UNIVERSITY OF SOUTHERN QUEENSLAND

SITE SUITABILITY ASSESSMENT OF SPOTTED GUM (*Corymbia citriodora* subspecies *Variegata*) FOREST PLANTATION IN SOUTH EAST QUEENSLAND FOR CARBON SEQUESTRATION

A Dissertation

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ABSTRACT

The inevitable development brought about by human intervention in the global natural ecosystem has led to a continuous increase in greenhouse gas (GHG) emissions into the atmosphere (IPCC 2013), thereby warming the earth. Forest and other vegetation landscapes have the potential to mitigate this warming by serving as the sinks or storages of carbon dioxide. However, land suitability for carbon sink enterprises must be identified to effect a more productive, profitable and efficient sequestration. Additionally, the impact of soil salinity in the suitability of potential forestation sites and carbon sequestration capacity of forest plantation in saline affected areas is not well understood.

This research addressed the problem of site suitability by applying the most appropriate process based model particularly the 3-PG (Physiological Principle in Predicting Growth) to enhance the accuracy of estimated biomass for spotted gum. Salinity was incorporated through the mortality impact of varying salt concentrations in the spotted gum. As carbon sequestration endeavour via forestation was deemed risky in marginal areas such as those with salinity problems, the net present value (NPV) of spotted gum forest plantation was incorporated to determine its financial benefits. Site suitability of this forestation endeavour in southeast Queensland was determined and visualised using the geographical information system (GIS).

Mathematical models for spotted gum mortality and soil salinity were developed and integrated with the 3-PG model. Parameterisation of the model using specific climatic and bio-physical parameters for spotted gum was conducted prior to the simulation. These provided confidence in the biomass simulation and projection of carbon sequestered until the end of the rotation period. The estimated total biomass (aboveground and belowground biomass) were converted to carbon and tabulated. The tabulated results were converted into maps using GIS techniques and the Net Present Value of spotted gum was calculated based from its potential for timber, carbon and salinity amelioration. The utilisation of spatial mapping tools, specifically GIS, generated potential suitable sites for carbon sequestration activities in the SEQ region.

The study generated maps to identify potential locations suitable for Carbon Farming Initiative (CFI) eligible carbon sequestration projects. The site suitability index (SSI) map showed suitable sites in the northern part of the study area located at SEQ 1 and in the southern part at SEQ 2 and SEQ 8. The SSI map also indicated locations for potential investment in forestation projects. It also suggested that success of the carbon sequestration activities cannot be guaranteed in high rainfall areas where salinity could pose a challenge.

If spotted gum plantations are established in southeast Queensland and only the conventional timber is accounted as the source of revenue, then the financial benefits are limited to high rainfall areas with a mean annual increment (MAI) of more than 18 m^3 ha^{-1} yr^{-1}. However, under high saline conditions the viability is questionable. When established under high saline affected areas with carbon and salt amelioration incorporated, then carbon sequestration may become profitable.

However, this may only be applicable in a scenario where the carbon price was increased and a conventional timber is added with carbon and soil amelioration

benefits. Though suitable sites are limited where this activity is profitable, the potential of spotted gum for soil amelioration under saline affected areas is significant even for an extended long period of time.

CERTIFICATION OF DISSERTATION

I certify that the ideas, investigations, analysis, results, discussions and conclusions reported in this dissertation are solely my own work, except where otherwise acknowledged. I also certify that this is an original work and has not been previously used to earn academic degrees or awards.

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PUBLICATION AND SEMINAR PRESENTATIONS

During the study a paper was published out of the result of this study:

a) Salcedo, P., Maraseni, T.N. & McDougall, K. 2012. Carbon sequestration potential of spotted gum (*Corymbia citriodora* subspecies *Variegata*) in South East Queensland, Australia. *International Journal of Environmental Studies*. DOI. 10.1080/00207233.2012.715833.

Similarly, this research won first prize (2010) and second prize (2012) in two different postgraduate seminars attended by international postgraduate students:

a) ACSC Postgraduate Seminar. 2010. Australian Centre for Sustainable Catchments, University of Southern Queensland, Australia.

b) ACSC Postgraduate Seminar. 2012. Australian Centre for Sustainable Catchments, University of Southern Queensland, Australia.

ABBREVIATIONS AND ACRONYMS

3-PG	Physiological Principle Predicting Growth Model
ACCU	Australian Carbon Credit Unit
ACSC	Australian Centre for Sustainable Catchments
AGB	Above-Ground Biomass
AGO	Australian Greenhouse Office
ANN	Artificial Neural Networks
APAR	Absorbed Photosynthetically Active Radiation
AR	Afforestation and Reforestation
ASDD	Australian Spatial Data Directory
BGB	Below-Ground Biomass
BOM	Bureau of Meteorology
CaBala	Carbon Balance
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide Equivalents
CAI	Current Annual Increment
CAMFor	Carbon Accounting Model for Forestry
CCV	*Corymbia citriodora* subspecies *Variegata*
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CFI	Carbon Farming Initiative
CPM	Carbon Price Mechanism
CRA	Comprehensive Regional Assessment
DAFF	Department of Agriculture, Fisheries and Forestry
DAP	Direct Action Plan
DBH	Diameter at Breast Height
DERM	Department of Environment, Resources and Management
DNR	Department of Natural Resources
EC	Electrical Conductance
ERU	Emission Reduction Unit
EU-ETS	European Union-Emission Trading System
FR	Fertility Rating
FullCAM	Full Carbon Accounting Model
GHG	Greenhouse Gas
GIS	Geographical Information System
GPP	Gross Primary Production
Ha	Hectare
IBRA	Interim Biogeographic Regionalisation for Australia
IET	International Emission Trading
IPCC AR5	Intergovernmental Panel for Climate Change Fifth Assessment Report
JI	Joint Initiative
KP	Kyoto Protocol
LAI	Leaf Area Index
LMA	Leaf Mass per Area
LULUCF	Land Use, Land Use Change and Forestry
MAI	Mean Annual Increment
MCDA	Multi-Criteria Decision Analysis

MSY	Maximum Sustained Yield
NCAT	National Carbon Accounting Toolbox
NLWRA	National Land and Water Resources Audit
NPP	Net Primary Productivity
NPV	Net Present Value
PBM	Process Based Model
REDD+	Reducing Emissions from Deforestation, Forest Degradation, Sustainable Forest Management and Conservation
RFA	Regional Forest Agreement
SEQ	South East Queensland
SI	Site Index
SLA	Specific Leaf Area
SOM	Soil Organic Matter
tDM	Ton of Dry Matter
UNFCCC	United Nations Framework Conventions on Climate Change
WLC	Weighted Linear Combination

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Introduction

*"**Wisdom** is the principal thing; Therefore get **wisdom**.*
And in all your getting, get understanding"

Jedidiah, *Book of Wisdom*, 970 – 928 BCE

1.1 Background

Development brought about by human intervention in the global natural ecosystem has led to a continuous increase in greenhouse gas (GHG) emission (IPCC 2013), warming the earth faster than that which naturally occurs. It is widely expected that the impact of climate change will result to an irreversible damage to plants, wildlife and humans. Many factors play into the complex equation that determines the impact of GHG emissions and concentration in the atmosphere (Zomer et al. 2008). The Intergovernmental Panel on Climate Change (IPCC 2013) clearly indicates in its fifth assessment report (IPCC AR5) that the atmospheric concentrations of GHG have increased to levels unprecedented in the past 800,000 years. Carbon dioxide concentrations alone have increased by 40% since pre-industrial times. This increase was attributed mainly to fossil fuel emissions followed by the land use change emissions (IPCC 2013). From 1750 to 2011, carbon dioxide emissions from fuel combustion and cement production have emitted an average of 375 GtC to the atmosphere whilst deforestation and other land use change released an estimated of 180 GtC (Stocker et al. 2013). These cumulative anthropogenic carbon dioxide (termed as cumulative carbon emissions) can perturb the Earth's radiation budget, producing a radiative forcing that affects climate (Cubasch et al. 2013).

The complex mix of natural and anthropogenic substances and processes that create an alteration in the Earth's energy budget result in climate change (IPCC 2013). Extreme weather conditions like drought, torrential rains, hurricanes, and increased frequency and intensity of forest fires and loss of biodiversity amongst others are identified elements which have an impact on the environment (IPCC 2011). Catastrophic events such as cyclones, extreme flooding and prolonged droughts are likely to occur (Cubasch et al. 2013). These events are not only risks to human lives, but are hazardous to vulnerable communities such as the case of the Philippines and other Asian countries (ADB 2012).

In many cases, the social and economic activities of the society cause vulnerabilities such as rising temperature, fire, insect outbreak (Herawati & Santoso 2011) and even poverty (Smith et al. 2014). The contemporary land use change and the subsequent effects include deforestation of approximately 64,000 km^2 yr^{-1} for the entire tropical forest ecosystem of the earth, whilst natural forests regeneration on abandoned land is estimated at 21,500 km^2 yr^{-1} (Wright 2010). An estimated 17,500 km^2 of forest were lost from protected areas in several humid tropical forests globally between 2000 and 2005 releasing 0.25 - 0.33 gigatonnes of carbon (GtC) (Dunning et al. 2010).

Among the GHGs, carbon dioxide is the major cause of anthropogenic climate change (IPCC 2007) and has the largest climate forcing (Smith 2009) with a significant warming influence on the global climate system. Carbon dioxide global annual emissions have grown between 1970 and 2004 by approximately 80% (IPCC 2007), from 21 to 38 GtC. However, the rate at which it is sequestered, is far less than the terrestrial ecosystems sequester rate of approximately 3 gigatonnes of global carbon annually (Canadell & Raupach 2008).

On an international level, it is viewed that reducing emissions from deforestation, forest degradation, sustainable forest management and conservation (REDD+) is one of the most promising mechanisms to combat climate change. It was seen to be of high significance in the protection and conservation of the tropical forests of the world (Glenday 2006). The role of forests in carbon sequestration and the mitigation of climate change was recognized through the Kyoto Protocol (KP). The IPCC identified the forestry sector as the second leading cause of anthropogenic GHG emissions after the energy sector, responsible for approximately 17% of emissions, largely as a result of deforestation (Pachauri & Reisinger 2007).

Forestation such as afforestation[1] and reforestation[2] are part of several mitigating measures in the Kyoto Protocol portfolio which it is believed will directly aid in climate change alleviation (UNFCCC 1998). The Kyoto Protocol agreement has promoted and encouraged forestation projects to increase carbon sequestration around the world *via* several measures. The Clean Development Mechanism (CDM) is one of the flexible mechanisms through which Annex-1 countries (developing nations) can accrue carbon credits through carbon offsetting whilst providing compliance markets for Non-Annex-1 countries (developed nations) (UNFCCC 2012).

The commitments of the signatory nations resulted in the reconstruction of their environmental policies, and the creation of forestry programs leading to carbon offsetting together with the implementation of carbon trading. As a result, several issues and concerns were identified during the policy implementation phase, including land use conflict and allocations (forestry *vs* agriculture), food production, land suitability, leakage, additionality, economic return on forestation and other related matters. These became shared concerns of both Annex-1 and Non-Annex-1 nations including Australia, although there are varying forestation issues and concerns.

[1] "Afforestation" is the direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources UNFCCC (1998) Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations.

[2] "Reforestation" is the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested but that has been converted to non-forested land. For the first commitment period, reforestation activities will be limited to reforestation occurring on those lands that did not contain forest on 31 December 1989 Ibid.

Consequently, one of the objectives of this study is to address the issue of land suitability by identifying potential sites suitable for carbon sequestration.

Emission reduction via carbon sequestration also provides potential for significant economic benefits, which at the same time, will assist in the reduction of tropical deforestation (Hamilton et al. 2007). Although the current estimate of the global voluntary carbon market value is US$ 432 million (Diaz et al. 2011), landholders in Australia have mixed perceptions on the benefits of forestry (Petheram et al. 2000). The widespread land use change to commercial forestry is perceived to be unviable in marginal areas (Pearman 2004) including areas with salinity problems. Increasing land use for forestry purposes was also viewed as a threat to agricultural food production.

For example, in Queensland, forest plantations established in low to medium rainfall areas (600-800 mm yr^{-1}) are not financially attractive when its economic viability is conventionally assessed using timber as the only parameter (Venn 2005). Therefore, it is necessary to determine the potential suitable sites for plantation and integrating other intangible services when establishing forest plantation. The inclusion of the environmental services such as carbon sequestration and soil amelioration could contribute to the profitability of the forest plantation (Venn 2005). Similarly, this study intends to fill the gap on the financial benefits that can be derived from carbon sequestration endeavours which are aimed at incorporating environmental services such as soil amelioration in saline areas.

Process Based Modelling (PBM), Net Present Value (NPV) and Geographic Information Systems (GIS) are tools that can be applied to address the identified problems. Process based models can be used to determine forest plantation biomass accumulation and carbon sequestration. Net present value (NPV) has diverse applications and is the most commonly used economic profitability method to measure financial returns in forestry. Similarly, GIS has been globally established in the scientific arena and can aid in spatial decision making particularly involving forestry and land suitability issues. This study is expected to substantially contribute to identifying the existing gaps in the carbon sequestration endeavours, particularly in the Southeast Queensland region of Australia.

1.2 Statement of the problem

The creation of GHG abatement measures have resulted in policy development and structural changes in government and private institutions in both Australia and internationally. The Australian Government has encouraged farmers to engage in forestation on degraded lands (e.g. salt-affected areas) through a programme of specified tree planting via the Carbon Farming Initiative (CFI). The specified tree planting is not allowed in areas with a mean annual rainfall of >600 mm unless water implications are considered. Carbon offset via planting will only be considered if it is permanent, and is established according to the guidelines on water access entitlements set by the National Water Commission (DCCEE 2012a). However, the planting can be permitted if it contributes to the mitigation of the issues surrounding dry land salinity of the region, and would be exempted from the water access entitlements.

There are many additional factors to be considered when establishing forest plantation such as soil nutrients, soil types, temperature and other required elements aimed at stimulating and sustaining tree growth.

Though the Carbon Farming Initiative policies exist, there are serious problems in its implementation due to the absence of clear land delineation, especially as to where carbon sequestration activities are to be suitably implemented. Presently, regional land suitability maps specific for hardwood forest plantations are lacking. Suitable species for forestation and productivity maps that could significantly aid the farmers in terms of land use decision making are also wanting. This clearly highlights a need for regional spatial mapping.

Additionally, limited studies in Australia (e.g. Venn 2005; Maraseni 2007) have been conducted on land use suitability for *Corymbia citriodora* sp *variegata* (CCV) (spotted gum) carbon sequestration and the financial benefits derived therein. Spotted gum is fast growing (Dickinson 2009) and one of the most efficient trees in terms of carbon sequestration (Lee et al. 2011). It is considered as the most significant commercial native hardwood species and identified as a priority species by the Queensland government (Lee et al. 2005). At this point in time, a specific methodology for carbon accounting and impact of soil salinity in the carbon sequestration capacity of spotted gum plantations has not been well documented.

Further studies are required to determine the optimum level of hardwood production and suitability of lands within Queensland. The absence of regional information pertaining to site suitability and productivity has resulted in problems such as land use conflict (e.g. agriculture *versus* forestry), land use mis-allocation, non-prioritisation, non-productivity, species-site mismatch or non-suitability, unaccounted carbon credit, unabated pollution and related issues. These problems draw attention to significant gaps in the current pool of technical and scientific knowledge which is necessary to effect a positive impact on carbon sequestration of the Southeast Queensland (SEQ) region.

This research will therefore address the problem associated with identifying suitable locations for carbon sequestration investments, particularly hardwood plantations, which could maximize the yield with the integration of timber, carbon credit, and soil salinity amelioration.

1.3 Research aim and objectives of the study

The aim of this study is to develop a GIS-based land suitability assessment model for carbon sequestration, incorporating soil salinity impact on various land use systems in South East Queensland (SEQ). The specific objectives of the research are:

1. To review appropriate literature to identify the knowledge gaps in carbon sequestration of spotted gum in saline areas for Carbon Farming Initiative (CFI) eligibility;

2. To determine the carbon sequestration capability of spotted gum plantations in South East Queensland using a process based model (PBM);

3. To estimate the net value of soil salinity amelioration in relation to carbon sequestration *via* spotted gum plantations; and

4. To identify suitable sites for spotted gum carbon sequestration investments using geographic information system (GIS).

1.4 Hypothesis of the study

This research has the following hypotheses:

Hypothesis 1: The inclusion of soil salinity as an input parameter in the carbon accounting of spotted gum will enable a more accurate estimate of the biomass accumulation, carbon sequestration capability, and value of hardwood forest plantations.

Hypothesis 2: The incorporation of soil salinity value in the Net Present Value (NPV) determination of the economic benefits will further refine the assessment of land suitability and increased financial benefits for the stakeholders.

1.5 Justification of the study

The estimated forest area in the world is more than 4 billion hectares (31% of the total land area) with an annual global deforestation of 13 million hectares (FAO 2010). Though the deforestation rate has declined from 16 million to 13 million hectares per year during the past 10 years, the rate is still alarming (UN 2010).

As at 31 January 2015, there were 7,597 Clean Development Mechanism (CDM) projects (in Non-Annex-1 countries) registered worldwide under 26 investing countries (in Annex-1) with UK and Northern Ireland on top with 2326 projects (30.62%) followed by Switzerland with 1530 (20.14%) and Netherland with 658 (8.66%) whilst Australia has 43 projects (0.56%) (UNFCCC 2015).

Australia is an Annex-1 country and therefore is not eligible to host CDM projects, however information on the worldwide need for CDM schemes could be useful in implementing forestation activities in least developed countries. Similarly, knowledge in CDM methodologies could provide benchmark information for Australia's national and local carbon emissions endeavours such as the Carbon Farming Initiative (CFI). It could also be beneficial in developing the methodological framework of Australia's currently proposed emission reduction projects (Department of the Environment 2015a).

The current demand for carbon emission reduction credits (both Kyoto and non-Kyoto compliant) provides an added incentive for Australian farmers, project developers, financial institutions, and technology owners to engage in the business of generating, buying, selling and funding emission reductions under the CFI. Farmers and other landholders are particularly uncertain when it comes to the identification of suitable land which could provide them with optimum economic benefits. Furthermore, the carbon accounting methods that could integrate other environmental services derived from plantation such as soil amelioration is still lacking.

The Australian Government is encouraging farmers to reduce emissions via CFI. Rapid changes in land use in areas dependent on agriculture have led to anxiety in the community as government is inclined to favour forestation (Race 2004). At the same time, soil salinity which is presently happening in the south east region (Falkiner et al. 2006; Venn 2005; NLWRA 2001) affects both agricultural and forest productivity whilst suitability of land for forestation is questionable. The landowners are subsequently faced with the dilemma as to which system of land use is financially profitable and suitable for their land. Information on financial returns from such land use is necessary prior to making a decision on whether to shift from agriculture to forestry. The Australian Government is to address the climate change and carbon emissions via a Direct Action Plan (DAP) that will provide a mechanism to achieve the nation's commitment to reduce GHG emissions by at least 5% on 2000 levels by 2020. CFI is one of the main platforms of the DAP which proposes the expansion of the project eligibility, shortening the carbon sequestration project permanence and revising mechanism methodologies (Witt et al. 2011). Therefore, the result of this research will be beneficial for local and international farmers and investors who anticipate a venture into forest production and carbon sequestration enterprises.

In Queensland, forest hardwood plantations increased sharply during the late 1990s up to the early 2000s (ABARE 2011). Most of these plantations were comprised of spotted gum species (TQ-DAFF 2012). This species has a significant potential to be marketed due to its excellent quality and suitability for forestation activities, as it can thrive even in poor soil conditions. As dryland salinity is one of the environmental problems experienced in the southern part of Australia (Falkiner et al. 2006), it is appropriate to integrate the soil amelioration benefits in the carbon sequestration services of this plantation, in addition to the conventional timber benefit. This provides an excellent and timely opportunity to develop a methodology that will incorporate a net present value of salinity in timber and carbon sequestration as this is significantly important not only in Australia but at an international level as well.

Australia could also benefit from forestation as significant goods and services from the planted forests can be derived. As well as being a carbon sink, forests generally provide essential ecosystem services to humanity such as food, shelter, water quality, the diversity of life and a liveable climate (Van Oosterzee & Garnet 2008). However, the alarming rate of forest deforestation presents one of the international community's greatest environmental concerns (Brockerhoff et al. 2013). The transformations of world's ecosystem brought about by deforestation and degradation had serious impacts both in the ecological and social system. If left unabated, over 30% of the remaining natural forests will be lost by the end of the century (Brockerhoff et al. 2013). Plantations, in particular eucalypts, continue to expand worldwide. Wood demand from native forest decreases as a result of available timber supply coming from plantations (Warman 2014). This leads to increased protection of native forests against logging (Battaglia et al. 2007) and presents a clear alternative to reduce resource conflicts in natural forests (Warman 2014). Plantation forestry can help mitigate climate change through carbon sequestration via increased productivity, alleviation of pressures on natural forests, and restoration of ecological balance (Paquette & Messier 2010).

As the Regional Forest Agreement (RFA) has yet to be finalised in SEQ, there is an opportunity for the result of this study to serve as a guide during the process. RFA incorporates the direction of forestry, and will serve as the blueprint for any relevant forestry plans in the region. It would be highly beneficial to enhance the existing comprehensive regional assessment (CRA) of 1998 (CRA-RFA 1999a) with the result of this study as carbon sequestration was not included in the previous RFA report.

The Queensland Government asserts ownership of all timber on leasehold land except for freehold (non-government and non-public but owned by private companies) and in so doing, makes no provision for differentiating natural timber from planted timber. With the presence of so many forestry laws and policies in active practice, in particular the expansion of commercial forestry, it would be difficult to meet the current climate change guidelines in CFI due to land use conflicts and permanency. Forest plantations that will actively absorb carbon dioxide from the atmosphere for long periods of time are favoured against short rotation plantations.

However, forest plantations, in particular the privatised commercial plantations, in most cases are to be harvested after 20 years, whereas environmental planting is to be preserved for up until 100 years. Commercial plantations clearly violates the permanency (Whitbread et al. 2003) as it relates to carbon sink, thus leaving limited options particularly in terms of areas suitable for CFI implementation. The challenge lies in the use of appropriate tools such as process based models, financial evaluation and GIS in achieving the goal of this PhD research.

1.6 Significance of the study

Although suitability can be determined by analysing the site characteristics and models available, the mere knowledge of plantation suitability in carbon sequestration projects is insufficient. With the expected increase in demand from the local and international investors for suitable sites specifically for carbon sequestration, it is important that appropriate assessments are done prior to plantation establishment. Carbon sequestered and forestry services must be at a level that will provide the highest return and furthermore optimise land utilization. An area may be suited to tree plantations but it may not be financially viable to shift from agricultural production to forestry. Models can be used to aid in determining productivity. With the creation of policies relating to climate change and forestation opportunities in Australia, efforts have focused on developing forest growth models for biomass production and carbon accounting. Consequently, forest growth models created must accurately determine the value of productivity if carbon trading is to be pursued.

It is necessary that plantations are established on sites that maximise production, carbon sequestration, and financial benefits while prioritising land use to assist in resolving land use conflict and result in a better decision. The use of an appropriate model that will accurately account for carbon can aid in spatially mapping and locating suitable and appropriate areas.

1.7 Scope and limitations of the study

The large and rapid changes in atmosphere CO_2 concentration and climate are expected to significantly affect carbon cycling in the terrestrial biome (Foody et al. 1996; Clark 2004; Malhi & Phillips 2004). These changes have impact on the biogeochemical and biogeophysical processes of terrestrial ecosystems, especially to the productivity. The impact of climate change on the ability of terrestrial forests to sequester carbon dioxide is not yet fully known (Foster 2007). Although there is some evidence suggesting the impact on tree productivity, this study will not deal with the issues of global warming, nor on the impact of atmospheric carbon dioxide concentration in the carbon sequestration capability of hardwood forest plantations. It will also not address the sustainability of forest plantations on a saline environment due to time and financial constraints.

As long time series (20-100 years) forest plantation yield and production are lacking, the available primary datasets (16 years) and parameters from other studies were used to parameterise the growth modelling software. The use of the results is specific to SEQ only and caution must be applied in the use of the results in other areas. Lastly, the mechanism of carbon trading is also excluded in the study.

1.8 Structure of the thesis

The first chapter deals with the problem, aim, objectives, justification, significance, scope and limitations of the study whilst chapters two and three investigates the previous studies in relation to carbon accounting methods, spotted gum yield, salinity, spatial analysis and site suitability, and the economic benefits of carbon, timber, and salinity amelioration. It also highlights the gaps of each topic and discusses the issues concerning each methodology. Chapter four discusses the materials used and methods applied. Reasons for the choice of models and tools are also discussed in this chapter. Chapter five provides a comprehensive discussion on the simulated biomass accumulation and identifies the carbon sequestration potential of the sub-regions in the study. Chapter six discusses the results of salinity and financial benefits with a focus on the net present value of benefits of carbon sequestration projects with timber, carbon, and salt. Chapter seven discusses the generated potential suitable sites with GIS mapping. The last chapter is the conclusion of the study with local and international implications and recommendations. The diagram below (Figure 1.1) shows the flow of the chapters and the corresponding chapters that will fulfil the requirements of the identified objectives.

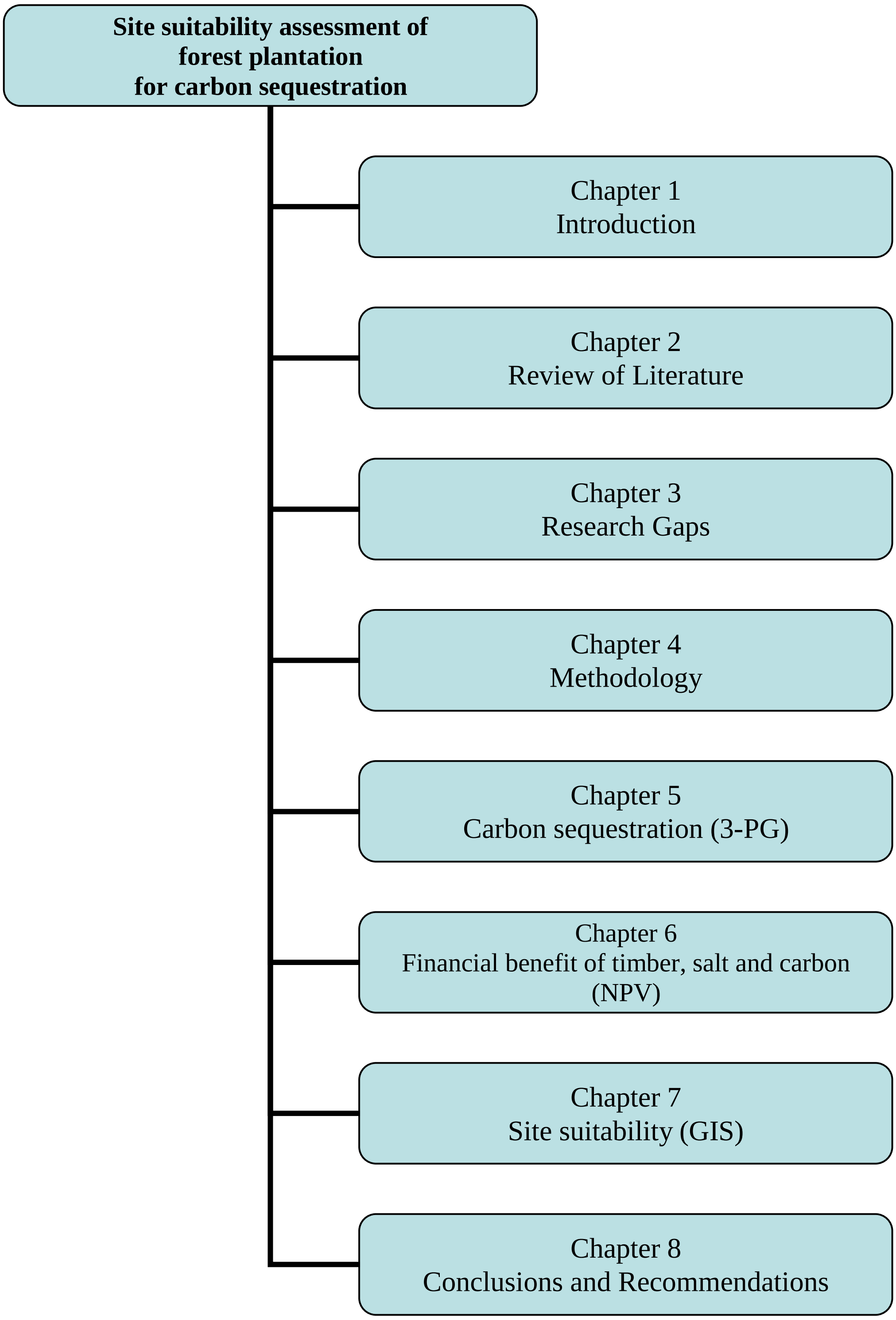

Figure 1.1 Structural diagram of the study

1.9 Conclusion

The background stated in this chapter provides an overall perspective on the increasing atmospheric carbon brought about by global anthropogenic activities (e.g. deforestation). Adverse impacts are probable to occur regardless of one's geographical location on earth. These impacts can be detrimental not only to the biological resources (e.g. flora and fauna) but to human society. Internationally, forestation is one of the identified legitimate measures that could mitigate widespread deforestation.

However, significant gaps in the technical knowledge on hardwood carbon sequestration, productivity, suitability and related scientific knowledge are limiting the success of carbon sequestration endeavours at the international, national, regional and local levels. In the Australian context, particularly at a regional level, there is a serious need to bridge these gaps, which is why this research has been undertaken. The proceeding chapters will investigate more fully the appropriate tools, methods, strategies and provide results as the discussion progresses until the conclusion has been reached.

CHAPTER 2

Developments in Carbon Sequestration Initiatives

"But where shall ***wisdom*** *be found?*
and where is the place of understanding?"

Jedidiah, *Book of Wisdom*, 970 – 928 BCE

2.1 Introduction

The Kyoto Protocol (KP) has changed the forestry paradigm of the world. Some of the signatory nations to this protocol have placed commitments *via* several mechanisms and strategies including Australia. Some of the signatory nations have committed to the Kyoto Protocol for the reduction and abatement of carbon emission through strategies such as forestation for carbon sequestration through the Clean Development Mechanism. With these commitments, forestry practices have evolved into highly dynamic systems including the intangible services in the inventory and accounting of forest production. There are 55 afforestation and reforestation (A/R) projects out of 7,597 officially registered CDM projects (UNFCCC 2015), which represents only 0.72% of the whole. Nevertheless, carbon in addition to the conventional timber yield, is now incorporated as a tangible benefit derived from forestation and provides potential opportunity for future market.

Similarly, the standard methods on forest mensuration were extended to the development of carbon sequestration accounting. However, such developments are not well established which led to some issues and concerns including accuracy of carbon accounting methods, land suitability, spatial modelling and land conflicts. The Australian Government is also experiencing the challenges in regard to forestation activities and carbon sequestration endeavours due to previously mentioned concerns.

This chapter provides a general overview and background of international drivers on carbon initiatives. It then aims to identify issues and concerns facing Australian forests, its deforestation, afforestation and reforestation in relation to carbon footprints and carbon sequestration. This chapter also reviews international carbon sequestration initiatives and examines strategies of the Australian Government in response to its commitment to reduce carbon emissions.

2.2 Global forest resources degradation and climate change impact

It was stated in the IPCC Fifth Assessment Report that the earth's climate is changing. It projected a future with an increase of catastrophic events brought about by climate change (IPCC 2013). For instance, the Philippines had the annual average temperature rose by 0.65°C from 1951 to 2010 (ADB 2012) whilst Indonesia was predicted to experience temperature increase of approximately 0.8°C by 2030 (Oktaviani et al. 2011). Vulnerability of these countries to changes in the climate is higher as intensity and frequency of disasters increase. The rural poor are the most affected by the adverse impact leaving these countries in dire difficulty (Folland et al. 2001).

