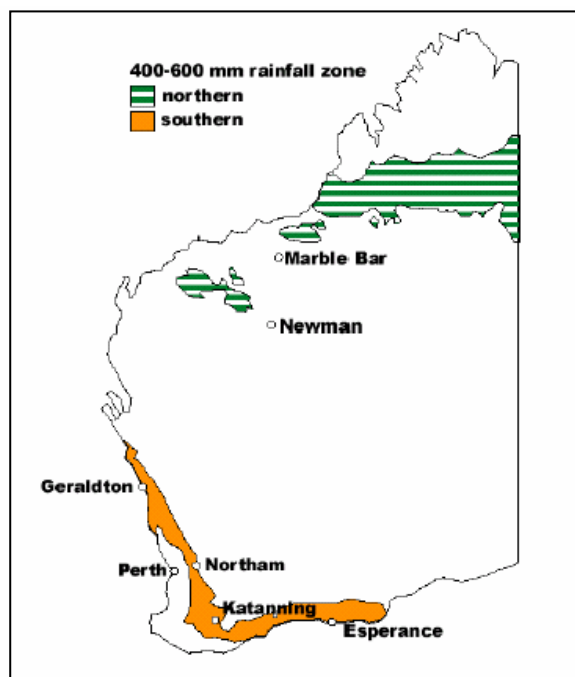


Figure 1: 400-600 mm Rainfall Regions of Western Australia (Harwood et al. 2001)

Forestry in these regions is likely to be integrated with other agricultural land uses and occur on a smaller scale than that in higher rainfall areas. Ryan et al. (2002) present the need for plantations to be multipurpose in order to meet environmental and economic targets. In conditions where plantation performance and hence productivity is variable and often low, the feasibility of a project relies on economic input from many sources. This leads to the key finding which has been addressed and reiterated throughout: there is the need for more research into expanding and developing the forestry industry into new areas, for new purposes, using new methods. The need is urgent, if the purpose of such forestry is to be met.

Harper et al. (2005) present a study on the factors influencing the optimal distribution of plantations across a dryland region. They have presented a method which uses existing soil and climatic data to assess the availability of suitable land at a catchment scale. Plantation performance has been assessed in terms of carbon sequestration and groundwater recharge rates. This study is important as it addresses the need for accurate suitability assessment of a region before embarking on forestry projects. The use of readily available data is significant in that it allows for the formation of a directly applicable method. The resolution of the soil data does, however, limit the scale at which this method can be applied. The resolution of this dataset is $\pm 10\text{m}$, which is sufficient for assessments at the catchment scale, although greater resolution would be required for application at a farm scale.

The management of dryland salinity was one factor Harper et al.(2005) discussed, although a more extensive study has been conducted by Lefroy et al. (2005). Their aim was to assess the options for plant based salinity control and determine where and how it would be effective. One of these options was farm forestry. They analysed four agro-ecological zones, one of which included the agricultural regions of Western Australia. Their results showed that, based on current profitability levels and rates of adoption, it would not be viable to introduce the levels of perennial plant species required to effectively manage dryland salinity.

They did however make some important recommendations for improving this result. They suggest that it is best to tackle salinity at a farm scale, rather than approaching an entire catchment. This is particularly relevant to Western Australia given the localised occurrences of salinity (Lefroy et al. 2005). They also identify the need for research to be directed towards developing viable solutions at this scale, rather than focussing on what, ideally, could be achieved over a larger region. There is currently a distinct difference in approach at the different scales. This must be overcome so that information and expertise from environmental and economic perspectives are incorporated into all assessments. The study by Harper et al. (2005) was an example of attempting to meet this need for equal treatment of all purposes and objectives of forestry, throughout the analysis process. The study presented in this dissertation will focus on developing an inclusive farm scale assessment technique.

The urgency associated with developing dryland forestry is reflected by the rapid progression of the Forest Products Commission's *Tree Farming and Industry Development Plan* (2006a). The most recent update of the plan was published in July 2006 and describes the current forestry situation and intentions for expansion into new regions from the industry perspective.

The section of this report most relevant to this study is that which describes future plans for the area encompassing the "central south-west recovery catchments". This area is a dryland region identified as being likely to benefit from an increase in forestry due to widespread salinity. There are extensive areas which are both in need of landuse management from environmental perspectives, as well as being suitable for viable timber plantations. The area is highlighted in Figure 2, below, and the location of the study site of this dissertation is also shown.

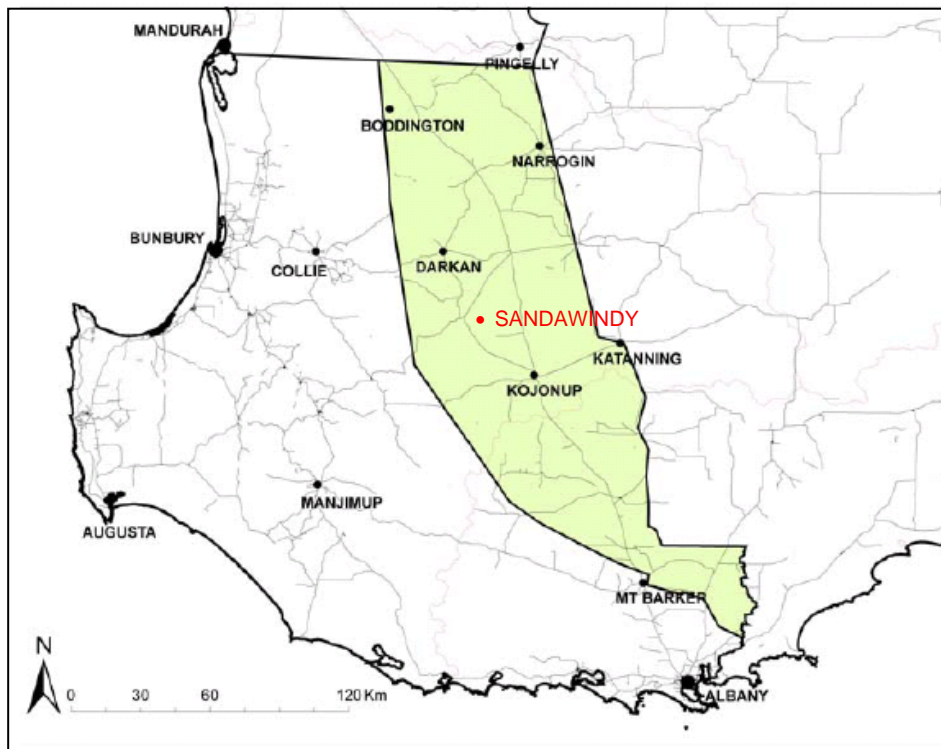


Figure 2: Central South-West Recovery Catchments and Sandawindy Location (Forest Products Commission 2006a)

In the introduction of the report states that:

“Planting the right trees in the right places in the right quantities will deliver the environmental, economic and social benefits to ... local industries and communities.”

The planting of trees in the right places, and associated environmental and economic benefits are explored throughout this dissertation.

Although the need to manage salinity, waterlogging and the subsequent threats to biodiversity, are presented as drivers for the central south-west recovery catchments project, the report consists mainly of a presentation of the economic viability of establishing plantations in the area. Their economic findings are based on treating the area as a whole and there has been little mention of the actual viability at a farm scale. Given the comments made by Lefroy et al. (2005) few conclusions can be drawn about the effects the project will have on salinity management of the region or the economic implications to land users of the region.

The major funding sources for the project are existing FPC plantations, sharefarming programs, federal salinity funds and the private sector (Forest Products Commission 2006a). Importantly they have noted that the establishment of carbon trading markets and salinity credits will increase the viability of much of the planned forestry. The link between the

economic inputs from these sources and their effect on farm scale forestry is discussed further in the following section.

2.2.2 Carbon Sequestration as an Economic Input

The literature relating to emissions offsetting and dryland salinity management both predict an increase in dryland forestry and, although driven by different objectives, there are common points made. Both perspectives recognise that multipurpose forestry is the key to achieving all economic and environmental aims. The importance of maximising viability through investigation of all economic inputs is discussed in this section.

As a direct response to the Kyoto Protocol of 1997, the Department of Conservation and Land Management presented a report on the future potential for carbon sequestration in Western Australia (Shea 1998). They speculated as to the amount of carbon sequestration which could occur in Western Australia, and hence whether the national target could feasibly be met. At this time it was still unknown whether Australia would ratify the protocol. The conclusions were that carbon sequestration in Western Australia would provide a significant contribution to emissions offsetting and in doing so allow for emissions reduction technology to be developed and implemented. Despite the unclear carbon accounting rules and trading possibilities, it was deemed important to proceed immediately with forestry and revegetation if maximum growth and thus sequestration was to be reached in time to meet the targets set for 2008-2012 (Shea 1998).

Six years later research purposes had progressed beyond achievement of emissions targets and on to the economic possibilities of future carbon trading markets within Australia. If, in the future, Australia were to ratify the Protocol, there would be an increase in greenhouse gas abatement schemes and emissions trading due to the necessary governmental input. Under these circumstances Petersen et al. (2003) question how the agricultural industry would fare, and suggest that there would be economically driven changes to land use in order to cope with the carbon sequestration demand. They present a study on the possible results of introducing greenhouse gas and salinity abatement schemes which address emissions reduction through voluntary participation or, alternatively, with tax driven enforcement.

They concluded that in Western Australia, any policy which did not involve farmers converting some percentage of their landuse to sequestration purposes, would result in negative impacts on grazing agriculture. The options with carbon trading possibilities were

seen as economically attractive and thus able to promote the inclusion of farm forestry amongst other agricultural practices. They found, however, that the viability of this land use change was maximised when a combined option of carbon sequestration and salinity abatement schemes was available (Petersen 2003).

Petersen's findings are in agreement with comments made in the *Opportunities for the Western Australian land management sector arising from greenhouse gas abatement* report (CRC for Greenhouse Accounting 2004). This report summarised the potential for carbon trading markets and carbon sequestration driven forestry. They conclude that the best method for greenhouse gas abatement is through the establishment of emissions offsetting carbon sequestration, and that it will only be economically viable if done in conjunction with commercial forestry and/or salinity abatement schemes. The carbon trading possibilities associated with sequestration would only be marginally viable as a stand alone project, even if markets were further developed. Again, the need for multipurpose integrated forestry to be applied at a large scale across agricultural region of Western Australia is presented.

The need to expand forestry operations which was expressed in the CALM report of 1998 was driven by the possibility of the carbon sequestration demands associated with meeting the 2008-2012 Kyoto target. The focus has since shifted to the need for dryland salinity management, although carbon sequestration remains an important economic input (Shea 1998; Lefroy et al. 2005; Forest Products Commission 2006a).

2.3 Site Selection to Optimise Plantation Productivity

Plantation site selection methods are integral to ensuring that optimal economic and environmental standards can be reached. This section examines current site selection methods and suggestions for improving them.

2.3.1 Current Site Selection Methods

Traditional site selection methods involve the measurement or estimation of a number of land characteristics, and the subsequent formation of a set of independent land qualities. Ryan et al. (2002) consider some of these land qualities to be: radiation regime, temperature regime, water availability and drainage. They are derived from the latitude, aspect, annual net rainfall, soil depth and texture, and elevation to name a few of the contributing land characteristics. The full set of qualities serves to describe the productivity of the site as well as giving direction to site management of the plantation and control of possible land degradation hazards.

As an example the site assessment for *E. globulus* plantations in Western Australia is given in Table 1, below.

Table 1: Site Assessment for *E. globulus* in WA. (Ryan et al. 2002)

- 1 Estimate potential productivity ($\text{m}^3 \text{ha}^{-1}$) from annual rainfall and evaporation
- 2 Identify farmed areas with slopes $<15\%$, unlikely to be inundated with water. Survey the remainder of the property
- 3 Survey site at scale of 1:10,000 using air-photo interpretation and ground survey. Undertake ground survey using drill-rigs/back-hoes and EM 38 salinity meters at observation density of 1 observation per hectare
- 4 Identify sites with shallow ($<2 \text{ m}$) soils overlying bedrock, saline soils ($\text{EC} > 50 \text{ mS m}^{-1}$) and with sand horizons $>2 \text{ m}$ deep. Do not plant these
- 5 Identify sites with hardpans within 1 m of the soil surface that can be rectified by ripping. Hardpan includes ferricrete and iron-organic pans. If hard material is basement rock ripping will not increase soil depth—do not plant these sites
- 6 For sites, which have no overt limitations, take 0–10 cm soil samples, using a standard soil sampler. Take 15–20 sub-samples in a Z-shaped pattern. Send samples to laboratory, with location details. These samples will be used to predict fertiliser requirement
- 7 In sites with $<800 \text{ mm}$ rainfall integrate trees into landscape as strips, rather than using block plantations. Avoid hill crests and areas that are likely to become saline
- 8 Undertake economic analysis using land value, likely productivity and risk

The relationships between land characteristics, tree species and productivity vary with different combinations of these factors, meaning that site specific empirical relationships must be used (Moore 1998b). These relationships have been developed for common plantation species in the traditional forestry regions of Western Australia, and can be used to maximise the survival rates and productivity at a site. The relationships for species such as *E. globulus* and *P. radiata*, within the areas of $>600 \text{ mm}$ annual rainfall, have been assessed using plantation performance data (Ryan et al. 2002). They found that water supply to the trees was the major aspect affecting their growth. This confirms that water availability is the primary limiting factor to tree growth in Australia (Cremer 1990). Thus all qualities which govern the availability and use of this supply, such as rainfall, evaporation, soil volume, soil fertility and plantation density, were identified as the key components to be considered in a site selection methodology. This need exposes two weak points in the current site selection methods, which will limit the accuracy and applicability of the criteria as a means for effective establishment of future farm forestry plantations (Ryan et al. 2002).

The first limitation relates to the type of soil survey performed and hence the accuracy of the land quality information derived from the data. The current procedure is to use general soil surveys conducted at a site, which focus on the soil profile, the texture and the colour of the soils present. These field surveys allow for a rough classification of the soil into known soil types and allow for an estimation of the performance of a tree species. They do not, however, include factors such as soil depth, water holding capacity, fertility and salinity which are vital for an accurate prediction of tree response (Ryan et al. 2002). Practically, it would be more useful to delineate key aspects of the soil rather than aiming to apply a standard classification system. The conclusion is that soil surveys need to become specifically

adjusted to context in which they will be assessed, if they are to be optimally used (Tunstall 2003).

The second limitation relates to the inflexibility of current site selection methods in their applicability to new areas of farm forestry. There are currently no criteria for accurate prediction in dryland areas and for species other than blue gums and pines (Ryan et al. 2002). This is due to the lack of trial sites, and hence data, required for the development of regionally applicable empirical relationships. Work in this area has been done by the Australian Low Rainfall Tree Improvement Group (ALRTIG), who identified species which would be suitable to 400 – 600 mm rainfall areas. Amongst them was the *E. cladocalyx* species (Harwood et al. 2001). Essentially more trials, more studies and research needs to be performed in order to build a knowledge base from which site selection requirements can be drawn.

The next step in understanding growth in these regions is to establish growth curves specific to the relevant species and climatic conditions. After growth curves have been implemented into growth models such as 3-PG and ProMod, more effective site selection criteria begin to be established. The flexibility of these models will still, however, be limited by the accuracy of data used to characterise the variations in available water content and soil fertility. It has been noted that soils vary on the hillslope scale and hence it is vital for high resolution and detailed soil characterisation to be performed (Thwaites & Slater 2000; Ryan et al. 2002). This can be achieved if growth models are adapted to include detailed spatial variance and operated within a GIS (Ryan et al. 2002).

The need for accurate location and application-specific information has lead to the identification of soil surveying as the key area for improvement for current site selection methods. An alternative method of soil surveying which provides high resolution information and focuses on soil qualities rather than classifications is required. The next section presents an approach which has the potential to meet these requirements.

2.3.2 Radiometric Data Interpretation in Site Selection Methods

Gamma ray spectrometry, or radiometrics, is increasingly being used in soil and landscape mapping. The dataset can be used to delineate a range of soil characteristics and attributes for use in applications of landscape modelling, land resource assessment, and land classification for agriculture or forestry. The details of data collection, processing and analysis associated with radiometrics are outlined in Section 3.2.1. The different approaches and results relevant to this dissertation are presented below.

The recognition of remote sensing as a data collection technique for land resource assessment (LRA) methodologies is linked to the concept of approaching soils from a geomorphological perspective. This approach treats soils as a product of, and part of, three dimensional landscape processes. In his article entitled *An opportunity for Quantitative Land Resource Assessment in Queensland Forestry*, Thwaites (1995) presents this approach as an alternative to what he describes as ad hoc soil sampling which "...falls far short of being adequate for land evaluation purposes." An expression of the need to classify soil qualities and attributes rather than specific soil types is the most important point made in this paper. This idea has been carried through later studies as researchers aim to introduce radiometric information as a means of delineating soil attributes within a landscape modelling approach.

In 1997 a team of experts in soil and land suitability assessment, lead by Phil Bierwirth of the Australian Geological Survey Organisation (AGSO), conducted a workshop to investigate the potential of using Digital Elevation Models (DEMs) and airborne radiometric data for generating effective and efficient methods of land evaluation (Bierwirth et al. 1997). They found that the radiometric data was very useful for predicting a range of soil attributes, particularly in lower lying areas where topography could not be used as an indicator of soil type.

One of their major findings was that the potassium radiometric layer could be used to determine the composition of bedrock and parent material for soils on the upper slopes and crests as well as differentiating between recent and older alluvial soils. They also showed that the separation of soils derived from tertiary weathered sediments and andesite clay soils could only be done with the inclusion of magnetic remote sensing data. Their analysis resulted in the classification of the study area into soil types differentiated by texture, drainage properties and levels of leaching and nutrients. Although they relied upon extensive prior knowledge of the area, ground truthing and other previously established radiometric-soil relationships, their conclusion was that it would be possible to determine empirical rules to relate radiometric data to key landscape processes and hence soil types. That study marked the start of geological, geophysical and geomorphological approaches to soil classification and land evaluation methods, for Australian landscapes. Subsequent research in the area of radiometrics has followed this trend and not only reinforced their findings, but extended them.

Wong and Harper (1999) performed a study on the *Use of on-ground gamma-ray spectrometry to measure plant-available potassium and other topsoil attributes*. Although they focussed on the use of ground based spectrometry, they suggest that once definite relationships had been established, they could easily be extended to employ remotely sensed data. Their study investigated a number of sites near Jerramungup, in Western Australia, and was done within the context of potassium deficiency as a limitation to plant growth in crops and forestry. They conducted tests to determine relationships between potassium concentrations detected with the spectroscopy and the plant available potassium. Their conclusion was that there was a relationship, although it failed at the low concentrations associated with limitations to growth. The recommendation was that gamma ray spectrometry could be used to determine where best to sample, but that it would not be sufficiently accurate to allow for direct input into fertilising regimes.

The other aspects of their study, in determining correlations between potassium count and topsoil attributes proved more successful. They support Bierwirth et al.'s (1997) conclusions that gamma ray spectrometry is a useful technique for soil mapping where it can be used to delineate attributes such as water retention, water repellance, wind erosion risk and soil fertility. It was noted however that relationships relying on radiometric data would always have to be locally calibrated.

Both the Wong & Harper and Bierwirth studies have shown that basic soil types can be mapped using radiometrics. Both have identified the detection of potassium in surface soils as particularly useful, due to its association with weathering processes and hence mobility within the landscape. The most important points to note are the indirect relationships between soil texture and water retention, or clay and organic carbon content, for example. These highlight the potential of using radiometric data to delineate not only landscape characteristics, but landscape qualities as well.

A more recent report on the use of radiometrics in soil mapping, has highlighted some important issues regarding the purpose of soil surveys and the ability of new methods to meet these requirements. Brian Tunstall of the Environmental Resources and Information Consortium (ERIC) reports (2003) that soil survey techniques are becoming more specific to the application for which they will be used. Soil surveys performed for different reasons require the identification of different attributes, and hence there is the need for versatile, site specific soil mapping methods. As the developer of the SoilSelect soil classification method which relies primarily on radiometric data, he has been influential in promoting the use of radiometrics. Their approach has been used for a variety of soil classification purposes,

although the main focus at ERIC is on classification for the purposes of salinity delineation and remediation.

Tunstall (2003) comments that using numerical analysis of radiometrics, together with minimal ground truthing, it is possible to create soil maps which overcome the need for extensive knowledge of soil classification methods and systems. These maps are designed for application, not merely to exist as a classification of a region. This is particularly important to the study conducted in this dissertation, as soil mapping is being performed as a part of a site selection process.

Work in the area of radiometric soil mapping is advancing, and its application to site selection is being called for. In an article on the *Relationships between soil properties and high resolution radiometrics, central eastern Wheatbelt, Western Australia* (Taylor et al. 2002) has presented an investigation into the identification of surface soil properties derived from airborne and ground radiometric data sets. Their most important findings were that areas of shallow soil over bedrock, presence of ironstone gravel and percentage clay in the top 10 cm exhibit strong linear relationships with values derived from the radiometric data. In the case of bedrock, a Digital Elevation Model (DEM) was an additional factor in the relationship. These results are particularly important as they are quantitatively presenting what many studies declare are possible, but do not carry out or publish. They have not only presented observations, and known radiometric/landscape relationships but also numerical proof that these relationships hold within the study area. This is an important step in acceptance and wider inclusion of radiometric methods.

Much work has been done to identify and propose the use of radiometrics in soil mapping. Some areas of research have merely expressed the need for changes in soil and resource mapping practice while others have been focussed on determining empirical relationships with important soil attributes (Tunstall & Gourlay 2006; Taylor et al. 2002; Wong & Harper 1999; Bierwirth et al. 1997). In the area of farm-scale forestry there is the urgent need for these research areas to be combined, such that site specific, effective site selection methods can be derived from already established relationships between soil characteristics and qualities. Ryan et al. (2002) have presented set of principles designed to guide the improvement and expansion of site selection methodologies. An integral aspect to the implementation of these principles, is the use of airborne radiometric data and the associated quantitative analysis which can be achieved using GIS methods. Similar calls for the inclusion of radiometrics into landscape assessments have been made by Harper et al.

(2005), as they state that many of the limitations associated with current soil survey datasets may be overcome with the inclusion of radiometric information.

2.3.3 Importance of Scale

When considering the accuracy of site selection methods, and particularly with regards to the inclusion of new datasets such as radiometrics, it is important to consider the scale at which the land is being assessed and hence the required data resolution.

In the presentation of an ideal conceptual site selection method by Ryan et al. (2002) they emphasise the consideration of scale factors. They discuss the grain and extent of both temporal and spatial scales which are required to accurately represent all biological and physical aspects of a landscape. The grain refers to the finest scale at which the data can be presented and the extent is the area covered by the dataset. The basic scale requirements for temporally and spatially variant datasets are as follows: Climatic data is temporally variant requiring only a coarse grain dataset and hence long term annual averages are best used; and topographic data is spatially variant requiring fine-grain resolution for applications such as soil mapping.

In general climatic data is easily obtained for assessments at any location on any scale. There is, however, great variation in the scale at which topographic data is produced and in general a lack of high resolution data as needed for small scale landscape analysis. For example, readily available soil datasets, such as that from the Atlas of Australian soils, have a grain size of 8000 ha (Ryan et al. 2002). This is not of sufficient resolution for site assessment at a farm scale, as the data cannot be downscaled to represent variations across a hillslope. Instead, individual field surveys must be performed. The final issue raised with regards to the resolution of site assessment is the lack of temporal variation included in analysis methods. The long term changes in a landscape with respect to water and nutrient availability are poorly considered.

Ryan et al. (2002) note that the use of GIS in site assessment is particularly useful in performing the interpolation, scaling up or down as required to achieve a grain size and extent relevant to the scale of assessment. This ability to manipulate a dataset allows for the comparison and inclusion of many different data types within one model. It can lead to the formation of growth models with accurate spatial and temporal variation, which aim to address the resolution inadequacies mentioned above.

One example of a landscape model which aims to implement these concepts and overcome the problems associated with the resolution of input data, is the forest resource assessment and modelling study (FRAMS) presented by Thwaites and Slater (2000). They are aiming to establish a model which can be applied at any scale – hillslope, catenary or landscape. They first explain the changes in data resolution associated with a landscape assessment at different scales as the need for a greater number of variables and a re-weighting of the common attributes as downscaling occurs. Then by treating the soils and landscape as a 'soil-landscape system' and applying known links between landscape attributes across different scales, an assessment can be made regardless of the resolution of the input data. They apply indices to landscape attributes, and then adjust these indices according to a set of predefined rules representing the changes to the landscape system as the assessment scale varies.

At the time of writing they had identified the key input datasets, the relationships required for scaling up and down and hence were able to produce landscape assessment information at a resolution required for a given scale of the assessment. This was defined as 50m resolution at the landscape scale, 10 m at a catenary scale and 5m at a hillslope scale. However, their results were yet to be verified against field surveys at the study sites.

There is the recognition that the development of complex landscape assessment models, such as the FRAMS, may not meet the urgent need for farm scale site assessment, as is required by the forestry industry in Western Australia. Therefore it is necessary to make use of readily available datasets to be applied at the relevant scale.