This can be partly attributed to forest denudation such as the case of the Philippines. Similarly, other nations such as Latin America (e.g. Argentina, Brazil, Bolivia, Colombia, Ecuador, Peru and Venezuela) who depended on the forest resources of the Amazonia for their survival could also experience adverse impacts from climate changes brought about by the anthropogenic pressures in their resources. For instance, the Amazon forest helps reduce GHG emission, and provides habitat for plants with cancer-fighting compounds. However, deforestation brought about by external pressures such as soybean production and cattle raising has been allowed in a massive 260,000 km^2 of Amazonian lands (Balaguer 2009). Degradation in tandem with the increase in temperature due to global warming can result in drastic changes to the agricultural production such as in Brazil. Patterns of cropping systems could change considerably as a result of climate change. For example, Brazil's cassava may vanish from the semi-arid region of the northeast and coffee may have a marginal chance of survival in the southeast; whilst the southern part of the country could become suitable for planting both crops as the occurrence of frost become less frequent (Assad & Pinto 2008). In Kenya, resource degradation coupled with frequent droughts that were experienced during the past three decades triggered high vulnerability to food insecurity (Schaffer et al. 2007). Furthermore, commercial logging is changing its focus from the Southeast Asia to Africa and South America (Wright 2010).

Ironically, while nations call for carbon emission reduction through forestation via carbon sequestration and emission avoidance, biological fuel or biofuel is gaining popularity as an alternative source of energy. For instance, a study conducted by Fargione et al. (2008) stated that one of the current major deforestation drivers is the European demand for biofuel and releases 17 to 420 times more CO_2 than the annual GHG reductions that these biofuels would provide. Anthropogenic forest degradation does not only affect climate but is a major driver of the current human-induced biodiversity crisis (Glenday 2006).

It is important that a response option or strategy along with climate change mitigation is considered (Kane & Shogren 2000) as even with the reductions in greenhouse gases emissions, global temperatures are expected to increase along with other extremes such as drought and sea level rise (White & Etkin 1997). Therefore, mitigating actions are highly necessary (Smith et al. 2013).

2.3 International carbon emission mechanisms and initiative

The Kyoto Protocol (KP) provides for three principal mechanisms which allow countries some flexibility in how they achieve their emission reductions namely: (1) International Emissions Trading (IET), (2) Joint Implementation (JI) and (3) the Clean Development Mechanism (CDM).

An international emissions permits trading regime enables developed nations to buy and sell emission credits or permits amongst themselves, for example, the European Union – Emissions Trading System (EU-ETS). The Joint Implementation (JI) provides for developed country parties (also termed as Annex-1 countries) to undertake projects in conjunction with, or within, other developed country parties borders.

The CDM and JI generate emission reductions through project-based mechanisms. CDM is based on the concept of emission reduction activities in Non-Annex-1 Parties (developing countries) whereas JI promotes emission reduction projects in Annex-1 Parties (developed countries). Certified Emission Reductions (CERs) can be generated from CDM whilst Emission Reduction Units (ERUs) can be produced from JI projects (UNFCCC 1998). Australia is ineligible to host CDM projects however, the approved CDM methods in afforestation and reforestation could be applied in developing the Australian carbon emission offsets.

At the global level, CDM is aimed at assisting developed countries to meet their GHG emission targets at the least cost under the Kyoto Protocol. This allows Annex-1 countries (developed nations) to implement greenhouse gas reduction or removal projects in Non-Annex-1 countries (developing nations) in order to generate Certified Emission Reductions (CERs). CERs can be used by Annex-1 countries to meet their KP targets (UNFCCC 1998). They can also be traded on the international carbon markets such as being practiced by several European nations.

CDM projects registered during the first commitment period of the Kyoto Protocol included more than 5,200 projects distributed in over 80 countries totalling to more than one billion certified emission reductions issued with an invested amount in excess of US$215 billion (Glowacki 2013.) Qualified projects are those activities that generate clean and renewable energy such as wind farm projects and hydro power projects. Projects may also qualify if they can reduce emissions by using fossil fuel alternatives like biogas projects, and landfill gas for electricity projects. Other projects that can avoid emissions through better treatment of waste such as composting projects and the sequestration of carbon through forestry sinks are also eligible CDM projects (Baker and McKenzie 2010).

One way a carbon sequestration CDM project can be implemented is by financing Afforestation and Reforestation projects (A/R) in Non-Annex-1 countries (developing nations). Afforestation is establishing plantations or forests on lands which had not been forested for at least 50 years, whereas reforestation refers to planting trees on areas that did not contain forest prior to 1990 (UNFCCC 2001).

Whilst least developed countries could implement afforestation and reforestation projects under the CDM, the developing nations have the opportunity to implement projects under the REDD+ mechanism. REDD+ is based on the concept of "reducing of emissions from deforestation and forest degradation, forest conservation, sustainable forest management, and enhancement of forest carbon stocks in developing countries" (Maraseni et al. 2014). There is a reasonably high degree of support for this mechanism from developing countries as many recognised that this may lead to significant inflows of capital and technology. As such, this mechanism is accepted to be one of the most promising options to combat climate change and to protect the natural resources (Gumpenberger et al. 2010). REDD+ also presents additional flexibility and options for Australia to implement afforestation and reforestation projects in developing countries.

As options for carbon emission offset mechanisms are presented, projects vary depending on committed nations. For instance, Europe finances emissions-reduction projects in developing countries like Africa and claims the carbon credits generated by these projects (Jindal et al. 2008).

In Indonesia, particularly in Sumatra, carbon sequestration activity is conducted in agricultural and degraded land by establishing oil palm plantations. An average carbon stock in oil plantation was estimated to be 52 t ha^{-1}. This opportunity provides benefits to Indonesian stakeholders as cassava plantations are degrading to *imperata* grasslands (Tomich et al. 1998). Similarly, Malaysia is also into oil palm and pulp plantations for renewable energy to reduce their emissions. Substituting or complementing fossil fuel with the use of biomass energy is also an acceptable strategy to reduce emission. However, the financial cost of processing biomass energy such as gas extraction is questionable as the viability of this strategy in the long run cannot be assured. For example, Brazil’s experience in renewable energy via oil palm plantation estimated the gasification cost of <$5/tC which may only be viable in remote areas (Tomich et al. 1998).

Nevertheless, oil palm and pulp plantations as sources of biomass energy can sequester and store carbon, reduce a country’s emission, and can be substituted for fossil fuels. These biomass plantations could reduce emissions permanently and at the same time qualify for carbon credits. Furthermore, it supplies the domestic energy, fibre and edible oil demands of the local community. Whilst these plantations are providing benefits to the community, they can also be a good export revenue for a country such as Indonesia. Oil palm plantations generated US$15 billion in foreign exchange in 2009 (Varkkey 2012) and provided employment to 3.2 million people in 2011 (Obidzinsky 2015).

Opportunities for commercial plantations and forestation strategies are substantial if established in appropriate and suitable areas. For example, regions with low population density, have limited timber resources and low agricultural productivity can be a potential sites e.g. savannas located in Latin America and Africa (Sayer et al. 1997). This may also apply in degraded regions of Australia where salinity is prevalent and limited agricultural crops can thrive. In China for instance, nearly 130 million hectares of degraded land can be reforested (Deying 1995) whilst India has 11 million hectares of government controlled denuded land (Ravindranath & Somashekhar 1995). These lands provide opportunities for CDM projects where commercial plantations are established. In the Philippines, CDM projects are implemented by the government involving private and local entities via strategies other than forestation such as clean and renewable energy (e.g. solar energy, biogas, wind farms, and waste recycling). In 2009, there were 32 registered CDM projects in the Philippines including 45 on the process of registration which were estimated to generate 22 million tons of carbon and earn revenues of approximately US$341.4 million – US$1.1 billion (₱13 billion – ₱40 billion) within a 10-year period (Docena 2010). Though China, India and Philippine CDM projects are primarily controlled by the government and can be politically motivated, there are cases where the local community dominates the implementation of the carbon project such as in the case of Mexico and Ecuador.

In Mexico, a carbon project assisted small scale farmers in planting pines in their fallow lands. The community is involved in the implementation of the project where the types of systems established on their farms is primarily decided by the farmers themselves. Similarly, carbon projects for CDM in Ecuador have been implemented. Farmers successfully established 23,000 hectares of plantations on land with few opportunity costs, such as steep slopes and degraded pastures with pine, eucalyptus, mixed pine, and indigenous species (CIFOR 2002).

The State and Trends of the Carbon Market Report 2012 stated that the market for primary CDM has dropped to its lowest level since 2004 due to declining demand of offsets, indicating a growing long-term oversupply of carbon offsets in the EU Emissions Trading scheme coupled with plummeting prices (Glowacki 2013). Whilst the situation for the carbon market in the European nations is not favourable, opportunities are promising for the developed new domestic and regional market mechanisms being implemented in various countries like Australia, America (e.g. California), Canada (e.g. Quebec), Mexico and South Korea.

Despite the benefits that entities and individuals may derive from the implementation of the CDM, it is not devoid of problems. Some of problems include additionality, measurement, baseline counting, and permanence. All CDM projects are required to ensure emission reduction capability, and possess financial and environmental "additionality" to the business-as-usual scenario. However, procedures and requirements to establish whether an emission reduction or avoidance activity is in addition to normal business-as-usual activity, and that the level of emission reduction or avoidance is below the level that would have occurred otherwise, is questionable. For instance, plantations established on marginal areas affected by salinity can clearly indicate an additionality after it had actually reduced soil salinity thereby alleviating the marginal condition of the land. However, there were issues relating to plantations as fast growing eucalyptus sown on previously bare and marginal land may reduce water yield and lower the aquifer or water tables in the watershed. Rather than providing additionality through soil amelioration, plantation may aggravate the condition of the land due to water concerns. As such, it is worth studying whether forestation can provide solutions on additionality issues related to carbon sequestration on saline affected areas.

Furthermore, the UNFCCC guidelines on methodology devised a general equation with parameters in an attempt to standardize measurement and accounting of carbon. Consequently, this attempt may be invaluable in cases where data or information on the equation's parameters are not available. Despite the maturity of forestry practice, it is surprising that there are countries where vital information on tree growth is not yet available such as Australia. It is therefore necessary that information on carbon accounting be available for regional or national applicability as tree growth are dependent on geographical locations and climatic variations. Similarly, methodologies on how additionality of the project can be measured and accounted for are still lacking. For instance, there is no clear methodology on how additionality in forestation established on saline affected areas can be measured and accounted for. Discrepancies in national carbon statistics reported by different government institutions in Australia, for instance, is a clear indication that baseline emission data has to be considered in regards to its measurement accuracy.

Permanence on the other hand is considered an issue as assurance for emission removals by an activity must be permanent and not reversed in the future without recourse. Plantations in the long run are expected to absorb and store carbon however, with the incidence of rotational harvesting or forest fire, it can be reversed. An approach such as forestation is expected to bridge the gap on this issue.

Importantly, productivity and yield data are not readily available for public use and in most cases lacking. Suitable areas are not mapped spatially and are not accessible for stakeholders to facilitate decision making.

2.4 Australian forestry in overview

Forests provide significant tangible and intangible benefits to society. These can be in the forms of protection, production, aesthetic and recreation values. Protection values may come in the form of soil conservation against erosion and landslides, or buffer during strong winds and cyclonic events. Production may come in various products from timber to non-timber products such as extractives, rattan, edible fungi, honey and other important commercial products. Forests also provide a cool microclimate in tropical areas, offer rest and recreation invaluable to human health, a place for scientific research, heritage to cultural minorities and habitat for wildlife and diverse species. Measurable tangible and intangible benefits are derived in forests and have been a key source of resources since time immemorial, however their wise use and conservation has always been a challenge to humanity.

In Australia, the nation’s landscape has changed significantly since the settlement of Europeans (Musselwhite & Herath 2005). Land use change was inevitable due to the extensive conversion of the vast areas of native forest lands to agricultural production and infrastructure developments. Despite the changes in the land use and land patterns, forest remains a significant natural resource for the benefit of the society (Powell 1998). Land use change in Australia during the past few years has been imminent. Forest has been extensively cleared for cropping and grazing that led to deforestation. These areas are viewed as potential sites for forestation for hardwood plantation such as spotted gum.

It was only after 1990 that plantation areas for hardwood species began to increase rapidly in Australia, with a focus on eucalypts species. The report by Timber Queensland in 2012 identified that Australia had a total forest area of 149.4 million hectares. Approximately 147.4 million hectares was native forest and around 2 million hectares was forestry plantation, with hardwood plantation comprising of 980,000 hectares and softwood species covering 1,025,000 hectares (ABARE 2012).

It is projected that the potential log supply from hardwood plantations will rise rapidly in the next few years because the large areas established from the mid-1990s will be reaching a rotation age of 25 years. The vast majority of those plantations are managed to produce pulpwood for pulp and paper manufacturing. Hardwood sawlog supply from plantations is estimated to rise slowly to 2030 then stabilize at a low level or even decline to 2050 (BRS 2010). These, together with logs harvested from native forests and imported material, are used to manufacture the 21 million cubic metres of timber products consumed in Australia each year. Plantations provide more than two-thirds of the logs produced in Australia, yet comprise only a little over 1% of the forest area (BRS 2010). On the other hand, one-third of the logs come from native forests (ABARE 2012), indicating an insufficient supply from Australia's plantation forests to meet the total wood demands.

The total carbon stored in Australian forests in 2011 was estimated to be more than 12 Gt (BRS 2012) whereas the total carbon emission of Australia in 2011 were estimated to be 570.5 Mt CO_2-e, an increase of 0.6% compared to 2010 (Gavran & Parsons 2011). These emissions originate from sectors such as energy, industrial processes agriculture, waste and land use, land use change and forestry (LULUCF). Net emissions from land use, land use change and forestry (LULUCF) activities were estimated at 24.2 Mt CO_2-e in 2011, consisting of 45.9 Mt CO_2-e net emissions from deforestation whilst sequestration from afforestation and reforestation (A/R) was 21.7 Mt CO_2-e (DCCEE 2011a). These statistics show carbon sequestration is lagging behind the level of net emission for the year 2011. However, as Australia is committed to Article 3.3 only (e.g. afforestation, reforestation and avoided deforestation), it could be claimed that Australia is on target to meet its Kyoto Commitment (108%) and is expected that it will have surplus carbon credits. Nevertheless, it has to address the country's carbon sequestration lag. Similarly, as commercial plantations are harvested on a periodic cycle, of which majority are used for the nations' timber demands, the guarantee that these plantations can reduce the carbon emissions of Australia during its commitment period is uncertain. It is worth noting that Australia's trade deficit in forest products is around AU$2 billion each year as domestic production of most forest products is less than the consumption, and so substantial volumes are imported to meet the population's demands.

In Queensland, forest production, management and trading continues to be part of the state's primary industry. In fact, it is one of Queensland's oldest and most durable industries. On 30 June 2010, the Queensland Government's plantation timber business was sold through a 99-year plantation license agreement to Forestry Plantations Queensland Pty Limited (FPQ Pty Limited) now owned by Hancock Queensland Plantations Pty Ltd. (DERM 2010). This privatization may impact on how the land-use and patterns of landscape will change. Being owned by a private entity, there is limited access to the business information including the datasets on the growth and yield of the established plantations. Given the very scant data on the hardwood plantation and native forest-based timber industries in Queensland, the long term datasets for hardwood plantations are difficult to find and to access.

Queensland has a total plantation area of 256,389 hectares of which 190,663 hectares is softwood (74.4%), 63,618 hectares is hardwood (24.8%) whilst the remainder belongs to other categories (ABARE 2012). On a regional level, South East Queensland (SEQ) has a total forest plantation of 191,800 hectares of which 155,800 hectares (81.2%) are softwood, while its hardwood plantation is only 29,400 hectares (15.3%) and the rest is mixed (ABARE 2011). SEQ has one of the highest percentage of softwood plantations in Australia together with the Murray Valley and Green Triangle (Gavran & Parsons 2011) and is considered to have a significant role in the country in terms of forestry trading and industry. Although these figures provide forest statistics on how much area is available for plantation types, it does not offer substantial information on carbon sequestration capability of each land use nor the suitability of land for sequestration purposes. Nevertheless, these statistics are useful as a benchmark in carbon sequestration studies.

Literature reviewed showed that carbon sequestration studies in SEQ particularly on spotted gum is limited. For instance in 1998, a commercial plantation land capability analysis of SEQ was conducted by the Queensland Government and Commonwealth of Australia for the consideration of a Regional Forestry Agreement (RFA) implementation (CRA-RFA 1999b). The study identified the potential for spotted gum as a forestry species in the area. However, the efforts of both parties did not lead to the establishment of the Regional Forest Agreement.

2.4.1 Drivers of deforestation in Australia

Forestry degradation in Australia occurred as early as the European invasion with the cutting of trees (Powell 1998). A century of largely uncontrolled clearing (Kellas & Hateley 1991), extensive depletion of some species in the wild such as Red Cedars (Boland et al. 1989) and Bog Onion (Floyd 1990) led to a range of environmental problems such as disrupted food chain, loss of animal habitat and soil erosion. This was aggravated further by the provisions of the *1868 Land Act* that encouraged clearing of land for improvement. Forest land had been widely exploited with existing technology, wilderness, biodiversity, and other forest values under threat (Musselwhite & Herath 2004). Utilization of softwood species were preferred over hardwoods due to familiarity with the softwood timbers, were easily worked on with the existing technology and there was limited knowledge of hardwood species at that time (Powell 1998).

Today, some of the practices continue to operate such as conversion of forest lands mainly due to agricultural and infrastructure developments. The country's rates of conversion have declined throughout the years but they are still highly significant at about 260,000 ha yr^{-1} of forest clearings each year (2000-2004) while the net plantation area increase is only 61,000 ha yr^{-1} (BRS 2010). Factors affecting forest utilization include economics, environmental and social influences, political mechanisms, agricultural research and development, technological breakthrough and land resources profits. All these, although beneficial on a human's point of view are in fact causing forest destruction leading to serious impacts in the natural environment. It must be borne in mind that the past decisions and actions has significant impacts on the contemporary state of Australia's forest resources and therefore must serve as a lesson and guide to forest utilization and land allocation in particular for forestation.

2.4.2 Impact of forest degradation in the environment

Forest degradation brings about changes in landscape patterns whilst dynamics of land use can change the whole biological system. As changes in these patterns occur, the forest ecosystem brings new complex forest dynamics. The huge areas of the world's tropical forests (e.g. Brazil, Indonesia, Philippines, Vietnam etc.) are being degraded (Mayuga 2012) resulting to various environmental issues such as loss of species diversity (Lamb 1998), reduced timber production and loss of soil fertility (Tang 2012).

In Australia's case, two thirds of the original tree cover in its native forests has been indiscriminately removed since European settlement (Musselwhite & Herath 2004) which has threatened its native biodiversity (Wilson et al. 2002). It was estimated that 30-75% of a former 4-8 million hectares of Australia's rainforest was cleared after the European settlement (Cofinas & Creighton 2001). Whilst between 1991-1995, 81% of the 1.2 million ha of forest clearings in Australia for agricultural, pastoral and other non-forestry related land uses occurred in Queensland (Barson et al. 2000).

In most cases, after clearing the vegetation, fertile top soil is eroded and siltation of bodies of water occurred. The organic matter in soil is washed out easily and the land stripped of its fertility. As lands are bare and no roots to hold it in place, soil nutrients are easily leached particularly the highly mobile elements (e.g nitrogen and potassium). Continuous exposure to rain, wind and other natural forces has made the soil thin. Eventually, the area becomes marginalised and the plants struggle to survive. In extensive vegetation clearing, impacts can extend to loss of habitat (for both flora and fauna), increased greenhouse gas emissions, and expansions of dryland salinity (Boulter et al. 2000) leading to environmental problems. For instance, vegetation clearings in Australia resulted in the occurrence of dryland salinity and degradation of about 2.5 million hectares of agricultural land (Booth 2005).

One way in which large areas of degraded tropical lands might be rehabilitated is by establishing timber plantations (Lamb 1998). However, Australia's timber plantations are usually harvested in a periodic cycle which questions the integrity of the plantation to permanently sequester carbon and continuously provide environmental services. To address the issue on permanence, it is necessary for sustainable forest plantings to be established. Longer-rotation sawlog plantations might offer many opportunities in comparison to short-rotation pulpwood plantations (Lamb 1998).

However, there is much debate about the role of plantation forestry in southeast Australia in helping control stream salinity and in exacerbating stream flow reductions (van Dijk et al. 2007). Spatial planning is likely to increase the effectiveness of reforestation against stream salinity by more than seven times (van Dijk et al. 2007). Appropriate tools such as geographic information systems (GIS) can assist in the assessment of the suitable sites for reforestation.

2.4.3 Afforestation and reforestation dynamics in Australia

In 1992 in Australia, the National Forest Policy Statement (NFPS) was conceived to provide a framework under which forest resources of the country would be protected and sustainably used (Musselwhite & Herath 2004). It gave way to the creation of Regional Forest Agreement (RFA) which is an agreement between the Commonwealth and the State. RFA is a 20-year plan for the conservation and sustainable management of Australia's native forest (DAFF 2009). There are four (4) stages of RFA development: (1) scoping agreements, (2) creation of world-class comprehensive regional assessment (CRA) (Janis criteria), (3) scientific CRA (environment, heritage, and socio-econ of the forests), and (4) negotiations for the final details of RFA (Department of Agriculture 2014). At the moment, there are ten (Table 2.1) existing RFAs in the four states of Australia: Western Australia, Victoria, Tasmania and New South Wales. The RFAs cover regions where commercial timber production is located in a major native forest (Department of Agriculture 2014).

Prior to the signing of a RFA, a comprehensive study has to be performed followed by the completion of a CRA. This is based on years of scientific study, consultation and negotiation covering a diverse range of interests. This also determines the future of the States' forests and defines those areas needed to form a comprehensive, adequate, and representative reserve system and those available for ecologically sustainable commercial use. Furthermore, this provides the scientific basis on which the State and Commonwealth Governments signed an RFA for the forests of a specific state (Table 2.1).

Table 2. 1 RFA regions and date signed (Ananda 2003 as cited by Musselwhite and Herath 2004).

RFA region	Date signed
ueensland	
(1) South East	RFA not signed
New South Wales	
(2) North East (Upper and Lower)	31 March 2000
(3) Southern	24 April 2001
(4) Eden	26 August 1999
Victoria	
(5) East Gippsland	3 February 1997
(6) Gippsland	31 March 2000
(7) North East	23 August 1999
(8) Central Highlands	27 March 1998
(9) West	31 March 2000
Tasmania	
(10) Tasmania	8 November 1997
West Australia	
(11) South West	4 May 1999

Several of the States in Australia completed an RFA including Queensland governments. A completed CRA for the South East Queensland (SEQ) in March 1999 was presented and negotiations between the Commonwealth Government and the Queensland State to finalise a RFA ended in February 2000, however, they did not sign an RFA (Department of Agriculture 2014).

The completed CRA serves as a blueprint for forestry and biodiversity planning and conservation in the region. The document incorporates commercial plantation land capability analysis of SEQ for the consideration of a RFA implementation (CRA-RFA 1999b). The study identified the potential for spotted gum as a forestry species in the area. Though the results of the analysis was significant, it cannot be used as a guide for forestry carbon sequestration purposes.

2.4.4 Benefits of afforestation and reforestation

The Vision 2020 was launched in 1997 by the Commonwealth, State and Territory Governments together with the plantation growing and processing industries with an aim to expand commercial plantations by 3 million ha by the year 2020 (DPIE 1997). This strategic partnership supported the existing forest policies and was also in support of the efforts to withdraw dependence from what remains in the native forests. As dependence of timber extraction from the native forests is greatly reduced, this provides new opportunities to establish new plantations to supply the timber necessary for local and international markets. As commercial plantations are required to supplement the demand for wood-based products of forest industries, it is anticipated that more plantations will be established for these purposes. The carbon sequestration capability of plantation provided an innovative perspective in the benefits derived from forestry. Moreover, the recent creation and legislation of the Carbon Farming Initiative (CFI), not only changed the forestry scenario but offers additional and beneficial options for land use.

It is well understood that reforestation projects can provide a wide range of goods and services including timber, carbon, habitat for plants and animals, erosion control, water quality (Kanowski & Catterall 2010) and environmental amelioration. However, there are reforestation issues such as site suitability, water consumption and productivity in saline environments. The benefits of forestation to supply timber, sequester carbon whilst alleviating salinity must be well understood. For instance, studies showed that fast growing eucalyptus planted on previously treeless ground may reduce water yield and lower water tables in watersheds particularly in semi-arid regions whilst the impact on soil fertility is less clear due to the absence of understorey vegetation that can thrive with it (Davidson 1985). It is worth investigating if the eucalyptus plantations particularly spotted gum ameliorates soil whilst sequestering and storing carbon.

Furthermore, it was estimated that a 1000 ha plantation in Murray-Darling Basin (MDB) can reduce salinity to approximately 0.05 electrical conductivity (EC) units for a total cost of AU$100,000 EC^{-1} (Connor et al. 2008). The MDB salinity benefits were valued at about AU$5 ha^{-1} yr^{-1}. This appears a poor return when compared with the opportunity costs of the water resource (some 20 times greater) (van Dijk et al. 2007) utilised for agricultural production and other domestic consumption. However, this figure was believed to be an over estimate of the real water consumption (van Dijk et al. 2007). Although there is risks establishing forest plantations in the drier areas due to productivity issues, its long term effect in the amelioration of saline areas are not accounted for. Survival of forest species in saline areas are questionable. Whether plantation establishment in saline environments can be beneficial and profitable in the long term whilst it can sustainably sequester carbon needs further study. Currently, studies on financial benefits of forestation for carbon sequestration endeavours in Queensland are limited. It is necessary to conduct studies that will verify the benefits of forestation for timber production with carbon sequestration and soil amelioration.

2.4.5 Queensland's carbon emissions

Global and local concerns about the impacts of anthropogenic emissions of CO_2 have attracted interest in the potential of forestation projects to sequester carbon from the atmosphere (Greenhalgh et al. 2006). Forests are reservoirs of trees that serve as carbon sinks and have great potential for the mitigation of carbon dioxide through appropriate conservation and management (FAO 1997). Trees and other plants are capable of sequestering enormous carbon dioxide from the atmosphere through the process of photosynthesis (Song & Woodcock 2003) at the same time accumulating biomass during their active growing stage. Biomass and carbon content are generally high in terrestrial forests ecosystem, reflecting their influence on the global carbon cycle. The removal of biosphere carbon by terrestrial vegetation and its biomass and soil storage is a significant process in the carbon cycle that could be utilized to manage carbon distribution (Nabuurs 2007).

On a state level, Queensland has estimated total emissions at 155.5 Mt CO_2-e for the year 2011 (DCCEE 2012b) which is 27.2% of the national level. The State's land use, land use change and forestry (LULUCF) estimated emission is 19 Mt CO_2-e from a total deforestation emission of 19.4 Mt CO_2-e less its net emission from afforestation and reforestation (A/R) of -0.4 Mt CO_2-e, which can be seen as far behind the level of CO_2 emission out from deforestation for year 2011. Similarly, the State's total emission contributes 27.2% to the national emission and is the highest among all the state's emission contribution. This emission figure clearly justifies the implementation of some mechanisms such as the Carbon Farming Initiative (CFI), but it is timely and beneficial to examine the implication of these currently implemented mechanisms.

2.5 Carbon Farming Initiative (CFI) of Australia

The global deforestation was conservatively estimated at about 130 million hectares in 2006 (FAO 2006). This figure does not include the increase in the area of degraded forest which is approximately 25% more (Markku et al. 2007), however carbon trading is continuously growing and capital investments have ballooned. Based on a World Bank report, the aggregated carbon market value has increased over US$10 billion in 2005 (Kapoor & Ambrosi 2006) and is currently at US$176 billion (Kossoy & Guigon 2012). The worldwide demand for forestry related offsets has been responded to by the global voluntary market. This identifies potential opportunities for foreign entrepreneurs to come in, as Australia provides new local market in response to the commitment for emission abatement.

Worldwide businesses have financed the management, conservation or expansion of 26.5 million hectares of forest. These were accomplished by the purchase of an estimated 28 $MtCO_2$-e of carbon offsets from forestry projects in 2012, valued at $216 million. Voluntary offset buyers drove 95% of all market activity (27 $MtCO_2$-e) with a value of $198 million. During the same year, there was a cumulative of 143 $MtCO_2$-e of offsets transacted from forest carbon projects. These were valued at an estimated $0.9 billion over time from the carbon management of 26.5 million hectares. This indicates a high demand for offsets from A/R projects globally (Peters-Stanley et al. 2013).

Carbon Farming Initiative or CFI is an Australian Government program where participants can be involved via implementation of the forestry carbon sequestration or emission reduction projects and obtain “carbon credit” which in return can be sold into the carbon markets locally and internationally (DCCEE 2011b). However, credits can also be sold in the international market when derived from a guaranteed carbon offset mechanisms as per rules on the market compliance. Its broad aim is to provide financial incentive to farmers, forest growers, land holders and landfill operators to develop projects that will reduce or sequester carbon emissions (DCCEE 2011b). The legislation was passed by the Federal Parliament on 23 August 2011 for implementation. All these are in line with the nation’s commitments to mitigating the impact of climate change via carbon offsetting.

The CFI accounts for carbon credits produced in Australia were subjected to several guidelines such as permanence, leakage, additionality, etc. This also provides for credits from forestation established in marginalised areas (e.g. saline affected areas). However, grey areas exist in the CFI methodology. For instance, CFI guidelines are not specific to the needs of the local areas, as specific carbon sequestration measurements in degraded areas brought about by salinity are not defined. Salinity impact on hardwood plantation particularly for carbon sequestration is not well understood particularly the short-term and long term effects. Salinity may have a short term effect on the carbon sequestration capability of hardwood trees depending on the species but trees may also provide long term land amelioration for saline problematic areas. It would be more appropriate if salt credits could be also incorporated on top of the carbon credits that can be achieved from environmental plantings. Another option may be to put an additional price to the land amelioration services of trees (e.g. on saline areas) in addition to the carbon price.

Currently, the Australian Government is keen to address the climate change and carbon emissions using the Direct Action Plan (DAP) in achieving the nation’s commitment to reduce GHG emissions by at least 5% on 2000 levels by 2020. CFI is one of the main platforms of the DAP which plans the expansion of the project eligibility, shortening the carbon sequestration project permanence and revising mechanism on methodologies (Witt et al. 2011). The DAP envisioned a shortened carbon sequestration period of 25 years as against the 100 year period of permanency. It also hopes to expand project eligibility in particular energy efficiency abatement activities such as waste recycling, composting, and other potential eligible projects. The adoption of CDM methodologies for CFI is also envisioned in the plan. This study is deemed timely as it clarifies some of these concerns in particular how spotted gum carbon sequestration under saline condition can be beneficial to stake holders.

2.6 Conclusion

Chapter 2 discusses the impact of global deforestation that has occurred and is presently happening including in Australia. It provides a history of Australia’s forestry practices that brought about the current scenario where deforestation and carbon emission has led to current environmental issues and concerns. In this chapter, afforestation and reforestation identifies an opportunity where stakeholders can engage into forestry plantation venture to earn Australian carbon credit units

(ACCUs). However, forestations as a potential land amelioration particularly in saline areas needs to be clarified. This chapter indicates the importance of a study in providing clarification on this issue. The next chapters will provide details on the suitability of the forest plantations with a focus on spotted gum for carbon sequestration.

CHAPTER 3

Spotted Gum Plantation Suitability and Mechanisms for Assessing its Carbon Sequestration Potential

*"For **wisdom** is better than rubies,*
And all the things one may desire cannot be compared with her"

Jedidiah, *Book of Wisdom*, 970 – 928 BCE

3.1 Introduction

The purpose of this chapter is to investigate the relevant research and issues which impact on the potential carbon sequestration of spotted gum in South East Queensland (SEQ). As suitability of forest sites vary depending on the local climatic conditions, it is envisaged that the sub-regions within the same regional area will exhibit a varied range of carbon sequestration potential based on a range of climatic, biological and physical parameters. This chapter also presents the basic information on biomass models, growth parameters, site suitability factors and carbon sequestration financial benefits to determine the gaps in the existing body of knowledge.