The plantation performance study presented by Harper et al. (2005) was done at a catchment scale. Their method is specifically designed for use in the first stages of forestry planning as they assess the overall suitability of a region using readily available data. At the catchment level it was sufficient to use soil and landform data accurate at a 1:100 000 scale. This data was sourced from the Department of Agriculture Western Australia soil survey, which maps soil landforms as opposed to individual soil types with a resolution of $\pm 10\text{m}$. Using this data, together with climatic and topographic information they were able to produce land suitability classifications over the Collie River catchment in Western Australia. Their conclusions were that the method is useful for the initial feasibility assessments of forestry planning, although for farm scale site selection and land management, resolution at 1:10 000 or 1:20 000 would be required.

3.0 Methods

3.1 Study Region

3.1.1 Study Site

A Forest Products Commission (FPC) plantation property, Sandawindy, was the study site for this project. The site was used for data collection and field observations, as required for the development and verification of the methods presented in this study. Sandawindy is located in the central south-west of Western Australia, 40 km north-west of Kojonup. It is situated in an agricultural region and surrounded by grazing and crop farming land uses as well as farm forestry plantations. The majority of the area has been cleared of the original jarrah and marri forest.

The property was purchased in 2003 as a plantation site for the FPC's Infinitree brand. Infinitree is an investment plantation program which connects investors and farmers to create economically viable farm plantations (Forest Products Commission 2006b). Of the 1180 hectares, 35% is intended for plantation while the remainder is available for sheep grazing and crops (Forest Products Commission 2004a). A map of the region showing Sandawindy's location is given in Figure 2.

The majority of the trees were planted in 2004, while some areas have recently been planted in 2006. There are a variety of species across the site and hence a variety of uses for the timber produced. Maritime pine will be used for chipboard and pallets, various eucalyptus species for sawlog (furniture and flooring) and sandalwood for essential oil production (Forest Products Commission 2004a). Figure 3 shows the plantation layout across the farm.

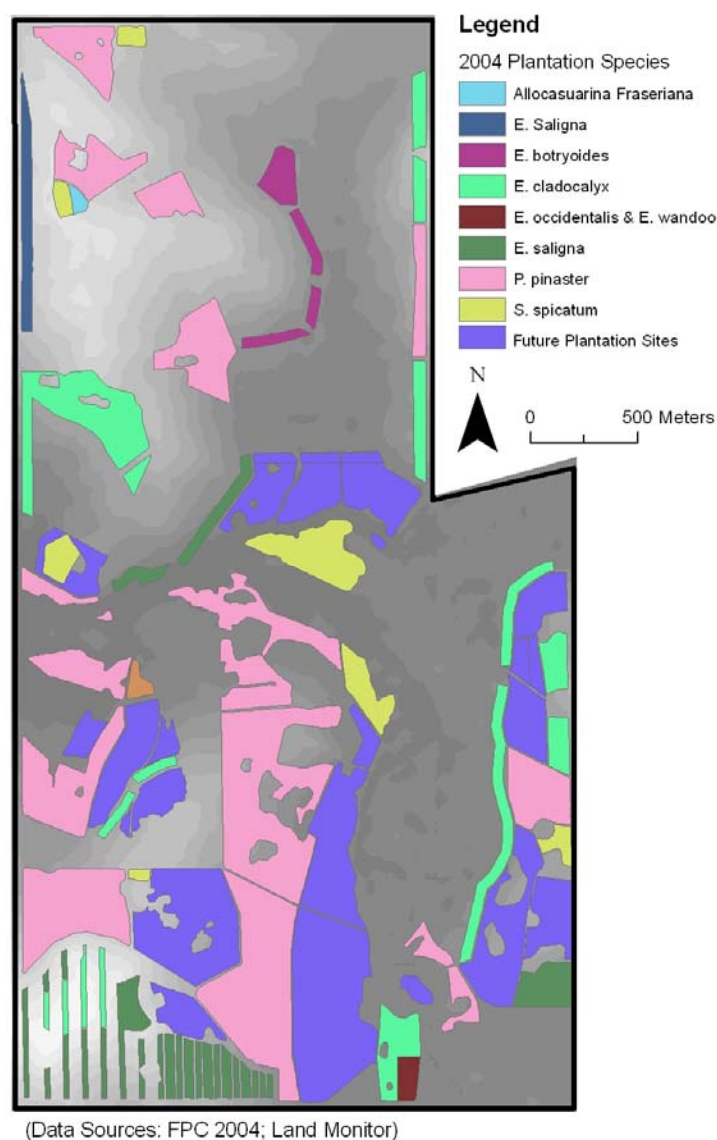


Figure 3: Sandawindy Plantation Layout Map

3.1.2 Landscape

The site lies within the 400 – 600 mm annual rainfall band shown in Figure 1 (Bureau of Meteorology 2006). The area is categorised as a dryland region. This means that not only is the rainfall low, but high potential evaporation rates and high levels of solar radiation can be expected. Water availability in dryland landscapes is particularly variable and hydrological conditions dominate both plant growth and levels of erosion (Wainwright et al. 1999).

Sandawindy is located within a gently undulating landscape, dominated by the presence of highly weathered low fertility soils. There are, however, a wide range of soil types and variations in soil fertility across the area. The characteristic deep sandy profiles and coarse textured surface layers are indicators of the high degrees of weathering which have

occurred. These profiles are formed by the erosion of the bedrock layer and the subsequent mineral leaching and laterisation processes. In this area most soils are derived from granitic bedrock (Moore 1998a).

The process of laterisation involves the accumulation of iron and aluminium minerals in the soil during wet and warm climatic conditions. These areas remain to form ferricrete caps across the landscape surface. Such areas exhibit high levels of ironstone gravel and surface laterite, above the sandy or loamy gravels of the deeply weathered soil profile. They are particularly important in this landscape as they affect the erosion patterns and hence hydrogeology of the area (Moore 1998a; McKenzie et al. 2004).

In areas where a lateritic cap has not formed, the weathered profile is subject to varying levels of erosion. Depending on the amount of erosion or accretion occurring at a particular location, the underlying bedrock may become exposed. Where this occurs, the weathering process starts again. The soils in these areas are usually red or brown loamy duplex soils which are closely related to the parent bedrock material and exhibit high levels of fertility. This is due to the presence of bedrock minerals which have yet to be leached out of the soil structure. Where present, the clays of the area are predominantly kaolinite or illite (Moore 1998a) .

The minerals leached from the soil structure by weathering and erosion processes, become stored as salts. As groundwater moves through the soil profile it mobilises these salts and causes them to accumulate in the lower lying regions of the landscape. In agricultural regions, where the replacement of native vegetation with shallow rooted agricultural crops has resulted in increased recharge to groundwater, the water table rises. This serves to concentrate the mobilised salts in the shallow subsurface, thereby inhibiting the growth of plants (McKenzie et al. 2004). This dryland salinity is a major environmental issue for the region. The methods of salinity mitigation and control have been presented in Section 2.2 of the literature review and will be further discussed in Section 5.0.

3.2 Data Sources

The radiometric, electromagnetic and Digital Elevation Model (DEM) datasets used in this study have been processed into a raster format, for use within a Geographic Information System (GIS). The datasets are referenced against the World Geodetic System 1984 (WGS84) or the Geodetic System of Australia 1994 (GDA94) which are common datums used in Australia. The variation between them is negligible and hence conversion between

datums was not necessary. All data was projected to the Map Grid of Australia (MGA) using the Universal Transverse Mercator (UTM) Zone 50 projection, and hence are correctly georeferenced to their location in the world and to each other.

3.2.1 Radiometric Data

Gamma Ray Spectrometry (or radiometrics) is a technique used to detect the presence of radioactive isotopes in shallow subsurface soils and rocks. The process involves the detection of the gamma rays emitted during the radioactive decay of these isotopes. The method can be ground or airborne based, although only airborne data collection is considered in this study.

In the natural landscape there are many sources of gamma rays, although only those associated with the decay of potassium (K), thorium (Th) and uranium (U) are sufficiently abundant and energetic to allow for clear detection. These high energy gamma rays are emitted from a radioactive isotope of potassium (K-40) as well as bismuth (Bi-214) and thallium (Tl-208), which are daughter isotopes of Th and U respectively.

Survey instrumentation is designed to detect gamma rays within an energy range of 0.4 to 2.82 MeV, thus covering the signals from the three major sources, as can be seen in Figure 4 (Ward 1981). The detection procedure involves a thallium activated sodium iodide crystal, in which atoms become excited by the energy of incident gamma rays. As these atoms decay back to their ground energy state they release the excess energy in the form of light. This light pulse is converted into an electrical signal using a photomultiplier. The amplitude of this signal is proportional to the energy of the incident gamma ray (Minty 1997). This occurs in the survey aircraft as it follows evenly spaced transects at a constant height above the ground.

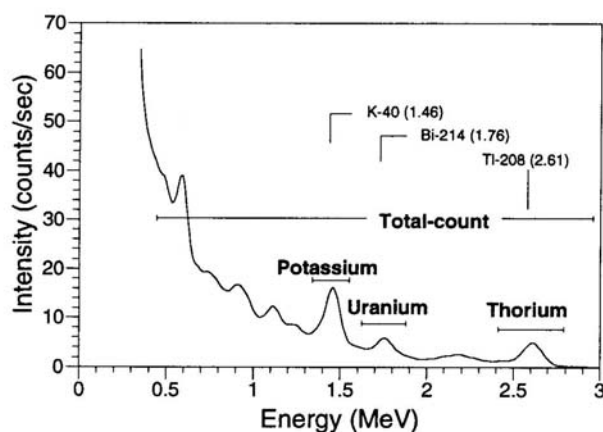


Figure 4:Gamma Ray Spectrometry Detection Range (Minty 1997)

The raw data is extensively processed in order to extract accurate ground concentrations for the K (%), Th (ppm), U (ppm) elements. The variations in the total gamma ray count, or dose rate (nGy/h), detected across the survey area are also presented. The major factors to be addressed in the processing procedure are the errors induced from: background radiation, gamma ray attenuation and variations in the field of view of the detector (Ward 1981). Due to the attenuation of gamma rays in soil and rock, the continuous concentration distributions only describe the top ~30 cm of the subsurface material. Significantly lower levels of attenuation through air make the airborne detection techniques possible (Cook et al. 1996). The final dataset consists of four individual datasets, although the K, Th and U data is often presented as a RGB ternary image showing the relative concentrations of each.

The method relies on the assumption that the radioactive decay chains of Th and U are in equilibrium within the landscape. Hence their equivalent concentrations (eTh and eU) can be determined from the detection of daughter isotopes, Bi and Tl. This assumption is often not correct however, and is therefore a source of error.

The radiometric data used in this study was flown and processed by Fugro in April and May 2004. A line spacing of 50 m and a terrain clearance of 50m above the surface was used (Fugro Airborne Surveys 2004). This dataset falls within the line spacing limitations (with maximum of ~100 m) recommended for this survey extent. An optimal terrain clearance, however, is between 20 and 40 metres (Pracilio et al. 2006). The data has been processed into a raster surface with a 10x10m grid size. This is a higher resolution than the standard grid spacing (of approximately a quarter of the line spacing) usually used for radiometric datasets (Pracilio et al. 2006).

3.2.2 Electromagnetic Data

Electromagnetics (EM) is a form of geophysical data collection which serves to map variations in electrical conductivity in the subsurface. This conductivity, in milli Seimens/metre (mS/m), can be used as a measure of salinity in landscapes where background levels are generally low. The surveys can be ground or air based (Dentith 2006).

The technique relies upon the principles of electromagnetic induction. The most common ground survey method is known as Time Domain Electromagnetics. This involves the generation of an alternating electric current by a transmitter in the survey equipment. The current has an associated magnetic field which extends into the subsurface to a depth governed by the amplitude of the electrical signal. This primary magnetic field induces a current to flow through the soil, which in turn has its own associated (secondary) magnetic field. Both the primary and secondary magnetic fields are detected by a receiver in the survey equipment. The relative magnitudes of the first and second magnetic fields gives a measure of the current induced in the soil and hence a measure of the conductivity of the subsurface material at that location (Dentith 2006).

The ground EM survey performed at Sandawindy was done by Geoforce in June 2004. They used a quad bike to tow the detection equipment and obtain continuous datasets at sample rates of 1 Hz (~3 to 5m). The transect spacing was 50m and conductivity at two different depths below the surface has been recorded. The processed data is presented as EM38 (0-50cm depth) and EM31 (1-4m depth) (Geoforce 2006). Some inaccessible areas could not be mapped and are shown as areas of No Data in the datasets (Geoforce 2004).

3.2.3 Digital Elevation Model (DEM)

Digital Elevation Models (DEMs) are datasets which contain continuous x, y and z data, thus giving a measure of the ground surface elevation at any location. The z coordinate is measured from a defined datum, which in Australia is usually the Geocentric Datum of Australia 1994 (GDA94).

The Digital Elevation Model (DEM) used in this study was obtained from the Land Monitor program and was initially created for the purpose of salinity mapping and monitoring. Land Monitor used contour data from the Department of Land Administration to create continuous DEMs of the south-west region (Department of Land Information 2004). The original elevation data is in the form of photographic images at a scale of 1:40 000 and the analysis

and digitisation process produces a DEM with an x and y grid size of 10 m, and a vertical accuracy of 1.5m (Land Monitor 2000).

3.2.4 Climatic Data

Rainfall data was obtained from the SILO Data Drill service operated by the Department of Natural Resources, Mines and Water in Queensland. Monthly averages from 1986 to 2006 were obtained for use in calculating drainage to groundwater at the site. This data is synthetic and has been obtained from the interpolation of point data (from Bureau of Meteorology stations) using splining and kriging methods (Department of Natural Resources Mines and Water 2006). A period of 20 years has been chosen to allow for the calculation of long term averages. The exact coordinates of Sandawindy used to order the data were 33°33" S and 116°45" E.

3.2.5 Field Survey Methods

A field survey was conducted at the site for two reasons. Firstly to make observations of key soil types and landscape features and, secondly, to survey the plantations. Sample measurements of tree dimensions were required for use in assessing the plantation performance predictions and in obtaining carbon sequestration rate estimates. The survey was conducted on the 11th August 2006.

Landscape observations included: the location of surface laterite, exposed granite, very sandy areas, waterlogged areas and variations in gravel content of the soil. The presence of these features can be identified through interpretation of the datasets presented above, hence the observations served as ground truthing data.

Measurements and notes regarding the growth of trees were made at 13 sample sites across seven *E. cladocalyx* plantations on the property. Refer to Appendix A for a map showing the location of the plantations and sample sites. At ten of these sites, measurements of tree height and trunk circumference at 10 cm above the ground were made. These trees were within close proximity to each other, and selected randomly. The sample sites coincided with the locations of important landscape features such as areas of laterite, surface granite, or where waterlogging was observed. This allows for verification of growth predictions derived from soil and landscape mapping. The tree dimensions were used in calculating approximate rates of carbon sequestration.

At all of the thirteen sites an estimate of the range of tree heights across the whole plantation was made. Where there was significant variation across the extent of the plantation, a relative rating of tree height was estimated at intervals along the plantations rows. These ranges were used for verification of the plantation performance prediction derived from the analysis methods presented in the following section.

A soil survey conducted by the Forest Products Commission when they purchased Sandawindy has been used for ground truthing purposes. See Appendix B for the survey logs.

3.3 Analysis Methods Outline

The methods used to achieve each of the three objectives and develop a site selection method are presented in the following sections of this chapter. Section 3.4 covers the first two stages of the process whereby radiometric data interpretation techniques and plant response relationships are identified. This information, in combination with the ground truthing data, is used to direct the analysis of the input data layers and produce a soil/landscape classification of the site. This process is described in Section 3.5. Following this classification a growth rating index is developed to allow for predictions of plantation performance with respect to key landscape features. The index is applied across the site to give a spatially continuous growth prediction. The accuracy of the prediction is assessed using the field observations outlined in Section 3.2.5.

The last section of the methodology, Section 3.6, describes the calculation of carbon sequestration and groundwater recharge rates, as well as the methods used to assess the extent of salinity across the study site.

3.4 Relationships and Growth Limitations

3.4.1 Growth Limitations and Soil-Growth Relationships

Known limitations to tree growth and the relationships between plant performance and soil properties have been applied in this study. The factors causing severe limitation to growth are those previously identified for eucalyptus plantations in the region. The guidelines for general performance variability are derived from the known responses of plants to their environment.

Limitations

There are many limitations to tree growth which become important in plantation site selection. The site assessment requirements compiled by Ryan et al. (2002) were presented in Table 1. The key limitations to growth were noted as being: steep slopes, waterlogging, salinity, shallow depth to bedrock and deep sandy profiles. Slopes of greater than 15% are deemed unsuitable, as are areas of seasonal waterlogging in the lower sections of the landscape. An upper limit to tolerable salinity is 50 mS/m and soils of less than 2m above bedrock will cause restricted growth due to lack of water storage in the soil profile. The deep sandy profiles are not likely to cause fatalities in a plantation, although they are associated with poor performance.

In a previous study conducted by Harper et al. (2005) weightings have been given to areas exhibiting each of these factors. Steep, waterlogged, saline or shallow bedrock areas have been given a rating of 0, while sandy areas receive a yield penalty of 20%, thus receiving a rating of 0.8. Although the weighting system has not been implemented in this methodology, their distinction between suitable, unsuitable and sandy areas has been used to create the basic suitability classification of the site (see Section 3.5.2).

Plantation Performance

The factors affecting the growth of trees are generally controlled by the climate, soil and position in the landscape. Over the scale of the Sandawindy study site, climatic variables are constant, hence only soil attributes and landscape position contribute to differences in growth across the site.

The specific effects of landscape position on radiation, evaporation rates and availability of water have not been considered in this study. This is due to a number of reasons: firstly, the existing plantations have been located on similar aspects thus preventing verification of different growth ratings for north or south facing slopes; secondly, the site is relatively flat with slopes of less than 15%, hence there is expected to be little variation due to hillslope position; and thirdly, the resolution of the available DEM was insufficient to calculate a wetness index at the study site scale. The inclusion of landscape position effects has, however, been inherent in the identification of different soil types as discussed below.

Variations within the soil which govern water and nutrient availability are assessed in terms of the soil parent material, the depth, texture, structure, colour and condition (Cremer 1990). Many of these features are governed by topography, as has been noted in the discussion of the geomorphological approach to soil mapping in Section 2.3.2. The extent to which each of

the soil variables has been assessed in this study, is dependant on the ability to characterise them using the radiometric and elevation datasets.

In the Sandawindy region the common rock types and hence parent material of soils are granite, gneiss and quartz (McKenzie et al. 2004). Soil fertility is dependant on the weathering potential of this rock and the age of the weathered layer, as both affect the availability of nutrients such as potassium (Cremer 1990). Since potassium is one of the elements most readily leached from soils, the variations in concentration indicate soil fertility. Areas of high potassium have therefore been identified as sites for good tree growth, provided they do not coincide with areas affected by the major growth limitations.

The depth between the surface and an impermeable layer (such as bedrock or ferricrete hardpans) determines the volume of soil from which plant roots can obtain nutrients and water. It also affects the potential for waterlogging which, as previously stated, is a major limitation to tree growth. For most soils the general relationship is that deeper soils correspond to better tree growth (Cremer 1990). It is, however, more likely that deeper soils are highly weathered and hence have lower fertility. Thus newly weathered, high potassium soils of depth greater than 2 m are associated with the best performance, followed by deeper, more weathered profiles. The presence of laterite at the surface and high ironstone gravel content are indicators of a deep, highly weathered profile, which is useful for identification using radiometric data (Wilford 1997). The influence of depth on growth has been used in the application of the growth index outlined in Section 3.5.4.

Soil texture is important in determining the amount of 'available soil water'. The ability for soil to drain or retain water amongst soil particles varies as the percentages of sand, silt and clay do (Cremer 1990). Sand is the most important texture-related feature affecting growth in this landscape as it is so widespread (McKenzie et al. 2004). As stated earlier in the Limitations Section, high sand content in the soil is considered to be a predictor of poor tree performance. Such areas have been used in developing the growth rating index.

The clay and silt components are important as they contribute to the formation of impermeable layers and increase the potential for waterlogging (Cremer 1990), although their influence on plant growth has not been considered in this study. Clays are generally present at lower lying areas of the landscape which are deemed unsuitable for plantations for other reasons, and waterlogging potential has been identified using elevation data.

Soil structure, subsoil condition and soil colour are measures used to determine the availability of water and nutrients and hence predict tree performance. These factors have not been considered in this methodology as they are more appropriate to field soil surveying techniques. They have, however, been considered in the interpretation of the FPC soil survey logs used for ground truthing.

3.4.2 Data Interpretation Techniques

Previously established relationships between airborne radiometric data and soil properties or landscape features have been utilised in this study. The specific features which have been identified as important to growth, and are able to be delineated using combinations of radiometric, EM and DEM data are: salinity, waterlogging, shallow soils, sand, high potassium areas, laterite and ironstone gravel. The relationships between these features and the relevant data are described in this section. The specific thresholds used to quantify these relationships have been determined through groundtruthing and analysis of the input datasets. The details of this analysis are presented in Section 3.5 and the exact thresholds applicable at the study site are presented with the results in Section 4.1.2.

Salinity

The ground electromagnetic survey data is used to delineate saline areas across the study site. The details of EM survey methods have been presented in Section 3.2.2 and the threshold to be applied to these layers is 50 mS/m as stated in Section 3.4.1. The EM38 dataset has been used for the site classification, as it is expected that two year old trees will be subject to the effects of salinity present in the shallow subsurface. Both the EM38 and deeper EM31 datasets have been used in the assessment of implication of salinity at the site, as presented in Section 3.6.3.

Waterlogging

The potential for waterlogging was determined by elevation. It was assumed that landscape position was the principle factor leading to waterlogging, as soil texture and structure could not be clearly identified using available data. A threshold, based on field observations, was applied to the DEM. Below this value the potential for waterlogging defines the land as unsuitable for plantations.

Shallow Soil

Areas of shallow soil over granitic bedrock can be identified using a combination of radiometric and DEM data. The shallow soils are at the early stages of the weathering

process and still have high mineral content, which is reflected as high potassium and high total count signals in the radiometric data (Taylor et al. 2002). Both these signals are associated with other landscape features such as potassium rich clays and laterite outcrops, respectively, hence the use of landscape position (elevation) to ensure detection of the correct feature. High total count and high elevation have been used to delineate areas of shallow soil.

Sand

Sandy areas have been leached of most mineral content including uranium, thorium and potassium. Taylor et al. (2002) found that the best relationship to identify sand was a negative correlation with the total count.

High Potassium

Areas exhibiting high potassium signals in the radiometric data were used to represent the plant available potassium within the soil. The radiometric detection of the element is sufficient to delineate clear changes in concentration, although variation at low concentrations cannot be detected (Wong & Harper 1999).

Laterite

Ferricrete caps atop deep weathered profiles are identified by laterite at the surface. These areas exhibit low potassium and high thorium and uranium counts. The high thorium count is thought to be associated with the presence of iron oxides, and low potassium is due to the levels of leaching reached under lateritic weathering conditions (Wilford 1997; Dickson & Scott 1997). These areas were found using a combination of low potassium, high thorium and high uranium concentrations.

Gravel

The presence of ironstone gravel is generally coincident with areas of surface laterite, although it does display a more extensive coverage and hence has been classified separately. The relationship best describing the presence of gravel is a positive correlation with the ratio of thorium:potassium (Taylor et al. 2002). Although the majority of the site is covered by gravel to some extent, only particularly high concentrations were delineated.

3.5 Site Classification

The data analysis approach implemented in this section study follows the basic GIS spatial analysis methodology presented in Figure 5, below. The radiometric, electromagnetic and

DEM data have been analysed according to these basic steps. They can be explained as follows: Stage 1 - initial visual assessment of the datasets; Stage 2 - compiling all input information within the GIS; Stage 3 - using ground truthing to analyse the input datasets; Stage 4 – extracting the key information from the analysis results (Anderson-Mayes 1997).

The application of this methodology within this study has been shown more specifically in Figure 6. The three major steps to result in three different classifications of the study site.

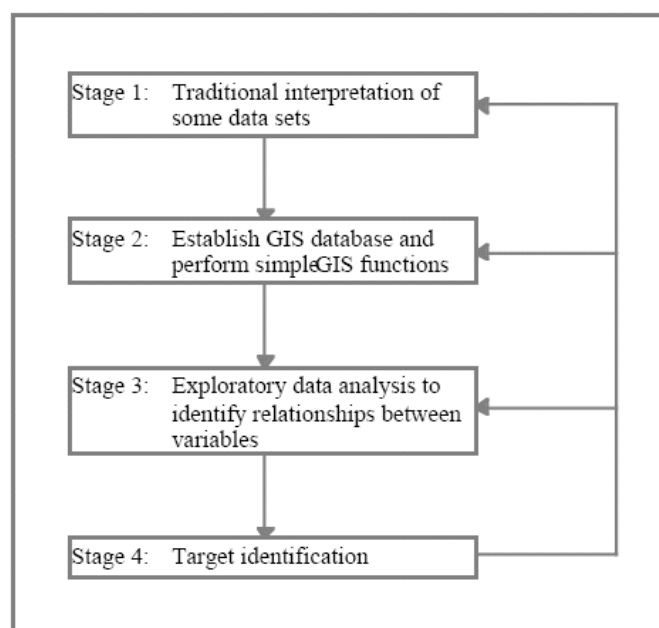


Figure 5: GIS-based Data Interpretation Methodology (Anderson-Mayes 1997)

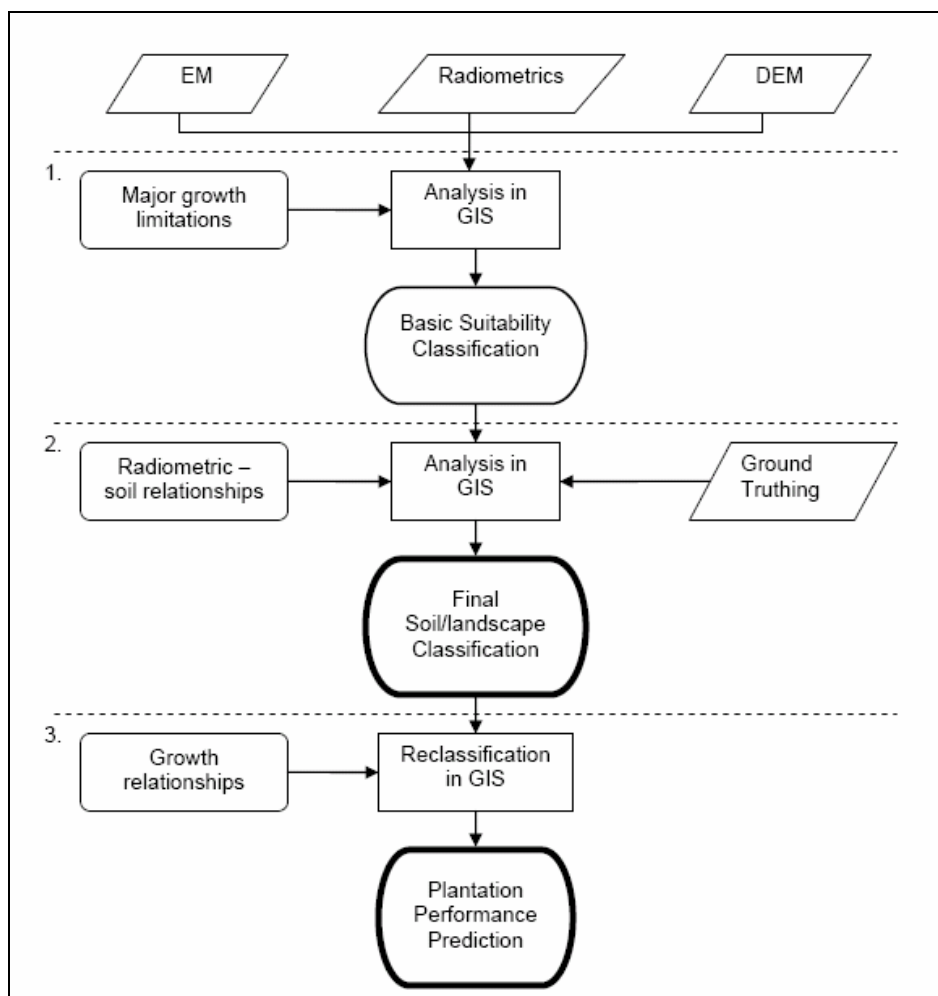


Figure 6: Flow Diagram of Site Classification Methodology

3.5.1 GIS Tools and Operators

The data analysis and site classification has been performed using Geographic Information System (GIS) software. ESRI's ArcGIS 9 package was used. In this section, the specific tasks associated with Steps 1-3 (from Figure 6) are outlined. The relationships and interpretation techniques presented in Section 3.4 are implemented.

The ArcGIS model building, which gives a visual representation of the input datasets and operators in the form of a flow chart, has been used to perform the numerical analyses. A string of operations can be entered into the model in order to achieve a single, meaningful output. The structure of the models required for site classification are presented in the following three sections. The actual models applied at the study site are given in Appendix E, Appendix F and Appendix G

The tools used within these models were the Reclass and the Single Output Map Algebra tools. Within Map Algebra the Combinational Or (CO_r) and Less Than (<) operators were used to apply thresholds and find all combinations of the input layer classes. The Reclass

tool allowed for meaningful reclassification of the, often complicated, CO_r output. Although the site classification could be performed using one model, the need to interpret the results and reclassify at intermediate stages means that the analysis has been split into three separate components.

3.5.2 Step 1: Basic Suitability Classification

The first step in the classification process was to apply the known limitations to tree growth and categorise the area into suitable, unsuitable and sandy areas. These major classes form the basis for the site selection assessment.

To perform this classification, layers showing the presence of sand, potential waterlogging, high salinity and shallow soils must be formed. The quantitative representation of these individual limitations was based on ground truthing and previously established thresholds as discussed in Section 3.4.1. The general form of the model used to form these four layers is shown in Figure 7, below.

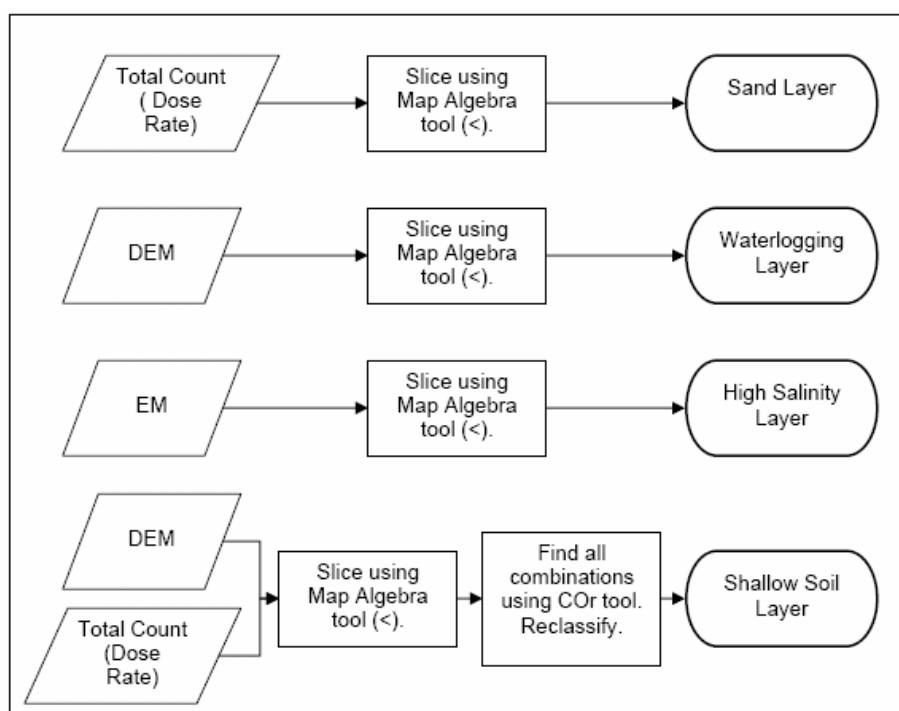


Figure 7: Creating Limitation Layers Flow Diagrams

To obtain the basic, three class classification using these input layers, the method shown in Figure 8 was used. The input limitation layers are those derived in Figure 7. An intermediate layer representing the combined variations of these limitations is found using the CO_r operator. This must then be reclassified into the three desired classes - suitable, unsuitable

and sandy - to give the initial basic classification of the site. It is important to perform the reclassification such that any combination class containing one or more of the major limitations (waterlogging, high salinity, shallow soils) becomes an unsuitable area. The remaining classes then become either sandy or suitable.

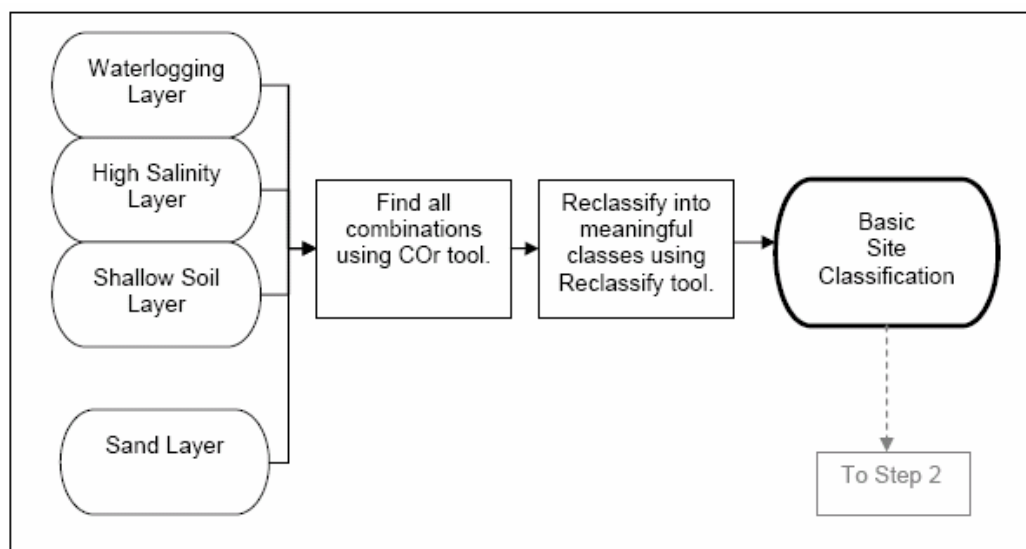


Figure 8: Basic Suitability Classification Flow Diagram

3.5.3 Step 2: Final Soil/Landscape Classification

The suitable class, within the basic classification formed in Step 1, can be further categorised in terms of potassium content, and the presence of laterite and ironstone gravel. This requires the formation of two more landscape feature input layers as shown in Figure 9. The layer labelled 'KTU' delineates areas of high and low potassium, thorium and uranium, while the second layer shows areas of high and low ironstone gravel content. The first layer, 'KTU', requires the input radiometric layers to be sliced according to ground truthing and natural breaks in the datasets. Combinations of these layers are then reclassified and interpreted according to the relationships discussed in Section 3.4.2. The second layer requires the use of a ratio layer (Th:K), which is produced using the Map Algebra Divide tool. Applying an appropriate threshold to this layer gives areas of high and low gravel content.

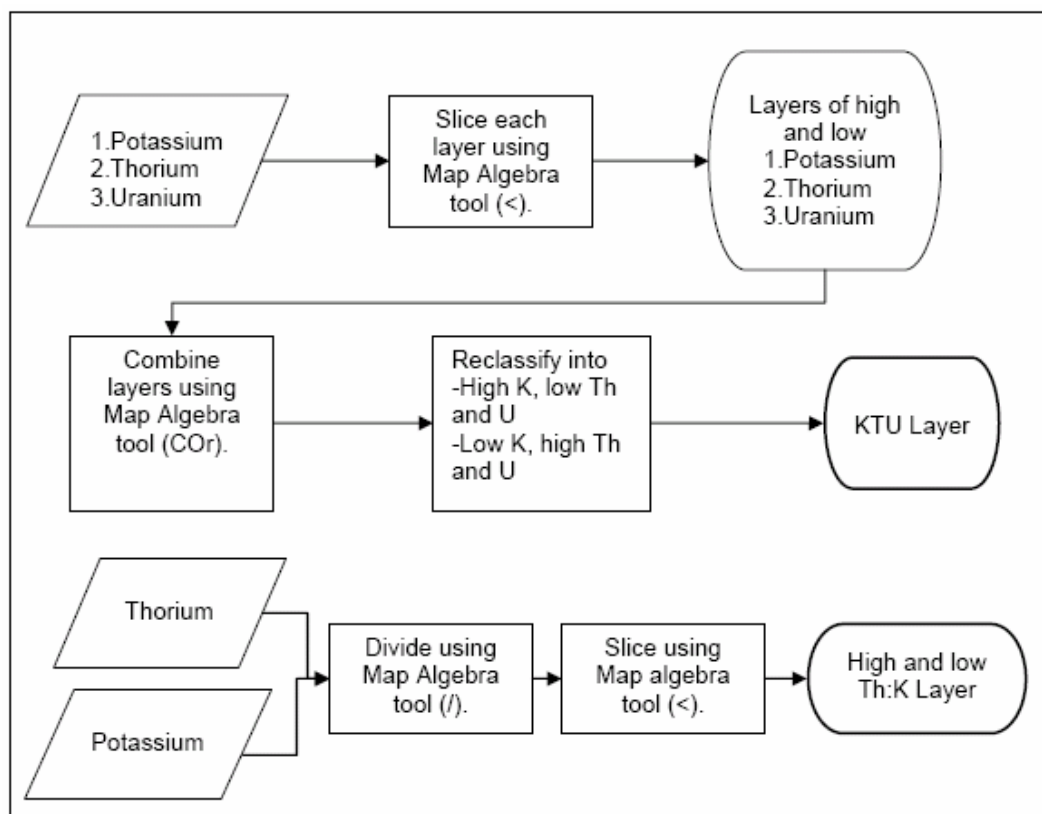


Figure 9: Creating Landscape Feature Layers Flow Diagram

The model required to determine the final classification of the site in terms of meaningful soil groups and landscape features is shown in Figure 10. It incorporates the initial basic classification from Step 1 and the new layers derived in Figure 9, above. Again, an intermediate layer showing the various combinations of the input layers is found and must be reclassified into meaningful classes. The classification must preserve the unsuitable and sandy areas defined in Step 1. Distinct classes showing areas of laterite, gravel and high potassium concentrations can be delineated within the 'suitable' area of the basic classification. The result is the final soil/landscape classification of the site, to be used for the application of a growth rating index in Step 3.

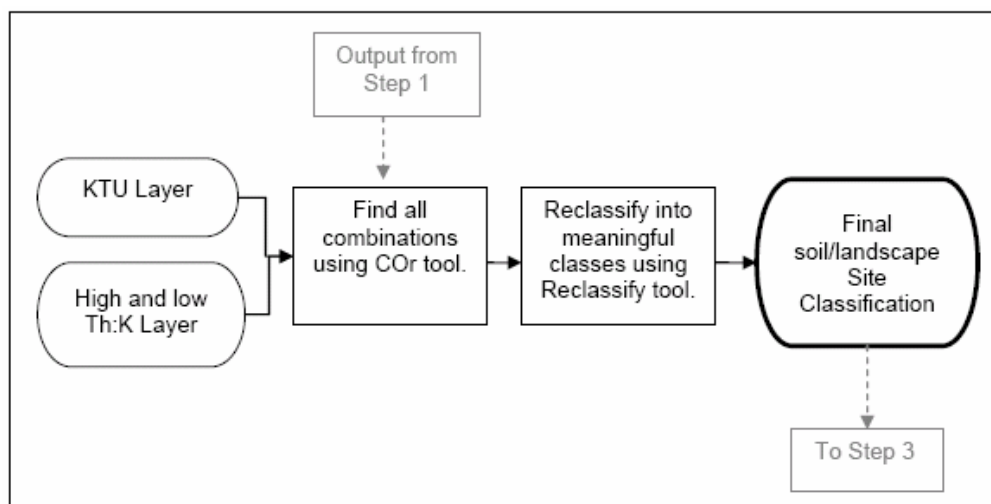


Figure 10: Final Soil/Landscape Classification Flow Diagram

3.5.4 Step 3: Predicted Growth Classification

The final step in the site assessment is to apply a growth rating index across the area. This involves reclassifying the soil and landscape classes formed in Step 2, into corresponding predictions of growth. The predictions are based on the plant responses discussed in Section 3.4.1.

Indices are commonly used in spatial analyses as they allow for a simple numerical representation of information, and consequently manipulation and visualisation within a GIS (Van Niel 2006). In this application an index is used to link soil and landscape features to a prediction of tree growth. The index is given as a scale from 1 to 5. Each value corresponds to a specific range of tree performance, represented by tree height. A rating of 1 represents a dead tree, while 5 corresponds to the height of the biggest tree at the site. An estimation of the maximum height for trees at a given age is required to calibrate the index. For the purposes of this study the value was obtained from the observations made during the field survey, described in Section 3.2.5. This index is temporally invariant, and hence must be recalibrated in order to predict growth at different plantation ages.

In order to apply this index to the classes formed in Step 2, the known responses of trees to their landscape are implemented. The key landscape factors can be ranked from worst to best (in terms of their effect on tree growth) as: unsuitable areas (saline, shallow soil or waterlogged areas); sandy areas; areas with high gravel content; deep weathered profile with surface laterite; and high potassium areas. According to this ranking, each class can be assigned an index value, or range of values, which best represents the expected

performance across that zone. This allows for the reinterpretation of the site classification in terms of predicted tree heights and, correspondingly, plantation performance.

The natural variation in growth within a class has been accounted for by using ranges of values to calibrate and applying the index. To allow for direct comparison, field survey results must be presented as a range of observed performance across a given area.

The process of applying the growth index is shown in Figure 11. The output of this reclassification analysis is the final step to the site assessment as it gives a measure of the expected plantation performance across the property.

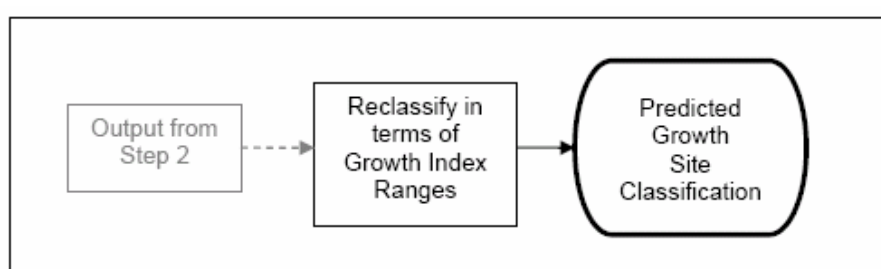


Figure 11: Growth Index Classification Flow Diagram

3.6 Plantation Purpose Assessment

In order to give a measure of the performance of the study site plantation with respect to the driving purposes of dryland forestry, the carbon sequestration and groundwater recharge rates have been calculated. Published allometric relationships and default values have been used to calculate the carbon sequestration, while the water balance model, AgET, gives a measure of the drainage to groundwater.

An assessment of the effects of salinity on the Sandawindy plantations has also been performed. The extent of the unsuitable class, of which saline areas are a component, and the proportion of the plantation which lies within this class has been computed. The current effects are assessed using the EM38 dataset which delineates salinity in the top 50cm, while future effects are determined using the EM31 measurements at a depth of 1-4m.

3.6.1 Carbon Sequestration

In order to determine the performance of a plantation with respect to emissions offsetting purposes, the amount of carbon being sequestered must be calculated. Robust and consistent accounting methods are required when there is a monetary value associated with

sequestered carbon units. The method presented in this section implements default values and published allometric relationships, applicable to eucalyptus plantation species in Western Australia. The method follows that presented by Harper et al. (2005).

An estimate of the rate of carbon sequestration requires measurements of tree height and trunk diameter as well as plantation dimensions. The site survey described in Section 3.2.5 provides this data. The calculation procedure involves computing the tree volume, the tree biomass and hence carbon content. This calculation is outlined in Figure 12, below.

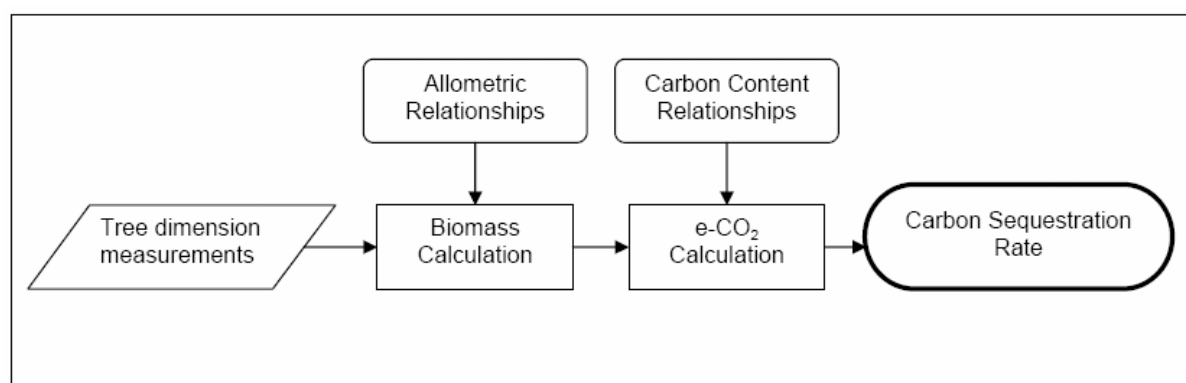


Figure 12: Carbon Sequestration Rate Calculation Flow Diagram

The volume of trees in each plantation is calculated with the following steps:

1. Area of ground per tree.

The area of ground available to each tree is calculated from the tree and row spacing measured at the sample sites.

$$area/tree = tree_spacing * row_spacing$$

Note: Each plantation site must be assessed individually due to the variations in tree spacing and row spacing.

2. Number of trees in the plantation.

$$No.trees = plantation_area / (area/tree)$$

3. Sample and plantation volumes

The volume of the sampled trees has been calculated using previously established allometric relationships between the height and diameter at breast height (DBH), published in the *Tree Measurement Manual for Farm Foresters* (Department of

Agriculture Fisheries and Forestry 2003). As mentioned in Section 3.2.5, the diameter at 10 cm (D_{10}) was measured in the field survey and hence has been used in place of DBH the following calculations.

First the Tree Basal Area (TBA) must be calculated for each of the sample trees using:

$$TBA[m^2] = 3.142 * (D_{10}[m] / 2)^2$$

The tree volume is then:

$$volume_of_sampled_tree = (TBA * height) / 3$$

The volume of all the sampled trees:

$$sample_volume = \sum volume_of_sampled_tree$$

And the volume of the plantation:

$$plantation_volume = (No.trees / No._sampled_trees) / sample_volume$$

4. Tree volume per hectare

$$volume / hectare = total_plantation_volume[m^3] / plantation_area[ha]$$

The following estimates of biomass and carbon content are based on published values.

5. Stem-wood mass

$$stem_mass / hectare = (volume / hectare) * tree_density$$

Where $tree_density = 0.758 \text{ t/m}^3$, as calculated for the *E. Cladocalyx* species (Ilich et al. 2000).

6. Above ground biomass

$$biomass_above / hectare = C * stem_mass / hectare$$

The conversion ratio, C , of stem-wood mass to above ground biomass is 1.3. The lower end of a range for harvestable age trees (Snowdon et al. 2000) and has been used to account for the age of the sampled trees.

7. Total biomass

$$biomass_total / hectare = (biomass_above * biomass_below) / hectare$$

The below surface biomass is given by:

$$biomass_below = RS * biomass_above$$

The ratio of above to below ground biomass, RS , is termed the root: shoot ratio. A default value of 0.25 for Eucalyptus species in Australia has been used (Snowdon et al. 2000).

7. Carbon mass

$$mass_carbon / hectare = CC * biomass_total / hectare$$

A standard value of the percentage carbon in tree biomass is $CC = 50\%$ (Specht & West 2003).

8. Carbon Dioxide equivalents

$$mass_CO_2 - e / hectare = CF * mass_carbon / hectare$$

The carbon mass is converted into carbon dioxide equivalents (CO_2 -e), which gives a measure of the amount of carbon dioxide which has been sequestered over the life of the tree to date. The molecular weights of C and CO_2 are 12.01 and 44.01, respectively, hence a conversion factor of $CF = 3.66$. This mass of CO_2 -e has units of t/ha.

9. Carbon Sequestration rate

$$mass_CO_2 - e / hectare / yr = (mass_CO_2 - e / hectare) / tree_age$$

Carbon Sequestration is commonly presented as a rate of t CO₂-e/ha/yr.

This analysis results in an estimate of the rate of carbon sequestration for each of the plantations surveyed at the site. An average rate can then be found, as well as the range and variance in sequestration between different locations across the property.

3.6.2 Groundwater Recharge

The amount of water infiltrated to groundwater, or deep drainage, is important when considering the formation and mitigation of dryland salinity. In order to assess the performance of a plantation with respect to reducing this drainage, the AgET water balance calculator can be used. The procedure is outlined in Figure 13, below.

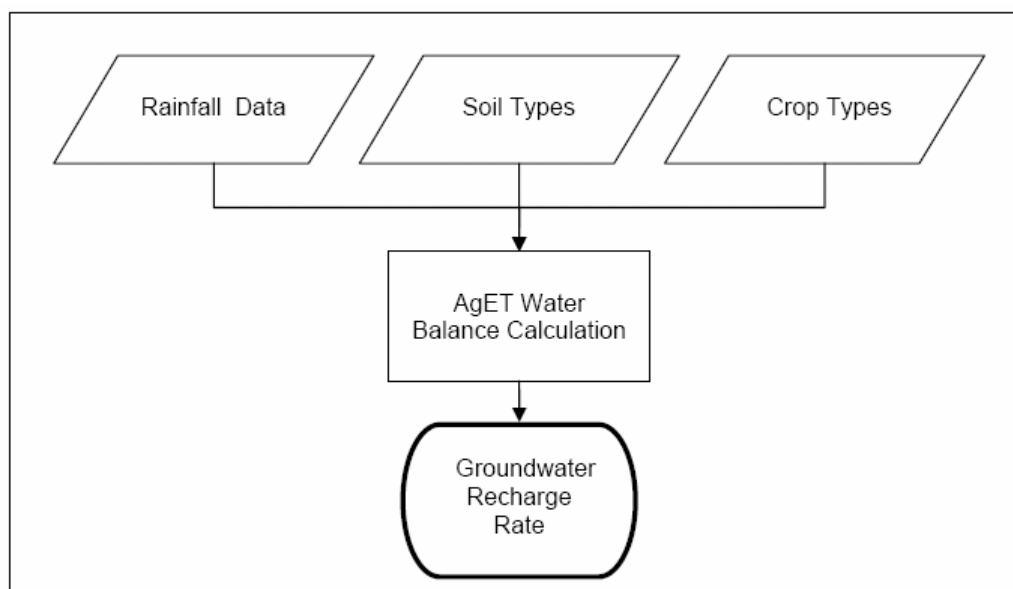


Figure 13: AgET Calculation Flow Diagram

AgET performs a simple water balance calculation based on soil type, crop type and mean annual rainfall, using sets of predefined representative parameters which can be adjusted by the user. It is a one dimensional calculation and uses the cascading bucket model to represent the flow of water down through the soil column (Harper et al. 2005). The water balance is as follows:

$$P = ET + R + D + \Delta S$$

Where P is precipitation, ET is evapotranspiration, R is runoff, D is deep drainage and ΔS is the change in soil storage. The deep drainage component is that which infiltrates down through the bottom layer of the cascade model and recharges groundwater.