This chapter is subdivided into seven sections and provides details for each theme. Section 3.1 provides an overall introduction and a contextual structure of the chapter. Section 3.2 discusses the site suitability and potential productivity of hardwood plantations whilst section 3.3 discusses the site suitability assessment with particular focus on soil salinity, soil nutrients and climate variation impact. Section 3.4 reviews the capability and description of growth modelling, in particular the Predicting Physiological Process for Growth or the 3-PG. This includes examination on growth variables and parameters as critical components of the model. Section 3.5 focuses on site suitability assessment, factors, approaches and techniques for carbon sequestration using GIS. Whilst section 3.6 examines the economic benefits of forest plantations and section 3.7 ends with a conclusion.

3.2 Forest plantation site suitability and potential productivity

Plantation establishments require capital intensive investment and involve long timeframes to develop. Significant effort is normally spent reducing the risk of this development by determining the site suitability which is a component of the broad land capability evaluation. Land capability assessment normally identifies the appropriate locations for the target species where its biological growth requirements are satisfied. This is best achieved by integrating the biophysical, economic and social variables to determine the economic viability of a piece of land for a particular purpose such as hardwood plantation for carbon sequestration enterprise. Suitability assessment of forest plantations is normally carried out prior to plantation establishments, not only to reduce risk of financial loss, but to determine the potential productivity of the site.

3.2.1 Site suitability for hardwood plantation

It is a common forestry practice to determine land suitability by comparing desired attributes with actual conditions at a set of sites and comparing suitability across the sites (Stoms et al. 2002). A site with highly desired attributes usually proves to be of potential suitability for an intended purpose. However, this may not always be the case as quality attributes of sites may not guarantee their suitability for an intended use, particularly if complex interactions of biophysical and climatic parameters are considered.

For instance, the technical suitability of forest land to sequester additional carbon in the continental part of tropical Asia was analysed using a geographic information system (GIS) approach (Iverson et al. 1993). Technical suitability was defined for forest lands with carbon stocks less than their maximum and therefore with the potential to increase its carbon storage. The study determined the actual and potential carbon sequestration of forests on a broad (Asia) regional scale where the areas were visualized based on its potential suitability ranked from lowest to highest. Quality control was exercised by multiple overlays however, it was not possible to completely validate each polygon for each thematic layer used in the analysis due to its broad extent (Iverson et al. 1993). It was suggested that some lands in the region may be technically suitable but not actually available, as land suitability is affected by social, economic and political constraints. As suitability can be utilized not only for biomass and carbon sequestration purposes, it is also beneficial for areas that need intensive protection and afforestation. Zomer et al. (2008) conducted a suitability study of (developing) Non-Annex-1 countries (as per UNFCCC definition) for afforestation using GIS. The map identified potential areas for afforestation/reforestation within the developing countries. Land suitability potential evaluation is not only beneficial in forestry but also in other fields such as agriculture and is an important step to detect the environmental limit in sustainable land use planning (Bandyopadhyay et al. 2009). In India for example, land suitability for crop production was assessed by studying indicators of land suitability through several parameters such as soil texture, organic matter content, soil depth, slope and land use/land cover. An integrated land suitability potential index was computed and categorized as good, fair, moderate, average, poor and not suitable by adopting the logical criteria and application of GIS. The focus was to determine the sustainable potential capability of land to support crop production for long periods of time.

In Australia, the plantation capability study conducted by the Regional Forest Assessment Committee (1998) of the Department of Natural Resources (DNR) in Queensland resulted in a list of priority species for SEQ and areas available for plantation establishment. However, the identified areas and their suitability are indicative only and may be under or over estimations due to the limitations specifically on species site data. At the same time areas are only considered capable of plantation, rather than either being available or financially feasible and does not include the carbon sequestration capability of the plantation (Regional Forest Assessments 1998).

Furthermore, the study focused solely on two key variables affecting plantation (e.g. soil and rainfall) which resulted in a broad and general assessment of the plantation capabilities of SEQ, inclusive of GIS spatial coverage restrictions on 25% slope limit, 20% crown cover, 10 hectares cleared lot size, and under cropping and pasture.

A valuable study on suitability of hardwood plantations, particularly spotted gum, made use of climatic and biophysical parameters (Polglase et al. 2008) however, the result is more appropriate for a macro scale analysis and could pose inaccuracies when used at a farm scale level. Maraseni (2007) conducted research on the suitability of carbon sequestration in ferrosol soils. The regression modelling used was primarily based on time series datasets of tree volume. Moreover, this study was site-specific and only applicable to a specified area (Kingaroy) and hence a wider coverage study is necessary to capture other edaphic and climatic conditions.

Whilst forestation is considered one of the most cost effective mitigating measures identified so far, just like any other development projects, it can result in environmental and socio-economic problems (Canadell & Raupach 2008) such as decreased food security, reduced water availability in streams and local incomes by earning carbon credits (Jackson et al. 2005), land use conflicts and land use change. Results of the studies conducted by Lawson et al. (2008) suggested that Australia’s agriculture sector may experience an increase in land use change in favour of forestation activities with the presence of carbon policy. This could adversely affect the activities and production of the agricultural sector. The possible ramifications of those impacts highlight the need for site suitability assessment and land use prioritisation for carbon sequestration and trading.

3.2.2 Carbon accounting, assessment of carbon and salinity value

Carbon sequestration is the transfer of atmospheric CO_2 into other global pools including oceanic, pedologic, biotic and geological strata to reduce the net rate of increase in atmospheric CO_2 (Lal 2008). Although several definitions can be found in literature such that carbon storage may mean keeping the carbon in geological strata and in oceans in contrast to storing it in living trees, carbon sequestration in this study will mean absorption of CO_2 from the atmosphere and storing them in living trees in the form of biomass. Quantification of carbon sequestration in forests is based on the amount of carbon stored over a given time period (stock change) and can be described in several units such as carbon and CO_2. Carbon can be derived from the quantity of living biomass of trees which is about 47% to 55% depending on species and other factors (Fahey & Knapp 2007b), however 50% is widely acceptable and used in converting biomass to carbon (Fahey et al. 2005; Drake et al. 2002). Carbon dioxide equivalent (CO_2-e) is a common emission scale used for all the greenhouse gases (Fuglestvedt 2009) to compare the global warming potential of GHGs measured through radiative forcing (IPCC 2009).

Carbon accounting is the process of assessing the amount of carbon found in different parts of a system. It is needed to estimate the amount of carbon that may be traded or used as an offset against greenhouse gas emissions. There are two main methods of carbon accounting in forests: (1) actually measuring carbon present in the trees, litter and soil, and (2) using models to estimate carbon present in forest systems (DIICCSRTE 2013). The first method requires significant time and resources as it usually employs destructive sampling while the latter method makes use of a process based model to estimate the carbon.

Field measurement procedures are built on well-established methods used in forestry and ecology. The main difference between standard commercial forestry volume inventories is the emphasis on assessing carbon in the whole system (i.e. aboveground biomass including litter and woody debris and belowground biomass) rather than just the wood volume that is used for products such as sawlogs or pulp. There will always be a need to carry out actual measurements to validate the predictions of simulation models, but field measurements are expensive. The use of models will be important to assess the potential of particular areas and species for potential carbon sequestration projects and to estimate the amount of carbon sequestered at particular times in on-going projects.

The CDM Executive Board under the UNFCCC/CCNUCC approved a simplified baseline and monitoring methodology for small-scale afforestation and reforestation project activities under the CDM implemented in lands having low inherent potential to support living biomass. One of the applicable conditions stated under Chapter 1 on "*Applicability conditions, carbon pools and project emissions"* stated that project activities are eligible if implemented on highly alkaline or saline soils (UNFCCC-CCNUCC 2006). As a rule, the most conservative method for carbon accounting appropriate for the country based on the results of scientific studies have to be applied. However, there was no method crafted specifically for each land use site conditions and up to this stage it is still highly debatable. For instance, the conversion of the volume of the commercial timber component of trees into carbon stock in above ground biomass via a biomass expansion factor (BEF) under saline areas varies significantly.

The assessment of the carbon value is considered necessary for land use prioritization. Venn (2005) concluded that forestation and forest plantings will be attractive to farmers in some regions of Queensland, if carbon values will be incorporated and land values determined. Similarly, Spencer et al. (1999) as stated by Venn (2005) had conducted a study where they estimated that the average value of land in SEQ biogeographic region (hardwood region 4, 6, 7 & 8) capable of yielding 15-20 m^3 ha^{-1} yr^{-1} of merchantable timber for the hardwood plantation to be AU$2,600 ha^{-1}. This figure may be underestimated as land values near major settlements in these regions are approximately AU$5,000 - AU$10,000 ha^{-1} as mentioned by Venn (2005).

Furthermore, Venn's (2005) study revealed that long-rotation hardwood plantations with growth rate of 20-25 m^3 ha^{-1} yr^{-1} are profitable in Queensland Hardwood Regions 1, 3 and 7 when rural land values are less than AU$2,300 ha^{-1} whilst it is financially profitable for plantations with 15 m^3 ha^{-1} yr^{-1} in hardwood regions 2, 4 and 8 when land values are less than AU$1,600 ha^{-1}. The author estimated the carbon sequestration of hardwood plantation in Queensland using the equation Eq. 3.1 below.

$$C = \sum_{t=0}^{T} (G_{wt} + G_{at} + G_{bt} - H_{wt} - H_{at} - H_{bt}) - (E_s + E_{ab}) \qquad \text{(Eq. 3.1)}$$

where C = net carbon sequestered per hectare of plantation (tonnes); G_{wt} G_{at} G_{bt} = carbon sequestered per hectare per year by the net growth of stem wood, non-stem wood above-ground biomass and below-ground biomass (tonnes), respectively; H_{wt} H_{at} H_{bt} = carbon emitted from the decomposition of stemwood, non-stemwood above-ground biomass (AGB) and below-ground biomass (BGB) (tonnes), respectively, following harvest; E_s E_{ab} = carbon emitted from the soil and pre-existing above- and below-ground biomass (tonnes), respectively, at plantation establishment; t = age of stand in years from establishment to clearfall (0,. . ,T). In Venn's (2005) study, total biomass of plantation was estimated by multiplying the stemwood biomass by an expansion factor of 1.4 and adopted a root:shoot ratio of 25%, respectively for both native forest and mature eucalypts plantation. As shoot:root ratio varies depending on species and environmental condition so is expansion factor which is species-specific and using a one off value could result to inaccurate estimate (Snowdon et al. 2000).

It was estimated that a plantation with 15, 20 and 25 m^3 ha^{-1} yr^{-1} MAI will have timber plus salinity amelioration values of AU$779, AU$2,516 and AU$4,254 ha^{-1}. Furthermore, the study found that carbon values and salinity amelioration may underestimate the true value of forest plantation. It is worth noting that a single value of AU$400 ha^{-1} for salinity amelioration in Queensland was utilized in the valuation of salinity amelioration process. Maraseni (2007) estimated a plantation value (inclusive of soil carbon) of AU$794 in 34 years in the South Burnett area of 9.7 m^3 ha^{-1} yr^{-1}. In this study however, the estimation was exclusive of the overhead and land costs.

In a separate study in Victoria, Australia, the cost of environmental services (e.g. salinity) was compared for two catchments (e.g. Gippsland and Corangamite) using an MBI (market-based instrument) in determining values based on fixed cost (administration, modelling and ground activities), operational cost, and a grant to landowners to reforest the area. Gippsland was found to have no salinity benefit whilst a value of AU$5,020 ha^{-1} of salinity benefit was estimated for Corangamite if considered in isolation to the economic forest plantation benefit (Lowell et al. 2007). In Tasmania, Australia the carbon sequestration value was estimated to be AU$1,667 ha^{-1} and salinity of AU$417 ha^{-1} for forest plantation (Freeman & Dumsday 2003).

Incorporating the economics of carbon and forest plantation is quite complicated as an economic aspect is a study in its own rights. This study will be limited to the assessment of the net present value of carbon and salinity amelioration in addition to the conventional timber value.

3.3 Forest plantation site suitability assessment

Several decades ago, when knowledge in forestry was still limited, site suitability assessment was primarily based on the height and girth of the trees planted. For instance, in searching for suitable sites for agricultural production, forested lands with tall and wide-girth trees would mean rich and fertile soil suitable for cultivation, and the forest would then undergo clearing for agricultural and settlement purposes (Powell 1998). It was only in late 1920s when knowledge on the importance of the genetic characteristics of trees as the source of seeds for plantation was understood. The 1940s to 1950s saw the selection of phenotypically-superior seeds for forest plantations and later on followed by the breakthrough on the scientific research on the genetic make-up of superior trees as seed source (Davidson 1996). However, when nutritional requirements of trees are limiting and its environment is not conducive to trees attaining its potential growth, the genotypic characteristics cannot be manifested phenotypically. For instance, potential productivity of eucalypt plantations can be seriously limited by low nutrient availability, however, if nutrient limitations are removed and all the factors are favourable for growth, high productivity can be attained in very young plantations (Binkley et al. 2002).

Furthermore, frost occurrence can result in high mortality rates during the first two (Smith et al. 2005) to three years of spotted gum (McMahon et al. 2010) when planted in areas with frequent frost occurrence (Dickinson 2009) and may not be suitable particularly in temperate regions. As the impact of climate on vegetation varies from global to regional and local scale (Vajda & Venalainen 2003) trees can only photosynthesize the available nutrients, water and sunlight that the environment has to offer as the reception of solar radiation and rainfall are dependent on geographical locations. Topography also plays a significant role in forest tree growth. For instance, local topography significantly affects spatial variations of climate and soil-water availability affecting the distribution and productivity of ecosystem. A study conducted by Chen et al. (2007) on the topographic effects on the productivity strengthens the correlation and impact of climate in the food production process of the plants. The study focused its analysis on the integration of climatic variables affecting the carbon assimilation of plants via photosynthesis (Chen et al. 2007). Similarly, vegetation generally varies in high altitude in contrast with that located on low-lying areas as topography also affects the reception of solar radiation, exposure to natural elements such as wind, available soil nutrients and amount of rainfall. The case of a mossy forest found in high elevation of Mt. Amuyao, Philippines and anywhere else in the world would indicate that trees in high elevations are often stunted due to exposure to strong wind and extreme natural conditions (Gonzales-Salcedo 2001).

In Australia, spotted gums are gaining popularity in the forest plantation industry and studies are underway to enhance the potential of this species. This tree species is native to Australia and can thrive in various soil conditions. This study has focused on hardwood forest species, particularly spotted gum, for their potential to effectively store carbon from the atmosphere and also because there have been limited carbon sequestration studies conducted particularly in the sub-regions of south east Queensland. Spotted gum are the most important commercial hardwood plantation species for high quality timber in the humid and sub-humid zones of Queensland (Lee et al. 2005). The species also produces high quality timber thus making it a marketable product (Lee et al. 2009). Additionally, the spotted gum is a native species in Queensland, fast growing (Dickinson 2009), resistant to borers (e.g. in northern Queensland), one of the most efficient trees in terms of carbon sequestration (Lee et al. 2011), the most widely adapted species for planting in Queensland (Morgan 2010), can perform well across many sites (Lee 2007), and has environmental plasticity and resistance to pest and diseases (Dickinson et al. 2004). This tree species has sufficiently high wood density, hardness and stiffness for wood products (Blakemore et al. 2002; Harwood et al. 2007). This species can survive in a wide variety of soils conditions such as in very poor nutrient soils and can be recommended for reforestation and fibre production in marginal areas. Although it is also highly susceptible to frost (Dickinson 2009) it is also drought tolerant.

3.3.1 Salinity impact on spotted gum plantation

Australia is affected by salinity which is an environmental concern particularly in agricultural production, costing the country approximately AU$3.5 billion annually (Bhati 2001). It affects many parts of Australia (Wamick 2006), and accounts for an estimated 2 million hectares of agricultural lands (Trewin 2002). Salinity was also identified as a threat to natural ecosystems, water resources, agricultural lands and infrastructure (Eamus et al. 2006). Soil salinity is caused by the mobilization of salts stored within deep regolith by rising groundwater to the surface of the soil (Peck & Hatton 2003) mainly through land clearing. There are various types of salinity such as primary salinity (e.g. naturally occurring – weathering, climate change) and secondary salinity (e.g. caused by human activities - land development, agriculture and land clearing). This study will be limited to secondary salinity particularly dryland salinity and will not deal with the various complexities on the process of its occurrence.

Dryland salinity is a problem in Queensland and is one of the environmental concerns in the south eastern part of the State (Venn 2005) and the potential that carbon sequestration capability of forest plantations in this area will be impacted. The NLWRA (2001) estimated an area of 3.1 million hectares of high risk areas to occur by 2050 in Queensland alone. As trees have the ability to restore the degraded land, it seems appropriate to incorporate salinity credit as an intangible benefit. Forestry plantations would be more attractive and beneficial for the farmers and land owners if salt credits via soil amelioration were incorporated in the forest carbon sequestration activities.

Reports of salt-affected land have been concentrated in the south-east, south and central Queensland regions and were commonly associated with basalt areas that receive an average of 500 to 1,200 mm of rainfall annually. In Queensland, average annual rainfall is a useful indicator of salinity risk as areas receiving an average annual rainfall of 700 to 1,100 mm yr^{-1} are considered at the highest risk of water table salting (DNR 1997). The latest Australian Bureau of Statistics (ABS) farm survey in 2002 accounted 107,000 hectares of agricultural land showing signs of salinity (Trewin 2002). The study conducted by the NLWRA (2001) resulted in an estimated area at risk of salinity based on water table height whereas that of Trewin (2002) was an estimate of the area showing signs of salinity, thereby resulting in wide discrepancies. Furthermore, the ABS salinity survey was confined mainly to agricultural areas assessed through a close ended questionnaire and may be an underestimate of the actual values. As such, the statistics of salinity may be higher when all land uses are considered and may vary once a sophisticated scientific means of assessment is applied.

Salinity risk situation could impact eucalypt growth and may result to mortality. Mortality of eucalypts varies on stocking density, environment (Dwyer et al. 2010), age (e.g. seedlings *vs* mature trees) (Landsberg & Sands 2011), and the stress factors (Keith et al. 2012) such as salinity (Wei 2002). Previous studies of eucalypts in SEQ showed variations in mortality at a particular stage. An impact of a combined stress from drought and insects can result in high mortality of eucalypt trees (*E. delegatensis*) in a mature stand (approx. 80 years old) with as much as 5-60% showing a marked growth reduction of 45-80% (Keith et al. 2012). Whereas, varied extent of drought can have an impact of up to 75% on *E. melliodora* and 34% mortality on *E. populnea* seedlings (7 months) (Huth et al. 2008). Lindenmayer and Wood (2010) found an average annual collapse rate of 4.4% (between 1983-1993) and 2.2% (between 1993-2007) on a mature stand of *E. regnans* (approx. 68 years old) due to hollow stems brought about by occurrence of fire and decay. There are no available long term mortality rate for spotted gum in south east Queensland as affected by salinity. As such, this study used datasets from previous studies in particular that of Madsen and Mulligan (2006) and Sun and Dickinson (1993) which formed part of its methodology in developing a mortality equation for saline areas.

Paydar et al. (2005) concluded that the viability of a plantation to act as a natural sink is likely to decrease with the salt accumulation. This could effectively decrease the potential carbon sequestration capability of spotted gum in reforestation areas. As the Carbon Farming Initiative (CFI) clearly identifies the inclusion of tree planting in degraded soil, particularly in salinity problem areas, it is timely and important to determine suitable sites. It also presents an opportunity to appropriately account carbon credits that can be derived from such areas.

Reforestation in areas with salinity problems and shallow groundwater is considered as “an environmentally-friendly” alternative to control salinity (Paydar et al. 2005). Trees actively use water and are efficient in reducing recharge (Morgan & Barton 2008) in particular in higher rainfall areas (greater than 500 mm yr^{-1}) without the need for engineering measures (NLWRA 2001). Results of the studies conducted by Benyon et al. (2006) showed that *Eucalyptus grandis* (rose gum) and *Corymbia maculata* (spotted gum) can use as much as 380 and 730mm per year of groundwater of low salinity under neutral sandy soil (41% and 53% total annual evapotranspiration, respectively). The same authors concluded that commonly grown eucalypts can use groundwater under a combination of light- or medium-textured soil and shallow depth to a low-salinity water table. Groundwater salinity was classified by the NLWRA (2001) as follows: (1) low – less than 2,000 mg l^{-1}; (2) moderate – ranging from 2,000 to 10,000 mg l^{-1}; (3) high – greater than 10,000 mg l^{-1}.

The effect of reforestation may vary depending on the groundwater salinity level (Paydar et al. 2005). Observations by the NLWRA concluded that to impact effective reduction in recharge, 30-50% reforestation in a catchment is necessary and probably even more if trees are to be harvested. However, CSIRO in its report found that tree planting of 25% between areas of recharge and discharge was considered to be sufficient to control salinity whilst reforestation will affect the deeper confined aquifers only if the trees are planted in the recharge areas (Otto 1993). However, salinity impact on the carbon sequestration capability of the forest plantation must be well understood as high salinity hazard/risk area is present in Queensland (NLWRA 2001; Venn 2005).

An *a priori* knowledge, the studies previously conducted by Spencer et al. (1999), Maraseni (2007), and Polglase et al. (2008) on spotted gum suitability analysis and economic viability could be utilised as benchmark information to further the studies. Whilst Venn (2005) conducted a financial and economic performance of long rotation hardwood plantation investments in Queensland, it did not identify nor quantify accurately and spatially the productivity of the plantation within SEQ. A single value (AU$400 ha^{-1}) for salinity amelioration was applied for the whole area of Queensland.

3.3.2 Soil fertility impact on spotted gum

Forest production can be sustained only if soil fertility is ensured (O'Connell et al. 2004) as large amount of nutrients particularly nitrogen (N) are exported during the rotation periods. Application of nitrogen (N) fertilizer are often recommended to increase soil organic matter (SOM), particularly on highly deficient lands caused by continuous cultivation (Schlesinger 2000) as there is a direct linear relationship between long term nitrogen additions and the accumulation of soil organic carbon (Rasmussen & Rohde 1988).

A study by Sands and Smethurst (1995) was able to prove that an addition of a limiting nutrient at an exponential rate could result in a similar exponential rate of growth which basically stabilizes the internal concentration of the nutrients in plant tissues. For instance, the relative growth rate of a plant is highly dependent on nitrogen as one of the macro nutrients required for vegetative growth. This was demonstrated and further explained by the model developed by Sands and Smethurst (1995) showing the different stages of plant growth as affected by variations in nitrogen concentration (Figure 3.1).

Figure 3.1 shows the effect of nitrogen concentration in plant tissues. The diagram indicates a stage where an excessive amount of nitrogen application can lead to toxicity level. Therefore, growth cannot be considered linear when a continuous increase in fertilizers are supplied. This concept was deemed applicable in the process of fertility rating (FR) calculations and the basis of map generation.

In Australia, soil organic matter has been adopted as an indicator of soil fertility based on the rationale that it contributes significantly to soil bio-physical, and chemical properties that affect vital ecosystem processes of forests (Hopmans et al. 2005). However, SOM and organic carbon that goes with it may vary in soils of eucalyptus plantations depending on the climatic variations, soil characteristics, forest management and time considered in each study (Zinn et al. 2002).

Furthermore, several study showed that the greatest growth response of eucalyptus plantation in tropical areas is usually observed for potassium (K) and phosphorus (P) fertilizer application (du Toit et al. 2010) whilst in Australia tree growth was found to be generally more dependent on nitrogen (N) (Smethurst et al. 2004). Eucalypts response to fertiliser applications could change depending on several factors such as age, location and environmental conditions.

In China, *E. citriodora* can survive in a highly marginalized soil at 5 - 8 m^3 ha^{-1} yr^{-1} (Libby 2002). Whilst assessment of eucalypt productivity in response to fertilization in Brazil found that N application can significantly accelerate tree growth until age 2.7 years (30 months) and stabilizes afterwards despite differences in treatment. However, K application strongly enhanced growth even after the early tree growth (Goncalves et al. 2008). As nitrogen (N), phosphorus (P) and potassium (K) are redistributed internally within the plant, an increase in their efficiency for biomass production results (Goncalves et al. 2008). An experiment on nitrogen fertilization of *E. grandis*

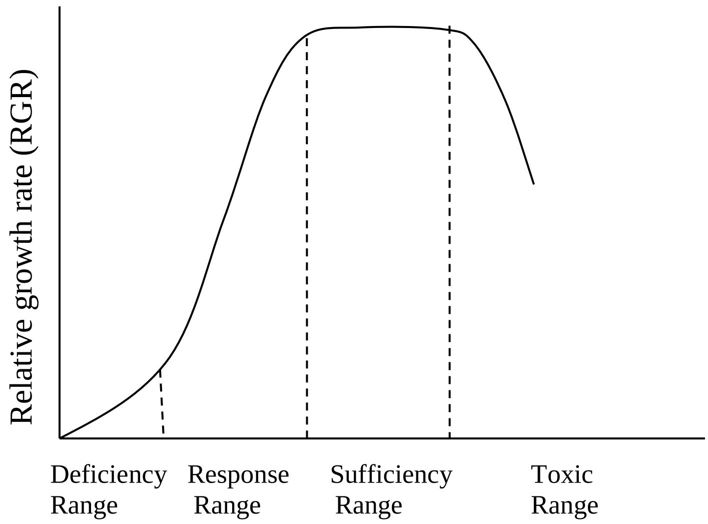

Figure 3.1 Plant tissue nitrogen (N) concentration (Sands and Smethurst 1995).

plantation resulted in a significant growth in stem biomass in the first two years after planting (Voigtlaender et al. 2011) while height is not affected by N fertilization at age three (Laclau et al. 2008). In Brazil, about 70-80% of the demand of each nutrient occurs during the first 4-5 years of stand growth (Santana et al. 1999). A separate experiment was conducted by Gava (1997) who developed a nutrient budget for *E. grandis* plantation with different scenarios (Table 3.1).

Nutrient requirements by the plant depend on its growth rate and the efficiency that it converts the absorbed nutrients into biomass. Using information from different genetic materials, ages, silvilcultural techniques and locations in Brazil, Santana et al. (1999) found that, except for sulfur, correlation coefficients between eucalypt trunk biomass and macronutrient content ranged from 0.76 to 0.96 ($p < 0.01$), the lower and upper extreme values were for P and K, respectively.

Moreover, results in growth modelling conducted on European trees showed that changes in nitrogen deposition changed forest growth and carbon sequestration whilst limitations in base cations especially magnesium (Mg) and phosphorus (P) may significantly affect the future tree growth (De Vries & Posch 2011). The same result was found to be true in a study of seedling growth in Costa Rica showing a high correlation between growth and soil nutrients with particular importance on effects of base cations such as potassium (K), magnesium (Mg) and calcium (Ca), followed by nitrogen (N) and phosphorus (P) (Holste et al. 2011).

Table 3.1 Nutrient budget of *E. grandis* under different scenario (Gava 1997).

Component	Element (kg ha^{-1})				
	N	P	K	Ca	Mg
Initial nutrient store **in the soil (S; 0-200cm)**	1900	55	550	3800	800
Nutrient store in biomass					
Leaf	70	6	25	30	10
Branch	20	5	10	22	5
Wood	270	25	130	135	20
Bark	45	15	60	115	18
Litter	225	12	45	250	30
Root (coarse and fine)	120	5	35	30	12
Nutrient loss					
By burning logging residues and litter (F)	310	23	69	46	18
By bark removal (B)	45	15	60	115	18
By wood removal (W)	270	25	130	135	20
By wood and bark removal (W+B)	315	40	190	250	38
Nutrient addition through fertilization (NA)	64	32	80	300	50
Nutrient budget					
Scenario A: (S) – (W) + (NA)	1694	62	500	3965	830
Scenario B: (S) – (W+B) + (NA)	1649	47	440	3850	812
Scenario C: (S) – (F) - (W+B) + (NA)	1339	24	371	3804	794
Potential number of 7-year rotations					
Scenario A	>7	>7	>7	>7	>7
Scenario B	7	6	5	>7	>7
Scenario C	3	1	3	>7	>7

An estimated nutrient budget and potential number of seven-year-rotation crops under three levels of management scenarios for clonal plantation of Eucalyptus grandis established in a red-yellow latosol (typical hapludox), loamy, dystrophic soil (seven years, MAI 45 m^3 ha^{-1} yr^{-1}, total wood biomass 160 Mg ha^{-1}.)

Another element with equal importance is boron (B). Boron is found to cause a significant impact in the productivity of eucalypt plantation worldwide (Goncalves & Valeri 2001). Boron is likely to be retained by clays and its concentration in soil solution is relatively high, ranging from 67 – 3000 mg per litre; whilst average B contents in soil may vary from 9 – 88 mg/kg. Adsorbed B on soil minerals is rather easily leachable whilst it increases as soil alkalinity increases (up to 9) (Kabata-Pendias A 2001). Furthermore, B concentration is relatively low in basalt with 0.1 –

6 mg/kg and higher in evolved rocks such as granite with 85 mg/kg (Aggarwal 1997). However, it was recorded to be in extremely high values such as 9000 mg/kg B in coal ash showing a marked affinity for organic matter (Ure & Berrow 1982).

Experiments conducted by Smith (2005) found out that deficiency of Boron on spotted gum (CCV) caused loss of apical dominance. Boron is an element necessary for binding the microfibrils of the cells in plants. Deficiency will manifest usually in the first year of establishment with growth reduction and dieback as its main symptoms. It is interesting to know that CCV is one of the most sensitive species to B deficiency whilst at the same time one of the most productive under water deficient environment (Goncalves et al. 2008).

A study conducted in the estimation of the critical external B requirements for *E. globulus* seedlings, shoot and root dry weight were similar in their sensitivity to B deficiency showing a satisfactory model fit (R^2 = 0.81–0.89). Critical values of B concentrations in the young leaf were in the range of 12-16 mg B kg^{-1} dry weight whilst 10-14 mg B kg^{-1} dry weight in the whole shoot (Sakya et al. 2002). This matched with the experiments in 1 - 3 year old *E. globulus* plantations in south China and Australia (Dell & Malajczuk 2011) with less than 12 mg B kg^{-1} dry weight showing a response to the application of 0.5–1.5 kg B ha^{-1}, whereas trees with more than 20 mg B kg^{-1} dry weight did not respond to the application of B fertiliser. Likewise, it was reported that B deficiency symptoms appeared when the B concentration in the seedlings of 3-month-old *E. globulus* fell below 12 mg B kg^{-1} dry weight whilst healthy trees had 20–30 mg B kg^{-1} dry weight (Dell et al. 2001). Furthermore, a separate study concluded the external boron levels associated with maximum dry matter production in 74-day-old plants were 9.25 μM B for *E. citriodora* and *E. grandis* (Novelino et al. 1982). Contrary to this outcome is the result that *E. citriodora* is tolerant to the boron and that plant development was not limited from 37 to 202 mg kg^{-1} of boron concentration (Silveira et al. 2000)

Macronutrient Calcium (Ca) and micronutrient Boron (B) were found to have essential roles on the formation of good tree form. These nutrients bind the pectin in the primary cell walls of all cells in the tree (Smith 2005). Soil types may vary in B concentrations available to trees. Variations in B supply can be attributed to different concentrations of clay content, sesquioxides (iron and aluminium oxides), organic matter, soil pH, and soil water. For this reason, soil type variations need to be accounted for when interpreting soil chemical data and determining fertilization rate (Smith 2005). The marginal level of calcium and boron concentrations will not affect negatively the vegetative growth of the spotted gum, however deficiencies of these elements will lead to poor tree form and wood quality (Smith 2005).

Eucalypt plantations can maintain a good growth at a rate of 100 kg ha^{-1} N application during its initial year whilst an amount of 1600 – 1900 kg ha^{-1} can sustain an optimum plantation growth (MAI = 45 m^3 ha^{-1} yr^{-1}) for more than 7 years as reported by Goncalves et al. (2008) and Gava (1997) with the assumption that there will be no logging within this period. In Australia, application in hardwood plantation varies. For instance, the average rate of nitrogen application as per 2002-2004 survey was 48 kg ha^{-1} in hardwood species (May et al. 2009).