For the assessment of eucalyptus plantations the model is used to determine the reduction in deep drainage due to a land use change from seasonal crops to forestry. The inputs required for the model are: the basic soil units for the study area, the desired crops to be compared and the long term Mean Annual Rainfall (MAR).

3.6.3 Salinity Assessment

In order to further assess the current and future productivity of the Sandawindy plantations, the effects of unsuitable areas on tree growth have been quantified. This has involved the calculation of the proportion of the plantation area which lies within the unsuitable region, as it was defined in Section 3.5.2. These unsuitable areas are made up of high salinity zones, potentially waterlogged areas and shallow soil areas. The effects of the latter two components can only be assessed at long term timescales, while salinity on the other hand can be assessed for both its current and future effects on tree growth. This is due to the availability of two datasets, EM38 and EM31, describing salinity concentrations in the shallow (0-50 cm) and deep (1-4m) subsurface, respectively. As trees mature their root system extends deeper into the soil column, and hence the presence of salinity at different depths is noticed at different tree ages. This allows for a temporal assessment of the effects of salinity on a plantation at a given location.

The procedure used to quantify these effects is shown in Figure 14, below. The method of creating the 'Unsuitable area' input layer was presented in Section 3.5.2, and must be done for both EM38 and EM31 datasets. Two sets of results are then obtained from this analysis.

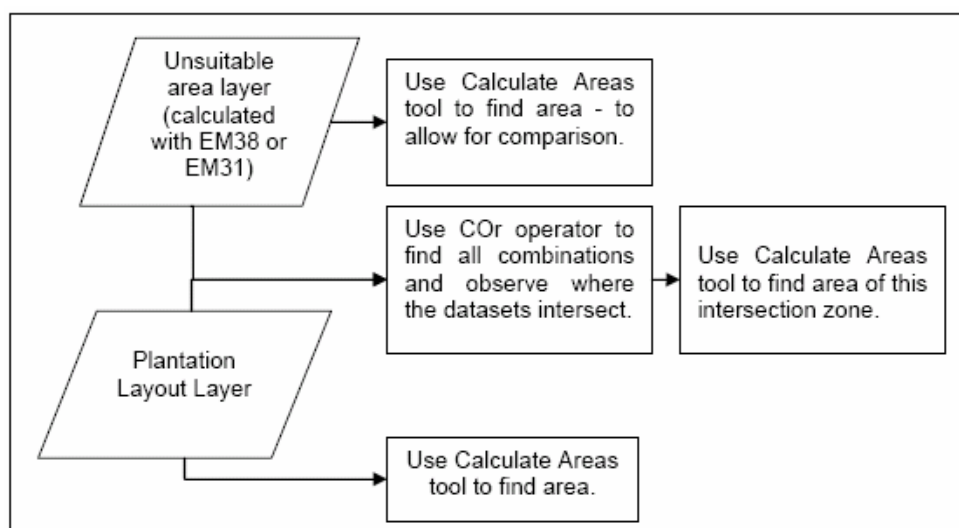


Figure 14: Salinity Assessment Calculation Flow Diagram

4.0 Results

4.1 Site Classification

4.1.1 Landscape and Soil Survey Results

The notes and measurements made during the field survey of the study site are presented in Appendix C. See Appendix A for the locations of the sample sites and the observed landscape features which were used for ground truthing purposes. Areas of exposed granite, laterite, high sand or gravel content and observed surface water are noted on the map.

The logs of the 2004 Forest Products Commission soil survey of the site can be seen in Appendix B.

4.1.2 Thresholds

The relationships between the input datasets and key soil or landscape features were described in Section 3.4.2 and the corresponding ground truthing information was presented in the previous section.

The following tables show the thresholds to be applied to the data in order to delineate the key soil features. Table 2 shows the major growth inhibitors and Table 3 shows extra features used to categorise the site. The methods used to apply these thresholds were presented in Figure 7 and

Figure 9, and the actual GIS models used to perform the analysis are given in Appendix E and Appendix F.

Table 2: Thresholds for Delineating Growth Inhibitors

Limitation	Input Layer	Threshold to Input Layer
Sand	Dose Rate (Total Count)	30 nGy/h
Waterlogging	DEM	221 m
Salinity	EM31	50 mS/m
Shallow Soil	Dose Rate and DEM	100 nGy/h and 255 m

The thresholds for sand and waterlogging were identified using the FPC soil survey and field observations. The values used to delineate shallow soil areas were determined from natural breaks in the dose rate dataset as well as both sources of ground truthing information. The threshold for salinity tolerance is a published figure (Ryan et al. 2002).

Table 3: Thresholds for Delineating Landscape Features

Landscape Feature	Input Layer	Threshold to Input Layer
Potassium and Laterite Distribution	Thorium, Uranium and Potassium	15 ppm, 5 ppm and 0.7%
Presence of Gravel	Thorium:Potassium	180 ppm/ %K

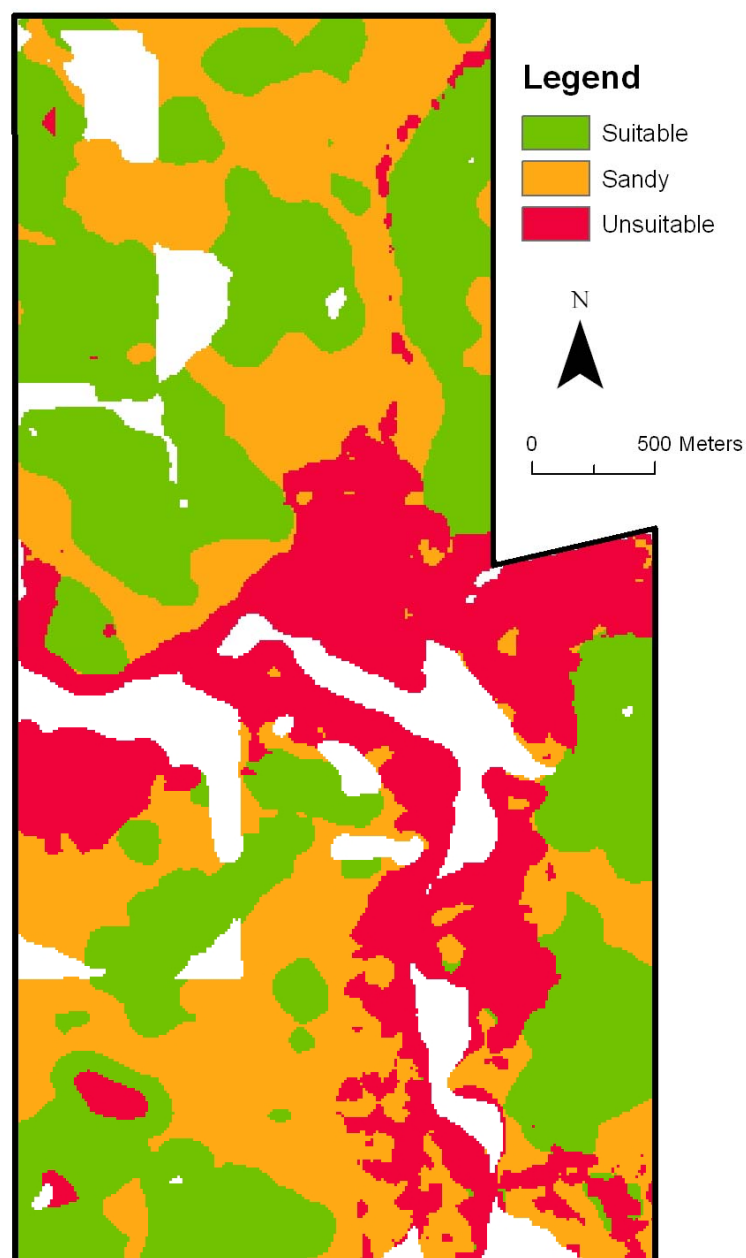
The thresholds for the thorium, uranium and potassium layers were derived from natural breaks in the datasets, as well as field observations. The threshold for Th:K is based on natural breaks in the dataset

The application of these thresholds, according to the methods presented in Sections 3.5.2 and 3.5.3, forms a set of individual layers associated with each of the limitations and landscape features. The GIS models used to create these layers are presented in Appendix E and Appendix F. The resultant images corresponding to each limitation and landscape feature are shown in Appendix H and Appendix I, respectively.

4.1.3 Landscape Classification

Two different classifications of the site have been derived from combinations of the individual soil and landscape layers, described above. The first classification consists of three categories: areas deemed sandy, suitable or unsuitable for successful tree growth. The GIS models used to perform this classification are presented in Appendix E and Appendix F. The resultant distribution of the three classes across the study area can be seen in Figure 15.

The second stage of classification was to derive a more detailed representation of the study site. The inclusion of two more data layers produced a classification with 13 categories, although interpretation and reclassification reduced these to six meaningful classes. This final classification maintains the sandy and unsuitable areas shown in Figure 15, but splits the suitable class into areas of moderate gravel content, surface laterite and high gravel content, deep weathered profile and high potassium. Note that the 'Deep Weathered Profile', 'Gravelly', and 'Surface Laterite' classes are all representative of areas with deep weathered soils, however, the separation into different classes reflects the varying amounts of ironstone gravel and surface laterite observed at the surface. The concentration of gravel and laterite represented by these classes is, in decreasing order: 'Surface Laterite', 'Gravelly' and 'Deep Weathered Profile'. The GIS model used to produce the image and the details of the reclassification are given in Appendix F. The resultant classification is shown in Figure 16.



(Data Sources: Geoforce 2004; Fugro 2004; Land Monitor)

Figure 15: Basic Site Classification

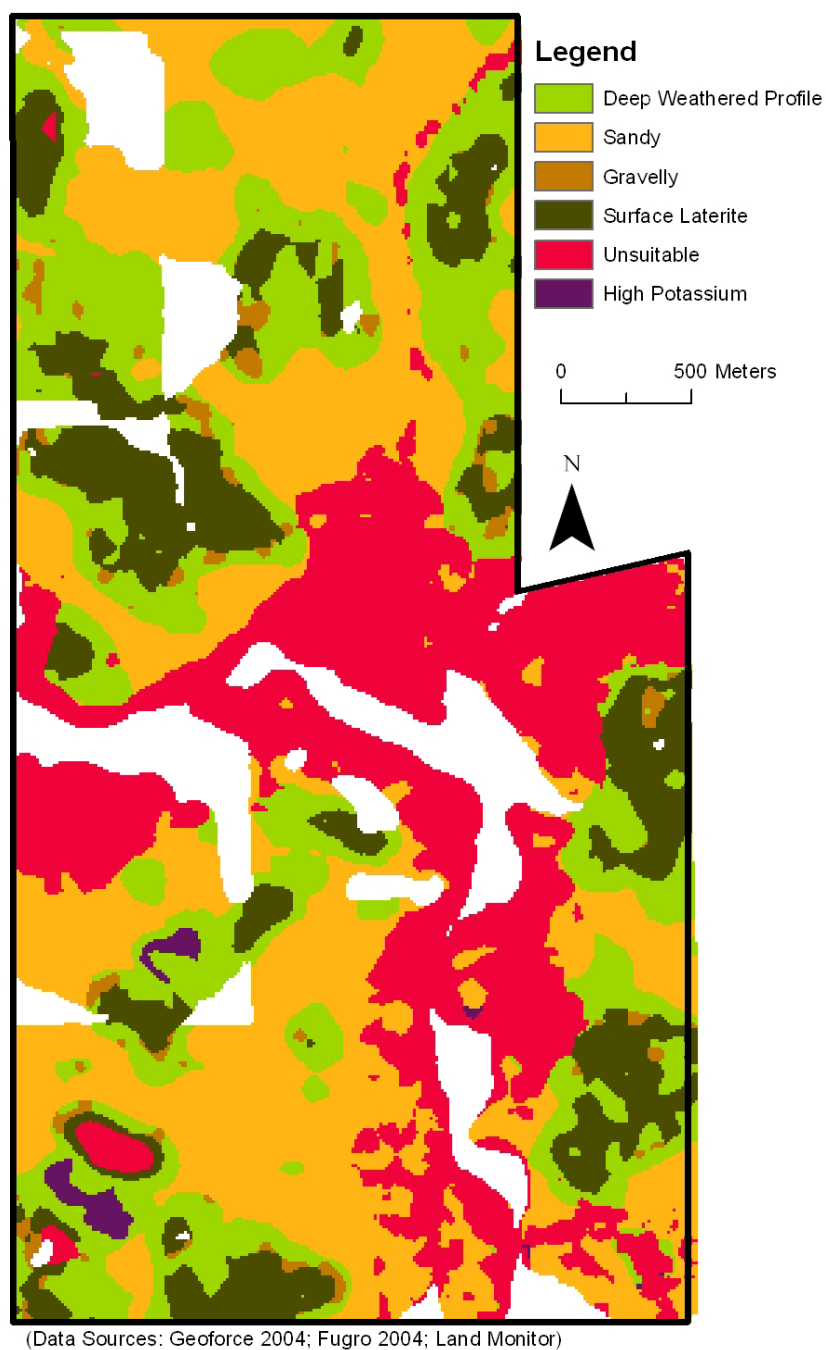


Figure 16: Final Soil/Landscape Site Classification

4.1.4 Growth Index Classification

As outlined in Section 3.5.4 the final stage of the GIS classification analysis was to apply a growth rating index to the site. Based on information presented in Section 3.4.1, a rating from a scale of 1 to 5 (increasing tree growth) was given to each of the 6 classes in the Final Soil/Landscape Classification. The results are given in Table 4. Ranges have been used to represent the expected variations in tree performance within each class. The model used to apply these ratings and produce this final site classification is given in Appendix G. The visual representation of this data is shown in Figure 17.

Table 4: Growth Rating Prediction

Class	Growth Prediction
High K	4 - 5
Surface Laterite and Gravel	3 - 4
Gravelly	3 - 4
Deep Weathered Profile	2 - 3
Sandy	2
Unsuitable	1 - 2

This growth index links a soil/landscape category to a growth prediction for trees at that site. The height of the tree was taken as a measure of growth, and the expected height range at the site was derived from field measurements. A range of 1m to 4m was observed across the whole study area. This led to the calibration of the index as shown in Table 5, below.

Table 5: Relating Growth Index to Tree Height

Index Value	Tree Height (m)
1	Dead
2	<1.4
3	1.4 – 1.8
4	1.8 – 2.5
5	>2.5

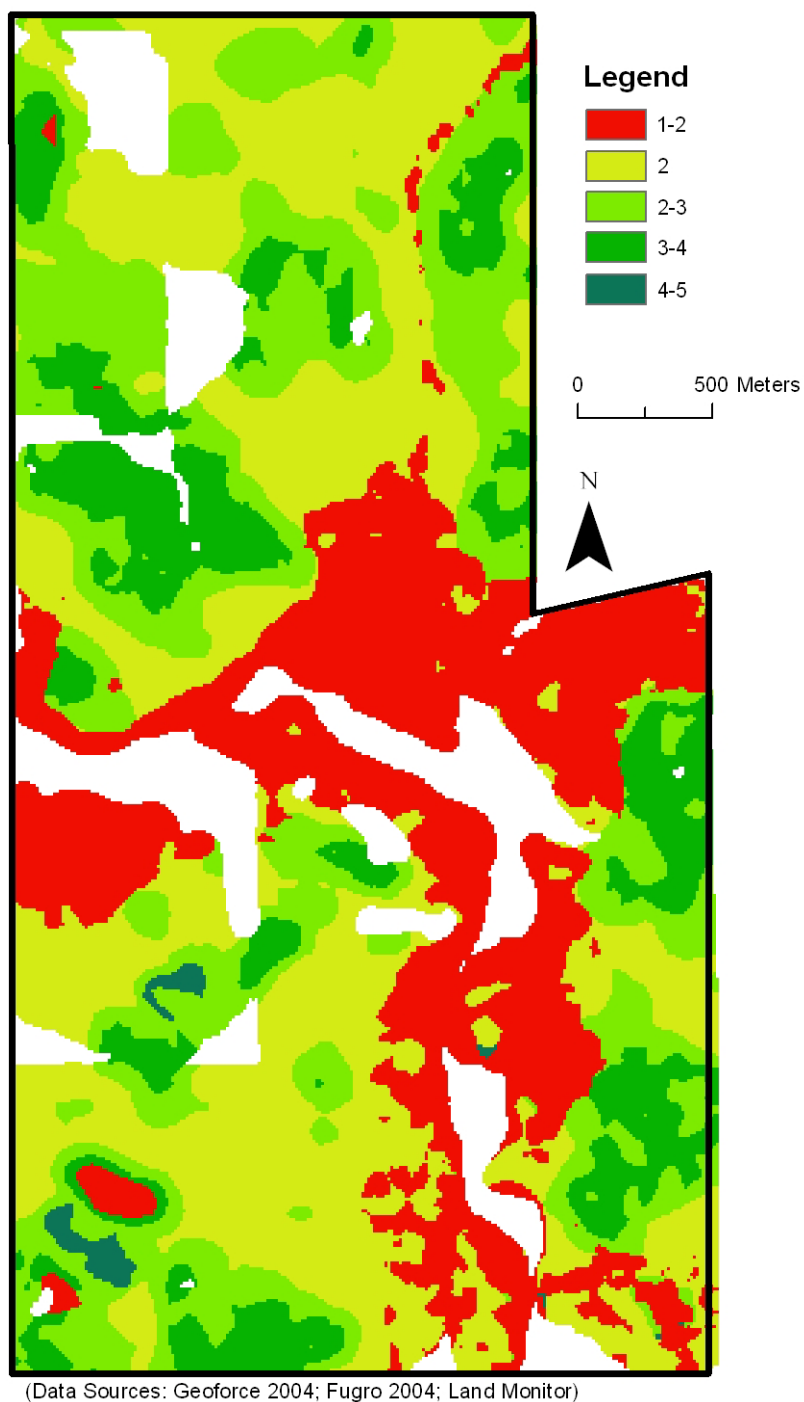


Figure 17: Growth Rating Classification

4.2 Observed Tree Growth

The measurements and observations of tree performance made during the site visit can be seen in Appendix C. This information shows that there are definite variations in tree performance across the study area and even within a single plantation.

The height measurements made at 12 of the sample sites have been converted into their equivalent growth index ratings, based on the conversion presented in Table 5. These ratings then apply to the soil/landscape category in which the sample site is located, hence the formation of a continuous spatial representation of the measured point data. Again index ranges have been given to best represent the observed growth variations.

The results of field measurements are presented in terms of an observed growth rating. The predicted and observed index values for each soil/landscape class are shown in Table 6.

Table 6: Predicted and Observed Growth Rating

Class	Growth Rating Prediction	Observed Growth Rating
High K	4 - 5	3 - 4.5
Surface Laterite and Gravel	3 - 4	3 - 4
Gravelly	3 - 4	3 - 4
Deep Weathered Profile	2 - 3	1.5 - 3
Sandy	2	2 - 3
Unsuitable	1 - 2	1 - 4

4.3 Sandawindy Plantation Performance

4.3.1 Carbon Sequestration

The current rate of carbon sequestration has been calculated based on the diameter (d_{10}), height and spacing of *E. cladocalyx* trees at sample sites across Sandawindy. The methods for this plantation survey were detailed in Section 3.2.5. Appendix A shows a map of the sample sites. The details of these calculations are presented in Appendix D based on the raw survey data presented in Appendix C.

Carbon sequestration has been calculated as the amount of carbon dioxide sequestered per area, over the time the trees have been growing. This gives an average cumulative rate of 4 t CO₂-e/ha for the two year old *E. cladocalyx* trees. This is approximately equivalent to a rate of 2 t CO₂-e/ha/yr, assuming that the trees have been growing at a constant rate over the two years.

4.3.2 Deep Ground Water Recharge

The calculation of the rate of drainage to deep flow at the study site was performed using AgET. The specific input parameters are as follows.

Soil

A summary of the soil units used and the modifications to predefined parameters are given in Table 7, below.

Table 7: Soil Information Used in AgET

Soil Unit	Horizon A Depth (m)	Horizon B Depth (m)
Deep Sandy Duplex	4	3
Deep Loam Duplex	4	3

Crops

The model was run for two different types of vegetation cover. The annual crop represents the land use of the property prior to plantation, and the eucalyptus crop represents the current plantation. Modifications have been made to eucalyptus root depths in order to account for the age of the trees. The changes are given in Table 8.

Table 8: Crop Information Used in AgET

Crop	Min. Root Depth (m)	Effective Root Depth (m)	Max. Root Depth (m)
Other Annual	0.1	0.3	1
Eucalyptus	1	2	3

Rainfall

Using the rainfall data obtained from the SILO Data Drill (for 1986 to 2006), the mean annual rainfall was calculated to be 497 mm/year.

Deep Flow

AgET was run for a period of ten years (1983 to 1993), for each soil unit, with a one year rotation between the annual crop and eucalyptus vegetation types. A summary of the results is given in Table 9. The reduction in recharge to groundwater across the site varies from 78 to 132 mm/year.

Table 9: Deep Flow Results from AgET

Soil Unit	Annual Crop Deep Flow (mm)	Eucalyptus Deep Flow (mm)	Difference in Deep Flow (mm)
Deep Sandy Duplex	139	7	-132
Deep Loam Duplex	78	0	-78

4.3.3 Effects of Salinity

After applying a salinity threshold of 50 mS/m to both the EM38 and EM31 datasets (as presented in Section 3.6.3), two corresponding unsuitable classes were formed. The area of each of these zones has been calculated and is shown in Table 10, below. This value has also been given as a percentage of the total property area.

Table 10: Extent of Saline Areas and Unsuitable Class with EM38 and EM31 Input Datasets

Input EM Dataset	Saline Area (with > 50mS/m) (ha)	Unsuitable Area (ha)	Saline area as percentage of Unsuitable Area (%)**	Unsuitable Area as percentage of total property area (1180 ha) (%)**
EM38 (0-50cm)	75	266	28	22
EM31(1-4m)	477	520	92	44

**Note that both EM datasets have some data missing, hence in the extent of saline, and therefore unsuitable, areas is likely to be greater than that presented here.

The area of Forest Products Commission plantation located within these unsuitable classes has been calculated. This is based on the current plantation layout obtained from the FPC (2004b). The values have been presented as a percentage of the total plantation area in Table 11, below.

Table 11: Plantation Area Within Unsuitable Classes

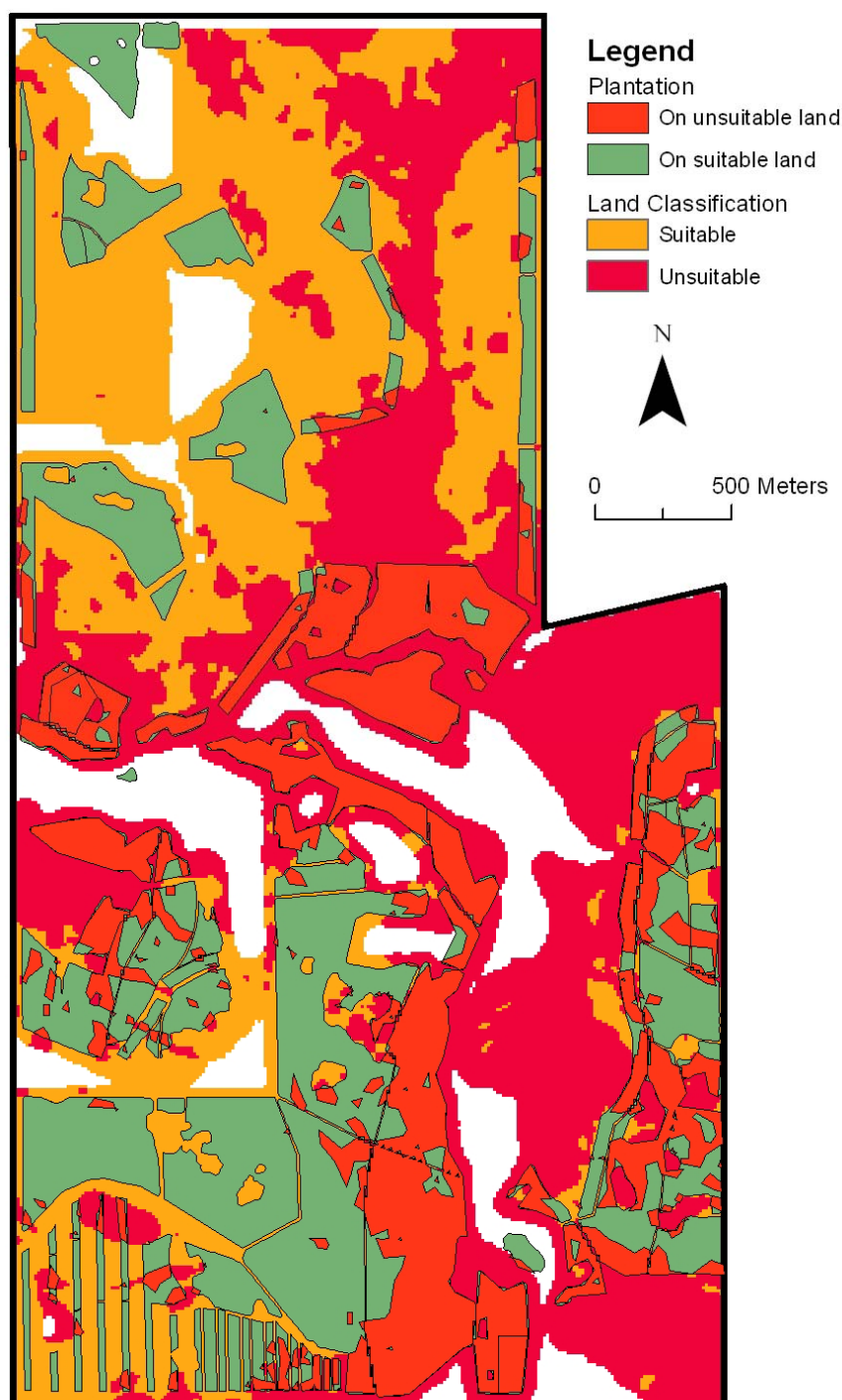
Input EM Dataset	Area of Plantation in Unsuitable Area (ha)	Percentage of total plantation area (%)
EM38 (0-50cm)	84	21
EM31(1-4m)	172	42

The plantation layout and unsuitable classes derived from EM38 and EM31 can be seen in Figure 18 and Figure 19, respectively.



(Data Sources: FPC 2004; Geoforce 2004; Fugro 2004;
Land Monitor)

Figure 18: Plantation Location and Unsuitable Class (with EM38 dataset) Map



(Data Sources: FPC 2004; Geoforce 2004; Fugro 2004;
Land Monitor)

Figure 19: Plantation Location and Unsuitable Class (with EM31 dataset) Map

5.0 Discussion

The following points will be addressed in this discussion:

1. an assessment of the Sandawindy plantation performance
2. the suitability of radiometrics as a data source for site selection methods
3. the implications of the site selection method presented, for dryland forestry in Western Australia.

5.1 Sandawindy Site Assessment

Carbon sequestration and salinity control are two of the driving factors behind dryland forestry. It is therefore important to assess the performance of a plantation with respect to these purposes. Methods of accounting for carbon sequestration and groundwater recharge reduction are continually being developed and refined, to allow for the establishment of abatement schemes and consistent management approaches. With continual monitoring of plantation performance under different conditions, the knowledge base required to drive these developments is formed. A performance assessment of the Sandawindy plantations provides information on the response of two year old *E. cladocalyx* trees, as well as general information regarding the effects of salinity across the property.

The Sandawindy site lies within a region which has been identified as having the potential to support viable carbon sink plantations (single purpose), should the value of carbon reach \$15/t CO₂-e (CRC for Greenhouse Accounting 2004). This result was based on a large scale study, and it is important to determine whether such predictions are verified by existing plantations in the area.

Carbon sequestration across the study site plantation is occurring at a rate of approximately 2 t CO₂-e/ha/yr. This value is low relative to the 12 - 14 t CO₂-e/ha/yr rates obtained for *E. globulus* plantations in the same region (Harper et al. 2005). They cannot, however, be directly compared, due to the age of the trees at the Sandawindy site. If a ten year plantation rotation is assumed, and the current sequestration rate maintained, then the total amount of sequestration is estimated to be 20 t CO₂-e/ha. This does not compare to the rates of 200-300 t CO₂-e/ha used to assess the suitability of the region for carbon sequestration plantations (CRC for Greenhouse Accounting 2004). The extension of this study to include future yield predictions would allow for a more accurate calculation of sequestration rates over the rotation timescale, and hence direct comparisons to predicted rates.

Dryland salinity is a major threat to the agricultural lands which surround the study site. Abatement schemes which aim to control the spread of salinity have been identified as a possible economic input to forestry across the region (Forest Products Commission 2006a). There is continuing doubt, however, that the inclusion of forestry and perennial crops into farming practise will be sufficient to control and mitigate the spread of salinity, particularly in lower rainfall areas (Lefroy et al. 2005).

The amount of water infiltrating to deep drainage can be used to assess plantation performance with respect to salinity control. A decrease in groundwater recharge of between 72 and 132 mm/year was calculated for a land use change from annual crops (such as is commonly farmed in the area) to eucalyptus plantations. The plantation, modelled on that at Sandawindy, produced recharge rates of 0 to 7 mm/year. The ranges are due to the variation in major soil types present at the study site. These results reflect the common assumption that there is no deep drainage in areas vegetated with deep rooted perennial crops (Pracilio et al. 2003b). A spatial distribution of the recharge rates could not be assessed with the available soil data.

Despite this reduction in groundwater recharge associated with eucalyptus plantations, it cannot be concluded that a significant change in the water table will result. It is not guaranteed, therefore, that the effects will be sufficient to control or mitigate salinity (Pannell & Ewing 2006). The response of a catchment to a plantation is highly variable. Consideration of the extent and placement of the plantation within the landscape offers a greater measure of its potential to address the threats of salinity.

The introduction of perennial crops and forestry into agricultural areas has the potential to control salinity only if done successfully on a large scale (Pracilio et al. 2003b). Studies have shown that in order to address dryland salinity over 50% and up to 80% of a catchment would need to be devoted to forestry or other deep rooted perennial crops (Pannell & Ewing 2006; George et al. 1999). Not only is it important to achieve this coverage, but to ensure that the plantations are correctly located such that they themselves are not limited by the effects of unsuitable land. More specifically, the purpose of the plantation – whether it is for local immediate land reclamation, or long term broader scale salinity control – determines where best to locate the plantation (George et al. 1999).

A study of the Sandawindy plantations found that this requirement for correct plantation location was not being met. It was calculated that, of the existing and proposed plantations, 21% were planted in areas currently deemed unsuitable for tree growth. The extent of these

areas is presented in Figure 18. Trees in these zones are predicted to die or be severely limited in their growth and hence will not contribute to salinity control or carbon sequestration purposes of the plantation.

More important, however, is the consideration of the effects of salinity detected at greater depths below the surface. The area currently deemed unsuitable was derived from the presence of salinity in the shallow subsurface. It is predicted that the trees have only developed shallow root systems and hence will show responses to shallow soil properties. When the deeper dataset was used, the extent of the saline (and unsuitable) areas increased from 22 to 44% of the property. In turn the percentage of the plantation within this area increased to 42%. This is shown in Figure 19. The effects of this increase will only be observed once the trees' root systems have expanded into the deeper saline areas. This means that there will be more tree fatalities or severely limited growth as the plantation matures.

Although it has been shown that trees can survive in discharge (lower lying, higher salinity) areas of a landscape, their productivity and hence viability is low. Salinity mitigation plantations are commonly located in these areas, such that arable land remains available for crops (Archibald et al. 2006; George et al. 1999). With consideration of the poor performance with respect to salinity control (due to tree deaths) as well as poor yield, forestry should preferably be located in the recharge (higher elevation, higher performance) areas of a landscape. This does, however, require that the plantation is sufficiently attractive economically, to the land owner, such that it becomes a more viable land use option than the crop which would otherwise have occupied that land.

The analysis of salinity at the study site, highlights the need for consideration of both temporal and spatial variables when performing a site assessment. Within the timescale of a plantation duration its response to the landscape, and hence performance with respect to the economically and environmentally driven purposes, will vary. The potential for the site assessment method presented in this study to achieve the accuracy and efficiency required for optimal plantation location is discussed in the following two sections.

5.2 Applicability of Radiometrics as a Dataset for Site Selection

Methods

The rapid expansion of dryland forestry in Western Australia has resulted in the need for improvement of the accuracy and efficiency of site selection methods at a farm scale. Recent studies have identified a number of major limitations associated with the landscape mapping and site assessment techniques currently in use. These are primarily related to the resolution of available data and the corresponding inaccuracies inherent in derived soil and landscape qualities. The ability for radiometric datasets to mitigate these limitations is discussed in this section.

5.2.1 Representing the Landscape

Landscapes can be mapped using the interpretation of the potassium (K), thorium (Th), uranium (U) and total count (TC) signals derived from a gamma radiometric survey. Different rock and soil types exhibit identifiable signatures in these datasets, due to their mineral content and chemical composition. These signatures must, however, be interpreted in terms of landscape position and include some assessment of the spatial distribution of the rocks and soils due to weathering and erosion processes. The detection of K, Th or U has different implications, depending on the position in the landscape.

It is therefore necessary to include continuous topographic datasets, such as Digital Elevation Models (DEMs), into soil and landscape analysis. Observation of the topography allows for an understanding of past weathering and erosion processes occurring in the area. In turn these processes explain the leaching and distribution of minerals across the landscape. Slope and elevation are two factors which can be calculated from topographic data and allow for some measure of where water is likely to flow or be stored across the region. An approach to landscape mapping using these forms of data has developed into 3D regolith terrain analyses, whereby an understanding of the geomorphology of an area is the key to predicting soil characteristics. For the purposes of plantation site assessment only a limited number of these characteristics need to be defined. Hence only a fundamental understanding of geomorphological processes is required.

Even at the basic level required for forestry site selection, the knowledge of the geomorphology must be specific to the study area. There are many different types of landscapes within Western Australia and correspondingly, there are clear distinctions between the driving forces of weathering and erosion processes. Therefore the accuracy of

any landscape interpretation using radiometric and topographic data is dependent on availability of empirical soil/landscape relationships developed for that location. The study presented in this dissertation relies upon the cumulative research knowledge of dryland landscapes in Western Australia.

Despite the increasing accuracy with which radiometric data can be interpreted, due to this expanding body of knowledge, it is important to recognise the level of subjectivity involved. To minimise the reliance on the assessor's understanding of the landscape, the inclusion of hard data is essential. Ground truthing will therefore always be required. With the repetition of studies with similar aims, at similar locations, specific empirical relationships can be formed to relate radiometric data to the subsurface landscape. These relationships can be continually refined, although it is never sufficient to apply them to an assessment, without specific site calibration. This knowledge was a driving factor in developing the site selection method presented in this study.

5.2.2 Accuracy of Results

There are two major areas of work relevant to the use of radiometrics in forestry site selection. Research is being done on the improvement of site selection methods (Ryan et al. 2002; Harper et al. 2005; Thwaites & Slater 2000), while separate assessments of the use of radiometrics for soil and salinity mapping are being made (Tunstall 2003; Taylor et al. 2002; Pracilio et al. 2003a) . The study presented in this dissertation combines advances in both fields into one forestry site selection method. It has therefore been necessary to assess both the landscape classification, as well as the performance predictions derived from the limitations and requirements for successful tree growth. The implications of combining both qualitative and quantitative methods are also discussed.

The accuracy of the site assessment is discussed in three stages: firstly an assessment of the Final Soil/Landscape Classification as an isolated result; secondly, an assessment of the Growth Rating Classification in terms of the accuracy of both the radiometric interpretation and the growth rating index; and thirdly a comparison of the accuracy of traditional field soil survey approaches versus radiometric data interpretation. Both spatial and temporal accuracy are considered.

Soil/Landscape Classification

The soil types and landscape feature classes used in the landscape classification process were those noted as having distinct effects on tree growth. They were: shallow soils, areas of

potential waterlogging, high salinity areas, sandy areas, areas of high gravel content, surface laterite areas, and regions of high potassium.

Based on the field observations and available soil data the classification derived from the interpretation of radiometric and DEM data accurately delineates the extent of targeted landscape features. Without the availability of accurate soil survey logs, or further ground truthing data, it is not possible to refine the soil-landscape classification beyond that presented in Figure 16. It is therefore not possible to make further comment on its accuracy as a stand alone classification.

There are, however, two categories of the landscape map which are likely to be misclassifications. One is the high potassium class represented by the blue/green areas in Figure 16. It is possible that these areas have been incorrectly classified due to decisions made when applying thresholds to the relevant datasets. The shallow soil areas were delineated using the Dose Rate radiometric layer and the DEM. This involved slicing the DEM dataset at a high elevation in an aim to select the hilltops where shallow soils are expected to be found. The threshold used was selected as it produced the best correlation to field observations, however it only identified the hilltop of the highest hill in the area. Had it been applied at a lower elevation the areas classed as high potassium would have been classed as shallow soils. This was not done, however, as it would have produced conflicting results in other areas of the property.

The second region is the section classified as a 'Surface Laterite' area in the south-west corner of the property - the ring around the 'Unsuitable' class - as shown in Figure 16. It is unlikely that surface laterite would be exhibited in areas surrounding surface granite and shallow soils. This error is, again, due to the method of interpreting the dose rate when identifying shallow soils. The use of high thorium and uranium to define areas of surface laterite can lead to misclassification as these area often exhibit a high dose rate as well. Without sufficiently accurate landscape position representation to separate the two, the classes will often coincide.

These discrepancies reiterate the need for care to be taken when applying radiometric-soil relationships derived in other studies. For the Sandawindy site the topography was such that a basic elevation threshold could not give an accurate measure of landscape position. Hence radiometric data interpretation resulted in some areas of misclassification. In such situations it is important to have good knowledge of geomorphological processes in order to make an assessment of the result. Relying on purely quantitative methods is not possible.

Growth Rating Index

The second part of the site assessment was to derive the Growth Rating Classification. An assessment of the accuracy of this classification relies on two factors which cannot, however, be distinctly separated. Firstly the accuracy of delineating key landscape features (as was discussed previously) and secondly the success of applying known growth responses to these areas. The overall result of the study was that there was a clear positive correlation between the predicted and observed growth rating across the study area. This suggests that both the site classification and growth prediction were accurate although it cannot be conclusively stated.

It was found that the prediction of tree performance accurately reflected observations made at the site. There was only one discrepancy between the predicted and observed plantation performance. This was within the class defined as unsuitable for tree growth. The difference is due to the method by which the area was classified, and the generalisations made within this process.

The area defined as unsuitable consists of a combination of saline, shallow soil and waterlogged areas under one classification. In the long term, these different factors will produce the same (poor) response from trees and hence a consistently low growth rating of 1-2, across the class. The observed range of the index for that unsuitable class, however, was found to be 1-4. This range is due to the current variability of tree response to the limiting factors which make up the class. By separating the class into the contributing components and assessing the sample site results from each of these areas, it was revealed that the highest rating of 3-4 was observed at an area defined as a shallow soil zone.

This error can be explained by the age of the trees. The plantation trees at that location are two years old and hence their root structures have yet to reach beyond the shallow subsurface. This means that they are being effected by the presence of salinity (as described by the EM38 dataset) and waterlogging in the upper 1m of the soil column, but have yet to feel the effects of an impermeable layer at approximately 2m below the surface. In such areas of shallow soil, the volume available to the root system is limited and so too are the stores of water and nutrients. The effects of this restraint will only be felt once the tree reaches a size whereby insufficient water and nutrients can be sourced and hence growth becomes severely limited. Until such time the trees in these areas often exhibit very good growth due to the early stages of bedrock weathering and young, mineral rich soils (Moore 1998a).

The source of this error could be located with an understanding of the classification process, however it was not evident in the final classification images produced. This indicates that a classification should not be oversimplified and that the maintenance of specific classes is important for the accurate interpretation of results. For site classification relevant to the current age of the trees it would have been preferable to retain the areas of shallow soil, salinity and waterlogging as distinct classes. Over a longer timescale, however, it is expected that the predicted growth ratings will be verified and the generalisation within the unsuitable class will become irrelevant.

The classification accuracy with respect to temporal scales was considered in the assessment of the extent of salinity at different depths below the surface in Section 5.1. Again the difference between predicted and observed plantation performance is dependant on the timescale for which the prediction is applicable.

The final note to be made regarding the accuracy of the growth rating index is in regards to the extrapolation of point data. The field observations were made at thirteen sample sites across the study area and hence can only be seen to accurately represent a small portion of the total area. Based on the assumption that trees will respond differently to different soil types, but with relatively little variation within a soil class, the point data has been taken to represent the whole class within which the sample was located. Where there were multiple sample sites within one class the data was assessed as one set so that the overall maximum and minimum were presented as the observed index range. This means that there is a variation in sample size used to give the rating, as well as a variation in the extent over which it is applied. The results are, therefore, only an estimate of the growth occurring across that class. They were, however, sufficient to make basic conclusions about the performance of the site selection method.

Radiometric Data Interpretation

The method presented in this dissertation has highlighted the degree of accuracy with which farm scale site assessments can be performed using radiometric data. The radiometric dataset has a grid size of 10m, as does the DEM of the study site (Land Monitor 2000; Fugro Airborne Surveys 2004) . This data has been used to delineate five different plantation performance classes, with verified accuracy.

The incorrect classification of high potassium and shallow soil areas has been discussed and may be mitigated through the use of higher resolution datasets. It is recommended that a

resolution of 5m be used for hillslope scale assessment (Thwaites & Slater 2000), however, in reality this is difficult to feasibly achieve.

In comparison to the accuracy of landscape assessments performed using standard field soil survey information this method produces an equally, if not more detailed classification of the site. Field soil surveys cannot feasibly be performed to achieve a consistent 10m resolution across a farm scale area (Tunstall 2003). The use of radiometrics will overcome issues associated with extrapolation and interpolation of survey data and hence will always have the potential of providing a more accurate classification.

The resolution of the assessment was sufficient such that each of the five classes was assessed against field samples and the results deemed accurate. Not only was the area classified as suitable or unsuitable, but four different growth classes were identified. This gives a range of the predicted performance of trees across the property providing detailed, spatially accurate information for use in species selection or yield prediction. With detailed site delineation it is possible to achieve precision forestry whereby all factors of site selection and plantation management are optimised. In this way environmental and economic goals are best achieved.

5.2.3 GIS

The use of ArcGIS software as a data analysis and presentation tool is integral to the development of effective site assessment methods. As radiometric and DEM datasets were being introduced into soil mapping, GIS allowed for numerical assessment and landscape classifications to be performed (Tunstall 2003; Anderson-Mayes 1997). Now, however, most landscape and soil mapping is moving beyond the use of basic GIS software and into more complex 3D models (Thwaites & Slater 2000). Ideally such models will become available for use in farm forestry site selection in the future. At this point in time, however, efficient, simple and readily available analysis methods are required to meet the demands of a rapidly expanding forestry industry. The ArcGIS software is well equipped to meet these requirements.

Interpretation of the radiometric dataset has been used to accurately delineate landscape attributes relevant to tree growth and hence site selection. This has been largely due to its compatibility with other sources of information and the continuous spatial resolution it offers within the GIS analysis environment. The inclusion of radiometric data has provided an extra, independent dataset which compliments the traditionally used elevation data, field soil surveys and electromagnetic information. It is important to maintain independence of

datasets, and hence the inclusion of this form of data not only improves the spatial resolution of the assessment, but also its validity.

Analyses performed within GIS have the advantage of allowing for both quantitative and qualitative assessment to be performed using both point and continuous datasets. The layers associated with radiometrics – potassium, thorium, uranium and total count – are suited to this form of analysis as they can be interpreted both visually and numerically. The method outlined in this dissertation showed the translation of visual interpretation (spatially coincident radiometric signals and field observations) into numerical thresholds. Interpretation of four continuous datasets meant that minimal field observations and soil survey results were required to obtain an accurate and continuous classification over the site. Herein lies the efficiency associated with employing radiometric datasets for site selection methods within a GIS analysis environment.

5.3 Site Selection Methods for Dryland Forestry: Implications of this Method

The inclusion of the radiometric dataset within a site selection method for dryland forestry has many implications. They relate to the accuracy of the assessment, and hence the productivity of the resulting plantation, as well as the cost and efficiency of the site selection process. This section explores these aspects with respect to the successful expansion of farm forestry in dryland regions.

5.3.1 Cost

The viability of farm forestry in regions receiving 400-600mm annual rainfall has been discussed in Section 2.2 of the Literature Review. This section was presented in terms of the economic inputs associated with increasing demands for timber, carbon sequestration programs and salinity management abatement schemes. It is suggested, however, that the use of radiometrics in site selection should also be included as an economically significant factor. The cost reduction associated with employing radiometric data interpretation techniques has the potential to further increase the viability of dryland forestry.

As discussed in the previous section, and earlier in Section 2.3.2, the inclusion of radiometric datasets essentially replaces the need for field soil surveying. A soil and field survey of the landscape still needs to be conducted for ground truthing purposes, although the extent and density required of the survey is significantly reduced (Tunstall 2003). Field soil surveys are

expensive and time consuming, especially in comparison to the airborne radiometrics alternative. A cost analysis of airborne radiometric soil surveys, which includes the required ground truthing and is averaged over 5 years, gives a total cost of \$1/ha (Pracilio 2006). Pracilio et al. (2003a) presented a cost comparison of field soil sampling versus airborne radiometrics. They found that for a sample density of 100 samples per 100 km², the cost of the field sampling would be ~\$4250, while a radiometric dataset covering that extent would cost ~\$85. It can be seen, therefore, that not only will the economic viability of dryland forestry be driven by the formation of new economic sources, but also from the savings associated with the implementation of new landscape assessment methods.

5.3.2 Scale

At the regional or catchment scale, existing soil survey maps have sufficient resolution to allow for accurate landscape assessment. They are usually at a scale of 1:100 000 or coarser and have been used in the land suitability assessment study by Harper et al. (2005) and the Forest Products Commission's *Tree farming And Industry Development Plan* (2006a). A feasibility assessment performed at this scale is the first step in establishing viable forestry in a region. At the later stages of implementation, however, smaller scale assessments need to be performed at the farm scale, on the order of ~1 000 ha, as opposed to 100 000 ha. Therefore there is a corresponding need for higher resolution soil mapping. The use of radiometrics to provide data at this resolution has been proposed in many studies (Harper et al. 2005; Pracilio et al. 2006; Ryan et al. 2002), and investigated in this dissertation.

The site assessment performed in this study has shown the degree of accuracy which can be achieved at a farm scale using radiometric data. The dataset with a grid size of 10m has allowed for the classification of the site into five different growth classes. Each of these classes were verified as accurately representing the actual performance of trees at the study site.

Site assessment using radiometric data could be performed at larger scales. With wider flight line spacing, larger areas could easily be covered at the low resolution suitable for regional scale assessment. This is deemed unnecessary, however, due to the existent of the soil maps previously mentioned.

Larger scale radiometric surveys would, however, be beneficial for situations where a number of properties require farm scale site assessment. If radiometric data for the whole area could be obtained in one airborne survey the efficiency of the process would be

increased. This would change the extent of the dataset, however the resolution would need to be maintained at ~100m line spacing and 20 – 40 m terrain clearance in order to retain farm scale accuracy (Pracilio et al. 2006). This may become important in areas where farm scale forestry will be rapidly introduced within a defined area – such as is intended with the Forest Products Commission's *Tree farming And Industry Development Plan* (2006a) for the central south-west catchments of Western Australia. The feasibility of implementing the sawlog plantations, as planned, may become greater should a large scale airborne radiometric survey be performed over adjacent areas intended for forestry.

If radiometric surveys were coordinated to cover large extents, it may become feasible to increase the resolution of the dataset. Should viable 5m datasets be available, then the use of radiometrics within simple and effective site selection methods would provide the most accurate and cost effective form of site selection.

5.3.3 Productivity

The productivity of a plantation is central to achieving all economic and environmental aims of the project. The productivity governs the yield of timber being produced, the amount of carbon which can be sequestered, and the level of deep ground water recharge. These being the driving factors for the dryland forestry discussed throughout this dissertation. Site selection is the first stage to maximising the productivity of a plantation, to be followed by effective management. The productivity is also the only measure available for assessing site selection methods, such as the one presented in this study. Only through trials and the continual comparison of predictions and observations, will the best site selection methods be developed, and hence the maximal productivity of plantations achieved.

The classification of soil and landscape features, corresponding predictions of tree growth and the identification of five different growth classes across the area is significant in terms of selecting where to plant trees. Not only does a detailed classification of a site allow for more accurate prediction of the yield, but also provides more information for species selection and appropriate plantation distribution across the farm.

This has been illustrated by calculations of the proportion of the existing Sandawindy plantation which lies within areas defined as unsuitable for tree growth. Up to 42% of the plantation is likely to be subject to limited growth due to the effects of salinity, waterlogging and shallow soils. This has a direct impact on the overall performance of the site. If the

plantations were located according to the growth predictions made in this study, the overall productivity of the site would be increased.

The purpose of the forestry must be considered in assessing the performance of the plantation. As discussed in Section 5.1 there are different measures of performance, particularly with respect to salinity mitigation purposes. A plantation may be required for short term, local remediation of a saline area, and hence a low performance, within a saline zone may produce the required reduction in groundwater recharge, whilst allowing for viable crop production in other areas of the property. On the other hand a long term, catchment scale salinity control program is likely to benefit from trees grown with higher levels of productivity on the best sections of a property. Here the productivity would need to be high enough so that timber harvesting or carbon sequestration purposes become viable.

It is important to reflect the natural variability across a site in all management decisions and accounting calculations. The methods of carbon accounting and measurement of salinity control are always open for improvement. The conversion into monetary value requires an accountable and consistent method of quantifying the performance of the plantation with respect to these factors. By approaching site selection with precision from the beginning, it may be possible to maintain a consistently high level of accuracy and accountability, thus leading to the successful expansion of trading markets and abatement schemes.