In summary, it is important that soil fertility be included in the carbon modelling processes. This study will limit its focus on five soil nutrients including N, P, K, Ca, and Mg as these were found to be of high significance, limiting and sensitive in the growth of trees. Although Boron was found to be equally significant, lack of data inhibited the inclusion of this nutrient in the modelling. Furthermore, as most of the studies of spotted gum growth and soil fertility are limited and are not indicative of the quantitative range of nutrients for optimum growth, it would be impossible to include all the macro and micro nutrients present in the soil.

Whilst macronutrients are indispensable in plant growth, soil type and structure is an equally significant component in tree development. For instance in Queensland, spotted gum was found to thrive well in ferrosol soils with high iron content (DAFF 2012) in contrast to the marginal growth observed in hydrosols that tends to water log. Ferrosols are well drained and have low water holding capacity. The soil class and structure dictates the water absorptive capacity of soil such as sandy soil with good drainage properties whilst clayey medium tends to hold more moisture due to its porosity issues. This information is beneficial in ranking soil types and classes suitable for spotted gum however, soil element contents such as iron, and soil structure such as porosity were not included in the modelling and is one of the limitations of this study.

3.3.3 Climate change impact on carbon sequestration

Research on the climate change impact on forest growth and mortality conducted by Battles et al. (2008) in California showed conifer tree growth decline. Under extreme climate change, a 19% decrease in productivity of a mature stand will occur as projected for 2100. Additionally, they also observed a severe reduction of 25% in yield for pine plantations. These would mean a reduction in carbon sequestered as biomass accumulation can be directly related to carbon however, other factors such as soil fertility which is a significant element in tree growth was not integrated in the study.

One can deduce that climate change can impact plantation growth through biomass reduction as various climate modelling has shown varied results of terrestrial carbon storage decline (Bonan 2008), however the long term effect is unclear (Parry et al. 2007), especially with a saline environment. Similarly, Battaglia et al. (2009) identified three aspects of climate that could be of significant impact to forestry production namely: rise in temperature, changes in rainfall distribution and atmospheric CO_2 concentration change. Increasing temperatures, coupled with longer dry seasons (e.g. El Niño) and increasing atmospheric CO_2 concentrations over a prolonged period are expected to reduce the carbon sequestration capacity of forests.

Consequently, exposure of plants to elevated atmospheric CO_2 concentrations could lead to a CO_2 fertilization effect through enhanced photosynthetic activity (Nepstad et al. 2008; Ollinger et al. 2008; Saigusa et al. 2008). For instance, it was concluded that even under climate change, tropical forests could increase carbon uptake under elevated CO_2 (Gumpenberger et al. 2010) and enhance biomass production (Sturm et al. 2001). However, responses of plants to elevated CO_2 could vary.

The concept of a "tipping point", or a threshold beyond which a system shifts to a new state is becoming common in the discussion of the climate. This has led to increased studies focusing on effects of elevated CO_2 and temperature in the physiological processes of eucalypts (Jin et al. 2011; Medlyn et al. 2011; Xu et al. 2012; Crous et al. 2013; Duan et al. 2013; Gauthier et al. 2014). For instance, increased leaf mass per area (LMA) was observed in *E. saligna* and *E. globulus* seedlings under elevated CO_2 (Xu et al. 2012; Crous et al. 2013). These observations contradict what was observed in a study by Gauthier et al. (2014) where the LMA of *E. globulus* saplings did not vary significantly when subjected to similar temperature and CO_2 increases. Acclimatisation for eucalypt species may vary as its optimum temperature for photosynthesis could change depending on its age and native geographical range (Crous et al. 2013). Though elevated CO_2 could provide benefits in some eucalypts, the effect of warming could indicate variations in the plants' physiological reactions. Increased temperature could result in increased water stress in plants whilst elevated atmospheric CO_2 could enhance the plants' water use efficiency level (Medlyn et al. 2011). However, the net effect of these reactions on spotted gum is not well understood.

Literature on impacts of the climatic change to forest carbon sequestration were incorporated in this section as climatic parameters are indispensable components in the growth modelling of spotted gum. However, climate change is not the focus of this study and would form part of its limitations. The parameters used in the modelling will be discussed in detail as this chapter progresses however, are not directly linked to climate change.

3.4 Spotted gum growth modelling incorporating carbon

Carbon accounting is the process of assessing the amount of carbon found in different parts of a system. It is needed to estimate the amount of carbon that may be traded or used as an offset against greenhouse gas emissions. The conventional inventory and mensuration method most commonly practiced by foresters worldwide requires significant time and resources as it usually employs destructive sampling. Field measurement procedures are built on well-established methods and principles. There will always be a need to carry out actual measurements to validate the predictions of simulation models, but field measurements are expensive. The use of models will be important to assess the potential of particular areas and species for carbon sequestration projects. Applications of suitable models will also aid in estimating the current amounts of carbon sequestered at specific times in any forestation projects.

The Australian Greenhouse Office (AGO) developed the FullCAM model in association with the CSIRO and the Australian National University. FullCAM was designed to account for carbon stored in forest plantations and mixed plantings with silvicultural management. Carbon accounting software programs have been developed such as National Carbon Accounting Toolbox (NCAT) and which is used in many countries or organisations. NCAT can predict the amount of carbon stored in vegetation. However, further work is required to modify the NCAT, in particular the default growth curve based on the type of environmental plantings, previous land use, survival and competition. The FullCAM software can have an interface with NCAT which makes use of 1200 input parameters, of which most are not available or hard to find. NCAT is designed at a national scale and not on an individual plantation basis and so carbon sequestration can be underestimated by anything between 60% and 300% (Diacono 2009). Likewise, as it follows the IPCC's principle on the use of conservative model calculations, there would be a number of variations. The need to investigate key parameters of suitability whilst integrating a productivity model is required. This assists in the accurate determination of the carbon being sequestered by the plantation. Accurate determination of carbon stored in biomass will aid in efficient and profitable carbon trading for stakeholders.

Landsberg and Coops (1999) identified three classes of forest models used to simulate forest productivity across large areas and over long periods namely: (1) growth and yield models that are usually based on statistical relationships derived from tree measurements, (2) gap models that concern species succession and dynamics, and (3) carbon balance or biomass models. Growth and yield models are based on the historical inventory data collated in a specific area with specific vegetation type. This is normally site-species specific and correlation of specific variables such as height, age and site is usually determined. The gap model however, is based from the biogeochemical interactions and dynamic processes occurring in a specific ecosystem. Lastly, the carbon balance or biomass models are focused in determining the biomass of a forest stand or ecosystem based on several tree parameters (e.g. height, volume, etc.) and site variables (e.g. soil, climate, etc.).

West (2006) classified site productive capacity into three approaches: (1) site classification approach, (2) regression approach, and (3) process-based model approach. The site classification approach such as Laffan (1994), is normally based on the determination of site attributes. Whilst the regression approach (Walsh et al. 2008; Specht & West 2003) is based on mathematical statistical computations of growth derived from tree parameters in relation to the site attributes. Lastly, the process based model approach (Battaglia & Sands 1997; Mummery & Battaglia 2004; Paul et al. 2007) is based from detailed studies of the physiological processes of the plants.

The site classification approach is focused more on description of the area as to its suitability for a certain species and quantitative information such as annual biomass or tree growth is not possible. Site attributes which mainly consider the environmental factors are described and grouped in ranges suitable for tree growth such as climate and soil characteristics. This is site-species specific and could also be accurate if appropriate field measurements are undertaken. The regression approach makes use of past and present records such as inventory data on yield and growth of a plantation. This relies heavily on the statistical description of trees based on collected data from permanent or temporary sample plots on various sites and on varied years. This approach does not require knowledge of growth processes on trees whilst process based models are normally based on the concept of physiological and biological processes in plants (West 2006). The process based model such as 3-PG is founded on the principle that trees grow because their foliage is capable of capturing the sun's energy through the process of photosynthesis that converts carbon into carbohydrates and is utilized for respiration and growth. It is based on the calculation of radiation interception, canopy photosynthesis, estimation of respiratory losses and the allocation of the carbohydrates to component parts of the trees (Landsberg & Waring 1997).

Several process based models have been developed and applied in determining the Net Primary Production of Australian continent. Roxburgh et al. (2006) reviewed several models used in determining the NPP of Australia which is summarised in Appendix A. The result was an annual NPP of Australia averaged for a decade or longer. The models came up with varied annual carbon increments from the lowest of 0.67 Gt yr^{-1} (VAST) to the highest of 3.31 Gt yr^{-1} (RFBN). The result does not show the correlation in the number of parameter inputs needed to process the NPP and the complexity required of each model.

Apart from process-based models, some growth models developed are dendrocentric in approach (Walsh et al. 2008). Site index (height-age relationship) combined with calculations to determine site productivity and carbon sequestration of several eucalyptus species was applied in the study. This type of modelling is commonly completed by establishing plots, and directly measuring the tree parameters. Forestry sectors in some countries employ the empirical methods of determining productivity to monitor and determine growth, usually cutting trees, manually measuring the volume, height and diameter and weighing tree parts to determine the parameters needed. For some countries, this is part of a monitoring process and is done on a regular basis but for some it is rarely done. This method is accurate and straightforward, however, it is time consuming and costly (Laar & Akca 2007; Clutter et al. 1983). Others apply the geocentric approach (Laffan 1994) in forestry despite its accuracy being questionable as it is more appropriate for agricultural crops with short growth cycle. The laborious nature coupled with the high cost involved in the above-mentioned methods led to development of other means of assessing suitability and productivity.

In Australia (Landsberg & Waring 1997; Tickle et al. 2001; Paul et al. 2007) and even abroad such as Brazil (Almeida & Landsberg 2003; Almeida et al. 2004a; Almeida et al. 2004b), Canada (Beyhan et al. 2010; Coops et al. 2011), Finland (Landsberg et al. 2005), America (Coops et al. 2011), New Zealand (Landsberg & Waring 1997) South Africa (Esprey et al. 2004), Portugal (Fontes et al. 2006), Spain (Rodriguez-Suarez et al. 2010) and some parts of Asia, 3-PG is being parameterised, calibrated, validated and adopted, as the model is simple and based upon the photosynthetic process of the plants. The concept of 3-PG was developed by Landsberg and Waring (1997). This model places emphasis on the photosynthetic process of a tree which makes it a process-based model.

3-PG is anchored with the same principle applied in Forest-BGC (Running & Coughlan 1988) and Biomass models (McMurtrie et al. 1990). The model calculates gross primary production (GPP) from a simple linear relationship between absorbed photosynthetically active radiation (APAR) and carbon fixed by the canopy. Canopy quantum efficiency is constrained by humidity, through its effects on stomatal conductance, air temperature, water balance and vapour pressure deficit. The Net Primary Production is calculated from a simple ratio of NPP to GPP and then allocated to roots, stems, and foliage whilst biomass allocation to the various tree components relies on robust empirical allometric relationships (Bernier et al. 2003). It can determine the monthly and annual changes in stem mass and subsequently DBH, stand basal area and volume at any time, through a carbon partitioning procedure.

The difference between 3-PG and earlier models lies in the large simplifications made to process representation. Biological, physical, edaphic/soil and climatic variables for growth are encapsulated *via* input parameters. The effects of environmental constraints such as drought and frosts, or decrease in stand productivity with age, are encapsulated in simple modifiers that modulate the amount of light absorbed by the trees. Changes in stem populations are calculated using a specified thinning or the -3/2 power law for self-thinning (Bernier et al. 2003). Other models such as FullCAM are very complicated, need several hundred data entries which is not cost-effective and impractical to use, not accessible and in some cases not readily available at all.

3.5 Site suitability assessment using geographic information system (GIS)

Land evaluation is one of the crucial steps of land use planning and is beneficial particularly in areas where land resources are scarce (Bandyopadhyay et al. 2009). The need for land use allocation involves simultaneous analysis of multiple variables to determine how and where a project is best suited while resources are maximised (Kaale & Temu 1985). In forestry, a reliable site suitability assessment is necessary to eliminate loss of investments. Due to the high levels of capital investment and time involved, it is necessary that site suitability assessment be conducted. The need for site suitability assessment can be considered necessary for forest plantation establishment to determine the best possible locations particularly for carbon sequestration. In the process, one has to have good understanding on the factors affecting the growth of species under study and the site requirements necessary for species survival. Although 3-PG can perform growth simulation, the result is site-specific for a particular point of interest and would entail much time to simulate all points to cover a region. As site assessment normally involves large area of interest, the use of GIS is deemed most appropriate.

3.5.1 Site suitability factors for carbon sequestration

A worldwide study of forestation for carbon sequestration in developing countries conducted by Zomer et al. (2008) includes several factors such as rainfall, temperature and evapo-transpiration in the form of wetness/aridity index. Armin and Abdolrassoul (2010) conducted a site suitability study for afforestation with *Eucalyptus grandis* and used significant factors such as soil texture, soil pH, annual precipitation, minimum and maximum annual temperature, and topography (e.g. altitude and slope). The study on soil texture conducted by Henri (2001) on four eucalyptus species showed clay loam provides the optimum growing condition for all the eucalyptus species however for CCV, sandy loam provides the best growing condition. Soil types such as ferrosols, dermosols, chromosols, and kandosols provide good productivity for spotted gum but poorly-drained vertosols are to be avoided (DAFF 2012). However, there is no standard set of factors for land suitability assessment as factors are dependent on the species growth requirement, objectives of the project being implemented and the purpose of the assessment. As mentioned earlier, site suitability of species must be well understood to effect best land use allocation. This involves a thorough understanding of species growth requirements. For instance, spotted gum has the requirements tabulated in Table 3.2.

3.5.2 Site suitability approaches and techniques for carbon sequestration using geographic information system (GIS)

The qualitative systems approach for land evaluation particularly in land suitability assessment such as suggested and recommended by the United Nations Food and Agriculture Organisations (FAO) (1976) are normally applied in agriculture and forestry. The approach is normally implemented with the spatial science such as GIS and remote sensing.

In forestry, the conventional practice of site suitability is more of site quality assessment where the capability of land is determined *via* its productivity through direct measurements (Vanclay & Henry 1988; Landsberg & Coops 1999; Campion et al. 2003; Specht & West 2003; Walsh et al. 2008).

This is where mean annual increment (MAI) and site index (SI) are calculated. MAI is based on annual average growth with tree volume whilst SI is based on dominant height and age factors. Whilst SI is a more convenient method of assessment MAI is superior (Vanclay 1992) thus MAI was used as an indicator in determining the most suitable site in this study.

There are two conventional expressions of increment: *current annual increment (CAI)* and *mean annual increment (MAI)* (Figure 3.2). The mean annual volume increment or mean annual growth refers to the average growth per year a tree or stand of trees has exhibited/experienced to a specified age (total increment divided by age) (Laar and Akca, 2007). For example, a 20 year old tree that has a diameter at breast height (DBH) of 25.4 cm (10.0 inches) has an MAI of 1.27 cm (0.5 inches) per year. The current annual increment (CAI) is the increment over a period of one year at any stage in the tree's history. This growth parameter is desirable in measuring tree volume however, MAI cannot be measured directly for a single measure, but may be predicted from the height-age relationship (Vanclay 1992).

This research will use MAI and CAI as one of the variables in determining the volume of the timber and will be used in the analysis in comparing the most appropriate and suitable species.

Literature has provided an insight into studies conducted on suitability assessment using GIS (Bateman & Lovett 2000; Harper et al. 2005; El-Nahry & Khashaba 2006). Harper et al. (2005) estimated the performance of trees, carbon sequestration and recharge potential at the catchment scale in West Australia using GIS. The weighted average rating of soil and climatic data was applied and suitable sites were determined through multi-objective analysis. This procedure consisted of a multivariate numerical classification where principal component analyses were applied in successive steps resulting into suitability scores (Bojorquez-Tapia et al. 2001). In the decision-making context, multiple factors are considered and each has to be weighed depending on the purpose. As the analyses involves multiple criteria, multi criteria decision analysis (MCDA) is normally applicable where complex management decision making is necessary to provide better options.

Table 3.2 Growth requirements of spotted gum (source: varied authors).

Factor/Parameters	Range	Tolerance/Avoidance	Author
Soil Type	Vertosols	Avoid	(DAFF 2012)
	Ferrosols	Best Preferred	
	Dermosols	Prefers	
	Chromosols	Prefers	
	Kandosols	Prefers	
Drainage	Rapid	Prefer	(McMahon et al. 2010)
	Good	Prefer	
	Poor	Tolerates	
Mean Annual Rainfall (mm)	0 – 600		(McMahon et al. 2010)
	600 – 1200	Prefer	
	>1200	Prefer	
Temperature	Min	0 – 19	(Paul et al. 2007)
	Optimum	20-22	
	Max	23 – 45	
Frost (min Temp °C)	Light (> 2)	Tolerates	(McMahon et al. 2010)
	Medium (2 to -2)	Tolerates	
	Heavy (-2 to -6)	Avoid	
	Extreme (>-6)	-	
Salinity (dS/m)	Slight (2-4)	Tolerates	(McMahon et al. 2010)
	Moderate (4-8)	Avoid	
	High (8-16)	Avoid	
	Extreme (>16)	Avoid	
Soil fertility	Low	Tolerates	(McMahon et al. 2010)
	Moderate	Prefers	
	High	-	
Soil pH	0-4	-	(McMahon et al. 2010)
	4-6	Prefers	
	6-8	Prefers	
	8-10	Prefers	
	>10	-	
Surface soil texture	Light	Tolerates	(McMahon et al. 2010)
	Medium	Prefers	
	Heavy	Tolerates	
Landscape position	Ridge top	Prefers	(McMahon et al. 2010)
	Upper slope	Prefers	
	Mid slope	Prefers	
	Lower slope	Tolerates	
	Flat	Tolerates	
Soil fertility	Low	Tolerates	(McMahon et al. 2010)
	Moderate	Prefers	
	High	-	

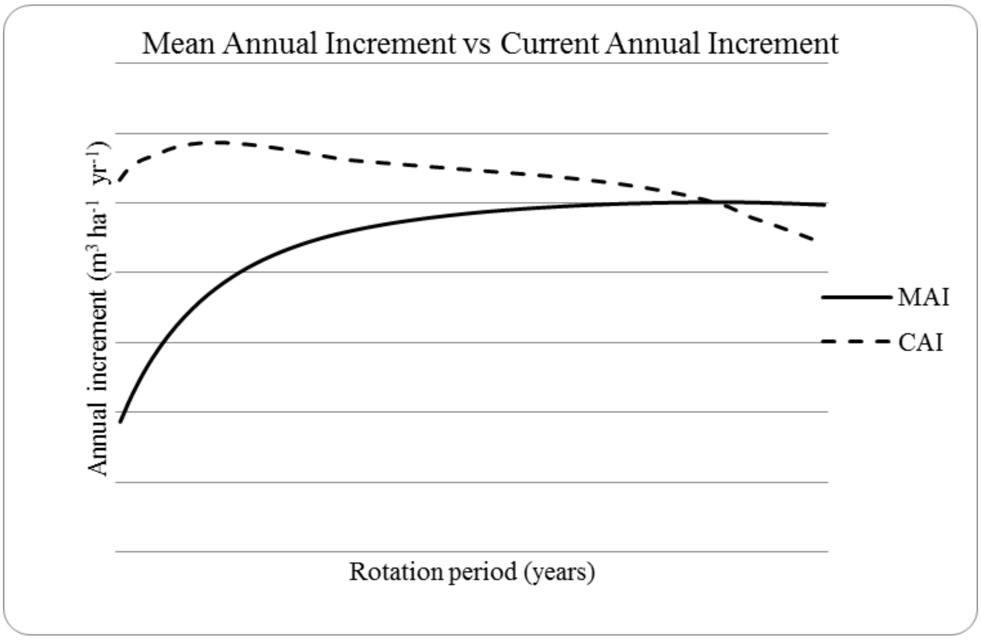

Figure 3.2 Current Annual Increment (CAI) vs Mean Annual Increment (MAI)

The conventional method of site suitability assessment usually involves weighted linear combination (WLC) of standardized input variables or parameters such as slope, aspect, and elevation within a geographic information system (GIS) framework. The variables are standardized into discrete classes with distinct boundary between each class (Basnet et al. 2001). It was recently dominated by a more complicated analysis using multi-criteria methods. For instance multi-criteria analysis that makes use of several criteria or elements interacting with each other that mimics the functionality of a system. The components are either added or multiplied, with or without weights to simulate the effects or impacts of a phenomena or system (Hill et al. 2003).

The advent of high performance computing has led to the development of several methods of MCDA which served as indispensable tools in land suitability assessment such as analytical hierarchy process (AHP), weighted linear combination, ordered weighted averaging and cellular automata (Boroushaki & Malczewski 2008; Giordano & Riedel 2008; Saaty 1980; Yu et al. 2011). Computer-based approaches have been developed to deliver MCDA, or elements thereof, in a range of forms such as ELECTRE III, ASSESS, DEFINITE, IDRISI GIS, GIWIN and MULINO-DSS (Roy 1991; Bowyer & Veitch 1994; Janssen & Van Herwijnen 1994; Eastman & Jiang 1995; Ren 1997; Giupponi et al. 2004). Malczewski (2006) reviewed literature on GIS-MCDA and found that this approach has been widely used to solve problems and make decisions in environmental planning/ecology and management, transportation, urban and regional planning, waste management, hydrology and water resources, agriculture and forestry. Most notably, the review showed that it has been most often used for land suitability problems.

Joerin et al. (2001) used a combination of GIS and multiple criteria decision analysis to assess the land suitability of a targeted site. As GIS can handle computational processing, the MCDA can do the grouping of the criteria into a suitability index

(Stoms et al. 2002). The major benefit of integrating the MCDA technique with GIS is that the decision makers can insert value judgments based on their preferences from evaluation criteria. In this manner, they would be able to receive feedback on its implications for policy evaluation that could be helpful in the decision and policy making (Malczewski 2006). Whilst a wide array of approaches to MCDA based on the analytical hierarchy process (Saaty 1980; Saaty 2000; Ramanathan 2001) and cognitive methods (Bisdorff 1999; Niskanen 2002; Mendoza & Prabhu 2003) were the results of the development of diverse methodology for application of MCDA in industry and government. These approaches address the decision process in detail and deal with a limited and clearly defined set of alternatives.

Hopkins (1977) comprehensively evaluated several methods for generating land suitability maps such as the Gestalt method, mathematical combination (*i.e.*, ordinal, linear and non-linear), identification of regions (*i.e.,* factor combination and cluster analysis) and logical combination (*i.e.,* rules of combination and hierarchical combination). Each of these methods has its own merits and demerits. For example, the Gestalt method can be easily used by non-skilled person as this involves a mere subdivision of land based on homogeneity. However, one of its limitations is the lack of identified factors in order to fully understand and communicate the output generated (Hopkins, 1977). This method is not capable of combining factors which is not appropriate when one is trying to evaluate the effects of several biological and physical factors in land suitability. The last three methods can overlay several factors, can be weighted and ranked, and eventually combined to obtain overall suitability rating.

The method used in this study was the weighted sum model or the weighted linear combination model. All the variables are weighted accordingly in which each has a corresponding thematic layer. The generated thematic layers are then multiplied by its determined weights or specific coefficients and overlayed with one another. The overlay process involves summation of all the weighted variables to come up with a final suitability map with value for each grid. This model is currently available as one of the spatial analytic tools and built-in the latest version of ArcGIS/ArcInfo. The presence of this functionality makes the analysis easier as it is readily available in the ArcGIS package.

3.5.3 Classification techniques

Doumpos and Zopounidis (2004) distinguished several multi-criteria classification approach such as statistics and econometrics (*e.g.* discriminant analysis, logistic regression), artificial intelligence (*e.g.* artificial neural networks and fuzzy set), mathematical programming and MCDA (*e.g.* ELECTRE). Some references make use of these classifications in mapping with GIS such as Hilbert and Muyzenberg (1999) and Garzon et al. (2006) who used GIS coupled with artificial neural networks (ANNs) as against a simple map overlay using Boolean logic to derive the suitable sites. The Boolean logic method classifies a range of attributes as either 1 or 0, in that case either suitable or unsuitable. Another method is the discrete classification where attributes are equally classed and given equal weights while continuous rescaling method rescales the group of attributes in a suitability value of 0 to 100 (Basnet 2008).

A continuous or fuzzy approach is an alternative method to express land suitability. Land suitability could be better expressed by a fuzzy approach as this approach allows the different factors that determine land use to be assessed in concert, rather than individually by separate rules (Triantafilis et al. 2001; IPCC 2013). Fuzzy logic is a useful method for characterising imprecise suitability criteria and for combining criteria into an overall suitability rating (Stoms et al. 2002). It is a multi-valued logic quantifying uncertain statements. The basic idea is to replace the two Boolean logical statements “true” and “false” by the continuous range of [0,...,1], where 0 means “false” and 1 means “true” and all values between 0 and 1 represent a transition between true and false (Benz et al. 2004).

Technically, a fuzzy set is a pair (A, m) where A is the set of a specific soil nutrients and $m: A \rightarrow [0, 1]$. For each $x \in$ A, $m(x)$ is considered the grade of membership of x in (A, m). For a finite set of soil nutrients A = {x_1,…, xn} the fuzzy set (A, m) is often denoted by {$m(x_1)/x_1$,…,$m(x_n)/x_n$}. If we let $x \in$ A, we can say that x is fully included in the fuzzy set (A,m) if $m(x) = 1$, while it is not included if $m(x) = 0$. In this case, x is called a fuzzy member if $0 < m(x) < 1$. Simply stated, as this process works on a principle where all values between 0 and 1 are included based on a fuzzy set, thereby all the soil nutrient values were captured. Due to its advantages, methods based on fuzzy logic have been used in many suitability analyses (Malczewski 2002; Joss et al. 2007; Armin & Abdolrassoul 2010) and in particular applied in forestry (Lexer et al. 2000).

Similarly, ANNs are computational mathematical models that emulate some of the observed properties of biological neural systems and draw on the analogies of adaptive biological learning. An ANN is composed of a number of interconnected processing elements that are similar to biological neurons. These processing elements are joined by weighted connections that are analogous to synapses in the human brain (Ashish et al. 2009). It allows decision rules of greater complexity to be applied in pattern classification. By formulating the land-suitability assessment problem, into a pattern-classification problem, neural networks can be used to achieve results of greater accuracy (Wang 1984; Yilmaz 2009). However, this technique involves much time and effort as the models has to be trained rigorously. It also requires use of high performance computer capable of handling bulk data for rigorous processing.

Many studies had been conducted on suitability assessment using GIS (Bateman & Lovett 2000; Harper et al. 2005; El-Nahry & Khashaba 2006). Harper et al. (2005) estimated the performance of trees, carbon sequestration and recharge potential at the catchment scale using GIS. Using soil and climatic data, weighted average rating was applied to determine the suitable sites in West Australia. Suitable sites were determined through GIS land suitability multi-objective analysis. This procedure consisted of a multivariate numerical classification where principal component analyses are applied in successive steps resulting into suitability scores (Bojorquez-Tapia et al. 2001). In the decision-making context, multiple factors are considered and each has to be weighed depending on the purpose. As the analyses involves multiple criteria, multi criteria decision analysis (MCDA) is normally applicable where complex management decision making is necessary to provide better options.

As an emphasis, 3-PG can only simulate growth of plantation on a particular and specific location and covering the whole region will take enormous time and efforts, it would be an advantage and easy task if GIS will be utilized to determine suitable site that encapsulates carbon benefits, salinity amelioration, and their present values on a sub-regional and regional level of application.

3.6 Economic benefits of forest plantation

Indeed, financial returns of forest plantations are an important concern everywhere in the world. Often, indicators for the assessment of its financial benefits are applied (Wang et al. 2014) such as the Net Present Value (NPV), Equivalent Annual Income (EAI) and Internal Rate of Return (IRR). Net present value determines the discounted cash flow of the project based on the theory of compounded interest. NPV allows the decision maker to calculate the total value of all the future costs and benefits associated with the forestry plantation (Klimas et al. 2011). EAI is similar to NPV except that it provides an annual income and is more beneficial for investments that generate yearly profit such as agricultural cropping ventures. Similarly, IRR is the discount rate at which the NPV is zero (Cubbage et al. 2007). As a general rule, it can be said that a project is acceptable if its IRR is equal to, or greater than the minimum acceptable discount rate (Lutz 2011). The three commonly applied discount rates in forestry are social (1.0 – 2.3 %), private (5.0 - 5.6 %) and commercial (10-12 %) (Polglase et al. 2011; Paul et al. 2013). These discount rates differ and could reflect a positive NPV depending on several factors such as rotation period, price of goods (e.g. timber), services (e.g. carbon sequestration), etc.

Whilst the IRR is simpler and easy to understand, the NPV method is preferred in this study because it explicitly provides an expected monetary value whilst the IRR cannot reflect a project's actual value.

The economic dimension of spotted gum plantations was incorporated in this study, however as it was not the intention of the study to undertake an economic analysis, a basic financial calculation of the net present value was deemed appropriate. In the past, forest economic valuations were conducted involving timber as the only source of profit for forest plantation. In Central Europe, forest rent has been a widely used criterion to evaluate long rotation forest plantations such as Faustmann's model (Cairns 2012) (Eq. 3.2):

$$LEV = \frac{CV_T - C_p\,(1 + r)^T}{(1 + r)^T - 1} \qquad \text{(Eq. 3.2)}$$

where, LEV is land expectation value, CV_T stands for cutting value at rotation period T, whilst C_p is the planting costs and r is the discount rate. The model conveys that the value of a forest plantation can be determined using the total discounted net cash flow over a specific rotation period. The concept of this model was based on the net present value (Eq. 3.3) of an even-aged plantation derived from a perpetual periodic series of harvesting revenues at the end of every rotation period. All the compounded costs and revenues are totalled at the end of the plantation cycle and a general present value formula is applied, such as:

$$V_0 \;=\; P / (1 + r)^T - 1 \qquad \text{(Eq. 3.3)}$$

where, V_0 is the net present value, P is represents the amount of fixed payment occurring every T years in a series, whereas r is the discount rate. The model conveys that the profitability of the forest plantation is dependent on several components such as rotation period, interest rate, planting expenses and timber price. The model is highly appropriate as a method for forestland valuation. Additionally, it is best known for providing a benchmark model for determining optimal rotation cycle that could maximize forest plantation value. Whilst the forest rent approach includes timber prices and regeneration costs. However, this still excludes an alternative investment option and assumes that a forest owner does not have any financial obligations from other funding agencies. Following forest rent may potentially lead to excess forestry investments and cause financial failure (Hyytiainen & Tahvonen 2003).

A literature review has been conducted on economics of forestry attaching values to carbon including studies of Burns et al. (1999), Eono (2001), and Benitez and Obersteiner (2006) who adopted a carbon price estimate of \$20/ tonne or \$5.45/tonne CO_2-e. As major concerns regarding the beneficial impact of forestry to ameliorate the environment arose, the incorporation of carbon and other intangible services became important. For instance, the incorporation of biodiversity benefits in addition to carbon values have been raised and related studies have been conducted. The study conducted by Venn (2005) adopted the same price estimated by the authors mentioned above and successfully incorporated salinity values in forestry. However, local variations in salinity values were not estimated as a single value of AU\$400 ha^{-1} per rotation was adapted. Similarly, Harper et al. (2005) had determined the suitability of carbon sequestration under saline soils but no economic value was placed. Cost data for long-rotation hardwood plantations are scarce in Queensland, and there is a lack of consistency between the estimates that are available (Venn 2005).

Whilst Venn (2005) conducted a financial and economic performance of long rotation hardwood plantation investments in Queensland, it did not identify nor quantify accurately and spatially the productivity of the plantation within SEQ. Furthermore, Maraseni (2007) provided a detailed estimate of carbon for a particular land use and soil type and is deemed more profitable for the farmers if the soil amelioration services, particularly the salinity values were added.

Several studies on suitability analysis of hardwood species were conducted to determine the economic viability of forest trees incorporating timber, and carbon such as Spencer et al. (1999), Maraseni (2007), and Polglase et al. (2008), however, soil salinity was not included in the study. Harper et al. (2005) conducted suitability including salinity and carbon sequestration but the economic benefits of the plantation were not tackled. The economic benefit of salinity amelioration derived from forest plantation has not been fully addressed.

In this study, the incorporation of net present value as a tool in determining the financial benefits of forestation will address the issues in the financial returns that will be derived from the plantation with the incorporation of intangible benefits such as carbon sequestration and soil amelioration.