The study presented in this dissertation has focussed on the verification of a site selection method using an existing plantation. For this reason, only one species was used for the comparison of predicted and observed plantation performance. When applying the method at a new site, however, the soil and landscape classes identified in the second stage of the site selection process will influence species selection and distribution. By including the specific responses of different species to the landscape, the growth rating index can be extended to cover more than one type of tree. It will therefore be possible to attain the maximum productivity from each species, and consequently the plantation site as a whole.

5.4 Successful Dryland Forestry

The drivers for the expansion of dryland forestry have been well researched. There are multiple reasons why dryland forestry is important from environmental perspectives and correspondingly a wide variety of economic inputs which will allow it to become increasingly feasible. The push towards establishing dryland forestry in Western Australia is mainly due to the need for salinity management programs, which aim to prevent the loss of agricultural and

ecologically important land. The degradation of land due to salinity not only has impacts on natural habitats and biodiversity, but also on the rural economy (Pracilio et al. 2003b). It is recognised that the integration of farm scale forestry into agricultural areas can provide a significant contribution to salinity mitigation through the resultant reduction in recharge to groundwater (Lefroy et al. 2005). The formation of salinity abatement schemes will serve to drive this land use change. Such schemes alone, however, will not provide the economic feasibility required to change farming practice on a sufficiently large scale (Petersen 2003).

Emissions offsetting schemes are another driving factor for forestry in Western Australia, and are important in terms of the economic input they provide for the industry. Carbon sequestration can, from some perspectives, be a stand alone purpose for forestry. The private sector within Western Australia is investing in plantations across the state in a bid to offset their carbon dioxide emissions (Forest Products Commission 2006b). On national and global scales carbon sequestration is being utilised as a key method for achieving emissions reduction targets outlined in the Kyoto protocol. Carbon trading markets are being established both intra- and internationally, whereby quantised amounts of carbon sequestration are given a monetary value and can be traded between participating parties. Although Australia is not able to join international markets operating under the Kyoto Protocol, there is still the potential for national trading schemes to be established within individual states or across the country (CRC for Greenhouse Accounting 2004). With this possibility it is important to recognise the impacts it will have on the demand for, and hence viability of, dryland forestry.

The most significant implication of the increase in carbon sequestration comes when viewed in the context of multipurpose forestry. Studies have found that salinity abatement schemes, when applied in conjunction with carbon trading offer the best economic situation for introducing forestry as a common land use across agricultural areas (Petersen 2003).

The third and perhaps most influential factor to establishing economically feasible dryland forestry is the increasing demand for timber. As restrictions on the harvesting of native forests are applied, the demand must be met by plantations. Such demand will increase the value of plantation timber, as well as driving the increase in infrastructure required to process the harvest. As outlined in the Forest Products Commission's *20 Year Industry Development Plan* (2006a) the demand for eucalypt sawlogs can be achieved whilst at the same time the plantations will serve to combat salinity problems over multiple catchment scales.

The purposes and economic inputs for dryland forestry are in place. The planning and large scale feasibility assessments have produced positive results for drylands regions across the south west of Western Australia. The process of implementing these plans now relies on the development of accurate and efficient site selection methods. The method presented in this dissertation has addressed these requirements. In order to realise the full potential of a property in terms of all plantation purposes, the site must be delineated into meaningful classes. According to the properties of these classes the plantation can be arranged in the landscape. At the farm scale, the use of radiometric data allows for the desired accuracy, cost effective efficiency and simplicity in procedure required for widespread application to dryland landscape assessment.

5.5 Limitations of the Study

There are limitations to this study which have affected the methods used, the accuracy achieved and the direct applicability of the method to plantation site selection. They have not, however, detracted from the formation of conclusions relevant to the project motivation and objectives.

For simplicity, the site assessment, and more specifically the application of the growth rating index, was done with respect to only one species. This allowed for the study to focus on the applicability of radiometrics in site selection and identification of the accuracy to which a site can be classified, rather than becoming focused on the different responses of species to their environment. The growth rating index was applied specifically for the *E. cladocalyx* species and correspondingly only the growth of these trees were assessed at the site. This does mean, however, that the method has not taken into account the intricacies of plant growth and cannot therefore be directly applied as a site selection method without further adjustment and improvement. As discussed in the last section, the productivity of a site depends not only on the plantation location but also correct species selection.

Another limitation to the complexity and hence applicability of the approach, was the lack of inclusion of a topographic index and hillslope position in the classification of the site. The topographic index is used to describe the potential for a soil to be saturated and hence is important in determining waterlogged areas and available soil water. The hillslope position is important as it describes the variations in drainage to groundwater with respect to the orientation of a plantation on the slope. This must be considered where plantations are required for salinity control purposes (Ryan et al. 2002). Neither were included due to the

resolution of the DEM. The site has low gradients and long slopes and hence a 10m grid size was not sufficient to accurately delineate these topographic features.

The last major limitation to the applicability of this method to future site selection assessment, was the age of the trees at the study site. As discussed in Section 5.2 there were discrepancies found in the results due to the fact that the trees have yet to reach maturity. For example the EM38 dataset was used to delineate salinity as it describes the shallow subsurface. In terms of a long term assessment the EM31 dataset would need to be used as the trees would begin responding to salinity at depths of over 1 metre. Similarly the shallow soil areas have yet to have an effect on tree growth, and hence the classification of these areas could not be accurately verified. The method used in this site assessment cannot therefore be used to select the optimal plantation position for long term productivity.

In addition to the limitations placed on the applicability of the method, there are a number of factors which reduced the level of accuracy of the results. Firstly, the availability of ground truthing data, and secondly the detail of the plantation survey.

A Forest Products Commission soil survey was used as ground truthing data, however it was only available in hardcopy with rough sample locations pencilled in. It was also very brief and hence only used to help delineate the major shallow soil changes. Although the method is not designed to rely on extensive ground truthing, for the purposes of this study a better assessment of the accuracy of the landscape interpretation could have been performed had a more detailed soil survey been available.

The bulk of the ground truthing was therefore derived from observations of the landscape, made during the field trip to the site. Recording the position of key landscape features provided the most useful form of data for developing the numerical thresholds required for site classification. These observations were, however, only of the surface and hence only indicators of the shallow subsurface structure.

This lack of accurate soil information, meant the assessment of the landscape classification was primarily based on the results of the tree growth survey. As mentioned in Section 5.2.2 this was not a direct assessment and hence the accuracy of the results could only be implied. The growth survey itself was limited in extent and accuracy, and gave only an estimate of the actual growth variation across the site. With respect to the purposes of the study, the information was sufficient to show that the site selection method could be useful to

farm forestry. More quantitatively accurate verifications of the site assessment method would need to include intensive sampling regimes for both the soil and growth observations.

The overall accuracy of the classifications were not only dependent on the ground truthing and plantation survey data but also on the resolution of the input datasets. The radiometric and DEM data both had grid sizes of 10m. It has been noted that this DEM was deemed too coarse to delineate some topographic parameters. Similarly the spatial resolution, and hence accuracy of the classification was limited. Data resolution of 5m is recommended for hillslope scale landscape assessment and thus this study has not been performed with optimum accuracy (Thwaites & Slater 2000). It may become important in multipurpose farm forestry, that site selection is performed at high precision.

6.0 Conclusions

Conclusions relating to the development of efficient and accurate site selection methods, the use of radiometric data interpretation within such methods and the accuracy with which plantation performance can be predicted, are drawn from this study. Despite limitations, the results are deemed useful to the improvement of farm scale landscape assessments required for dryland forestry.

The assessment of the performance of the plantation at the study site revealed that: carbon sequestration rates are low, although this is as expected; the growth of deep rooted perennial plants, such as eucalyptus trees, has the potential to reduce the groundwater recharge rates to zero; that a large portion of the plantation was located in saline or otherwise unsuitable zones and hence potentially subject to severely limited growth. This highlighted the need for detailed and integrated site selection, such that the performance of the plantation can be optimised in terms of economic and environmental goals.

The site assessment method presented, allowed for the successful interpretation of radiometric data, in order to delineate key landscape and soil features across the study site. Factors relevant to the growth of trees were detected through qualitative and quantitative analysis. Ground truthing and interpretation of natural breaks in the relevant datasets led to the formation of thresholds which were applied to the relevant datasets. Areas of shallow soil, high potassium, surface laterite, high gravel content and sand were distinctly classified. In addition to these, saline and potentially waterlogged areas were demarcated using electromagnetic and DEM datasets. Although only a limited assessment of this classification could be made, based on knowledge of the study site and field observations it was deemed sufficiently accurate for use in plantation site selection.

The formation and application of the growth rating index produced consistently accurate results across the study site. Four of the five growth classes were deemed accurate when compared to field survey results. The discrepancy in the final class could be explained by the lack of response to shallow soils due to the age of the trees. As the trees mature it is expected that they will behave as predicted by the index and hence allow for complete verification of the performance predicted by this landscape assessment approach.

In summary, the interpretation of radiometric data, as one of three input datasets, allows for detailed and accurate landscape classification. In turn the application of known growth responses allows for the classification to be reinterpreted in terms of a predicted plantation

performance. This method is effective, efficient and best suited to farm scale assessment, hence able to meet the requirements for application in dryland forestry.

7.0 Recommendations

The study presented in this dissertation has aimed to incorporate knowledge from various areas of research associated with dryland forestry and form a practically applicable, integrated approach to landscape assessment. This aim has been achieved and the results and implications discussed, however, there are many aspects of the study requiring expansion and completion in order to progress research in this area.

The most important recommendation derived from this study, is that inclusive and comprehensive site assessment techniques must be further developed and implemented into dryland forestry practice. The economic viability and environmental goals associated with multipurpose forestry can only be achieved if plantations are effectively located within the landscape. The methods must be easy to implement, however simplicity should not detract from the maintenance of accuracy. The method presented in this study lacks the detail required to address all facets of plantation performance, thus integration with other techniques and repetition of the study is recommended. Research should be directed towards the inclusion of a wide range of site selection requirements into one temporally and spatially accurate assessment procedure.

Recommendations for specific improvements to the method are discussed below. They involve the inclusion of more parameters into the landscape assessment procedure in the form of landscape position factors, the inclusion of a range of plantation species, greater representation of temporal variability and the consideration of climate change.

The assessment of landscape position with respect to groundwater recharge reduction is of primary importance. It was noted that the positioning of trees is significant when considering the temporal and spatial scales to which salinity mitigation is being targeted. If these targets were considered in the initial site assessment they would become a contributing factor in defining the range of site suitability across a property. This would require the inclusion of spatially variant deep drainage prediction techniques, such as that presented by Pracilio et al. (2003b). The site assessment would be extended beyond maximising plantation yield and include the optimisation of salinity mitigation.

The inclusion of individual species' response to a landscape is also recommended for improvement of site selection methods. By considering the variations in response, greater restrictions would be placed on the classification of the site. Some areas would be deemed suitable to one species but not another, thus the classification would reflect both the optimal

location for a plantation as well as species type best suited to that area. With repetition and development of empirical relationships, sufficient accuracy could be attained and detailed site classification performed. This is of concern to both the yield optimisation as well as salinity control.

This study has focussed primarily on the spatial variables important in a site selection process, hence the formation of the soil and landscape classification as the basis of the assessment procedure. It is, however, recommended that temporally variant factors be integrated into the method. The implications of salinity detected at different depths, and the timescale associated with the depth range has been discussed. These considerations must be further addressed. Temporally variant growth models are available, and should be used in conjunction with a spatial study in order to predict yield. Similarly, predicted changes in response to the landscape over time should be applied as limitations in the classification process, thus increasing the site selection accuracy.

Radiometric data interpretation has proved to be useful and effective in performing farm scale landscape assessments. With repetition of similar studies across dryland regions, the interpretation of these datasets can be further improved. This is particularly important when considering the inclusion of more variables and parameters, as discussed above, as the level of detail required of the interpretation will increase correspondingly. This study has presented a basic level of data interpretation, however, it will be possible to extend and develop the interpretation techniques. The aim should be to derive direct relationships between datasets and the parameters used to quantify carbon sequestration rates, timber yield and salinity mitigation.

Although intended for application at a farm scale, the site selection method presented in this study may be feasibly applied over larger scales. If input datasets are available at the required resolution, their assessment would allow for large scale land suitability classifications to be performed. This should be considered in following studies.

It would be beneficial for future landscape assessments to include some consideration of the effects of climate change. The availability of water to plants is the major limiting factor to growth, and highly reflective of climate change effects. Hence an understanding of the impacts of climate change in dryland regions will allow for forestry site selection to adapt with these changes.

8.0 References

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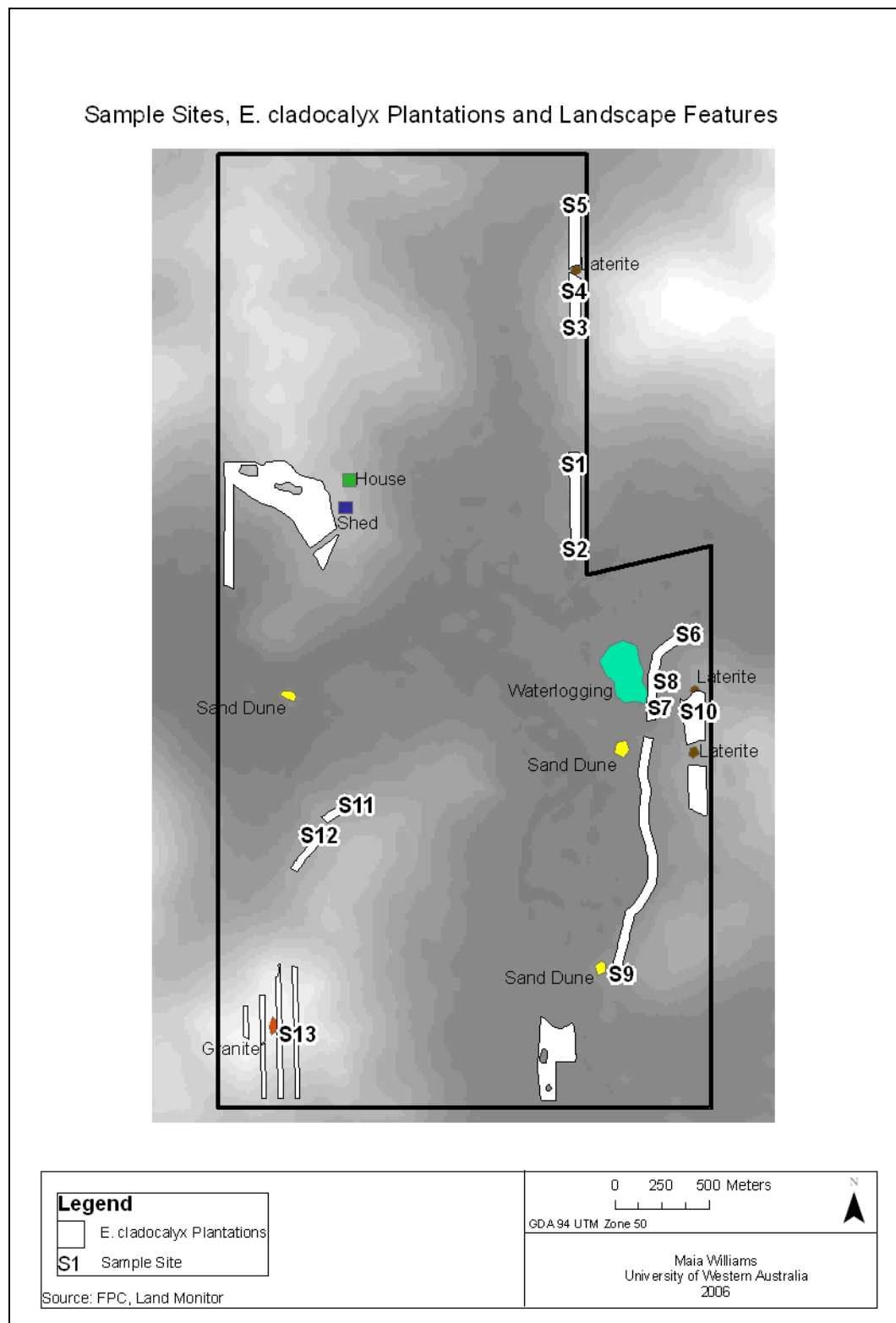
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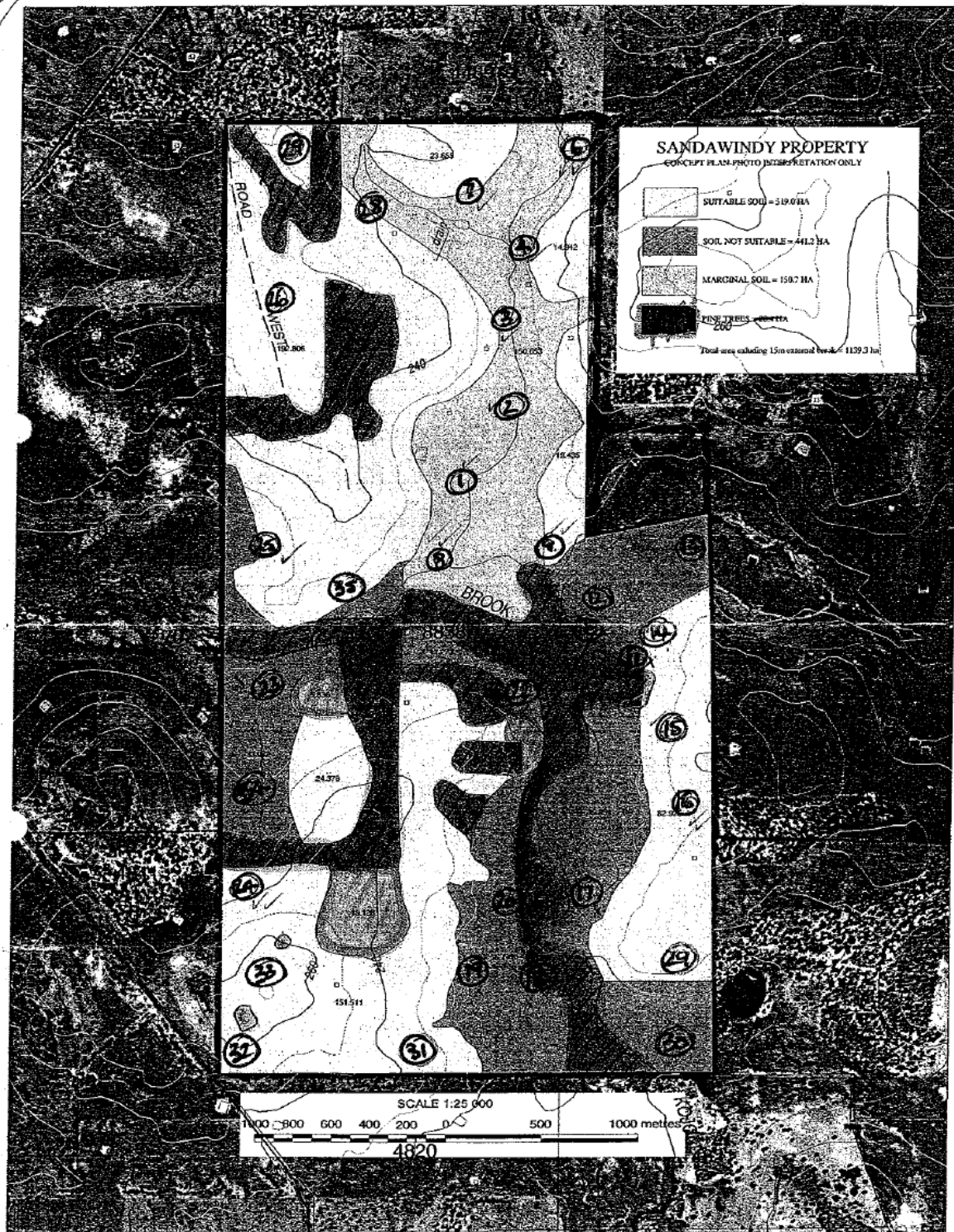
Appendix A: Sample Site Locations



Appendix B: Sandawindy Soil Survey (FPC 2004)

SOILS / SALINITY - SURVEY.

FILE



22 Mar. 2004 10:42:43 I:\gass\agency\nesi\collie\2004\concept\sandawindy04.dgn

SALINE

REMNANT VEG (ATR)

14 SAMPLE POINT

Initial Survey - Pre purchase. (G. Hobson)

4

PT 1

Southwest Sharefarms

Forest
Products
Commission
WESTERN AUSTRALIA

Property Name

Sondalindly

Drilled By

AS

on 1/12/03

Hole No	Soil Profile Description	Depth >2mts	General Comments
1	Br Coarse Sand 0.1 Gr Sand/Cl coarse 1.7 Lst Med Cl 2.2. Lst Sand Cl 2.4	✓	Low - Moist Good
2	Gr Sand 0.5 Gr Br Clay Sand 0.5-0.7 - moisture band. Gr Sand from 1.3 - fine Vltw Chl/ln 1.7 Red mottled sand/clay (loam) 2 } alluvial. Gr Lst Sandy Chl (loam) 2.4 }	✓	Gully floor Good 20 m ³ Good
3	HBr Sand 1.5 Gr Br Sandy Chl 2.0 " " " " " 2.4	✓	Gully floor Moist throughout Good
4	Gr Sand 1.4 Lst Br Sand 1.1 Br mlt sdy ch 1.8 Crs Br mlt sdy ch 2.0 Br mlt ch crs. 2.2 Crs wlt sdy ch 2.4	✓	MST - LOW LOW Good - red salt down to 45 mts Silt in creek
5	Gr Sand 1.2 Lst Sandy Ch 2 Quader fines Br Med Sdy/Ch 2.4	✓	moist & depth Good
6	Vltw Sandy Gravel 1.2 Vltw Br Sdy Lm 1.8 Red Ch/ln 2.4	✓	V. Good.
7	Gr Silt/cl 1.4 Vltw Silt/cl 2.2 Vltw Sand/Ch 2.4	✓	Mud slope Ex.
8	Ok Gr Silt/cl 0.7 Gr Silt 1.8 Gr Silt/Ch 2.4	✓	lower gully moist bridge over problem V. Good
9	Vltw Sand/ln 1.8 Vltw sand/Ch 2.4	✓	V. Good.
	Gr Sand 0.7 Gr Silt/Ch 1.8 Gr Ch 2.4	✓	Poor. 75-80 m ³

EUC's

EUC's

EUC's

EUC's /
SALINE

?

EUC's

PINE

PINE

PINE

EUC's

Hole No	Soil Profile Description	Depth >2mts	General Comments	
11	Gry sand 1.5 Hvy clayey clay 2.4	✓	V. Poor	unc's ?
12	Gry Sand/Lm 1.2 Yllw Lt Sand/Lm 1.6 Yllw Sand/Lm 2.4	✓	Good.	unc's
13	Gry Sand 0.8 Yllw Sand/Lm 1.5 Yllw Lt Clay 2.2 Wt Mod Clay 2.4	✓	Ave	unc's
14	Br Sand/Lm 0.8 Yllw Sand/Lm 1.2 Brn Mod/Hvy Clay 2.4	✓	Ave/Poor Middleage	unc's
15	Lt Sand/Grow 1.2 Yllw Sand/Grow 1.6 Rd Sand/Lm 1.9 Rd Lt Clay 2.4	✓	Good. Prob. Euc.	unc's
16	Gr Br Sand/Grow 1.2 Yllw Sand/Grow 1.8 Rd Sand/Lm 2.2 Rd Clay/Lm 2.4	✓	V. Good. (Pine)	PINE
17	Gry Sand 0.5 Lt Grey Clay 0.8 Hvy Grey Clay 2.4	✓	Poor	?
18	Gry Sand 0.3 Hvy Clay	✓	Poor	?
19	Gry Sand 1.0 Hvy Clay 2.4	✓	Poor	?
20	Gry Sand Hvy Clay	✓	Poor	?
21	Gry Sand Hvy Clay	✓	Poor	?
22	Gry Sand 0.4 Yllw Sand 0.8 Hvy Clay	✓	Poor	? unc's
23	SK-2			
24	Gr/Grey Sand 1.2 Br Sand/Grow 1.6 Yllw Lt Sand/Lm 2.4	✓	V. Good	PINE

**Forest
Products
Commission**
WESTERN AUSTRALIA

Property Name Endauendy

Drilled By _____ on 6/12/03

[illegible]

PT 2

Southwest Sharefarms



Forest
Products
Commission
WESTERN AUSTRALIA

Property Name StrathmoreDrilled By A.S / G.H on 30/3/04

Hole No	Soil Profile Description	Depth >2mts	General Comments
27	Lt. gravelly sand 1.1 Yellow sand 1.5 lt Yellow Sand Clay 2.5+ Pink Sandy Clay 2.6	✓	V. Good. PINE SOILS ENC POSSIBLY
28	Gravel 0.7 lt S. Gravel 1.1 Red Brown Med Clay 2.3+ (Mottled Clay)	✓	V. Good. (ENC. SOIL)
29	Yellow sand 2.1 Red Clay 2.5+	✓	V. Good. PINE (RADIATA) - RADIATA SITE
30	lt Clay 1.2 * lt Yellow Sandy Clay 1.6 lt Sand 2.1 (River Bed Sand) lt Yellow Sandy Clay 2.5	✓	Area - SALINE SOILS lt Clay to 1.5m. (BELT PLANTING)
31	lt Sand Gravel 1.1 lt Sandy Clay 1.5 lt Yellow Mottled Clay 1.8 lt White Mottled Clay - Quartz 2.5	✓	V. Good Sand Gravel (ENC)
32	lt Sandy Gravel 1.7 Red Pine Clay 1.9 Pink/white Red Clay 2.5	✓	OK. (PINE)
33	lt Yellow S/Clay Quartz/Gravel/Granite	X	Granite base @ ~ 1.6m. Unplatable Natural Strip across slope
34	lt Yellow Sand / Med. 1.4 lt Yellow Sand / coarse 1.8 Pink/lt Sand Clay 2.5 White Sandy Clay 2.5+	✓	Area - OK (PINE)
35	lt White Sand 1.8 lt Yellow Sand / Clay 2.4 Red Clay 2.5+	✓	V. Good Pine's - RADIATA SITE

Appendix C: Field Survey Notes and Measurements

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S1

Photo 1

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	17	2.71	5.41	0.0023	2.30	0.0018
2	16	2.55	5.09	0.0020	1.80	0.0012
3	23	3.66	7.32	0.0042	3.00	0.0042
4	17	2.71	5.41	0.0023	1.80	0.0014
5	19	3.02	6.05	0.0029	2.00	0.0019
6	20	3.18	6.37	0.0032	2.80	0.0030
7	18	2.86	5.73	0.0026	2.40	0.0021
8	17	2.71	5.41	0.0023	2.00	0.0015
Averages:	18.375				2.26	0.0021
Sums:						0.0171

Row spacing: 3.5 m

Tree spacing: 2.65 m (assumption)

Comments:

Samples from the 4 western rows

~70% gravel

Trees get bigger down the slope (E-W), but generally fairly consistent

Sandawindy Field Survey - 11 August 2006							
E. cladocalyx							
Site: S2							
Photo 2							
** No trees measured **							
Comments:							
Trees 1.8 - 2 m for the southern 100m of the belt							
(smaller than at S1)							
Could be change in slope or salinity??							