3.7 Conclusions

Forestation for carbon sequestration is one of the mitigating measures that could offset emissions whilst potential suitable sites needs to be established to secure financial profitability. However carbon accounting for specific species needs to be implemented to assure accuracy in crediting. Similarly, soil amelioration benefits (e.g. salinity) from plantation that could increase the forestation profitability need to be incorporated. It is believed that with an appropriate model that could integrate significant components affecting spotted gum growth could assist in addressing the issues in carbon accounting and crediting. Available established tools such as net present value and GIS could be used to identify potential suitable sites where carbon sequestration through forestation can be implemented successfully.

The general methods used in this study are discussed in the next chapter whilst details for each procedure conducted are incorporated in the specific chapters that follow.

CHAPTER 4

Methodology

*"**Wisdom** is in the sight of him who has understanding"*

Jedidiah, *Book of Wisdom*, 970 – 928 BCE

4.1 Introduction

This chapter describes the general methods used to address the research problem and issues discussed in the previous chapters. In particular, the general method follows the conceptual framework (Figure 4.1) to achieve the objectives of this study.

This chapter is divided into six sections and provides general description for each of the methods used. Section 4.1 provides an introduction whilst section 4.2 describes how the study conducted the methods and techniques to address the objectives of this study. It is further subdivided into sub-sections, each of which describes methods applied in meeting each of the objectives. This involves methods in carbon accounting and modelling for spotted gum particularly 3-PG; fertility rating index; salinity amelioration; net present value of timber, carbon and salt; and site suitability mapping. Section 4.3 describes the study area whilst section 4.4 deals with species description. As time and resources constraints were experienced during the conduct of this study, limitations form part of this chapter. Limitations of the study are detailed in section 4.5 and conclusions formed section 4.6. Details of the methods and techniques utilized are discussed progressively in the proceeding chapters.

4.2 Methods and techniques

The general method applied in this study was a sequence of procedures which started with the net primary production (NPP) modelling using the process based model (PBM). The Physiological Process Predicting Growth (3-PG) model was utilised in biomass simulation. This method was preferred due to its robustness and acceptability worldwide.

Other process based models were considered, such as CABALA (Carbon BALAnce) developed by Battaglia et al. (2004). CABALA has significant potential for application in projecting carbon sequestration of plantation (CSIRO 2014) but the limited validated parameter sets for CCV prohibited its application in this study. Another process-based model considered was the Landscape-DNDC (DeNitrification, DeComposition) which was recently developed by Haas et al. (2012).

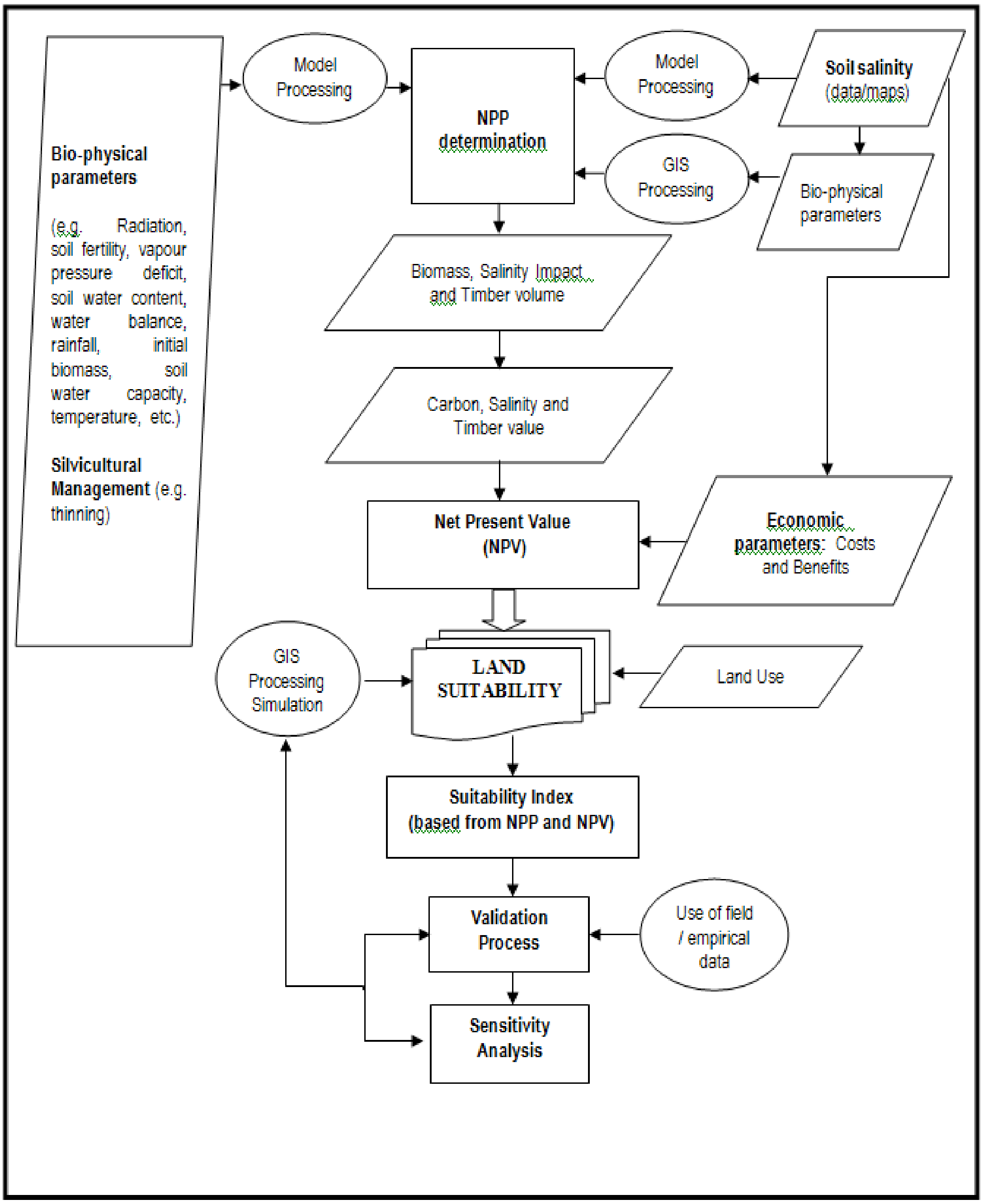

Figure 4.1 Methodological framework applied in the site suitability modelling

It was designed to simulate multiple ecosystems, however, this process-based model is difficult to use due to the lack of available input parameters for specific situation and the scarcity of data available to validate models (Gilhespy et al. 2014). The Farm forestry toolbox on the other hand was not considered as this toolbox was primarily designed for plantations in Tasmania with climatic parameters specific for that location. Tasmania and south east Queensland have significantly different environmental conditions. Whilst there is no available validated data for CCV in south east Queensland using this model, the application of this software was deemed inappropriate.

As 3-PG is excel-based, it is user-friendly, making the model easily accessible. The processing is not complicated rendering a fast simulation time. Additionally, the hardware requirements for memory do not entail high end specifications (Landsberg & Waring 1997). It also easily integrates with other suite of spatial mapping software without any interface issues. Parameters values and validated data for CCV are also available. Since 3-PG was developed earlier than the rest of the models, it has gained popularity, wide acceptability and use in the scientific community.

In the simulation process, the bio-physical parameters specific to each of the sub-regions were used as input variables. Prior to this, fertility rating of the study sites was derived using GIS modelling. The fertility rating modelling used the five most essential nutrients required for spotted gum growth. An equation was also developed for spotted gum mortality under saline areas using available datasets. Mortality values were added as an input parameter in 3-PG prior to simulations. The result of NPP modelling provided biomass yield where carbon was calculated. After this, the discounted costs and benefits of the plantation were calculated to arrive at the net present value.

Costs in this study comprised of spotted gum plantation establishments, annual maintenance, tree marking and harvesting whereas revenues come from thinning, timber produced, carbon sequestered and soil amelioration. The discounted costs were deducted from the discounted revenues where the net present value of timber, carbon and salt were derived. Eventually, land suitability was modelled using GIS where the results of NPP and NPV were used. The suitability modelling generated a map of production areas and suitable sites for biomass and carbon sequestration projects. For CFI eligibility, a rainfall map with high risk of salinity occurrence was overlaid to determine the extent of the potential carbon sequestration sites where salinity occurs whilst important land use types e.g. intensive agricultural lands, natural parks, heritage, etc. were masked out to avoid land use conflict. Finally, the results were validated and analysed.

The research methods and approaches used in this study was based on the result of the literature review and was found to be most suitable in achieving each goal. The proceeding discussion focuses on three sub-sections and the methods and techniques employed to attain the objectives.

4.2.1 Research approach for objective 1

To address the first objective of this study, on the identification of the knowledge gaps in carbon sequestration of spotted gum in saline areas for Carbon Farming Initiative (CFI) eligibility, intensive review of relevant literature was conducted. Journals and books were accessed from the University of Southern Queensland's digital library and were evaluated in the process. Personal communications and consultations with experts from different organisations were also undertaken.

4.2.2 Research approach for objective 2

To address the second objective of this study on the determination of the carbon sequestration capability of spotted gum, a Process Based Model (PBM) was utilized. The use of 3-PG was instrumental in achieving this objective. Initially, 315 sites within the southeast Queensland were randomly generated using *ArcGIS*. These points became the sampled sites which were finally reduced to 253 sites when outliers from various datasets were removed. The latitude was also used as input in 3-PG for calculations of the required climatic parameters such as solar radiation. Prior to carbon sequestration determination, the fertility ratings of the study site were modelled. The model was performed via integration of N, P, K Ca, and Mg data using the weighted summation technique. The model generated a fertility rating (FR) map which was used as input for 3-PG. Similarly, the bio-physical parameters specific for each of the sub-regions were collected and pre-processed as input parameters for 3-PG. Once the input parameters were completed, the biomass simulation was performed. To finally arrive at the results for the first objective, several methods were used and are described below.

4.2.2.1 Process based modelling

Previous studies (Paul et al. 2007; Beyhan et al. 2010; Coops et al. 2011) showed the accuracy and international acceptance on the use of process based modelling and the Physiological Process Predicting Growth (3-PG). This model was employed in the estimation of annual and rotational biomass growth of spotted gum plantation. Given the scarcity of tree growth datasets, the available secondary data for component variables (e.g. diameter, height, age, etc.) including the 16-year primary data for spotted gum were utilised to parameterize the model. The 16-year datasets were derived from the field experiments and served as the basis for the validation process. Bio-physical input parameters include specific local climatic variables using a 140-year historical dataset such as rainfall, temperature, frostdays, evaporation, solar radiation, soil types, and available soil water among others. Climatic data were pre-processed whereas some of the biological datasets were collected such as the specific leaf area (SLA) and leaf area index (LAI).

The specific leaf area (SLA) and leaf area index (LAI) for spotted gum were determined through the collection of spotted gum leaves which were initially weighed then oven dried. The final weight was determined after oven drying and its area measured. SLA and LAI were computed using the collected weight and leaf area.

Other biological input parameters required were adopted from the previous work of Paul et al. (2007).

Physical parameter inputs such as soil types and available soil water was extracted from soil thematic maps which were either downloaded from the government websites (www.asris.csiro.au) or provided by varied institutions such as the Department of Environment and Resource Management (DERM) (Biggs, A 2012, pers. comm., 11 April). Once the parameters were completed, biomass simulations were run and the results of several model runs provided the accumulated plantation biomass. The thematic layer for the biomass was named *DM100* map which corresponds to *Scenario 1* in 3-PG modelling.

Subsequently, growth trajectory for the entire rotation period of 100 years for each site was graphed, compared, and analysed. Carbon sequestered and stored in the plantation was calculated based on the biomass growth generated by the model. The results of the carbon sequestration for each sub-region was validated using the results of previous investigations on spotted gum plantations. The estimated carbon potential of each site was consequently utilized to spatially map the potential suitable sites for spotted gum plantation using GIS. Details of all these processes are discussed in Chapter 5.

4.2.2.2 Fertility rating index

A concurrent estimation of fertility rating (FR) was generated before the 3-PG model was run. Selected major soil nutrients critical for tree growth were identified such as nitrogen (N), phosphorous (P), potassium (K), calcium (Ca) and magnesium (Mg). Point datasets were downloaded and then interpolated across the study area. The use of the kriging interpolation technique was selected as it provided a chance to perform cross validation for the generated model. This also provided the accuracy of the equation modelled. The result was used to generate thematic layer for each of the five nutrients. These layers were then reclassified based on the nutrient requirements for spotted gum. Five nutrient levels were identified that corresponded to five classifications e.g. very low, low, medium, high and very high. Finally, the fertility rating (FR) map was created using the weighted summation technique in GIS. Values from this map were also used as variable input in 3-PG modelling. This procedure is fully discussed in Chapter 5.

It was important to incorporate soil fertility calculations in the methods as this is one of the significant components of the model to simulate the physiological processes of trees. The use of GIS modelling was employed to determine the final values for fertility rates of each soil type and to determine the unknown values on a map. GIS was deemed the most suitable tool as it is capable of overlaying several thematic maps and to arrive at an integrated result based on the combination of various ranges of soil nutrient maps.

4.2.3 Research approach for objective 3

Series of methods and techniques were applied to meet the third objective. First, the datasets available from two different studies on the effect of spotted gum in various salt concentrations were combined. Then, a percent mortality equation was developed for spotted gum growth in varying saline conditions. The generated equation was fitted and then overlaid with the salinity map provided by the Department of Environment and Resource Management. This process created a continuous map for the entire study site that aided in the visualization of spotted gum mortality under varying salt concentrations. The mortality values extracted from the generated map was also used in biomass modelling in saline affected areas.

The difference between the biomass produced under saline conditions and non-saline areas were determined by a mathematical expression using both thematic layers in GIS. The deviations in biomass were used to calculate the financial loss incurred in plantations with salinity. Forest plantations had proven to reduce salt load of saline affected areas from previous studies such as Tolmie et al. (2003) and Hill (2004). Their results were utilized in this study. A 60% salt reduction from the establishment of plantation was used to estimate the salt credit. Finally, the financial values of the biomass and carbon loss were divided by the salt credit to come up with the soil amelioration value or also termed as salt value of the plantation.

A financial approach was found suitable to meet this study’s objective on the net value estimation for soil amelioration. Specifically, the following procedures below were conducted.

4.2.3.1 Soil amelioration in saline areas

The capability of the spotted gum plantations to ameliorate the soil via the reduction in salinity has addressed the issue of additionality. The procedure involved determination of the behavior and response of spotted gum in various salinity levels using the data from two separate studies namely Madsen and Mulligan (2006) and Sun and Dickinson (1993). This made the creation of a mortality map possible.

An equation to fit the curve for the datasets was developed and overlaid with salinity map using ArcGIS software. The result created a percent mortality map of spotted gum under varied salt concentrations. Values from the mortality map were extracted to 253 points which were then used as input parameter for biomass simulation. The projected biomass were then spatially visualized using GIS. The resulting layer was named as *DM100_Salinity* map which corresponds to *Scenario 2* in 3-PG modelling.

The next step included raster calculations where the salinity thematic layer was deducted from the biomass thematic layer to get the biomass loss. As plantations are known to reduce the level of salinity, this phenomena was simulated in this process. A 60% salt reduction was multiplied by the salinity concentrations to arrive at the estimated salinity level that resulted in the plantation establishment. The raster calculation functionality in GIS was applied to create the salt credit map.

Both the carbon and the biomass loss were multiplied by their respective current market prices. Revenues from biomass loss and carbon loss were summed and then divided by the salt credit. This process determined the soil amelioration value which is termed as salt value in this study. The procedure was discussed in detail in Chapter 6 of this study.

4.2.3.2 Net present value (NPV)

As per literature review, the Net Present Value (NPV) tool was found to be most appropriate to determine the value of soil amelioration capability of spotted gum in relation to the carbon sequestration capability of the site. To effectively estimate the plantation's soil amelioration capability, its NPV was determined. This was done by projecting the net income (i.e. revenue-cost) then converting the derived amount into a present value. This procedure was also used to estimate the value of carbon and timber derived from the plantation.

The net present value of the spotted gum plantation was calculated using the costs and revenues. Values were tabulated using Microsoft Excel. The present value of spotted gum plantation system costs was derived from the literature e.g. AU$1,800 ha^{-1} for plantation establishment, AU$300 ha^{-1} for thinning, AU$100 ha^{-1} for marking cost, AU$40 ha^{-1} for annual maintenance cost e.g. fertilizer and pesticide and none for harvesting cost as this will be harvested by private firms who will buy the logs at a stumpage price. Revenues were calculated from the results of this study from thinning and harvesting. Benefits gained from harvesting at the rotation age were the conventional timber revenue, carbon and soil amelioration or also termed as salt credit in this study. Prices used for spotted gum sawlogs were derived from various studies within Queensland such as AU$98 m^{-3} ha^{-1} (pulpwood), AU$75 m^{-3} ha^{-1} (C grade sawlog), AU$100 m^{-3} ha^{-1} (stumpage for compulsory), AU$70 m^{-3} ha^{-1} (stumpage for optional) and AU$20 m^{-3} ha^{-1} (compulsory for landscape). All the prices were determined by the study of Polglase et al. (2008) except for the stumpage prices derived from Maraseni's (2007) study.

All the costs were discounted which formed the PV_{CR} except for the discounted annual cost of maintenance which resulted in the PV_{AC} discounted annuity. Similarly, revenues from carbon, timber and soil amelioration were discounted to translate the future values of plantation to the present value, PV_R. Finally, all the discounted costs were deducted from all the discounted revenues that provided the net present value of spotted gum plantation for carbon sequestration. Detailed procedures are discussed in Chapter 6 of this study.

4.2.4 Research approach for objective 4

The fourth objective of identification of potential suitable sites, was addressed with the use of Geographic Information Systems (GIS), particularly spatial modelling. The final procedure generated maps from the previous objectives incorporating spatial mapping techniques which were applied to meet this objective.

4.2.4.1 Site suitability mapping using GIS

The results from the first three objectives were used to determine suitable potential sites for carbon sequestration projects. The initial procedure was to mask out significant land use types e.g. productive agricultural areas, natural heritage, water bodies, built-up areas and parks from the land use map. This was performed to create an extent of sites devoid of land use conflict with food production and environment. This generated a production area (*Prod_Area* map) for carbon sequestration. Meanwhile, CFI eligibility was considered and a thematic layer of the mean annual rainfall (*MAR*) map was intersected with the production area. The mean annual rainfall (*MAR*) map was also intersected with the salinity layer (*EC* map) to generate an area showing the amount of rainfall that is received under saline areas (*MAR_EC* map). The result was reclassified to determine the areas where there was potential salinity in high rainfall areas ranging from 700 mm yr^{-1} – 1,100 mm yr^{-1} (*Prod_Area* map). To determine the extent of CFI eligible sites, saline areas receiving rainfall from 700 mm yr^{-1} – 1,100 mm yr^{-1} were extracted from the *Prod_ Area* map. The generated layer identifies the extent of potential CFI eligible sites for carbon sequestration located under high salinity risk areas (*Prod_Mar* map).

After the creation of production areas eligible for CFI, the *Prod_Mar* map was intersected with the biomass thematic layer, *DM100* map (*Scenario 1*) to extract the extent of potential sites for spotted gum biomass plantation. The same process was performed for *DM100_Salinity* map (*Scenario 2*). Production zones for both scenarios were created which were reclassified into four classes namely: Very Low (Zone 1), Low (Zone 2), Medium (Zone 3) and High (Zone 4). The classes were also called production zones to correspond to the four productive capability zones of the study area in terms of biomass and mean annual increment (MAI). Details on these procedures are discussed in Chapter 7.

The final process was mapping of these zones incorporating the values of the costs and revenues that provided the suitability map of potential sites for carbon sequestration projects.

4.3 Study site description

The study site was located in South East Queensland (SEQ) region (Figure 4.2). The SEQ biogeographical region covers an area of 6.1 million hectares of which 4.3 million hectares are privately owned and 1.8 million hectares are State owned (CRA-DNR 1999). Geologically, it is comprised of broad alluvial valleys, coastal sand masses and rugged volcanic mountain ranges that provide biologically diverse natural resources.

It is an area of significant biological and physical diversity including many types of plants, birds, frogs, reptiles and mammals that also serve as a major area for migratory species of birds (CRA-DNR 1999). The region is one of the fastest growing in Australia with its population concentrated mainly in the greater metropolitan areas around Brisbane, Gold Coast and Sunshine Coast. It also supports a wide range of forest-related industries including timber harvesting and processing, grazing, mining, recreation and tourism.

The South East Queensland (SEQ) plantation region extends north from the New South Wales border to Gladstone and west past Toowoomba and Kingaroy (Parsons et al. 2007). It is the State's premier timber production area, supporting some 90 per cent of the plantation estate (CRA-RFA 1999a) whilst employing about 80 per cent of the Queensland total timber industry workforce. SEQ hardwood plantations have been established mostly since 1995 resulting in insufficient long series datasets. In fact, the longest plantation data so far that has been acquired was only 16 years. Furthermore, the market opportunity and growing rating for hardwood plantations in SEQ was estimated to be high (Polglase et al. 2008) however suitable spatial locations remains to be determined.

SEQ has a humid sub-tropical climate with mild winters and warm summers (CRA-RFA 1999a) with most of the rain falling during summer (Dec - Feb) whilst fogs are more frequent in winter. July is the coolest month when risks of frost is highest (CRA-DNR 1999). It is one of the bioregions of Australia based on the Interim Biogeographic Regionalisation for Australia (IBRA) (Appendix B) created to prioritise the protection of the country’s ecosystem (NRS-DEH 2005).

The bioregions represent a landscape based approach to classifying the land surface including attributes of climate, geomorphology, landform, lithology, and characteristic flora and fauna (Department of the Environment 2015b). Vegetation community and land system mapping undertaken by the states and territories have been used to establish IBRA Region and Subregion Boundaries. At present there is no consistent identification and mapping of regional ecosystems in Australia and IBRA serves as a planning framework and tool for the National Reserve System (NRS) to identify and prioritise reservation targets (NRS-DEH 2005).

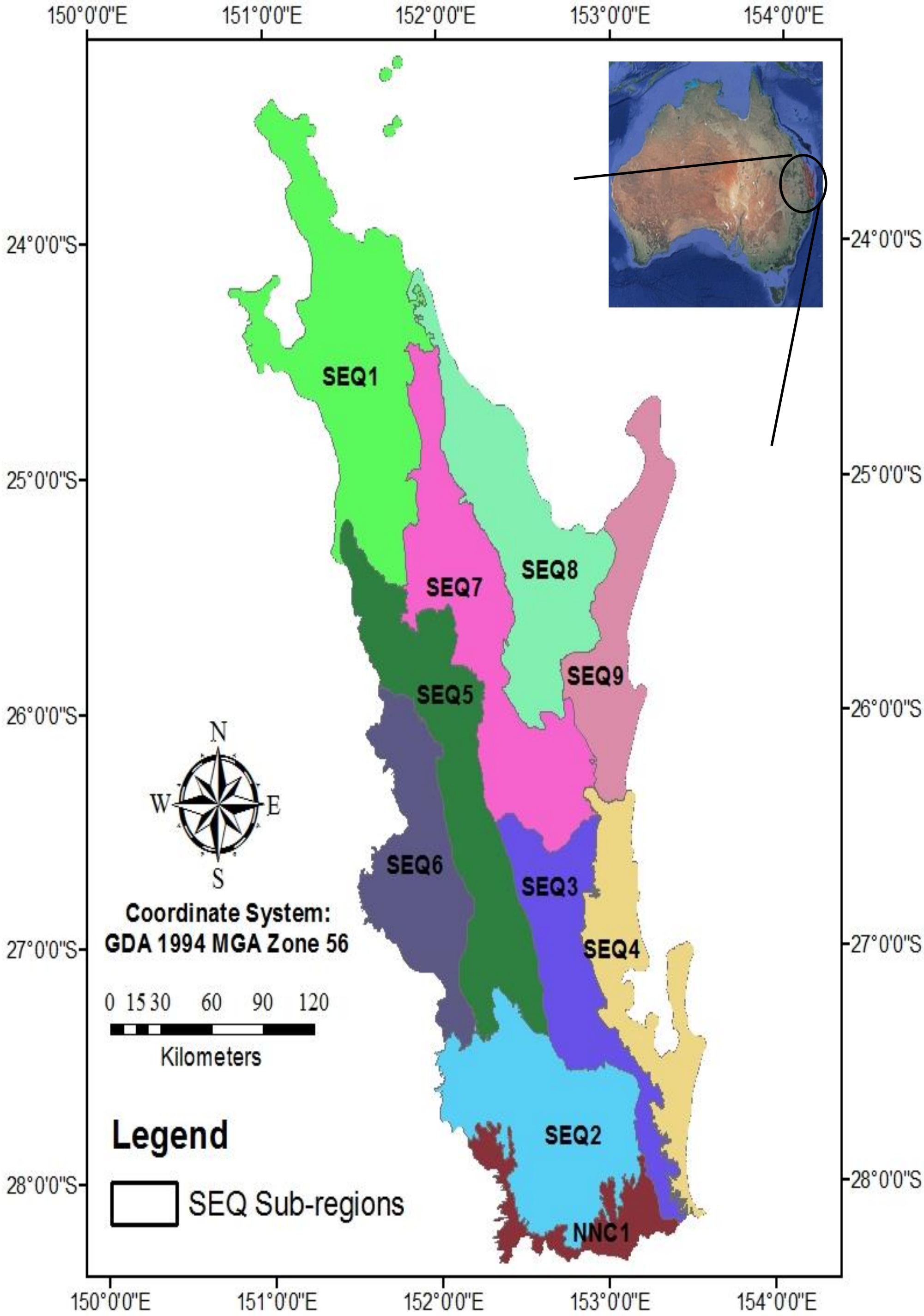

Figure 4.2 Geographic location of the South East Queensland (SEQ) Region

It is also one of the 13 bioregions of Queensland which are further subdivided into 9 sub-regions namely: SEQ 1 – Burnett-Curtis Hills and Ranges, SEQ 2 – Moreton Basin, SEQ 3 – Southeast Hills and Ranges, SEQ 4 – Southern Coastal Lowlands, SEQ 5 – Brisbane Barambah Volcanics, SEQ 6 – South Burnett, SEQ 7 – Gympie Block, SEQ 8 – Burnett – Curtis Coastal Lowlands, and SEQ 9 – Great Sandy (NRS-DEH 2005). The NNC1 – Scenic Rim located at the southern part adjacent to the boundary of New South Wales and Queensland also formed part of the map.

4.4 Spotted gum description

The species of native commercial hardwood modelled in this study was spotted gum (*Corymbia citriodora* subspecies *variegata*) or CCV, which is listed and identified as priority species under the CRA-RFA report (CRA-RFA 1999b) and identified as most significant commercial native hardwood species by the Department of Primary Industries – Forestry (2004) The species was also chosen based on its endemicity in Queensland, market potential, excellent timber quality, the presence of plantations in the study area and the availability of data and information on these species.

Spotted gum (*C. citriodora*) belongs to the family Myrtaceae and was formerly classified under the genus *Eucalyptus*. It is now classified under the genus *Corymbia* albeit the controversial taxonomy with species assignment challenging and reliant on either geographic origin, morphological characteristics (Shepherd et al. 2008) or genetic make-up. Its natural distribution in Queensland is from Maryborough to Mackay and is found in the higher, drier country of Atherton, Herberton and Mt. Garnet. Its wood is utilized for bridge construction, tool handles, framing, flooring and case manufacture as the wood is hard, strong, and tough. Wood grain is straight or interlocked and occasionally wavy (Boland et al. 1989). It thrives in well drained, sandy or sandy loam over 600 mm rainfall. It grows on a wide range of soil types of nutrient-poor to high fertility. However, it does not perform well in poorly-drained soils (e.g. wet heavy clayey soil) and extended waterlogging could result in significant reduction in growth and moderate mortality is expected. Similarly, during the first three years, it is highly susceptible to frost and cannot survive in heavy frost areas (DAFF 2012). However, once sturdy, it can survive and tolerate frost.

This tree can reach a height of 20-30 m tall and the trunks and branches are usually straight. The trees transforms its leaves as the juvenile leaves being lanceolate up to 6 inches (15 cm) long with a rough sandpapery feel becomes light green and glossy when adult. The adult leaves are known as phyllodes and are more highly drought adapted. In fact, phyllodes do not have a traditional leaf lamina instead the green leaf blade, in a developmental sense, is an outgrowth of the petiole (DBM-UO 2009). The citronella scented oils used in perfumery are extracted out of its leaves. This species needs full sun with a well-drained soil and can grow in very nutrient poor soils and fertilizer is not needed; however trees are very susceptible to frost. During the winter it is detrimental for spotted gum if the temperatures drops below 10°C at night as mortality could occur. Seeds germinate in 30-45 days at 22°C (DBM-UO 2009).

4.5 Limitations

Soil nutrients vary continuously in space and time, and as such it is a very difficult if not impossible task to measure soil variables at every point in a study site at a statistically significant and scientific manner. Thus, in order to represent the spatial variation of soil properties in nature, sample points have to be used (Siska & I-Kuai 2001). However, deciding on the sampling design is another challenge because of complexity, variability and dynamic processes of nature. To minimize errors, sample points need to be dispersed strategically over the study area to ensure representation of phenomena to be measured in the study area (Siska & I-Kuai 2001). Spatial analysis sampling is often performed on regular grid on irregular set of points that could potentially depict the true variation of the studied phenomena. However, due to limited available datasets, all the downloaded points were used. Nonetheless at the present moment this is one of the few feasible and economical methods to study soil nutrients and soil fertility on a regional scale (Siska & I-Kuai 2001).

Generally, stratified random sampling is often recommended for spatial analysis (Siska & I-Kuai 2001). This particular sampling method is available as one of the spatial analyst functionalities built in ArcMap v.10 package. This functionality was used in generating 315 sample points within the SEQ region.

4.6 Conclusion

The methods employed in this chapter enables salinity to be valued using an appropriate model. This provides a method for accurate accounting of spotted gum plantation's soil amelioration capability in relation to carbon sequestration. The methods that had been developed in this study accounted for carbon sequestration and soil amelioration capability of plantation in saline conditions. Accuracy in carbon accounting, methods, baseline information and additionality have been a persistent issue. Methods employed in this study provided options in resolving these issues in particular enhancement of accuracy of carbon accounting and the increased profitability of plantation via salinity alleviation. Furthermore, the developed models can assist in determining suitable sites eligible for carbon sequestration under CFI projects.

The proceeding chapters will discuss in detail specific methods, results and conclusions to address the objectives. As mentioned earlier, the first objective was attained through intensive review of literature thus, it will not be discussed in the proceeding chapters. However, the results of the review will be mentioned in some parts of the chapters to justify the application of specific methods.

Chapter 5 provides detailed discussion to address the second objective of the study. It also details the biomass simulation process using the 3-PG process based model. Chapter 6 elaborates on the procedure in addressing the third objective and contains discussions on the financial approach to assess salt, carbon and timber valuation. Chapter 7 explains how the most suitable potential sites for carbon sequestration in the SEQ region were determined.

CHAPTER 5

Biomass and carbon sequestration modelling of Spotted gum for SEQ

"How much better to get ***wisdom*** *than gold!*
And to get understanding is to be chosen rather than silver"

Jedidiah, *Book of Wisdom*, 970 – 928 BCE

5.1 Introduction

The previous chapters showed that biomass production is a variable dependent on different climatic and bio-physical factors. As these environmental conditions are not constant even in a single locality, it is necessary that tree growth parameters be determined to project the future biomass and carbon sequestration capability of a certain sub-region. Understanding how these growth parameters affect the biomass production of trees is highly significant. Similarly, knowledge on how trees are able to photosynthesize with the utilization of these growth parameters and biomass allocation is also an important component of this study. These physiological processes are significant in the carbon sequestration ability of the forest and is the focus of this chapter.

Furthermore, the fertility status of the soil also plays a vital role in the food manufacturing capability of trees. The previous chapters on literature reviews identified that soil nutrients are indispensable in tree growth as early as the seedling stage, therefore soil fertility was considered an important input. The fertility rating was identified as an appropriate mechanism where soil nutrients can be incorporated in the modelling. The utilization of the process based model, particularly the 3-PG, to simulate the biomass production of the spotted gum plantation with the required growth parameters, made the carbon sequestration projection possible. However, literature showed that there has been issues with the fertility rating in the 3-PG model that needed to be more objectively determined in order to come up with accurate carbon accounting.

The aim of this chapter is to address the second objective of the study which is to determine the carbon sequestration capability of the spotted gum plantation. It focuses on the result of the process based model growth simulation for all the sub-regions within the study site. This chapter is sub-divided into five (5) sections. Section 5.1 presents an introduction of the chapter's content and structure. Section 5.2 provides background information on the required variables and details the significant components of soil fertility, the bio-physical and climatic parameters as variable inputs required for tree growth simulation in the processed based modelling using 3-PG. The third section (5.3) describes the detailed methods conducted to meet the objective of this chapter. Section 5.4 provides the results and discussions on carbon sequestration within the different sub-regions of the study site. This chapter ends with section 5.5 where relevant conclusions are drawn.

5.2 Process based modelling, parameters and simulation

3-PG is robust, reliable and can be used with confidence to predict growth in areas where trees have not been grown (Landsberg et al. 2003). The study conducted by Tickle et al. (2001) showed that 3-PG performs better compared to the two conventional methods of determining forest productivity. This model was also integrated in the FullCAM (Full Carbon Accounting Model) particularly with CAMFor (Carbon Accounting Model for Forestry) which integrates every aspect of growth of trees including management (Richards 2001) primarily due its carbon cycling component via litter decomposition. It also bridges the gap between conventional, mensuration-based growth and yield, and process-based carbon balance models (Bernier et al. 2003) yet is easy to use, simple and requires only few parameter values which are readily available data as input (Landsberg et al. 2003). The key features of this model are simplification in process representation, minimal requirements of input data and a strong linkage to empirical datasets that give the model its robustness. Most of all, 3-PG can also be parameterised locally to suit the species and site and is applicable to forest plantations.

Process based models such as 3-PG can predict above-ground and below-ground biomass based on the required input variables or parameters for a species. As this research utilised 3-PG to assess the productivity of forest plantation within SEQ, input parameters for the chosen species such as spotted gum was necessary. A study conducted by Paul et al. (2007) on spotted gum plantations parameterised 3-PG variables (Appendix C) whilst Maraseni (2007) showed a promising result of a spotted gum study in Kingaroy, Queensland that is highly useful in this study. Furthermore, the data for root-shoot ratio from the study conducted by Snowdon et al. (2000) was considered appropriate for this research.

Past studies found that significant and sensitive variables for process based model development affecting tree productivity are foliar biomass (Yarie 1997); nitrogen, moisture (Running & Gower 1991; Yarie 1997; Smethurst et al. 2003); phosphorous (Smethurst et al. 2003); photosynthetic parameters, crown nutrition, soil nutrients, CO_2 concentration (Kirschbaum 1999); biomass allocation, water supply (Kirschbaum 1999; Stape et al. 2004); and weather (Thornton et al. 1997); whilst some studies showed that stem volume and soil texture were relatively insensitive to the initial biomass of tree components (Sands & Landsberg 2002; Esprey et al. 2004).

In 3-PG, Paul et al. (2007) found that the most sensitive environmental factors for simulated forest growth using 3-PG were rainfall, mean temperature, and the site fertility rating (0.0 – 1.0). The result revealed that soil fertility rating (FR) has significant effect on growth predictions of trees. The same finding was concluded by Miehle et al. (2009). Despite these efforts, soil fertility rating in 3-PG remains problematic and unsatisfactory (Landsberg et al. 2003) due to widespread inadequacy of soil survey data and poor quantitative understanding of the relationship between soil and plant growth. In fact, there was a suggestion that site fertility may be a stronger determinant of stand LAI than water availability (Hebert & Jack 1998).

As parameters and variables can be unlimited it is necessary to classify them into two major classifications and discuss their roles in the photosynthetic process as per classification below.

5.2.1 Climatic parameters

Food manufacturing process in plants is powered by complex interactions of several factors such as temperature, incident solar radiation, relative humidity, water vapour deficits, and frost. The requirements may vary depending on the type of species, phenology and geographic location.

5.2.1.1 Temperature and solar radiation

Temperature significantly affects the majority of plant processes (Ghannoum et al. 2010). It is a key determinant of the rate of metabolic processes of plants that impacts plant growth with particular influence in photosynthesis and respiration (Landsberg & Sands 2011). Generally, photosynthesis in trees generally achieves a temperature optimum in an operating range of approximately 7-40°C (Sage & Kubien 2007). However, daily minimum and maximum temperatures that plants can tolerate vary enormously for instance tropical trees will stop growing and may be damaged by temperature as low as 10°C whilst temperate species cannot survive in arid conditions where temperature may exceed 40°C (Landsberg & Sands 2011). Spotted gum can survive in a range of 0-32°C mean monthly temperature (McMahon et al. 2010) but germinates at 22°C and thrives in an optimum temperature of 20°C and was used in the study of Paul et al. (2007).

Similarly, solar radiation provides radiant energy that makes plant food production possible. The total amount of energy can also dictate the photosynthetic production of plantation that varies from geographic locations. Specifically, the photosynthetically active solar radiation (PAR) is a visible radiation. Generally termed as ‘light” and is actively involved in photosynthesis. It ranges from 400 – 700 nm within the electromagnetic spectrum. The ratio of light to total solar radiation ranges from 0.4 to 0.6 depending on atmospheric particles and condition and a value of 0.5 is normally used (Landsberg & Sands 2011).

5.2.1.2 Rainfall and frost

Water is an indispensable element in the life of plants. Water molecules and carbon dioxide are then combined in the process to generate organic carbon and oxygen necessary for human life. Through the process of transpiration, water and nutrients from the soil are carried and distributed to different parts of the trees. It is then that water also acts as a carrier of nutrients from one cell to another. In the absence of water such as in arid soil, plants have difficulty and may constrain its growth whereas water supplementation could increase its production. For example, a eucalyptus tree subjected to irrigation during the dry season resulted in increased efficiency. Research showed that eucalypts increased their wood production from 2.55 kg to 3.51 kg per cubic metre of water utilised. Increased water supply also resulted in increased efficiency of converting light energy into fixed carbon ranging from a low of 0.027 mol C to a high of 0.060 mol C per mol of absorbed photosynthetically active radiation (APAR), and the efficiency of bolewood production ranged from 0.78 to 1.98 g wood per MJ of APAR (Stape et al. 2008). Similarly, a study by Hubbard et al. (2010) concluded that increased production of eucalypt plantation was brought about by an increased in water utilization. Rainfall may vary in geographical locations and can result in variations in growth rate such as shown in Table 5.1 which identifies different locations around the study area.

Table 5.1 Growth of spotted gum over a range of rainfall conditions and in favourable soil types (from varied sources).

Sites	Mean annual rainfall (mm)	Growth (in height) (m yr^{-1})	Author
High rainfall area Kandosol (Tiaro)	1050	4.0 m yr^{-1} (12 m – age 3)	(DEEDI 2010); (DAFF 2012)
High rainfall area Ferrosol (Blackbutt)	950	3.3 m yr^{-1} (10 m - age 3)	(DAFF 2012)
Medium rainfall area (Gatton)	833	3.3 m yr^{-1} (10 m - age 3)	(DEEDI 2010); (DAFF 2012)
Low rainfall area Dermosol (Monto)	730	2.5 m yr^{-1} (5 m - age 2)	(DAFF 2012)
Low rainfall area (Warwick)	650	2.5 m yr^{-1} (5 m - age 2)	(DEEDI 2010)

Despite the fact that spotted gum has the capacity to thrive in various soil conditions even in marginalised (nutrient-poor) soil, one of its limitations is the susceptibility to frost (DAFF 2012). Mortality is expected during the first few years when exposed to frost (Dickinson 2009). Similarly, as it grows well in high rainfall areas, poorly-drained sites (e.g. clayey vertosols) with extended waterlogging can result to a moderate mortality and large reduction in growth (DAFF 2012).

5.2.1.3 Humidity and evapo-transpiration

When the temperature is high and humidity is very low whilst cells are saturated with water, plant transpiration is high. This can dry the soil and in the process can retard the growth if soil water is not replaced. Relative humidity, temperature and soil water are actively interacting in the process of transpiration that involves eucalypt tree water absorption. As dry materials can absorb water molecules from a highly humid environment, it is true to some plants and vapour gradients significantly affect plant processes such as transpiration. For instance, Eucalyptus trees showed a strong response to both water supply and atmospheric humidity during the dry season (Stape et al. 2008). At the stand level, increase in water supply (across geographic gradients or from irrigation) often show 50% increases in water utilization by trees and constant or increasing efficiency of water consumption leads to significant increase in stem growth (Binkley 2009).

A study conducted in Brazil showed high transpiration of eucalypt trees and annual water use was found to be 67% of annual rainfall whilst only 58% of the annual irrigation (Hubbard et al. 2010). The rate of net photosynthesis were found to be highly correlated and declined together with the rate of transpiration (MacFarlane et al. 2004). Similarly, rainfall, evapo-transpiration, vapour pressure deficit (VPD) and radiation were found highly correlated with each other affecting the irrigation response of plants (Stape et al. 2010). A study by Stape et al. (2010) also revealed differences in photosynthetic capacity in eucalypt as a result of variation in VPD. While the above mentioned parameters were considered significant to tree growth, the presence of nutrients however cannot be overlooked to be one of the factors affecting it which is discussed below.

5.2.2 Bio-physical parameters

Different models have variable input requirements depending on their purpose, structure and development. As such it is necessary to determine the critical elements composing each model. Waring and Running (2007) identified several bio-physical variables as key drivers for biomass and carbon accumulation such as: specific leaf area, leaf area index, age, biomass allocation, diameter, and density among others.

5.2.2.1 Specific leaf area (SLA) and leaf area index (LAI)

The characteristics of leaves greatly affect tree growth as it captures solar radiation for photosynthetic activities (Poorter & Rose 2005). The foliage has a significant role in the food production process and variation in biomass was mainly due to the difference in morphological and physiological traits such as specific leaf area (Shipley 2006). Moreover, foliage mass also depends on the number of leaves and the tree specific leaf area (SLA) (Landsberg & Sands 2011).

Specific leaf area (SLA), leaf area to mass ratio; $m^2\ kg^{-1}$, normally expressed in dry matter per unit leaf area (Simioni et al. 2003) strongly influences carbon and water fluxes between the vegetation and atmosphere (Kikuzawa 1995). Values range from 10-20 $m^2\ kg^{-1}$ for young eucalypts whilst 4-8 $m^2\ kg^{-1}$ for mature eucalypts (Cromer et al. 1993) whilst a value of 6.01 $m^2\ kg^{-1}$ for both young and mature was revealed by the study of Paul et al. (2007). As SLA can affect the tree canopy biomass and the interception of light, it also affects the leaf area index (LAI). For instance, Drake et al. (2002) and Fahey et al. (2007a) identified leaf area index as a requirement for models that based productivity on photosynthetic process as it provides a measure of the foliar surface area available for capturing solar radiation.

Leaf area index (LAI) is an excellent parameter to base calculations of CO_2 and water vapour exchange (Waring & Running 2007). It is also a key driver of forest plantations growth as it dictates the radiation, nutrient, water, and carbon utilization of trees (Simioni et al. 2003; Smethurst et al. 2003). However, it is environment-dependent and variation is expected from different site conditions (Smethurst et al. 2003). For instance, in several young eucalypt plantations, there was significant correlation between LAI and biomass production up to 3 years of age (Tome & Pereira 1991) and values vary. LAI for *E. globulus and E. nitens* was found was to have a value of 3.5

under water stress and 5.8 under optimal condition while an observed value of 6.0 was observed in Northern Tasmania and predicted to have a maximum of 6.2 (Battaglia et al. 1998).

A separate study showed values for the same species that ranged from 1.4 to 9.6 in 5-8 years of age plantation in Tasmania (Smethurst et al. 2003) whilst another study revealed 3 to 9.8 with fertilization (Smethurst et al. 2004). LAI of 15 was found for *E. globulus* plantations in several sites at south eastern Australia, western Australia and Tasmania under heavily fertilized soil conditions (Landsberg & Sands 2011). Huang et al. (2008) recorded a value of approximately 1.4 for 23 year old spotted gum in Proston located at SEQ on a site with 601 mm average annual rainfall under ferrosols soil whilst Paul et al. (2007) used a value of 3.0.

5.2.2.2 Tree parameters and biomass allocation

Biomass allocation to various part of the trees or commonly called as partitioning is dependent on a complex interplay between its external environment and internal processes. Although temperature, rainfall and soil nutrients have significant roles in growth, it is the internal condition of the trees as affected by these factors that determine biomass allocation on trees (Landsberg & Sands 2011). Allocation of biomass in trees is more complicated in comparison with vegetative plants as it involves storage of biomass in stems and coarse roots which needs to be considered.

Literature has shown discrepancies in the biomass allocation for the foliage, stem and roots of spotted gum. For instance, Smith et al. (2010) concluded that a 20% carbon pool was allocated in the below ground component of spotted gum whilst most of the literature use a 25% root biomass allocation with the rest allocated to the above ground components. Root biomass can be predicted as being 25.9% of the above-ground biomass (Specht & West 2003; Maraseni 2007). These are complicated by a different findings for *C. maculata* showing that 37-50% of carbon sequestered in the total tree biomass is in the stem while 18-27% is in branches and roots and the remainder is in bark and foliage (Paul et al. 2008). As 3-PG predictions of stem volume were relatively insensitive to the initial biomass of tree components, a default of 1 gram seedlings was initially set for all the sub-regions of SEQ (Sands & Landsberg 2002).

Height and diameter at breast height (dbh) are significant variables that determine a trees volume. Growth of trees is usually measured and its rate indicated by these two variables that are dependent on climatic and bio-physical factors. The volume increment which served as growth indicator are conventionally expressed either as a *current annual increment* (CAI) or *mean annual increment* (MAI). These growth parameters are desirable in measuring tree volume, however, MAI cannot be measured directly for a single measure, but may be predicted from the height-age relationship (Vanclay 1992) and from diameter and stem number (Landsberg & Sands 2011). This study will adopt MAI as an expression in determining the volume of the timber and was used in the analysis in comparing the most appropriate and suitable sites for plantation.

Wood density is important as it affects the wood biomass. Density is commonly derived from mass and volume of trees and is defined here as the oven-dry mass per unit of volume expressed in tons/m^3. These parameters may vary depending on the site attributes and age. For instance, Ximenes et al. (2008) reported the basic density (kg m^{-3}) of 71 trees ranging from 513 to 884 kg m^{-3} for spotted gum. Trees were sampled from low, medium and high quality sites for a 20 year old spotted gum in Queensland and New South Wales. However, Paul et al. (2007) assumed an average stem wood density for *C. maculata* to be 654 kg m^{-3} regardless of stand age or tree size. This value was not used as it can cause inaccuracy as most of the studies showed that density varies with age and size. Even trees found in a single plantation can vary. Values reported by Maraseni (2007) were used primarily for the modelling as those were specifically for spotted gum in Queensland. The minimum value of 644 kg m^{-3} for young (11 years) and 802 kg m^{-3} for mature tree (41 years) was used as input variables for basic density (DAFF 2012).

5.2.3 Soil parameters

Higher forest productivity means better carbon sequestration rates and stakeholders such as forest landowners can acquire higher carbon credits from forest plantations via soil fertilization. Fertilization is a common practice in forestry that can enhance site productivity through increased growth. This practice was considered in this study to catalyse the removal of carbon dioxide from the atmosphere and enhance the production of carbon in the spotted gum plantation. Soil nutrients must be provided at rates that will maintain plant growth rates and consistent with the maximum obtainable growth rates as plants mature (Ingestad 1982). The bio-physical parameters used in the initial fertility rating (FR) determination were often used in determining suitable sites for spotted gum and were mostly the contention of previous studies. This is because there has been no FR formula developed that can capture the complicated soil chemistry and its impact to plants. At the same time, it is ironic that through centuries of research, soil chemistry has not yet been fully understood as it affects the biomass accumulation in plants.

5.2.3.1 Soil fertility

Several studies have formulated a fertility rating in an attempt to establish a process based model that will capture the factors affecting plant growth through soil fertility and nutrition. In 3-PG, soil fertility rating (FR) is a concept involving empirical index that ranks soil fertility on a scale from optimum (1) to extremely infertile (0) (Almeida et al. 2010).

Soil fertility can be formulated in the form of nutrient limitation such as that of a concept by Resende et al. (1999) and applied by Gomes and Curi (2001). The study utilised weights on several factors such as natural and potential fertility, water, oxygen, management and topography. Each factor was ranked based on its limitations. The rankings allocated for each of the factor was dependent on the limitations such as 1.0 = null/no limitation, 0.8 = slight limitation, 0.6 = moderate limitation, 0.4 = strong limitation, and 0.2 = very strong limitation. The relative weight of each factor was given as follows: fertility limitation (FL) = 0.4, water limitation (WL) = 0.2, oxygen limitation (OL) = 0.1, management limitation (ML) =

0.2 and topography limitation (TL) = 0.1 and is given by the formula below (Eq. 5.1). The total weights are normally 100%, either 1.0 or an accumulated 100 points.

FR = (FL * 0.4) + (WL * 0.2) + (OL * 0.1) + (ML * 0.2) + (TL * 0.1)   (Eq. 5.1)

The formula was based on an idea that the effects of soil fertility on the growth of eucalypt plantations is not limited to soil chemical factors and should also include soil physical factors that can also influence nutrient uptake by the trees (Almeida et al. 2010). All the limitation values were estimated for each soil units identified in the study. This may seem acceptable for this study, however, the weightings of each factor lack justifications for eucalyptus plantation growth.

It must be emphasised here that the soil fertility rating in 3-PG remains problematic and unsatisfactory (Landsberg et al. 2003). The problem of how to assign site fertility indices for use with 3-PG has been widely raised issue and so far, there is no simple objective means for assigning FR on the basis of soil chemistry that is currently available (Landsberg & Sands 2011).

To increase the accuracy of the biomass modelling in this study, a fertility rating was formulated which incorporated five critical soil nutrient requirement of spotted gum to complement the growth simulation of spotted gum using 3-PG. This was detailed in the methodology section of this chapter.

5.2.3.2 Soil nutrients

Literature identified that nutrient requirements such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and boron (B) were identified to be the most important nutrients for tree production. The average rate of nitrogen application in hardwood plantation in Australia (2002-2004) was 48 kg N ha^{-1} in hardwood species (May et al. 2009). It must be noted that this value (48 kg N ha^{-1}) was for a year only and considered 50% of the total hardwood plantations across Australia and was not specific for eucalyptus. The level of fertilizer that will provide an acceptable growth and survival changes in unit wood value in response to fertilizer, effects on tree form, growth and timing of fertilizer applications were not considered in the study (May et al. 2009).

Knowledge of the accumulated nitrogen pool on the soil available for the plantation is necessary. Fertilization is commonly performed twice during the entire pre-determined life cycle of the plantation. Application is normally done during the initial stage of plantation establishment and during the mid-rotation on its seventh year. Determination of the total nitrogen available for trees is deemed appropriate in the fertility modelling to account both the fertilization period. The studies of Gava (1997) was used in this studies and thus accumulated fertilizer on soil for the whole plantation rotation was considered. This was applied in this study because of the long rotation period (100 years) involved in spotted gum plantation.

Nitrogen and phosphorous were reported to be the most common nutrients deficient anywhere in Australia (May et al. 2009). Whist nitrogen can be easily leached, there is a need for high nitrogen fertilization whereas phosphorous strongly adheres with soil particles and frequent fertilization is not necessary. Nitrogen fertilizer use in forestry is at 1.0% of the total applied across Australia each year, whilst 0.9% of phosphorus and 1.4% for potassium.

Favourable yield can only be sustained by ensuring soil fertility. Export of nutrients can diminish growth rates of trees making it necessary to apply fertilizers in order to maintain yield. Potassium is not mobile and leaching is not a problem for this nutrient. Leaching of fertilizer is not included in this study thus, will not be discussed nor elaborated here.

5.3 Methods

5.3.1 Process based modelling and parameterisation

During the data collection, it was found out that spotted gum time series empirical data were scant as hardwood plantations particularly for spotted gum was only established during the mid of 1990s. In addition to this, the recent commercialization and privatization of government plantations has made datasets difficult to acquire. There is also lack of full-rotation plantation growth data for spotted gum (Huth et al. 2004; Maraseni et al. 2008). As such, the available data from the literature was adopted as the primary source of estimation and extracting information on the potential productivity of the species under study.

5.3.1.1 Climatic parameters

Climatic data such as rainfall (mm), maximum and minimum temperature (°C), frost (days), solar radiation (MJ m^{-2}) ranging from various years were used as input in the growth simulation depending on the location of the 11 sampled simulation sites (Table 5.2). Average values of each parameter were calculated based from the available datasets for various years from 1891 up to 2011. Values were downloaded from the Bureau of Meteorology (BOM) website (www.bom.gov.au) with some dataset gaps filled by the use of *Rainman v.4.3* that was connected with the DERM's local weather station data.

Average monthly rainfall (mm) calculated from various years was summated to determine the mean annual rain occurring in the area while temperature, solar radiation and frost were average monthly occurrences. All of the climatic parameters used a specific local datasets from the nearest meteorological stations whereas an average value of 232.63 mm for the whole south east Australia derived from 35 years of historical data (1975-2009) for evaporation was applied due to lack of available datasets. This is acknowledged as a factor that may cause error in estimation, as evaporation may vary depending on rainfall and solar radiation. However, with the lack of datasets specifically on a regional scale, this was most suitable. The average evaporation for the whole south east is an estimate for the study area and thus, is a limitations of this study.

Simulations were run using the 16-year cycle of actual monthly climatic data collected from the nearest and adjacent meteorological stations of the sampled data. The 140-

year historical datasets for climatic datasets were used in simulating biomass for 100 year rotation period with the assumption that the climate would not drastically change within the next 100 years. The table 5.2 summarises the climatic variables existing in the sampled study site with annual mean for various years from 1891-2011.

Table 5.2 Climatic data (1891-2011) for selected sub-regions downloaded from the Bureau of Meteorology (BOM) and the Department of Resources and Management (DERM) websites.

Sub-region in SEQ	Longitude	Latitude	Rain (mm yr^{-1})	Mean Temp (°C)	Mean Solar Rad (MJ $m^{-2}\,yr^{-1}$)	Frost (days yr^{-1})
SEQ 9 - Great Sandy	152.82438	-25.78830	1257.19	21.84	19.51	5.72
SEQ 8 - Burnett Curtis Coastal	152.15924	-24.79059	1095.31	21.23	20.14	5.83
SEQ 8 a – Burnett Curtis Coastal	152.67926	-25.73993	1029.05	21.11	19.07	5.72
SEQ 7 - Gympie Block	152.42530	-26.03622	956.65	20.37	19.20	15.18
SEQ 7 a - Gympie Block	152.55833	-26.35065	1175.74	20.16	18.94	11.98
SEQ 7 b – Gympie Block	152.62484	-26.46554	1175.74	20.16	18.94	11.98
SEQ 6 - South Burnett	151.68760	-26.07855	724.60	21.23	19.65	16.00
SEQ 6 a - South Burnett	151.86295	-26.47763	765.16	18.58	19.45	27.30
SEQ 3 – South East Hills and Ranges	152.55833	-26.89485	953.76	19.74	18.87	8.88
SEQ 2 – Moreton Basin	152.57042	-27.56604	781.23	19.93	19.10	11.83
SEQ 2 a - Moreton Basin	152.49786	-28.00140	946.68	16.58	18.88	14.78

5.3.1.2 Bio-physical parameters

The parameter values in Table 5.3 were determined from literature (Paul et al. 2007) and calculated from the available datasets of Warrill View (Lee 2010b). These were then applied in this study whilst most of the parameter values were adopted from the intensive study of Paul et al. (2007) on spotted gum specifically the *C. maculata*. As there is no significant variance on the taxonomic identities of *C. maculata* and *C. citriodora* (Lee et al. 2009), and in the absence of data, similar parameter values were deemed applicable in this study. To increase accuracy of growth simulation specific for spotted gum, important parameters were fine-tuned using the 15-year empirical dataset (Lee 2010b).

The remainder of the variables not listed were set as default values from the studies of Sands and Landsberg (2002) for *E. globulus*. For instance, the canopy quantum coefficient (α) with a value of 0.06 and the conductance parameters found to be applicable for most of the hardwood species (Sands & Landsberg 2002). Similarly, default values for the light interception, minimum and maximum fraction of NPP to roots, litterfall, turnover rates and self-thinning were used as these values were derived from various studies and were acceptable. Rather than using the global average of the minimum and maximum ratio Net Primary Productivity/Gross Primary Productivity (NPP/GPP) (*Y*), a value of 0.47 for *E. globulus* was used being in the same family and genus.

Table 5.3 Parameters used for growth simulation.

Meaning	Name	Units	Values
Constant in the stem mass v. diam. Relationship	aS	-	0.184
Power in the stem mass v. diam. Relationship	nS	-	2.32
Optimum temperature for growth	Topt	deg. C	20
Specific leaf area at age 0	SLA0	m^2/kg	6.01
Specific leaf area for mature leaves	SLA1	m^2/kg	6.01
Branch and bark fraction at age 0	fracBB0	-	0.56
Branch and bark fraction for mature stands	fracBB1	-	0.35
Age at which fracBB = (fracBB0+fracBB1)/2	tBB	Years	9
Minimum basic density - for young trees	rhoMin	t/m^3	0.644
Maximum basic density - for older trees	rhoMax	t/m^3	0.802
Age at which rho = (rhoMin+rhoMax)/2	tRho	Years	26
Days production lost per frost day	kF	Days	1
Maximum stand age used in age modifier	MaxAge	Years	120
Power of relative age in function for fAge	nAge	-	10
Age at canopy cover	fullCanAge	Years	4
LAI for maximum rainfall interception	LAImaxIntcptn	-	6

Effect of salinity was incorporated *via* the seedling mortality parameter. Seedling mortality rate for each sampled site was dependent on the salinity level and values inputted vary from 0.08 to 0.83 percent per year. Seedling mortality rate (gammaN0) and large tree mortality rate (gammaNx) was given a zero value when healthy and devoid of any disease. Limited studies have been undertaken for long term plantations with most conducted for short-term rotation periods. This limitation coupled with the commercialization of forestry industries, has made time series data difficult to obtain. Therefore, the 15-year empirical dataset for spotted gum (Lee 2010b) and the available literature such as that of Maraseni (2007) were used to calibrate the 3-PG and calibrated spotted gum parameters based on 55 sites from the study conducted by Paul et al. (2007).

5.3.1.3 Height, diameter, density and biomass allocation

As biomass allocation for the foliage, stem and roots of spotted gum varies per literature, a default value of one gram seedling was initially set for all the sub-regions of SEQ (Sands & Landsberg 2002). This value assumes that each seedling attains a one gram weight at the initial stage of planting. As biomass calculation for spotted gum cannot proceed without the knowledge of tree volume at specific age, volume was determined first with the application of appropriate allometry. Whilst height and diameter (dbh) are related and are indispensable variables for volume determination, the 15-year raw data was initially used to predict height values from 16 years onward. Given the stocking density (in stems per hectare – sph), diameter, and allometric powers height prediction followed with the use of the formula (Eq. 5.2) below.

$$H = a_H d_B^{n_{HB}} (Ns\ /1000)^{n_{HN}} \qquad \text{(Eq. 5.2)}$$

Where H is the height, a_H is the scale factor, d_B is the stem diameter, n_{HB} and n_{HN} are the allometric powers and the division of N_s by 1000 is for numerical convenience (Landsberg & Sands 2011). In the same manner, volume was predicted using the following formula (Eq. 5.3):

$$V_s = a_V d_B^{n_{VB}} (Ns\ /1000)^{n_{VN}} \qquad \text{(Eq. 5.3)}$$

where, V_s is the volume, av is the allometric coefficients, d_B is the stem diameter, n_{VB} and n_{VN} are the allometric powers specific to the spotted gum after observed height and volume data were both fitted to observed diameter and stem number. The division of N_s by 1000 is for numerical convenience. The mean annual increment (MAI) was simply determined when V_s was divided by the plantation age. However, an approach applied in this study to determine stem volume under bark was based directly on the predicted stem biomass (Ws) by subtracting the biomass in branches and bark after which mass was converted to volume using the basic density. The process used information on the branch and bark fraction P_{BB} from the study of Paul et al. (2007) and the basic density ρ_w (kg m^{-3}), both of which are explicitly age-related. The volume under bark Vs (m^3 ha^{-1}) used Landsberg and Sands' (2011) formulation (Eq. 5.4) below:

$$Vs\ = 1000\ \frac{(1-P_{BB})Ws}{\rho_w}, \qquad \text{(Eq. 5.4)}$$

As the basic density is in the form of tonnes per cubic metre, it was necessary to include a value of 1000 to convert the tonnes to kilogram while the branch and bark fractions found by Paul et al. (2007) was used as default in the simulation.

The spotted gum wood density published by DAFF (2012) were used primarily for the modelling as those were specifically for spotted gum in Queensland. The minimum value of 644 kg m^{-3} (0.644 tm^{-3}) for young (age 11) and 802 kg m^{-3} (0.802 tm^{-3}) for mature (age 41) were used for basic density values with an average age of 26 used as input in the 3-PG parameterisation.

The seedling biomass during the initial stage was given component allocation of 50% for foliage biomass (W_f), 25% for root biomass (W_r), and 25% for stem biomass (W_s). This allocation was based on previous studies such as that conducted by (Landsberg & Waring 1997).

5.3.1.4 Specific leaf area (SLA) and leaf area index (LAI)

To validate the specific leaf area, 320 spotted gum leaves were collected and sampled. Two trees that were locally accessible were sampled by collecting equal amount of leaves for each. The trees were located in Toowoomba with a mean annual rainfall of 678 mm and solar radiation of 19.6 megajoules per square meter per year (MJ m^{-2} yr^{-1}) averaged for the past 10 years.

The canopy of each tree was subdivided based on vertical direction, the upper and the lower canopy. It was further subdivided into two horizontal directions (southeast and northwest) creating four (4) compartments for each canopy namely: upper northwest (UNW), lower northwest (LNW), upper southeast (USE) and lower southeast (LSE). Assistance from the USQ Technical Staff with the use of cherry picker was required and leaf samples were collected from sampled trees. Forty leaf samples were collected from each compartment after which all leaves were weighed individually using a portable digital balance (0.001g). Leaf area was also recorded using the planimeter. Immediately after measurements, all the leaves were oven-dried at 65°C temperature for 72 hours.

After oven-drying, the final weight and area was measured and recorded. Data was processed and results compared with that found by Paul et al. (2007) for *E. maculata*. The specific leaf area (SLA) was calculated using the equation (Eq. 5.5) below:

$$SLA\ (m^2\ kg^{-1}) = total\ leaf\ area\ (m^2)/leaf\ dry\ weight\ (kg) \qquad \text{(Eq. 5.5)}$$

The specific leaf area (SLA) of the trees was then used to calculate the leaf area index (LAI) *via* fundamental relationship of leaf area and foliage mass through the mathematical equation (Eq. 5.6) shown below.

$$\text{LAI} = 0.1 * \sigma_f * W_f \qquad \text{(Eq. 5.6)}$$

Where LAI stands for the leaf area index (dimensionless), 0.1 is a factor used to convert kg to tons and m^2 to hectare, σ_f is the foliage mass (m^2 kg^{-1}), and W_f is the stand foliage mass (ton ha^{-1}). The calculated SLA value of 5.94 m^2 kg^{-1} was used in LAI determination with the spotted gum stand foliage mass. LAI was used to determine how much photosynthetically active radiation (PAR) was intercepted by canopy that predicted the photosynthetic production of tree foliage. However, the computed SLA derived here was not used as input in 3-PG modelling. Instead, the Paul et al. (2007) value of 6.01 m^2 kg^{-1} was utilised as his sampling observations were intensive for Queensland. Similarly, a default value of 6.0 for LAI was also adopted.