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S3

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	14	2.23	4.46	0.0016	1.8	0.0009
2	12	1.91	3.82	0.0011	1.9	0.0007
3	14	2.23	4.46	0.0016	2.2	0.0011
4	20	3.18	6.37	0.0032	1.9	0.0020
5	18	2.86	5.73	0.0026	2.8	0.0024
6	15	2.39	4.77	0.0018	2	0.0012
7	17	2.71	5.41	0.0023	2.6	0.0020
8	18	2.86	5.73	0.0026	2.2	0.0019
Averages:	16			0.0021	2.175	0.0015
Sums:						0.0123
Comments:						
Sandier than S1, less and finer gravel						
Erosion/gully on the southern edge of the band						

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S4[Photos 3 & 4](#)

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	26	4.14	8.28	0.0054	3	0.0054
2	32	5.09	10.19	0.0081	2	0.0054
3	30	4.77	9.55	0.0072	2.4	0.0057
4	28	4.46	8.91	0.0062	2.3	0.0048
5	24	3.82	7.64	0.0046	2.6	0.0040
6	18	2.86	5.73	0.0026	2	0.0017
7	20	3.18	6.37	0.0032	2	0.0021
8	17	2.71	5.41	0.0023	2.8	0.0021
Averages:	24.375			0.0049	2.3875	0.0039
Sums:						0.0313
Comments:						
Laterite at the surface - should be able to pick that out on radiometrics						
sandy gravel (much more gravel than S3)						
deeply weathered profile because gravel at the surface						
Shallow soil area ?? (I think)						
Trees doing well						
sum S3 + S4						
0.012305						
0.0436						

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S5[Photo 5](#)

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	10	1.59	3.18	0.0008	1.7	0.0005
2	20	3.18	6.37	0.0032	2.1	0.0022
3	10	1.59	3.18	0.0008	1.8	0.0005
4	20	3.18	6.37	0.0032	2.3	0.0024
5	13	2.07	4.14	0.0013	1.5	0.0007
6	13	2.07	4.14	0.0013	1.8	0.0008
7	16	2.55	5.09	0.0020	1.9	0.0013
8	21	3.34	6.68	0.0035	2.2	0.0026
Averages:	15.375			0.0020	1.9125	0.0014
Sums:						0.0109

Row spacing: 4.5 m

Tree spacing: 2.65 m

Comments:

Gravelly

Going down slope towards the stream

Trees much smaller and sparser

Possibly getting saline??

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S6[Photo 9](#)

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	29	4.62	9.23	0.0067	2.6	0.0058
2	29	4.62	9.23	0.0067	2.8	0.0062
3	30	4.77	9.55	0.0072	2.6	0.0062
4	17	2.71	5.41	0.0023	1.8	0.0014
5	8	1.27	2.55	0.0005	1.3	0.0002
6	18	2.86	5.73	0.0026	2.8	0.0024
7	19	3.02	6.05	0.0029	1.2	0.0011
8	17	2.71	5.41	0.0023	1.8	0.0014
Averages:	20.875			0.0039	2.1125	0.0031
Sums:						0.0248

Row spacing: 4.5m

Tree spacing: 2m

Comments:

Sandy, with some fine gravel
Tree density of ~1400 trees/km2 ??

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S7

[Photos 10, 11 & 12](#)

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	6	0.95	1.91	0.0003	1.7	0.0002
2	10	1.59	3.18	0.0008	1.8	0.0005
3	6	0.95	1.91	0.0003	1	0.0001
4	15	2.39	4.77	0.0018	2.3	0.0014
5	18	2.86	5.73	0.0026	1.9	0.0016
6	6	0.95	1.91	0.0003	1.2	0.0001
7	9	1.43	2.86	0.0006	2.1	0.0005
8	10	1.59	3.18	0.0008	1.5	0.0004
Averages:	10			0.0009	1.6875	0.0006
Sums:						0.0047
Comments:						
All in waterlogged soil (2 western rows)						
Can see a clear distinction between rows 1&2 and 3 going east (growing much better after row 3)						
Soil all waterlogged for about 200m west of here						

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S8

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter d ₁₀ (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	20	3.18	6.37	0.0032	3	0.0032
2	28	4.46	8.91	0.0062	2.8	0.0058
3	17	2.71	5.41	0.0023	3	0.0023
4	22	3.50	7.00	0.0039	2.9	0.0037
5	18	2.86	5.73	0.0026	2.7	0.0023
6	14	2.23	4.46	0.0016	2.6	0.0014
7	25	3.98	7.96	0.0050	2.6	0.0043
8	10	1.59	3.18	0.0008	1.8	0.0005
Averages:	19.25			0.0032	2.675	0.0029
Sums:						0.0235
Comments:						
Same place as S7, just row 5.						
Not waterlogged, growing well						
sum S7+S8						
0.023489						
0.004705						

0.051683

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S9[Photo 13](#)

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	17	2.71	5.41	0.0023	1.8	0.0014
2	15	2.39	4.77	0.0018	1.9	0.0011
3	23	3.66	7.32	0.0042	2.6	0.0036
4	10	1.59	3.18	0.0008	1.5	0.0004
5	13	2.07	4.14	0.0013	2.2	0.0010
6	14	2.23	4.46	0.0016	1.9	0.0010
7	12	1.91	3.82	0.0011	1.3	0.0005
8	12	1.91	3.82	0.0011	1.3	0.0005
Averages:	14.5			0.0018	1.8125	0.0012
Sums:						0.0095
Comments:						
Sandy						
Sand dune directly west (from the creek and sand being blown around)						
Trees a bit yellowy						

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S10[Photo 14](#)

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	20	3.18	6.37	0.0032	2.2	0.0023
2	20	3.18	6.37	0.0032	2.6	0.0028
3	23	3.66	7.32	0.0042	2.7	0.0038
4	25	3.98	7.96	0.0050	2.7	0.0045
5	24	3.82	7.64	0.0046	2.5	0.0038
6	22	3.50	7.00	0.0039	2.6	0.0033
7	25	3.98	7.96	0.0050	3	0.0050
8	20	3.18	6.37	0.0032	2.3	0.0024
Averages:	22.375			0.0040	2.575	0.0035
Sums:						0.0279
Comments:						
Lots of gravel - big chunks						
Big healthy looking trees						

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S11

Comments:

Sandy

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S12

No measurements, but trees graded using the scale:

Height range:

1 - Dead

2 - Variable performance

poor white

soil

<1.4

more fertile red granite

3 - Intermediate

soil

1.4 - 1.8

4 - Good

1.8-2.5

5 - > 2.5m trees

> 2.5

Moving E-W along the belt:

2

3

3.5

2

3.5

Comments:

Granite on the surface - should be able to see that on the radiometrics

Trees 1.4 - 2m, not looking good

Sandawindy Field Survey - 11 August 2006

E. cladocalyx

Site: S13

Tree	Circumference @ 10 cm (cm)	Radius (cm)	Diameter (cm)	TBA (m ²)	Height (m)	Tree Volume (m ³)
1	25	3.98	7.96	0.0050	4	0.0066
2	30	4.77	9.55	0.0072	4	0.0095
3	33	5.25	10.50	0.0087	4	0.0116
4	32	5.09	10.19	0.0081	4	0.0109
5	32	5.09	10.19	0.0081	3.8	0.0103
6	32	5.09	10.19	0.0081	3.8	0.0103
7	30	4.77	9.55	0.0072	3.6	0.0086
8	20	3.18	6.37	0.0032	3.2	0.0034
Averages:	29.25			0.0069	3.8	0.0089
Sums:						0.0712

Moving N-S along the band:			Height range
3	gravel,	granite	1.4 - 1.8
4	good	at the	1.8-2.5
3	trees	surface	1.4 - 1.8
4			1.8-2.5
2	sandy surface		<1.4
	red		
4.5	sand		> 2.5
3			1.4 - 1.8
2.5			1.4 - 1.8
2	sandy		<1.4
	thin		
1.5	trees	Photo 15	<1.4
<p>Comments:</p> <p>red loamy, granite derived soils</p> <p>very big healthy trees</p> <p>The trees grow really well initially, on fertile soil and lots of water but then they reach 'canopy closure' and there's no storage water (cause of the granite rock layer close to surface) so they die</p>			

Appendix D: Calculating the current carbon sequestration rate

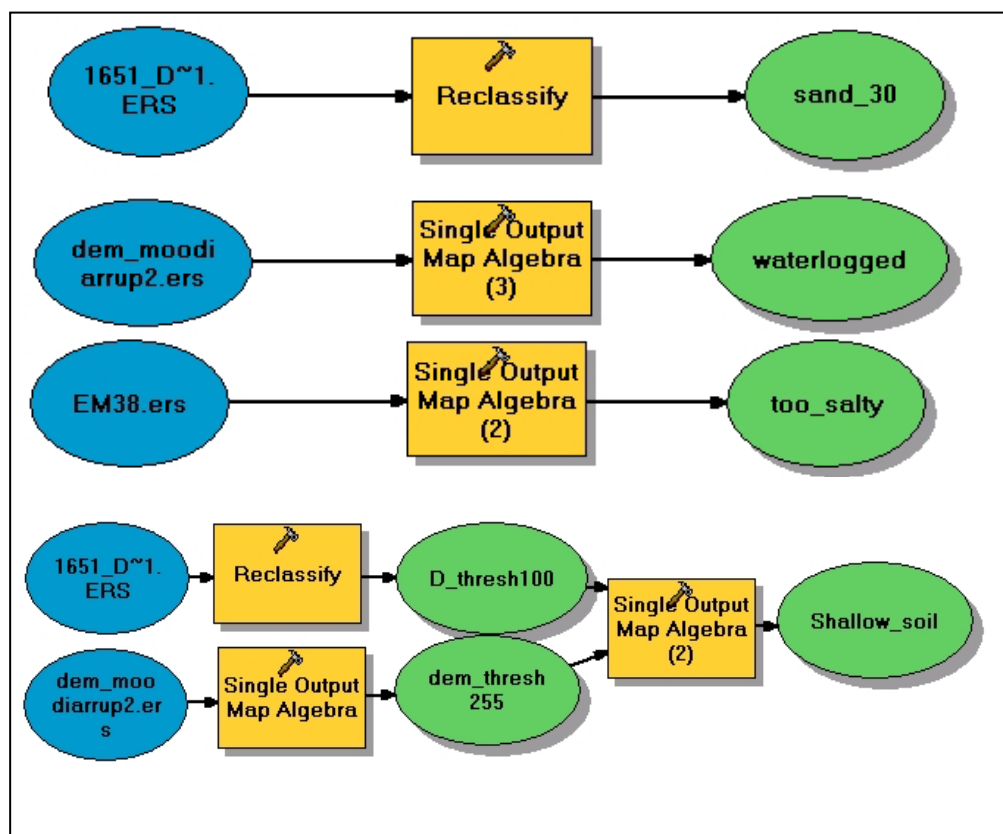
Sandawindy Field Survey - 11 August 2006

The calculation of Carbon Sequestration Rates for plantations P1-7

	P1	P2	P3	P4	P5	P6	P7
Study sites	S5	S3,S4	S1,S2	S6,S7,S8	S10	S9	
Row spacing (m)	4.5	3.5	3.5	4.5	3.5	3.5	3.5
Tree spacing (m)	2.65	2.65	2.65	2	2.65	2.65	2.65
Area/tree (m ²)	11.925	9.275	9.275	9	9.275	9.275	9.275
Total area of plantation (ha)	2.2	1.8	3.1	2.9	2.9	6.7	0.9
Number of trees in plantation	1845	1941	3342	3222	3127	7224	970
Number of trees in sample	8	16	8	24	8	8	8
Sample volume (m ³) *	0.0109	0.04359	0.017057	0.052983	0.017057	0.009527	0.01094
Total plantation tree volume (m ³)**	2.5229	5.2872	7.1262	7.1135	6.6664	8.6028	1.3270
Tree volume/ha (m ³ /ha)	1.1468	2.9373	2.2988	2.4529	2.2988	1.2840	1.4744
Stem Mass (t/ha) ^	0.8698	2.2279	1.7436	1.8605	1.7436	0.9739	1.1183
Above Ground Biomass (t) ^^	1.1308	2.8963	2.2667	2.4187	2.2667	1.2661	1.4538
Total Biomass (t/ha) ^^^	1.4134	3.6204	2.8334	3.0234	2.8334	1.5826	1.8173
Carbon Mass (t/ha) #	0.7067	1.8102	1.4167	1.5117	1.4167	0.7913	0.9086
CO ₂ -e (t/ha) ###	2.5866	6.6254	5.1851	5.5328	5.1851	2.8962	3.3256
CO ₂ -e (t/ha.yr) ###	1.2933	3.3127	2.5925	2.7664	2.5925	1.4481	1.6628
Mean CO ₂ -e (t/ha)	4.4767	* From the field survey spreadsheet - sum of volume of all sampled trees ** Using (total number of trees/number in sample)*sample volume ^ using a density of 0.758 t/m ³ (Ilich et al. 2000) ^^ using a ratio of 1.3 (Snowdon 2000) ^^^ using a root:shoot ratio of 0.25 (Snowdon 2000) # using standard value of 50% carbon content of wood (Specht 2003) ## equivalent CO ₂ using conversion factor of 3.66, from molecular weight of C and O ### two year old trees					
Mean CO ₂ -e (t/ha.yr)	2.2383						
Range CO ₂ -e (t/ha.yr)	1.4481 to 3.3127						
(x-mean) ²	0.893029326						
Variance CO ₂ -e (t/ha.yr)	0.504683968						
St. Dev. CO ₂ -e (t/ha.yr)	0.710411126						

Appendix E: GIS Models – Limitation Layers

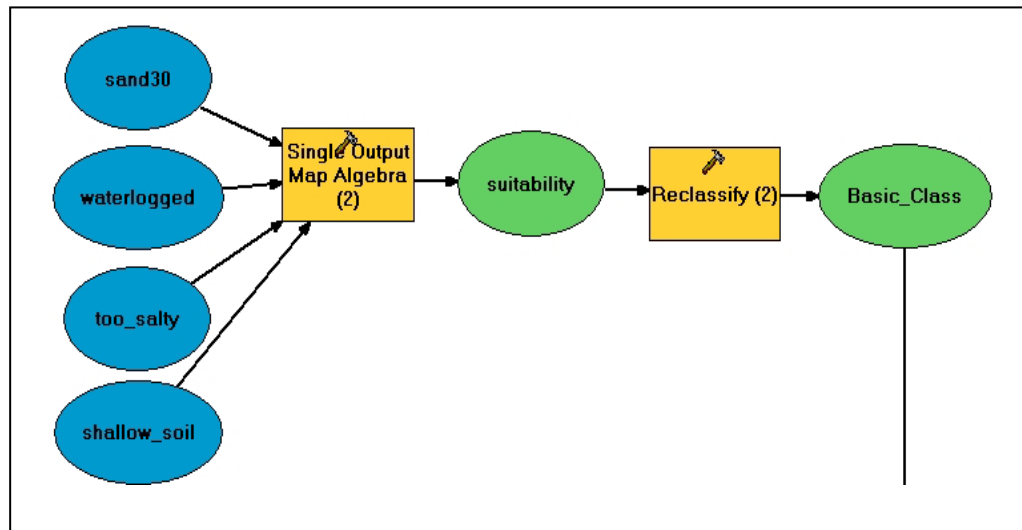
The following diagram shows the actual GIS model used for the analysis presented in Figure 7 within the Methods section. It shows the formation of the individual limitation layers. The images of these layers are presented in Appendix H, images (a), (b), (c) and (e).



Note that:

- 1651_D~1.ERS – Dose Rate Layer, Radiometrics
- Dem_moodiarrup2.ers – DEM
- EM38.ers – Shallow Electromagnetics

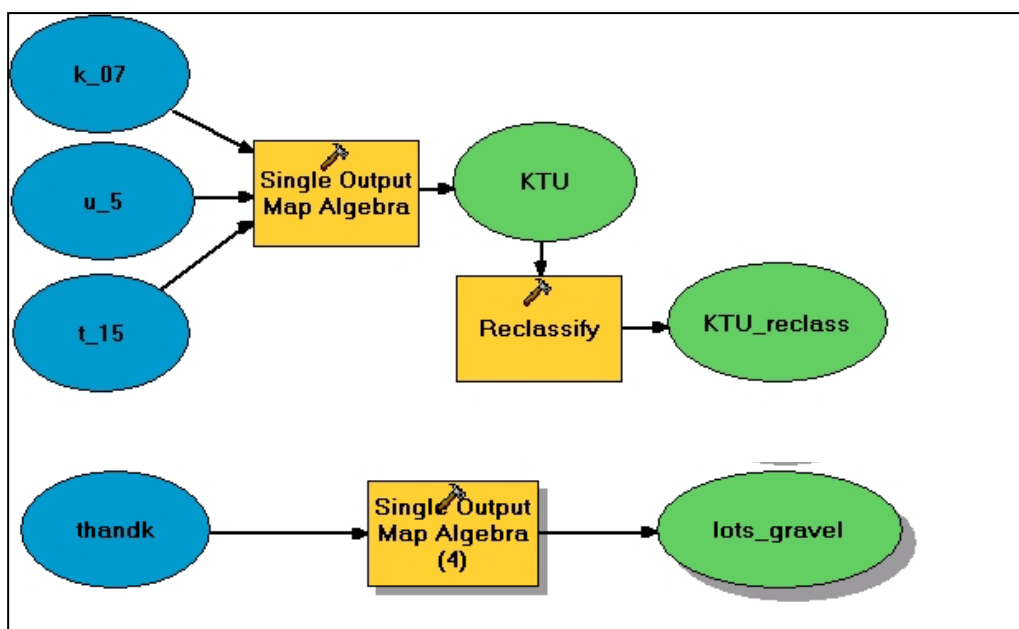
The next model was used to form the basic classification of the site, as outlined in Figure 8 in the Methods section. The outcome, 'Basic Class', is shown in Figure 15 of the Results section. An intermediate classification of the unsuitable areas alone is shown in Appendix H, image (d).



Appendix F: GIS Models – Key Landscape Features Layers

The following diagram shows the actual GIS model used for the analysis presented in

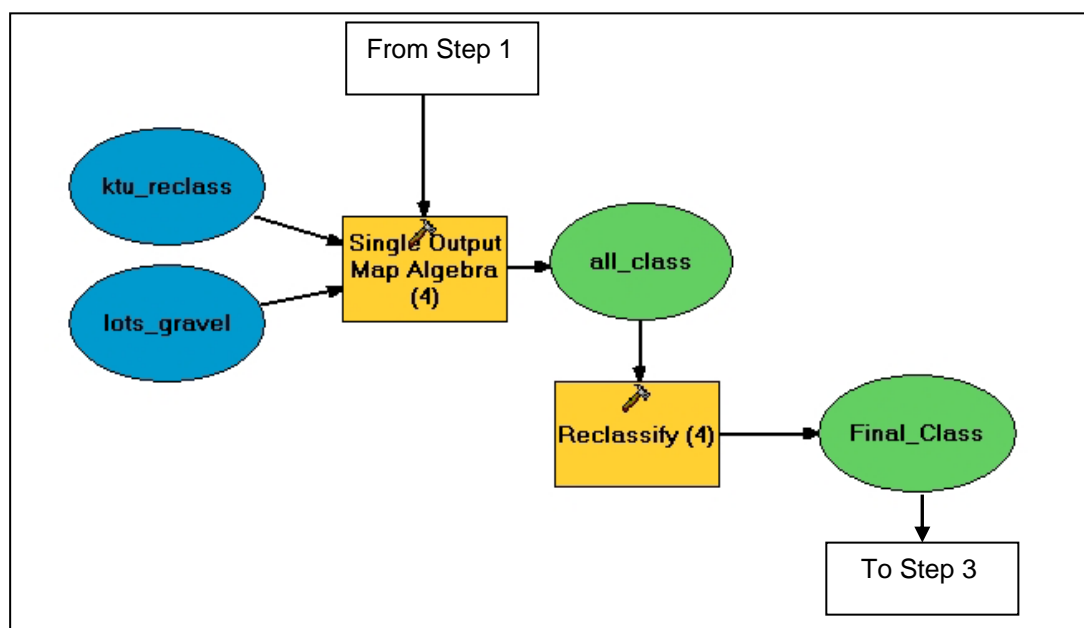
Figure 9 within the Methods section. It shows the formation of the individual landscape feature layers. These layers are presented in Appendix I, images (a) and (b).



Note:

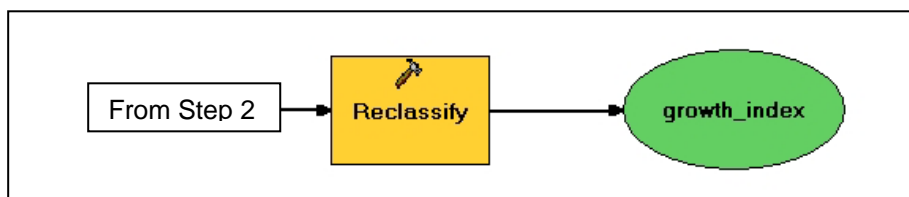
- K_07 – Potassium layer sliced at 0.7 %
- U_5 – Uranium layer sliced at 5 ppm
- T_15 – Thorium layer sliced at 15 ppm

The following diagram shows the model used to create the final soil/landscape classification of the site. The general method was shown in Figure 10 within the methods section. The 'Final_Class' image is presented in Figure 16 of the Results section.