5.3.2 Nutrient unit conversion

Some of the nutrient data, in particular calcium and magnesium were in the meq $100g^{-1}$ unit of measurements whereas nitrogen, potassium and phosphorous were in mg kg^{-1}. Calcium and magnesium were converted to mg kg^{-1} for a uniform and standard measurement. Specifically, both calcium and magnesium with the meq $100g^{-1}$ units were converted to mg kg^{-1} by using an appropriate formula derived from DA-KSU (2014) (Eq. 5.7) that involves use of the nutrients' valence and atomic weights. To compare the datasets with the most common unit of measurement, values were also converted to kg ha^{-1} using equation 5.8 indicated below.

$$Nutrient\ (mg\ kg^{-1}) = (([AW/V] * Eq) * k \qquad \text{(Eq. 5.7)}$$

$$Nutrient\ (kg\ ha^{-1}) = (([Eq * A]/V) * (AW/A)) * K \qquad \text{(Eq. 5.8)}$$

where, *Eq* equals 1 meq/1000, *V* stands for valence and *AW* is the atomic weight of the element. The constant number *k* representing the number 100 that was used to convert g $100g^{-1}$ into mg $kg^{-}1$, *A* stands for Avogadro's number which is 6.02 x 10^{23}, whereas *K* is a constant number 22400, used to convert g $100g^{-1}$ into kg ha^{-1}. The valence of calcium and magnesium is both 2.0 whereas its atomic weights are 40.078 and 24.305, respectively as indicated in the periodic table.

There was no mathematical manipulations applied in converting the initial units of measurement for nitrogen, phosphorous and potassium as they were in mg kg^{-1} form and therefore, values were retained.

5.3.3 Fertility rating

This study preferred to adopt FR that could capture soil fertility through the incorporation of soil nutrients. As soil nutrients play a significant role in the growth stages of trees, fertility rating was further enhanced by evaluating the most limiting nutrients that can impact the growth of spotted gum. This was assessed to be a more objective approach in the derivation of fertility rating.

The five soil nutrient requirements sensitive for spotted gum growth as a result of literature review were employed for fertility rating modelling. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and boron (B) were identified to be the most important nutrients. However, due to lack of data, boron was excluded in the analysis. Information on the required level for each elements was gathered from literature. Optimum level for each nutrient that provides the best condition for spotted gum growth was searched from past studies. The table below (Table 5.4) was used in determining the optimum level of each nutrient for spotted gum.

Thematic layers of each soil nutrients were downloaded from the website of the Australian Spatial Data Directory (ASDD) (http://asdd.ga.gov.au) under the Nutrient Status of Australian Agricultural Soils (1989-1999) page. The datasets were primarily managed by the Department of Agriculture Fisheries and Forestry: Australian Bureau of Agricultural and Resource Economics and Sciences. As soil nutrient datasets acquired were points, interpolation was necessary to come up with values for the whole study site. Thus, all of the points of each soil nutrients (e.g. N, P, K, Ca, Mg) were interpolated using the geostatistic method. As mentioned previously, the raw datasets (Table 5.5) were converted to a common unit (mg kg^{-1}) prior to interpolation and GIS processing.

Table 5.4 Nutrient requirements of spotted gum for more than 7 years rotation period on a top 30 cm soil surface.

Nutrient/ Element	Category	Range (kg ha^{-1})
Nitrogen	Very low	0 – 500
	Low	501 – 1000
	Medium	1001 – 1559
	High/Opt.	1600 – 1900
	Very high	> 1900
Phosphorus	Very low	0 – 24
	Low	25 – 45
	Medium	46 – 71
	High/Opt.	72 – 137
	Very high	> 137
Potassium	Very low	0 – 100
	Low	101 – 200
	Medium	201 – 300
	High/Opt.	301 – 500
	Very high	> 500
Calcium	Very low	0 – 160
	Low	161 – 1007
	Medium	1008 - 1200
	High/Opt.	1201 – 4000
	Very high	> 4000
Magnesium	Very low	0 – 45
	Low	46 – 83
	Medium	84 – 295
	High/Opt.	296 – 800
	Very high	> 800

Table 5.5 Datasets of soil nutrients processed for fertility rating determination.

Nutrient/ Element	Soil depth (cm)	Soil test	Units
Nitrogen (N)	0-60	Colwell test	mg kg^{-1}
Phosphorus (P)	0-15	Colwell test	mg kg^{-1}
Potassium (K)	0-15	Colwell test	mg kg^{-1}
Calcium (Ca)	0-15	Exchangeable Mg	mEq100g^{-1}
Magnesium (Mg)	0-15	Exchangeable Mg	mEq100g^{-1}

5.3.4 Spatial interpolation

The downloaded point datasets of the five soil elements for SEQ were interpolated using the geostatistical analysis tool in ArcGIS v.10. This process created a polygon with continuous values for each grid of the study site, providing information on the unsampled cells. Soil nutrient datasets were interpolated using appropriate techniques. Although there are several methods available for interpolating soil properties, the kriging model was used due to the following reasons: (1) it suits best the soil parameter characteristics, (2) provided the optimal spatial estimate, (3) generated the most unbiased estimate at each location, (4) employed a variogram model, and (5) provided the lowest errors as compared to inverse distance weighting (IDW) and spline.

The nature of spatial correlation between two nutrient samples on the study area was assumed to be dependent mainly on its distance which can be visualised using the variogram. Universal and ordinary kriging were the two surface estimators that best fitted the soil nutrients in this study. Universal kriging best fitted the nitrogen (N), phosphorous (P) and potassium (K) whilst ordinary kriging was found to be the most appropriate estimator for calcium (Ca) and magnesium (Mg). Finally, a cross validation test was conducted for each nutrients.

Several models were generated from the kriging techniques in which two models with the lowest root mean squared (RMS) were chosen. These models were further subjected to statistical analysis and were compared. The final model with the highest R^2 was used in further processing.

5.3.5 Fuzzy classification

After the interpolation process and nutrient level assessment, soil nutrients were classified. The fuzzy membership technique was applied to all the nutrients to come up with a common range of classification, 0 to 1. Null values (0) were considered the least fertile whereas a value of 1 provides a maximum value for soil without nutrient limitation. The fuzzy tool was preferred as it includes all the values in the datasets and provides a model for assigning values to each members in the population.

Prior to fuzzy classification, the effects of each nutrient in the growth of spotted gum as per literature review were modelled using the following Gaussian function (Eq. 5.9).

$$\mu(x) = e^{-fi * (x-f2)^2} \qquad \text{(Eq. 5.9)}$$

where, x is a fuzzy membership, fi is the spread and $f2$ is the midpoint. A value of 0.1 was used as spread for all the soil nutrients while midpoints vary depending on the average optimum nutrient requirements of the spotted gum. The spread in this case is the slope while the midpoint used was the optimum values or sufficiency range of soil nutrients that provides the best growth.

This concept was adopted from Sands and Smethurst (1995) showing the different stages of trees as affected by variations in nutrients. It further theorised that an excessive amount of nitrogen application can lead to toxicity level and therefore, growth cannot be considered linear as more and more fertilizers are supplied. The Gaussian function in the fuzzy membership tools is considered appropriate in the reclassification of the soil nutrients due to the following reasons: (a) it fits the behaviour of the tree response to each nutrient, (b) it has flexibility that meets the required adjustments based on the behaviour of the dependent variable, and (c) suitable for variables that has no clear delineation or boundary (Banai 1993). Fuzzy logic was used to generate weights as it is capable of including the gray area between 0 and 1 which was not being captured by the Boolean logical principle.

After the fuzzication method, the spatial analyst tools were used to further process all the thematic layers to generate the fertility rating. The weighted summation in the spatial analyst tool was applied in developing the fertility rating (FR) map. The use of weighted average (Eq. 5.10) created the final rating.

$$FR_i = N_i\ (w_N) + P_i\ (w_P) + K_i\ (w_K) + Ca_i\ (w_{Ca}) + Mg_i\ (w_{Mg}) \qquad \text{(Eq. 5.10)}$$

where, FR_i is the fertility rating of the *i*th cell derived from the summation of corresponding nutrients for each cell location. N_i is the value of nitrogen, P_i is the phosphorous value, K_i stands for potassium value, Ca_i is the calcium value, and Mg_i is the value of magnesium for each and every *i*th cell. Distribution of weights (*i.e.*, w_P, w_K, w_{Ca}, w_{Mg}) for each nutrient was designated to all the nutrients and were as follows: $w_N = 41.67$, $w_P = 3.78$, $w_K = 16.94$, $w_{Ca} = 32.33$, $w_{Mg} = 5.28$. This values were based from the allocated need of spotted gum as determined from the literature. After the *FR* map was created, it was standardised with the use of raster calculator algorithm in ArcGIS following the equation below (Eq. 5.11).

$$S_i = (X_i - X_{min}) / (X_{max} - X_{min}) \qquad \text{(Eq. 5.11)}$$

Where S_i is the standardised value, X_i is the *i*th cell value, X_{min} is the minimum value and X_{max} stands for the maximum value. Finally, FR values for all the sampled sites were extracted from the created FR map and were used as a parameter input in the biomass simulation with 3-PG.

The thematic *FR* layer was reclassified into five classes to determine where the most fertile soils are located. The map was equally classified into five levels of fertility ranging from 0 to 1.0 and named as very low, low, moderate, high (or optimum) and very high corresponding to five classifications for the nutrient requirements of the spotted gums.

5.3.6 Analysis and validation

Sub-region 6a was chosen for sensitivity analysis for ease of validation. The analysis was conducted through biomass simulation with various rainfall levels. The simulation was reiterated at every 100 mm rainfall interval starting from 400 to 1200 mm. After this, the biomass and MAI percent change were calculated. The results were analysed to elicit information on the sensitivity of spotted gum growth rate to the changes in the amount of rainfall.

As there were no studies conducted specifically for spotted gum in SEQ on this area of research, the results of this study were compared with the previous work of several authors particularly the map generated by the CSIRO which also utilised GIS. Statistical analysis including correlations and model efficiency were applied to determine the validity of this research. The accuracy of the simulation was further assessed by calculating the variation of the observations using the root mean square error, *RMSE* (Eq. 5.12) and coefficient of determination, *CD* (Eq. 5.13).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Pi-Oi)^2}{N}} \quad \text{(Eq. 5.12)}$$

$$CD = \sqrt{\frac{\sum_{i=1}^{n}(Oi-\bar{O})^2}{\sum_{i=1}^{n}(Pi-\bar{O})^2}} \quad \text{(Eq. 5.13)}$$

where, *RMSE* is the root mean square error, P_i is the estimations, O_i is the observations and N is the number of observations. This equation was used to determine the variation or the mean distance of the observations from the estimated simulations measured along a vertical line (Fontes et al. 2006). The closer the computed coefficient to 0, the more accurate the model is. Lastly, the coefficient of determination (CD) is a measure of the proportion of the total variation in the observations that was explained by the simulation. Results may range from 0 to any number. A value of 1 or more may mean that the deviations of the simulations from the mean of the measured values are less than that observed in the measurements. Conversely, value less than 1 indicates that the deviation from the mean is greater than observed in the measurements.

5.4 Results and discussion

5.4.1 Soil nutrients interpolation and validation

In determining the best interpolation model to use, it is best if the model is subjected to statistical analysis. The results of the statistical analysis for the interpolated soil nutrients showed a degree of variations for each nutrients. The model with the lowest root mean square error (RMSE), mean standard error (MSE) and root mean square standardised (RMSS) was chosen for each training data set and is tabulated below (Table 5.6).

The generated validation table indicated the choice of the techniques most appropriate for each nutrient (Table 5.7). In addition, the performance of coefficient of determination (R^2) was able to measure the variability of all the data sets in response to its location as explained by the model.

Table 5.6 Statistical errors from the geostatistical processing.

Error Stat	N (n = 31)	P (n = 350)	K (n = 345)	Ca (n = 357)	Mg (n = 356)
Mean	0.08	-0.22	22.31	0.05	0.05
Root mean square error (RMSE)	10.36	28.12	108.36	5.16	3.62
Average standard error (ASE)	10.06	29.92	108.25	5.52	3.83
Root mean square standardised (RMSS)	0.90	0.94	0.96	0.93	0.95

Table 5.7 Interpolation techniques and correlation results for soil nutrients.

Elements	Interpolation technique	R^2
N	Universal Kriging	0.89
P	Universal Kriging	0.65
K	Universal Kriging	0.66
Ca	Ordinary Kriging	0.76
Mg	Ordinary Kriging	0.82

Values for each sub-regions were extracted from soil nutrients interpolated map. The result was tabulated below (Table 5.8) providing information on the spatial variation of soil nutrients in different sub-regions.

Table 5.8 Soil nutrient values for each sampled sites.

Sub-region	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)	Ca ($kg\ ha^{-1}$)	Mg ($kg\ ha^{-1}$)
9	5.91	42.57	166.28	919.10	327.66
8	6.06	38.38	146.41	1125.49	337.45
8a	2.00	55.86	96.34	811.39	214.88
7	7.63	28.63	130.92	1668.62	608.25
7a	8.24	43.21	260.74	1517.80	717.57
7b	7.72	31.73	265.48	2542.10	1068.43
6	7.23	57.98	252.60	2288.38	751.58
6a	8.98	48.86	186.24	1463.36	448.17
3	12.12	78.77	409.84	2406.30	1239.93
2	9.21	30.18	363.39	3147.51	1240.81
2a	10.51	21.56	284.95	2419.91	1039.50

5.4.1.1 Nitrogen (N)

Geostatistical processing showed statistical errors of nitrogen with root mean square (RMSE) of 10.36 and average standard error of 10.06. Discrepancies may come from technical or manual errors. It must be noted that nutrient datasets used in this study were derived from a secondary source and not the primary output of this research. Results of the data processing may have been affected by the nature of the data itself such as the limited number of samples taken from an expanse of SEQ area. Due to the absence of sufficient data, all the downloaded points for nitrogen were considered as samples. It is worth mentioning that samples for nitrogen (n = 31) was not statistically significant considering the expanse of the study site, however in the absence of primary data for nitrogen, this was deemed useful albeit one of the limitations of this modelling. The level of nitrogen sufficiency with the corresponding amount as per kriging technique was presented below (Table 5.9).

Nitrogen (N) was found to be very low at all sub-regions (Figure 5.1) which ranged from 0.38 – 38.74 kg ha^{-1}. The map shown in Fig. 5.1 was further categorised into three for classification purposes nevertheless, the whole region is technically considered as “very low” in nitrogen content.

Table 5.9 Nitrogen values derived for each sampled sites.

Sub-region	N (kg ha^{-1})	Nutrient Level
9	5.91	Very low
8	6.06	Very low
8a	2.00	Very low
7	7.63	Very low
7a	8.24	Very low
7b	7.72	Very low
6	7.23	Very low
6a	8.98	Very low
3	12.12	Very low
2	9.21	Very low
2a	10.51	Very low

Based on the 7-year growth requirement of the plantation indicated in the table of nutrient requirement, the level of nitrogen found in the results showed a clear indication that nitrogen is a limiting element. These levels are considered highly deficient and cannot sustain a one year plantation growth except when fertilisation is conducted on a regular period. These values are possible as nitrogen are highly leachable. Similarly, the tabulated results indicated the contents of nitrogen in all eleven sampled sites are very low.

It must be noted that mostly, hardwood plantation has 100 kg ha^{-1} whilst 126 kg ha^{-1} is considered high rate fertilizer application for Eucalyptus plantation as reported by Stape et al. (2004). Though this amount is for one time application only which is usually performed during the seventh year, it is useful in terms of comparison of the levels of nitrogen concentration of the site, if only a year of fertilisation is considered. However, given the length of the rotation period of spotted gum plantation, this amount is not sufficient and the tabulated nutrient requirement must be referred to if the aim is to reach an optimum level of biomass for the plantation. For a one year (7^{th} year) nitrogen application, the optimum level adequate to maintain forest trees ranges from 112-168 kg ha^{-1} and 95 kg ha^{-1} is considered as a critical threshold. In this case, the nitrogen range on the study site (0.38 – 38.74 kg ha^{-1}) can be considered of very low level.

It is assumed that changes in soil use will not occur within the rotation period and therefore mineralization of organic matter will not alter the main source of N for trees in addition to N supplementation via fertilization. This assures that trees can easily take up nitrogen in all sub-regions that can effect a yield increase so long as fire will not be used as silvicultural management as fire can easily deplete nitrogen supply in soil and diminish soil fertility.

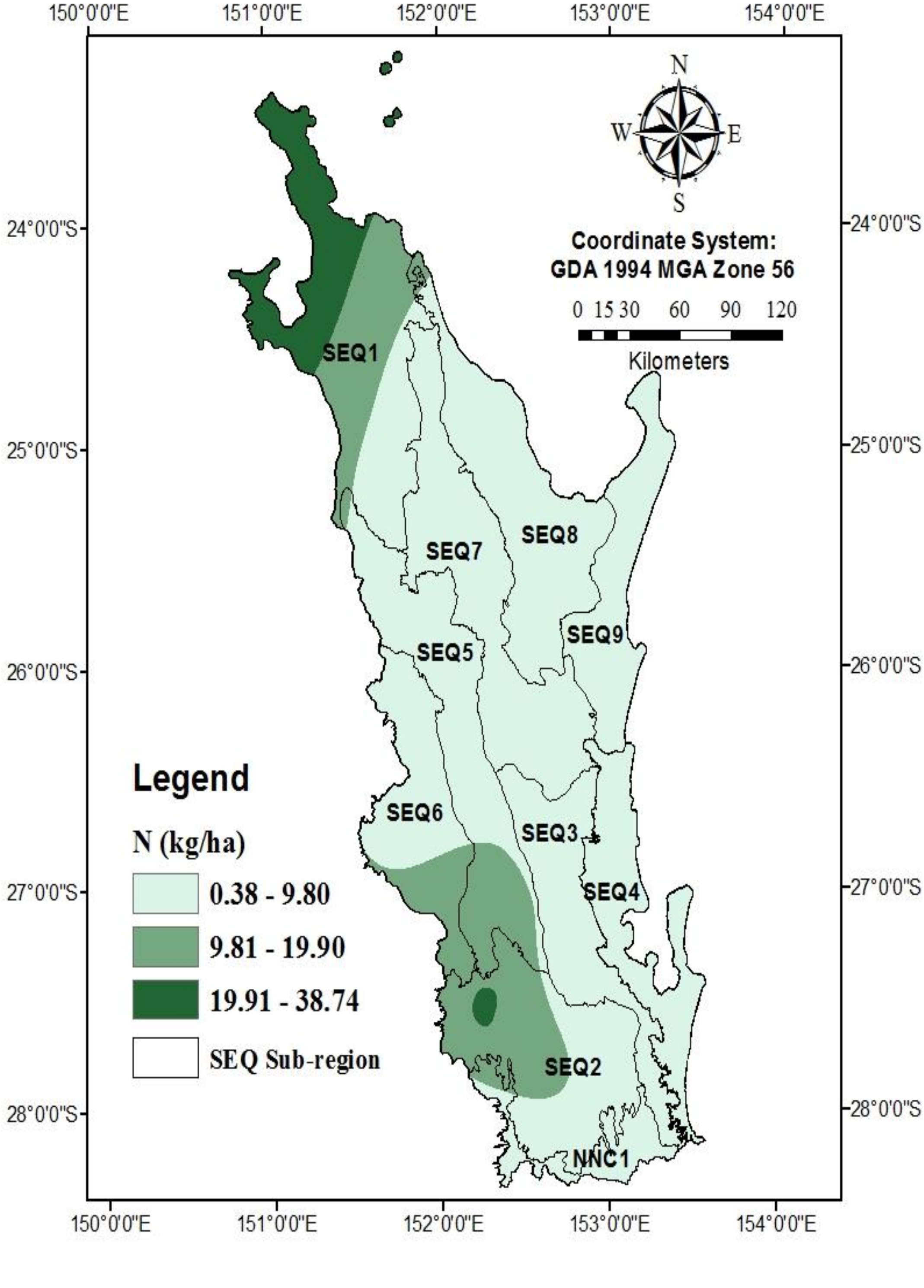

Figure 5.1 Nitrogen concentration and distribution in the study area

5.4.1.2 Phosphorous (P)

The result of phosphorous sampling in selected sites provided a range within very low to high level (Table 5.10). There is high variation in the concentration of this element that could provide differences in the yield of spotted gum throughout the regions.

Table 5.10 Phosphorus values derived for each sampled sites.

Sub-region	P (kg ha^{-1})	Nutrient Level
9	42.57	Low
8	38.38	Low
8a	55.86	Moderate
7	28.63	Low
7a	43.21	Low
7b	31.73	Low
6	57.98	Moderate
6a	48.86	Moderate
3	78.77	High
2	30.18	Low
2a	21.56	Very Low

The result of P visualization showed a very low to high level of this element in the study site (Figure 5.2) ranging from 1.20 – 97.00 kg ha^{-1}. As shown in the map, the concentration of the element is sporadic and there was no pattern of its distribution though it can be seen that high levels are mainly concentrated at sub-regions 2, 4 and 6 which were concentrated on the southern part of SEQ. This can be attributed to the different land use practices throughout the area. The variations of nutrient concentration in relation to land use practices cannot be concluded fully in this research as it is a study in itself.

Nitrogen and phosphorous were found to be deficient in most of the areas in Australia as stated by the survey participants in May et al. (2009) study. The same study indicated an average rate of phosphorous application of 25 kg P ha^{-1} in hardwood species. However, as plantation normally involves long rotation period which ends up to 25 years or more, the amount of phosphorous available in all the sub-regions of the study site is insufficient. This was also proven by the result of the survey conducted by May et al. (2009) where 85% of hardwood growers reported nitrogen and phosphorous to be the most common nutrient deficiencies in their areas.

Phosphorous available in the sampled areas of sub-regions 6, 6a, and 8a is moderate and can be expected to become low as availability of this nutrient tends to decrease in cool, wet areas (Marx et al. 1999). Sub-regions that experience high frost days annually must practice higher fertilizer application especially those areas with low temperature and high rainfall. Despite the moderate level of some sampled sites above, there is a need for fertilization in particular areas with “very low” and “low” phosphorus content located at the northern (Sub-region 1) and southern part of the map (Sub-region 2 and 4).

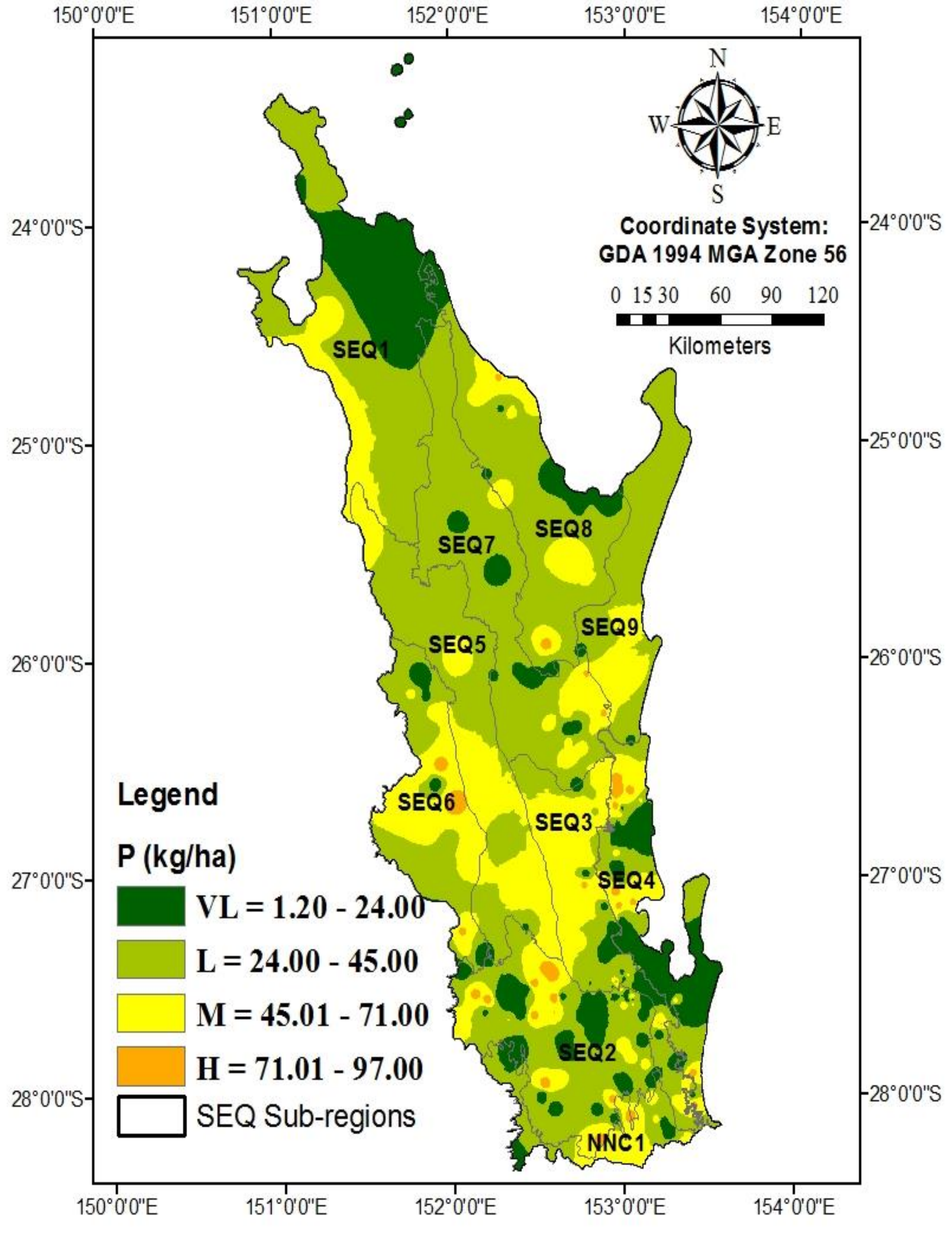

Figure 5.2 Phosphorous concentration and distribution in the study area

Phosphorous available in soil ranging from 0 to 24 kg ha^{-1} is considered very low, 25 to 45 kg ha^{-1} is low, 46 to 71 kg ha^{-1} is medium, 72 to 137 kg ha^{-1} is considered as high and more than 137 kg ha^{-1} is of very high category. As this nutrient is not easily leached because it adheres strongly with soil particles, there is no need for high P fertilization in some parts of the sub-regions. Nevertheless, monitoring of phosphorous applications and the past history of fertilisation is necessary.

5.4.1.3 Potassium (K)

Table 5.11 indicated that almost all of the sampled sites have low a level of potassium except for the South East Hills and Ranges and Moreton Bay sub-regions. Trees in these areas could benefit from its high soil potassium content.

Table 5.11 Potassium values derived for each sampled sites.

Sub-region	K (kg ha^{-1})	Nutrient Level
9	166.28	Low
8	146.41	Low
8a	96.34	Very Low
7	130.92	Low
7a	260.74	Moderate
7b	265.48	Moderate
6	252.60	Moderate
6a	186.24	Low
3	409.84	High
2	363.39	High
2a	284.95	Moderate

An estimated amount of potassium available for trees in the whole area ranged from 22.38 – 951.59 kg ha^{-1} where the lowest levels are found in the northern part along the coastal areas in particular sub-regions 1, 4, 8 and 9. The highest levels were found to concentrate in the south west part of the map (Figure 5.3).

Perhaps this may be due to the density of agricultural farms located in the western side of the regions whereas the northern portion along the coast this scenario is not to be expected. Favourable yield can only be sustained via an increase of soil fertility. Export of nutrients can diminish growth rates of trees making it necessary to apply fertilizers in order to maintain yield. Potassium is not mobile and leaching is not a problem for this nutrient. Leaching of fertilizer is not included in this study thus, will not be discussed nor elaborated here.

Trees also need K in larger amounts approximately similar to that of nitrogen demand. Soils in most of the sampled sub-regions (e.g. 9, 8, 8a, 7, and 6a) have very low to low potassium contents and spotted gum in these areas are in danger of stunted growth and poor root development. These areas need fertilization to assure vigorous vegetative growth, improved disease resistance and increased drought tolerance of trees.

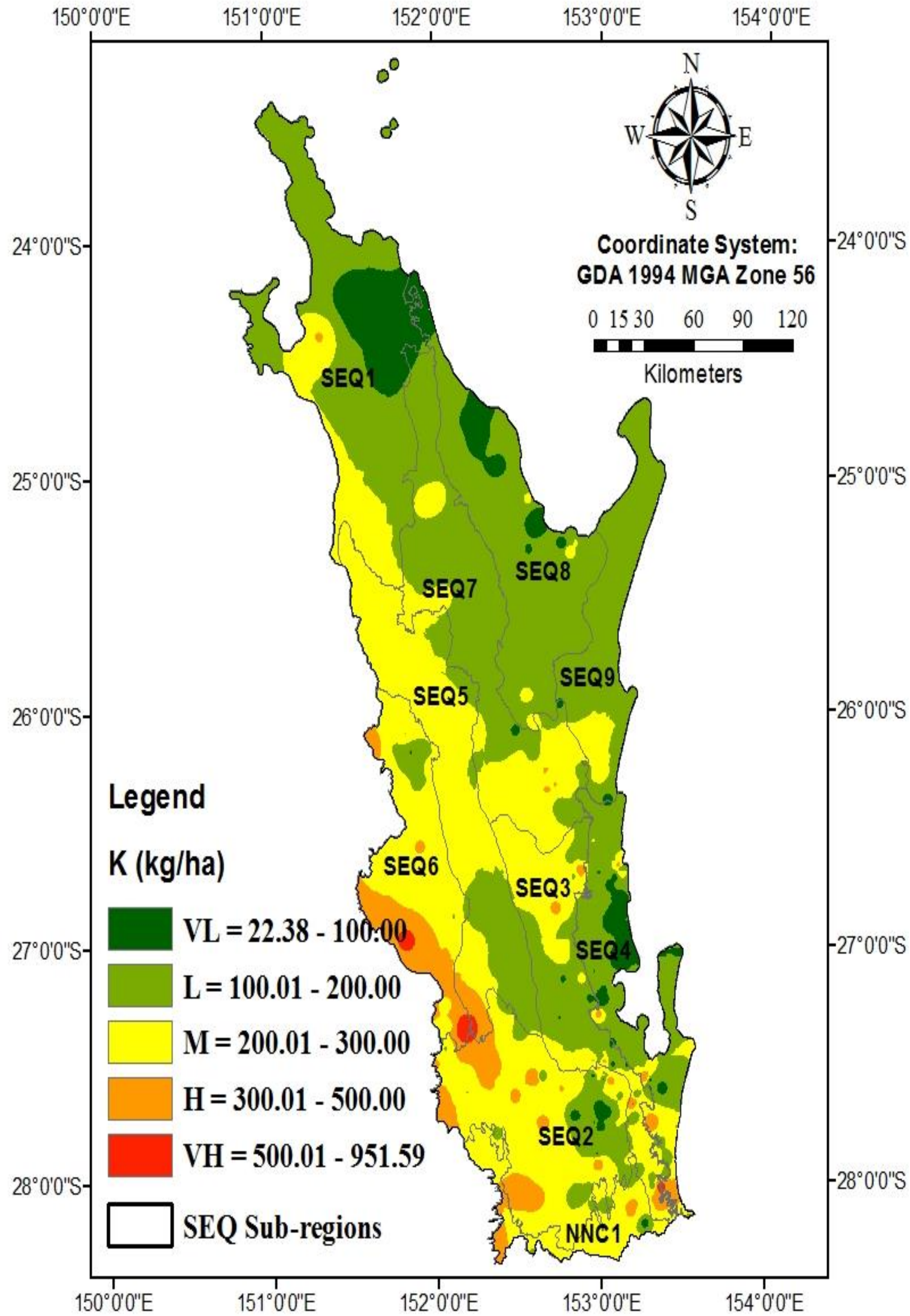

Figure 5.3 Potassium concentration and distribution in the study area

Levels of potassium were classified as very low with K ranging from 0 to 100 kg ha^{-1}, low with a range from 101 to 200 kg ha^{-1}, medium under 201 to 300 kg ha^{-1}, high if ranging from 301 to 500 kg ha^{-1} and very high if its K content is more than 500 kg ha^{-1}. This classification was also based on the accumulated demand of spotted gum for long rotation plantation production.