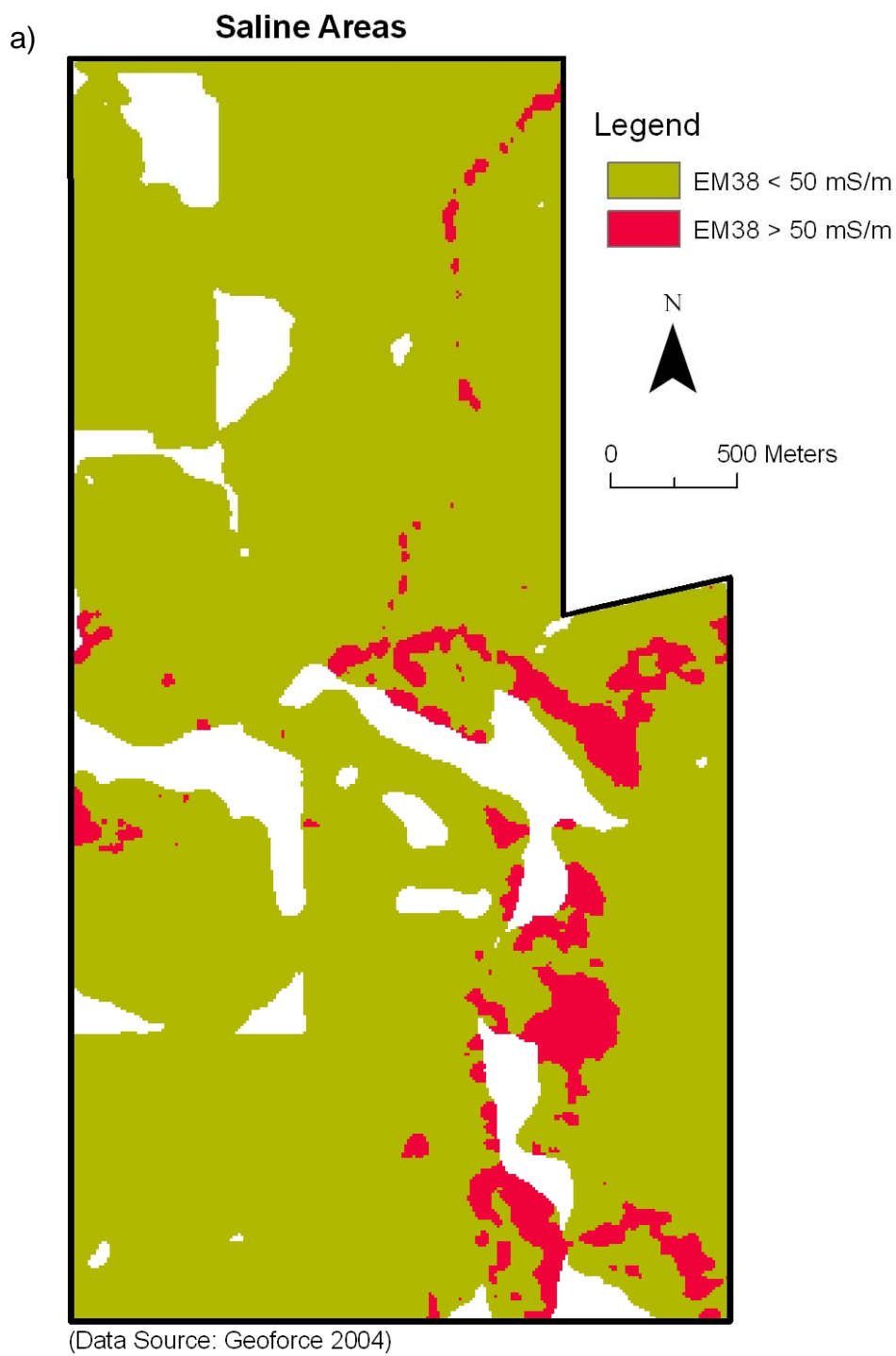


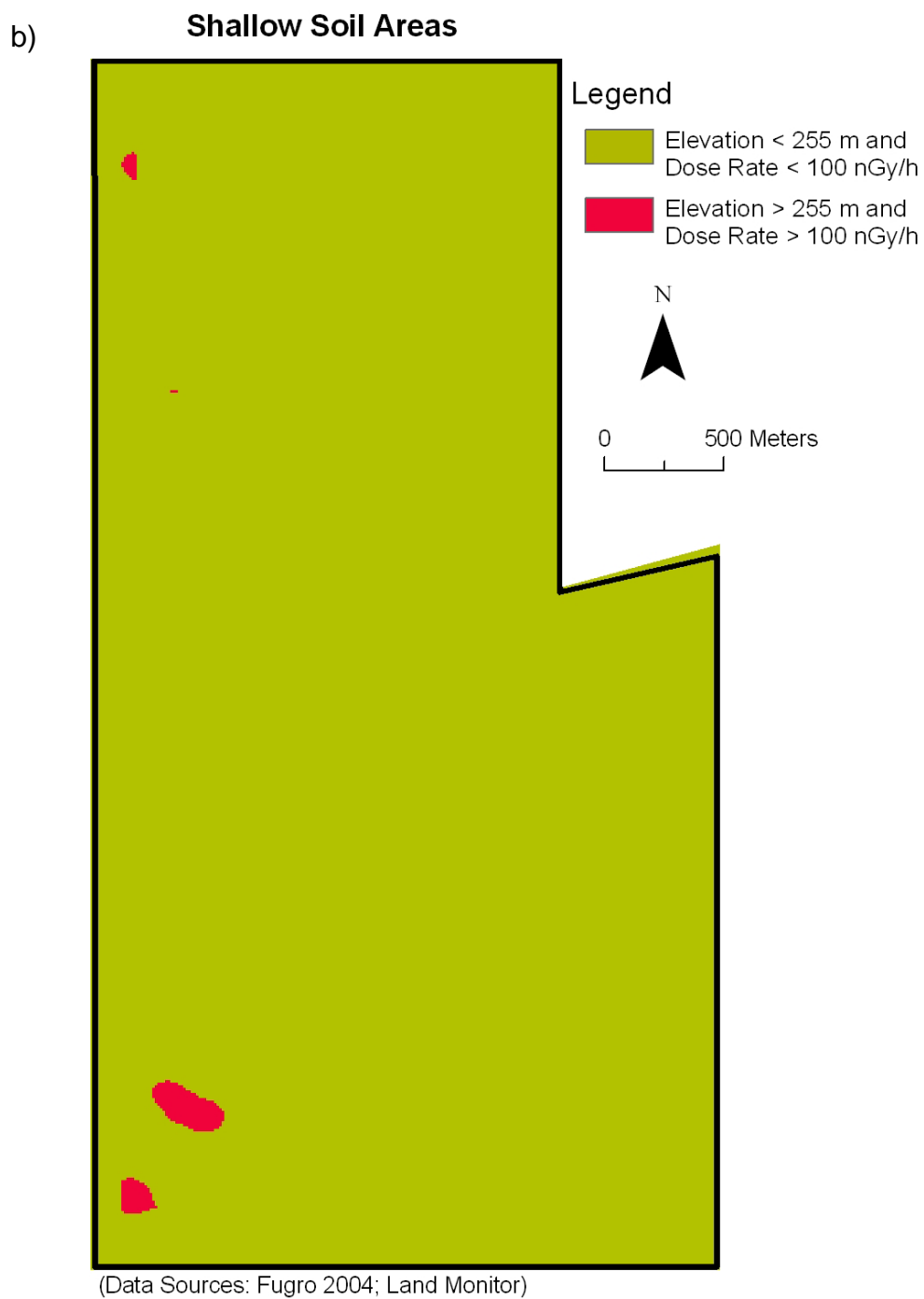
Appendix G: GIS Models - Growth Rating Index

The following diagram shows the model used to reclassify the final soil/landscape image using the index range associated with each class. The values used in the classification are presented in Table 4 of the Results section. The image produced is given in Figure 17 of the Results section.

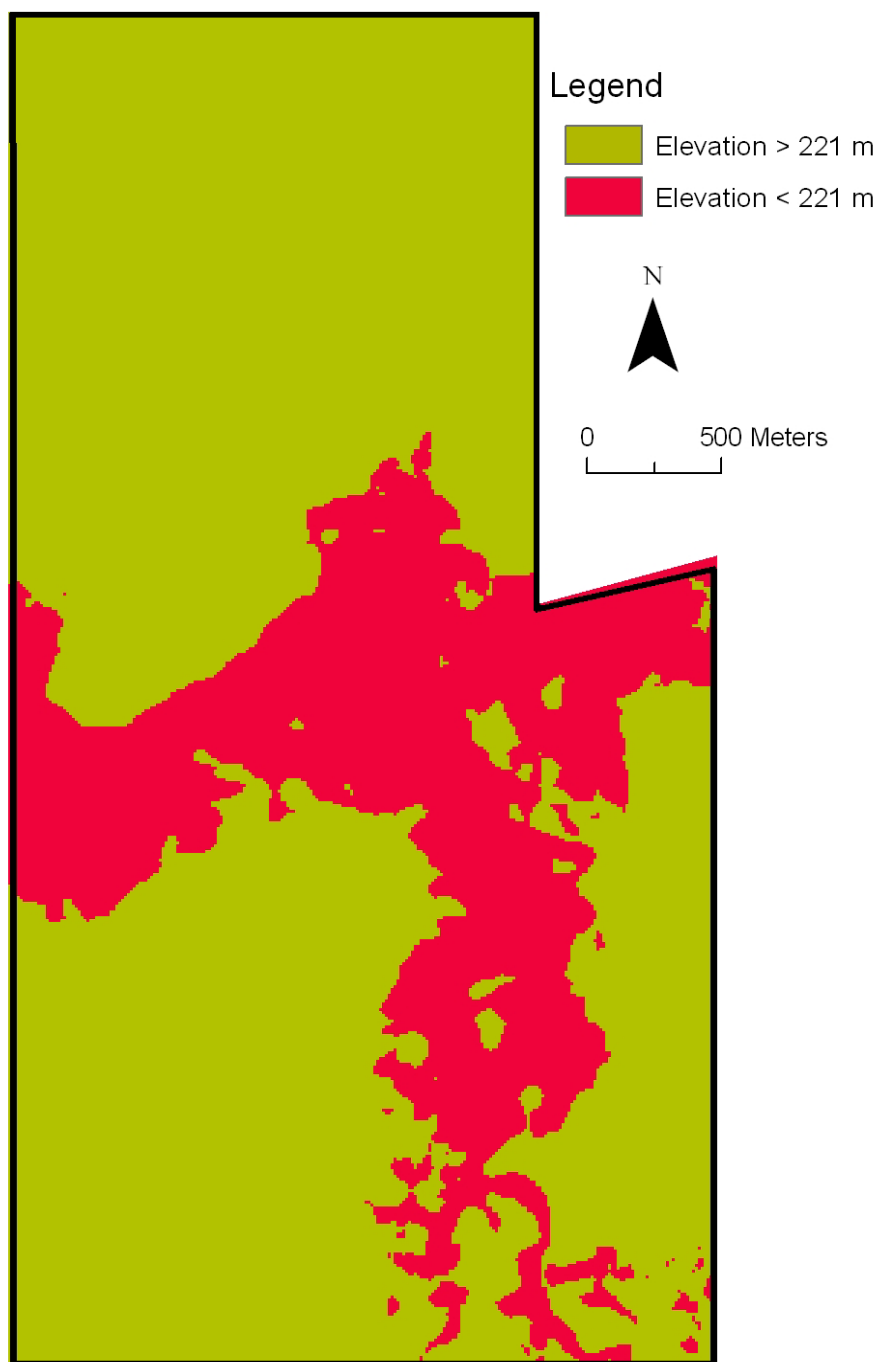


Appendix H: Step 1 Results - Limitation Layers

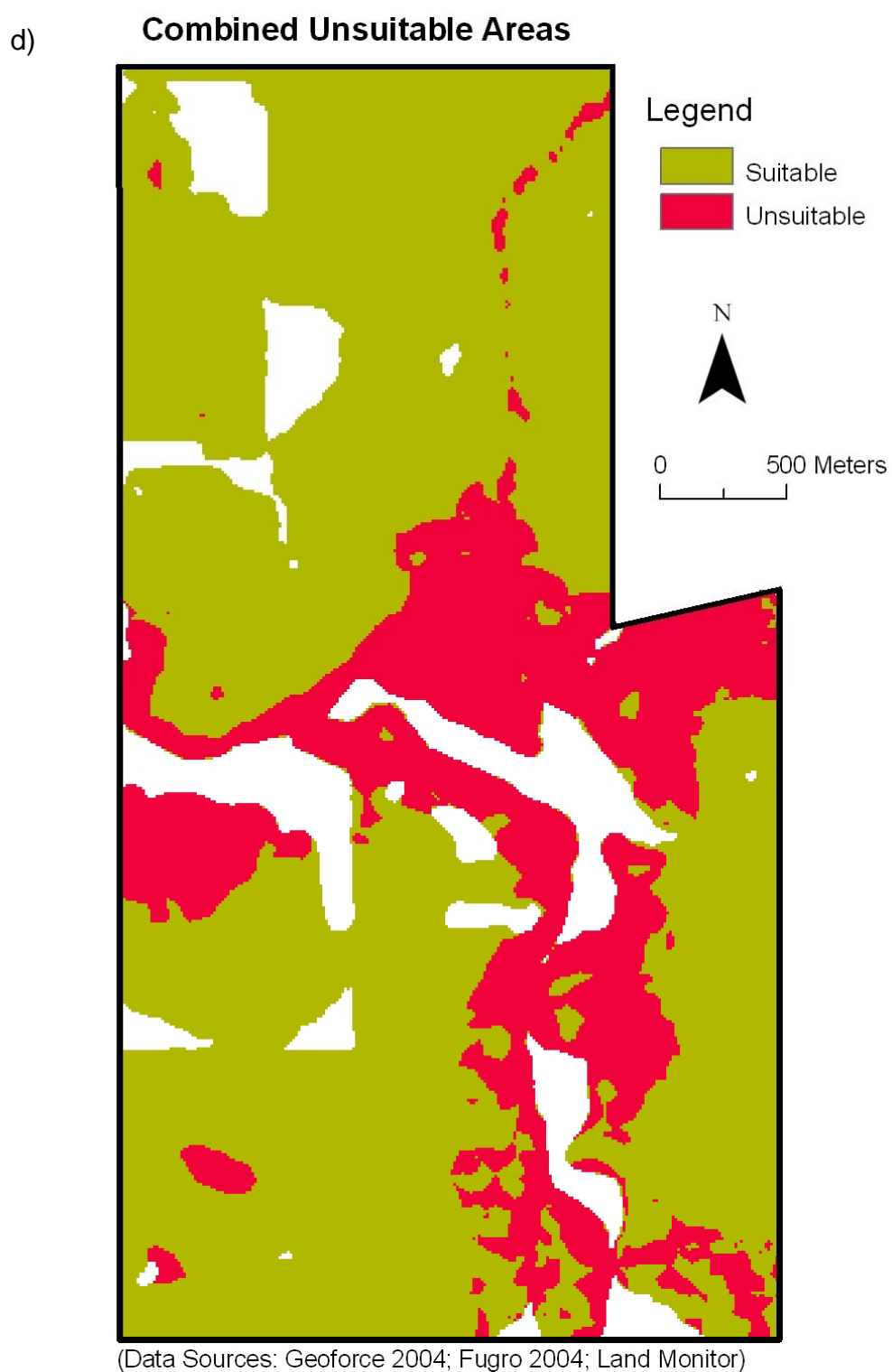




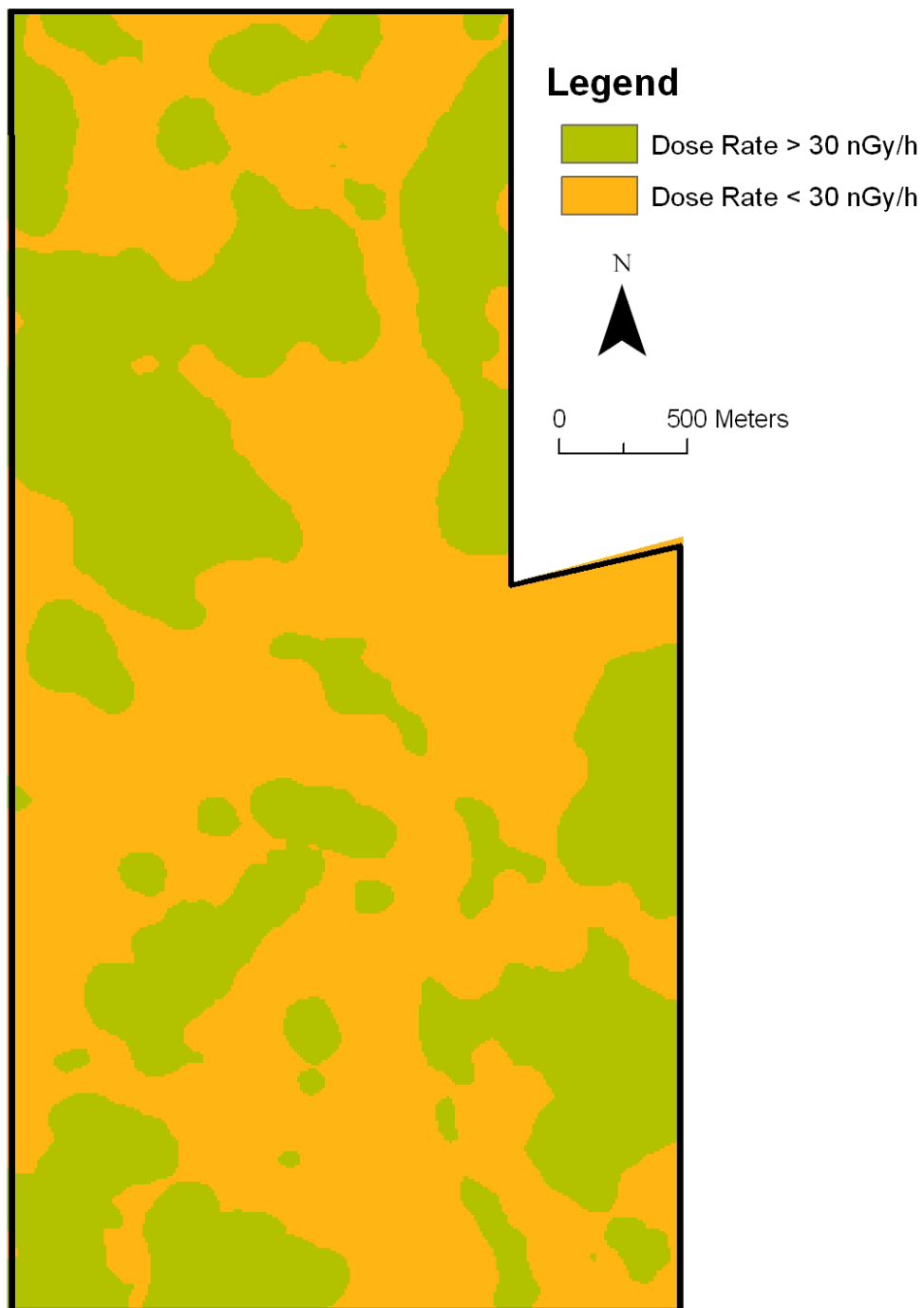
c)

Potentially Waterlogged Areas

(Data Source: Land Monitor)



e) Sandy Areas

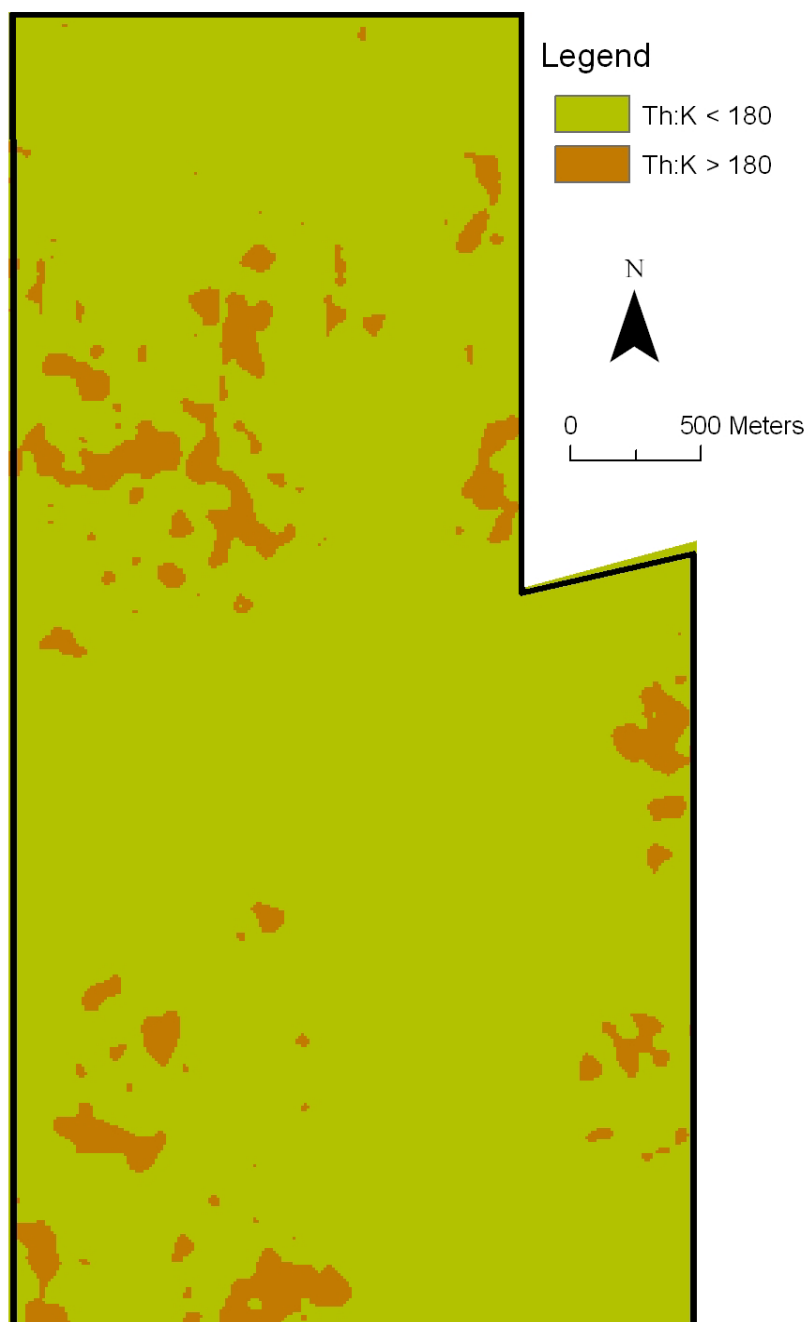


(Data Source: Fugro 2004)

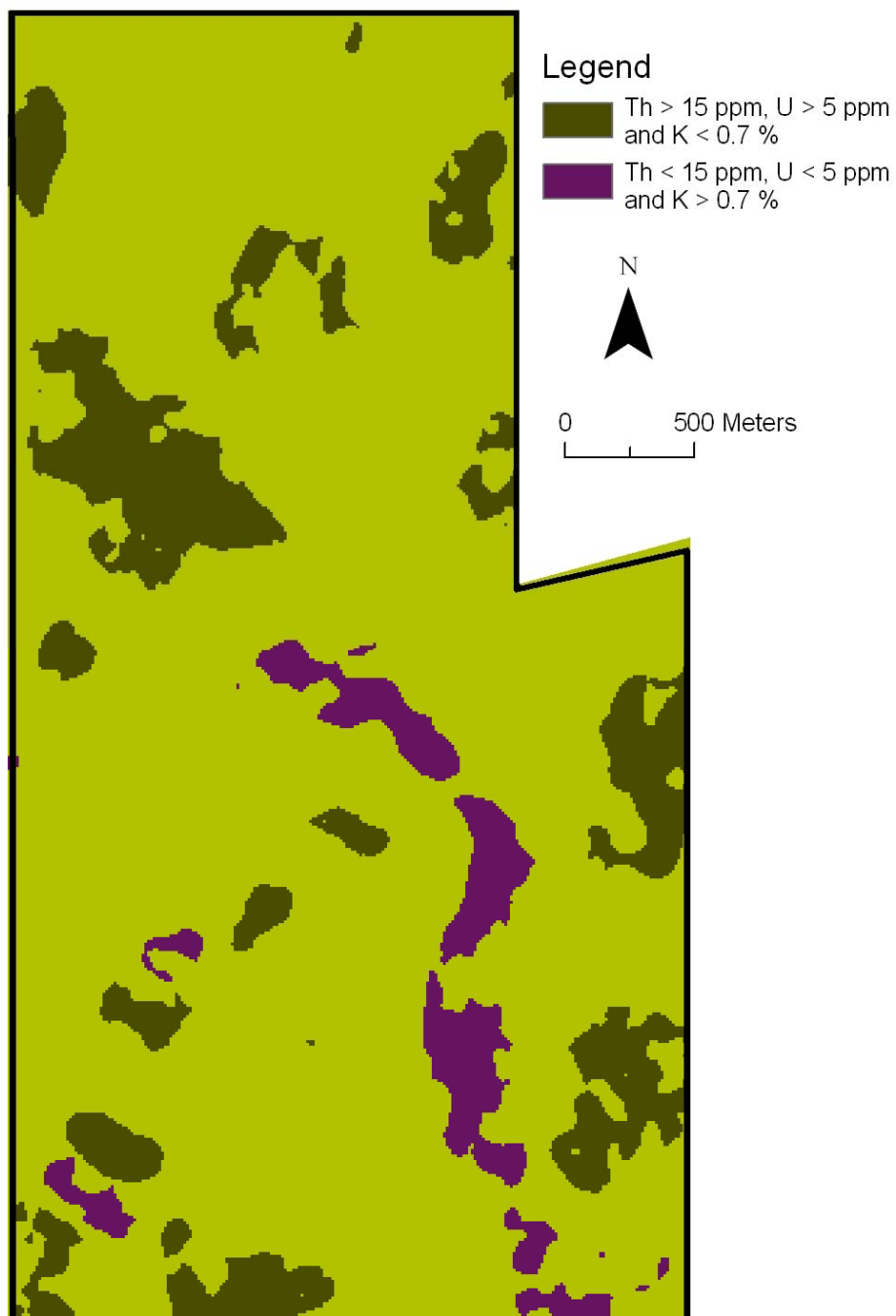
Appendix I: Step 2 Results - Landscape Feature Layers

a)

Gravelly Areas



(Data Sources: Fugro 2004)












b) **Lateritic and Very Gravelly Areas**

(Data Sources: Fugro 2004)












Appendix J: AgET Output

These images show the AgET results obtained using the input information presented in Section 4.3.2.

Region: H4	Station: Arthur River	Long Term MAR (mm): 497	Go Back
Unit: 1	Soil Type: Deep Sand Duplex	MAR for Selected Period (mm): 486	
Current Rotation: Other Annual			
New Rotation: Eucalyptus			

<u>Balance Summary - Average Annual Values</u>		Current Rotation	New Rotation
	Evapotranspiration	321 	441 
	Surface Runoff	26 	12 
	Deep Flow (mm)	139 	7 
	Storage Change	0 	25 
	Days of Runoff	2.27	.63

Region: H4	Station: Arthur River	Long Term MAR (mm): 497	Go Back
Unit: 2	Soil Type: Deep Loam Duplex	MAR for Selected Period (mm): 486	
Current Rotation: Other Annual			
New Rotation: Eucalyptus			

<u>Balance Summary - Average Annual Values</u>		Current Rotation	New Rotation
	Evapotranspiration	352 	470 
	Surface Runoff	55 	12 
	Deep Flow (mm)	78 	0 
	Storage Change	0 	3 
	Days of Runoff	6.9	.63