5.4.1.4 Calcium (Ca)

It is surprising to know that the amount of calcium in the sampled sites is more than adequate to sustain the growth of trees for several years. In most cases, calcium is deficient due to its high leaching characteristics (May et al. 2009). The level of calcium ranged from the lowest of 75.60 kg ha^{-1} to highest of 4,820.54 kg ha^{-1} as visualised in the map below (Figure 5.4).

The western part of the south east region is endowed with high calcium concentrated in the soil as shown in the map whereas the lowest concentrations are found in the eastern side with a small portion of high areas at the tip of the Great Sandy sub-region. The sampled sites provided a very positive result as most of the areas contained a more than adequate calcium level (Table 5.12) sufficient enough to sustain biomass production in those areas.

These results indicated high calcium sufficiency for the provision of an optimum growth requirement of trees for more than 25 year rotation period. Particular caution and monitoring of this element is necessary in sites with deficient supply such as reflected on the map.

Table 5.12 Calcium values derived for each sampled sites.

Sub-region	Ca (kg ha^{-1})	Nutrient Level
9	919.10	Low
8	1125.49	Moderate
8a	811.39	Low
7	1668.62	High
7a	1517.80	High
7b	2542.10	High
6	2288.38	High
6a	1463.36	High
3	2406.30	High
2	3147.51	High
2a	2419.91	High

There was also an indication of deficiencies of this nutrient in sampled sites 9 and 8a where low levels were found. As calcium deficiencies are usually found on very acid soils (Marx et al. 1999), we can conclude that areas located at the eastern side, in particular along the coastal areas, generally indicated soil acidity problems. Sub-regions 9, 8, 4 and 1 may require liming when such deficiency occurs.

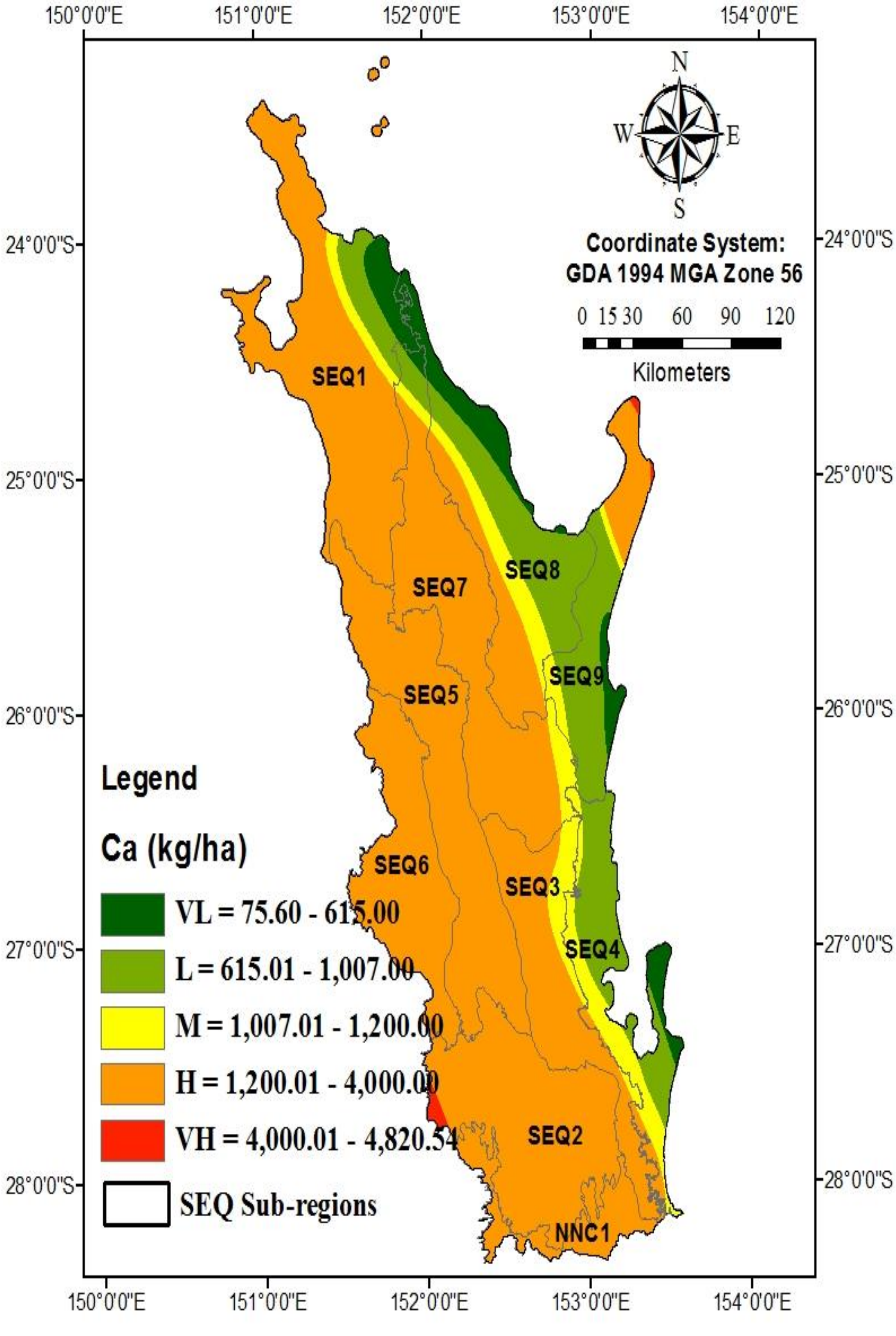

Figure 5.4 Calcium concentration and distribution in the study area

This nutrient is not readily leached and it is expected that the high calcium supply in areas found is enough to promote healthy foliage and root growth. This nutrient was also categorized into five classes such as very low (0 to 615 kg ha^{-1}), low (616 to 1007 kg ha^{-1}), medium (1008 to 1200 kg ha^{-1}), high (1201 to 4000 kg ha^{-1}), and very high (more than 4000 kg ha^{-1}) based on a plantation's perennial life cycle.

5.4.1.5 Magnesium (Mg)

Similar results were found for the available magnesium in the study site. Magnesium level was found to be moderate to more than highly sufficient (105.39 kg ha^{-1} – 2095.13 kg ha^{-1}) for the plantation establishment (Figure 5.5). Moderate magnesium levels were found mainly located at the eastern part and increases in level as it reaches towards the western part where high to very high levels were concentrated.

The table below (Table 5.13) provided a high to very high level on sampled sites and ranged from a high value of 476 kg ha^{-1} to very high at 2931 kg ha^{-1}.

Table 5.13 Magnesium values derived for each sampled sites.

Sub-region	Mg (kg ha^{-1})	Nutrient Level
9	327.66	High
8	337.45	High
8a	214.88	High
7	608.25	High
7a	717.57	High
7b	1068.43	Very high
6	751.58	High
6a	448.17	High
3	1239.93	Very high
2	1240.81	Very high
2a	1039.50	Very high

Plantations can have a sufficient supply of magnesium due to the presence of "high" to "very high" levels of this nutrient in the study site. The site is capable of supplying this essential nutrient requirement of trees during its rotation period. This indicates that the plantations in all the sub-regions can capture energy from the sun more efficiently for its growth and development. This can provide an edge for trees as this nutrients plays a major role in the physiological processes especial in food manufacture. In this particular instance where magnesium is abundant, high food production is likely. As biomass production relies on the photosynthetic products of the trees, with the sufficient supply of the magnesium, carbon sequestration is also expected.

A similar process for nutrient level classification was followed such as very low (0 to 45 kg ha^{-1}), low (46 to 83 kg ha^{-1}), medium (84 to 295 kg ha^{-1}), high (296 to 800 kg ha^{-1}), and very high (more than 800 kg ha^{-1}).

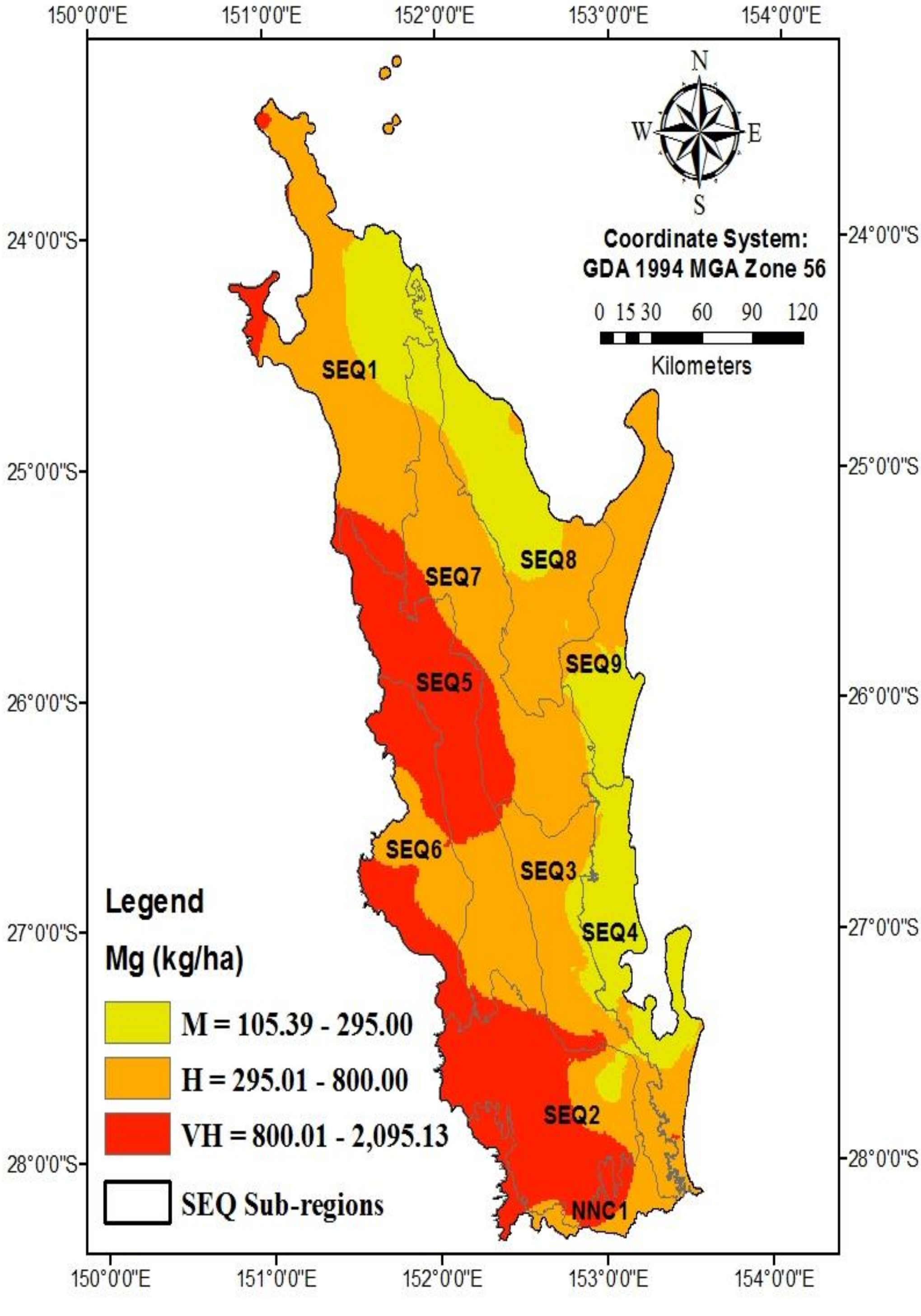

Figure 5.5 Magnesium concentration and distribution in the study area.

5.4.2 Fertility rating

The result of soil fertility modelling was visualized and is presented as a map in Figure 5.6. The fertility rating derived from the weighted summation in a GIS environment generated a non-unit value of 0 – 1. This provided information on the fertility condition of the soil and served as input in the biomass simulation.

The areas located along the coastal areas had shown a comparatively lower fertility rating whereas sub-regions inland in the western side had a better fertility. The tabulated fertility rating for all the sampled sites (Table 5.14) also showed this result and provided details for each site.

Table 5.14 Fertility rating values derived from the soil nutrients.

Sub-region in SEQ	Longitude	Latitude	FR (Values)
SEQ 9 - Great Sandy	152.67926	-25.73993	0.17
SEQ 8 - Burnett Curtis Coastal	152.82438	-25.78830	0.18
SEQ 8 a - Burnett Curtis Coastal	152.15924	-24.79059	0.10
SEQ 7 - Gympie Block	152.42530	-26.03622	0.27
SEQ 7 a - Gympie Block	152.55833	-26.35065	0.37
SEQ 7 b - Gympie Block	151.68760	-26.07855	0.54
SEQ 6 - South Burnett	151.86295	-26.47763	0.44
SEQ 6 a - South Burnett	152.55833	-26.89485	0.25
SEQ 3 – South East Hills and Ranges	152.57042	-27.56604	0.64
SEQ 2 - Moreton Basin	152.49786	-28.00140	0.70
SEQ 2 a - Moreton Basin	152.67926	-25.73993	0.56

SEQ 2 Moreton Basin sampled sites has the highest rating based from the five nutrient components and SEQ8a Burnett Coastal Region has the lowest fertility status. It is noticeable that most of the highly fertile areas are located on the western side of the study site that cuts across from the northern to the southern part of the south east region. This is mainly attributed to the presence of nutrient rich soils but as previously discussed, rainfall, temperature and other factors impact on the productivity. In general, these external variables can have a complex dynamic that could impact the physiological processes of the trees particularly its biomass production and carbon sequestration mechanisms.

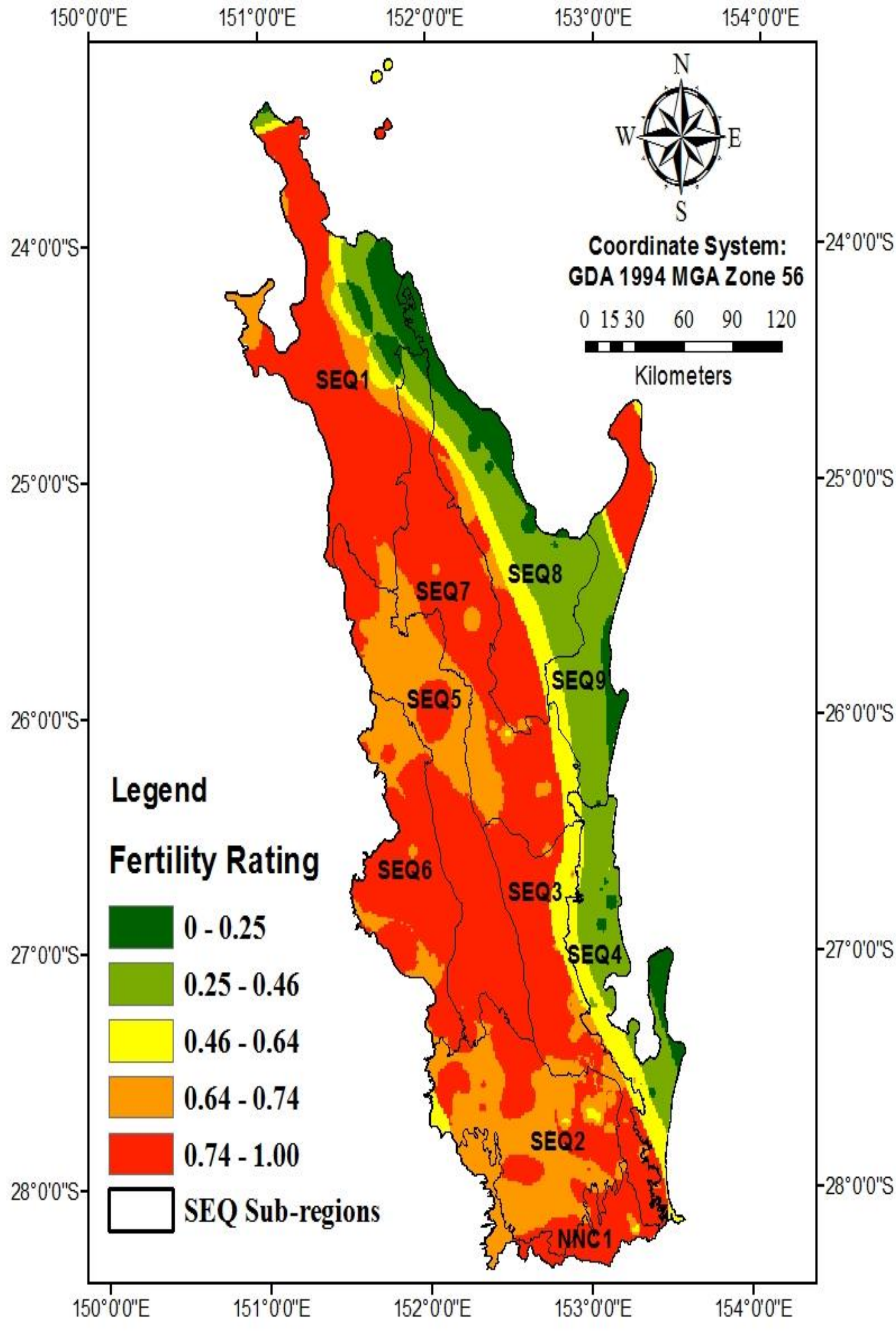

Figure 5.6 Generated fertility rating of the study site

5.4.3 South East Queensland biomass and carbon sequestration

This section discusses the results of biomass simulation for eleven sampled sites from the whole study area. It highlights the effects of geographical location, climatic and bio-physical factors as trees sequester carbon and accumulate biomass during their lifetime. Productivity is discussed as it compares the benefits for the commercialization of the spotted gum plantation. The result of biomass simulation for all the sub-regions in the study site (Table 5.15) shows the highest value of biomass for Great Sandy site as determined by its geographical position and intrinsic climatic data.

The tabulated data can be explained by the variations and complexity of interacting biophysical variables used in the simulation of biomass. The MAIs at maximum sustained yield levels of the study site range from 11.40 m^3 ha^{-1} yr^{-1} to 19.98 m^3 ha^{-1} yr^{-1}. The carbon dioxide equivalents at the end of the rotation period range from 2539 ton per hectare to 4157 ton per hectare. The results also present a range of total dry matter from 1422 tDM ha^{-1} to 2329 tDM ha^{-1} at the end of the production cycle. The results for each sub-regions are discussed in detail in the following sub-sections.

Table 5.15 Summary of growth and productivity of spotted gum on selected sites.

Sub-region in SEQ	MAI_{MSY} (m^3 ha^{-1} yr^{-1})	Stand $volume_{100}$ (m^3 ha^{-1})	Mean DBH_{100} (cm)	Total DM_{100} (tDM ha^{-1})	CO_2-e_{100} (ton ha^{-1})
SEQ9 – Great Sandy	19.98	1872.80	116.28	2329	4157
SEQ8 – Burnett Curtis Coastal	15.98	1497.70	105.60	1867	3332
SEQ8 a – Burnett Curtis Coastal	17.95	1717.95	112.03	2142	3824
SEQ7 – Gympie Block	14.87	1421.51	103.25	1774	3167
SEQ7 a – Gympie Block	18.15	1650.04	110.10	2051	3662
SEQ7 b – Gympie Block	18.15	1650.04	110.10	2051	3662
SEQ6 – South Burnett	11.40	1129.76	93.52	1422	2539
SEQ6 a – South Burnett	12.86	1251.04	97.72	1566	2795
SEQ3 – South East Hills and Ranges	16.43	1571.94	108.06	1971	3519
SEQ2 – Moreton Basin	12.99	1280.53	98.71	1607	2869
SEQ2 a – Moreton Basin	14.08	1295.36	99.20	1611	2875

NB: MAI_{MSY} – Mean Annual Increment at its maximum sustained yield level; DBH_{100} – Diameter at Breast Height at year 100; DM100 – Dry matter (Biomass) at year 100; CO_2-e_{100} – Carbon dioxide equivalent (standard unit) at year 100.

5.4.3.1 Sub-region 9 – Great Sandy

The sub-region is located at the eastern part of SEQ with an area of 230,000 hectares. Its geographical location being along the coastline made the existing climatic conditions favourable to growth of spotted gum. In addition, minimal annual occurrence of frost (5.7 days yr^{-1}) assisted in the establishment of the trees. In addition, the kandosol soil type available for the tree species provided beneficial nutrient requirements as this species can also survive in poor-fertility soils. It is worth noting that this sub-region provided the highest rainfall of 1257.19 mm to the plantation making biomass accumulation faster in comparison with areas of low rainfall. The biomass produced was high at a value of 2329 tDm ha^{-1}. Carbon sequestration as it is dependent on the accumulated biomass of trees is also high at a maximum of 1164.50 tDm C ha^{-1} at the end of its rotation.

The high rainfall coupled with a solar radiation at a range favourable to growth of trees provided better stand volume and maximum sustained yield (MSY) that was attained at earlier years. MSY for this sub-region was attained at year 61 with a mean annual increment of 19.98 m^3 ha^{-1} yr^{-1}.

5.4.3.2 Sub-region 8 – Burnett Curtis Coastal

The sub-region is located at the northern portion of SEQ, south eastern side of Queensland with an average area of 787,000 hectares. The area experiences an average annual rainfall of 1062 mm for the two sites sampled whilst its average mean temperature is 21.17 °C. Similarly, minimal annual frost occurrence of 5.8 days yr^{-1} does not impact the growth and establishment of seedlings in this sub-region. The area is exposed to an average amount of 19.60 MJ m^{-2} yr^{-1} solar radiation as it traverses longitudinally along the coastal area of SEQ immediately at the northern part of sub-region 9.

There were two sampled sites for this area. One site sampled located at latitude 25.78830° South and longitude 152.82438° East accumulated a biomass of 1867 tDm ha^{-1} at the end of its rotation period with a volume of 1497.70 m^3 ha^{-1} and mean annual increment of 15.98 m^3 ha^{-1} yr^{-1}. The second site located in the same sub-region (S 24.79059, E 152.15924) accumulated a higher biomass of 2142 tDm ha^{-1} with a better volume of 1717.19 m^3 ha^{-1} and mean annual increment of 17.95 m^3 ha^{-1} yr^{-1}. Both sites have kandosol soil type appropriate for commercialization of spotted gum plantations.

5.4.3.3 Sub-region 7 – Gympie Block

The Gympie Block sub-region is located at the heart of south east Queensland. It is bounded by sub-region 1 at the north and sub-region 3 at the southern end while sub-region 8 and 9 lies at the eastern side and sub-region 5 at the west. The area covered is approximately 858,000 hectares. Three sites were sampled on this sub-region namely: 7, 7a and 7b. An annual rainfall reception at the three areas averaged at 1066 mm whilst the frost occurrence varies from 11.98 to 15.18 days yr^{-1} annually. This is higher in comparison with that experienced by the adjacent areas in particular the eastern sub-region. The mean annual solar radiation experienced is at 18.94 to a maximum of 19.20 MJ m^{-2} yr^{-1}. The two sampled sites (7a and 7b) experienced almost the same climatic conditions while sub-region 7 varies. Sub-region 7 located at latitude 26.03622° South and longitude 152.42530° East accumulated a lower biomass in comparison to sites sampled at the sub-regions 7a and 7b. A significant difference in mean annual increment was noticeable as the sub-region 7 attained an MAI value of 14.87 m^3 ha^{-1} yr^{-1} while the other sites had 18.15 m^3 ha^{-1} yr^{-1}. This is indicative of the biophysical conditions of the site primarily the presence of more frost at the sub-region 7 and a lower amount of rainfall in comparison with the two other sites. The former site is also located in dermosol soils while the latter has a good ferrosol soils. Although the exposure to the mean temperature and solar radiation is almost the same, the biomass accumulation is quite different.

5.4.3.4 Sub-region 6 – South Burnett

The South Burnett region is one of the interesting study sites located at the south western portion of the SEQ area. The area covers approximately 564,000 hectares. Two sampled sites were located in this sub-region with SEQ 6 at latitude 26.07855 South and longitude 151.68760 East whilst SEQ 6a lies at latitude 26.47763 South and longitude 151.86295 East. Both sites had attained a low amount of dry matter of biomass at 1422 tDm ha^{-1} (SEQ 6) and 1566 tDm ha^{-1} (SEQ 6a). Stand volumes were also low at 1129.76 to 1251.04 m^3 ha^{-1} as illustrated by the low mean annual increment of 11.40 and 12.86 m^3 ha^{-1} yr^{-1}, respectively.

Despite the presence of a medium amount of annual rainfall in the area at an average of 745 mm, with a solar exposure of 19.55 MJ m^{-2} yr^{-1}, dry matter yield is low. This can be understood as the high occurrence of annual frost reduces the sites' biomass production, as frost can cause mortality during the early stage of seedling establishment. The medium amount of rain falling in this environment does not provide conducive habitat for optimum growth of the trees despite the presence of ferrosol soils.

5.4.3.5 Sub-region 3 – South East Hills and Ranges

The South East Hills and Ranges is at the southern part of the south east Queensland and is bounded by sub-region 7 at its northern part, sub-region at its north, whilst sub-region 5 divides it at the western side and sub-region 4 at its east. It is located at latitude 26.89485° South and longitude 152.55833° East is the smallest sub-region sampled with a coverage area of 533,000 hectares. This site is endowed by high rainfall annually and a minimal frost occurrence of 8.88 days yr^{-1}. Mean temperature is experienced at 19.74 °C with a fair solar exposure at 18.87 19.55 MJ m^{-2} yr^{-1}.

The bio-physical parameters of the area gave rise to a better biomass production of 1971 tDm ha^{-1}. Stand volume was attained at a value of 1572 m^3 ha^{-1} showing and a better mean annual increment of 16.43 m^3 ha^{-1} yr^{-1} in comparison with the other adjacent areas. Soil type present in both sites is dermosols.

5.4.3.6 Sub-region 2 – Moreton Bay

The Moreton Bay sub-region is at the southernmost part of the south east Queensland with a total land area of 784,000 hectares. The upper part is bounded by sub-regions 3, 4, 5, and 6 while the lower is traversed by the boundary between Queensland and New South Wales states. Two sites were sampled at this sub-region with SEQ 2 and SEQ 2a. The former site is located at latitude 27.56604° South and longitude 152.57042° East, whilst the latter is at 28.00140° South and longitude 152.49786° East, respectively. Rainfall experienced in the former site is 781.23 mm and is lower than the 946.68 mm for the latter site. However, the biomass production of 1607 and 1611 does not indicate a prominent variation whilst the mean annual increment does not significantly differ for the two sites sampled in this sub-region.

This can be explained by the soil nutrients available in the soil. The fertility rating of the sampled site at sub-region 2, with a lower rainfall, is 0.7 whereas the fertility rating of the latter site with a higher rainfall is only 0.56. A higher soil fertility compensates for a reduced amount of rainfall and vice versa, resulting in a close gap in the biomass yield of the two sites.

5.4.4 Biomass and carbon sequestration in relation to climatic and biophysical factors

5.4.4.1 Growth and biomass production of spotted gum

The results of modelling for plantation growth scenarios in the various sub-regions of SEQ are summarized in Table 5.15 above. The mean annual increment (MAI) of the plantation at its maximum sustained yield (MSY) level was greatest in the Great Sandy sub-region with a value of 19.98 m^3 ha^{-1}. In contrast, the lowest value was found in one of the two sites of the South Burnett sub-region estimated at 11.40 m^3 ha^{-1}. It is not uncommon for plantations to attain higher productivity in higher rainfall areas as water is one of the critical factors in the growth requirement of spotted gum. As expected, higher rainfall areas provide opportunity for trees to reach potential maximum growth.

Similarly, the highest biomass (dry weight) of 2329 tDm ha^{-1} was also predicted at the Great Sandy area with carbon dioxide equivalent of 4157 ton ha^{-1} at the end of the rotation period. Whilst the lowest biomass (dry weight) and carbon dioxide equivalent during the full period was estimated to occur at the South Burnett with values of 1422 tDm ha^{-1} and 2539 ton ha^{-1}, respectively. Likewise, the volume and mean diameter at breast height (DBH) at the end of the rotation period varies depending on the climatic factors occurring in the site and corresponds with the increase in biomass. The estimated stand volume ranged from 1130 to 1873 m^3 ha^{-1} with a DBH range of 94 to 116 cm.

5.4.4.2 Carbon sequestration and climate

The result of the growth simulation revealed variations in carbon sequestration potential in various sub-regions. The graph below (Figure 5.7) shows the carbon sequestration capability for each of the sub–regions ranged from 711 to 1165 (tC ha^{-1}) at the end of the rotation period. Variations in carbon sequestration capability can be attributed to variations in different attributes of the biophysical components of the site such as precipitation, solar radiation, frost and site conditions.

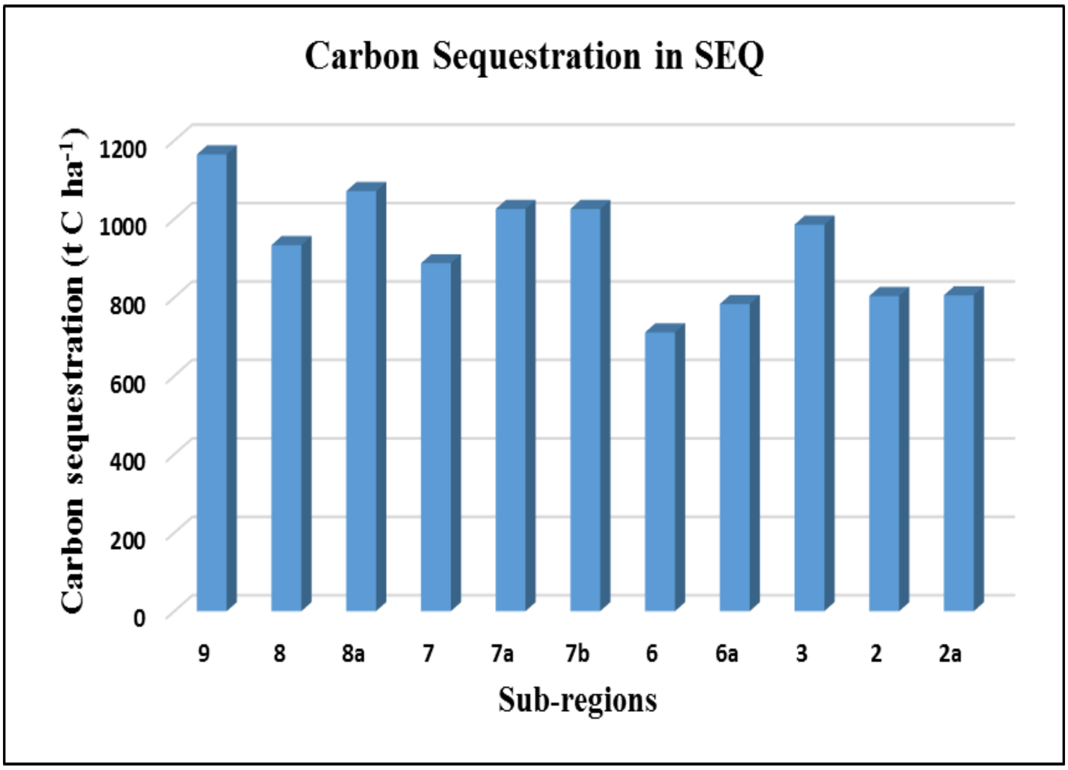

Figure 5.7 Estimated carbon sequestration potential on different sub-regions of SEQ at the end of the rotation

Notably, the highest carbon sequestration potential can be found at the Great Sandy area while its neighbouring sub-region is expected to have varying levels of productivity depending on the complex interactions of climate with the target species. As rainfall is quite high in the Great Sandy sub-region with a mean annual amount of 1257 mm (63-year mean data), it is expected that the species will be more productive in this sub-region as biomass and rainfall showed high correlation (R^2 = 0.80) (Figure 5.8). Under high precipitation coupled with the favourable condition, the species can grow faster and can attain its maximum stem biomass at an early stage. Consequently, natural thinning starts early compared to other species in the South Burnett areas, which have less available water.

In South Burnett, carbon sequestration is lower as the species does not exhibit full growth potential due to the integrated effects of several factors such as limited soil moisture and less favourable climatic conditions intrinsic to the area. As a result, tree species on this site attains its maximum stem biomass at a later stage leading to a late commencement of defoliation. Similarly, as fast-growing trees become dominant, the understorey vegetation experiences suppression resulting to death. This gives more space to the dominant tree to attain more girth.

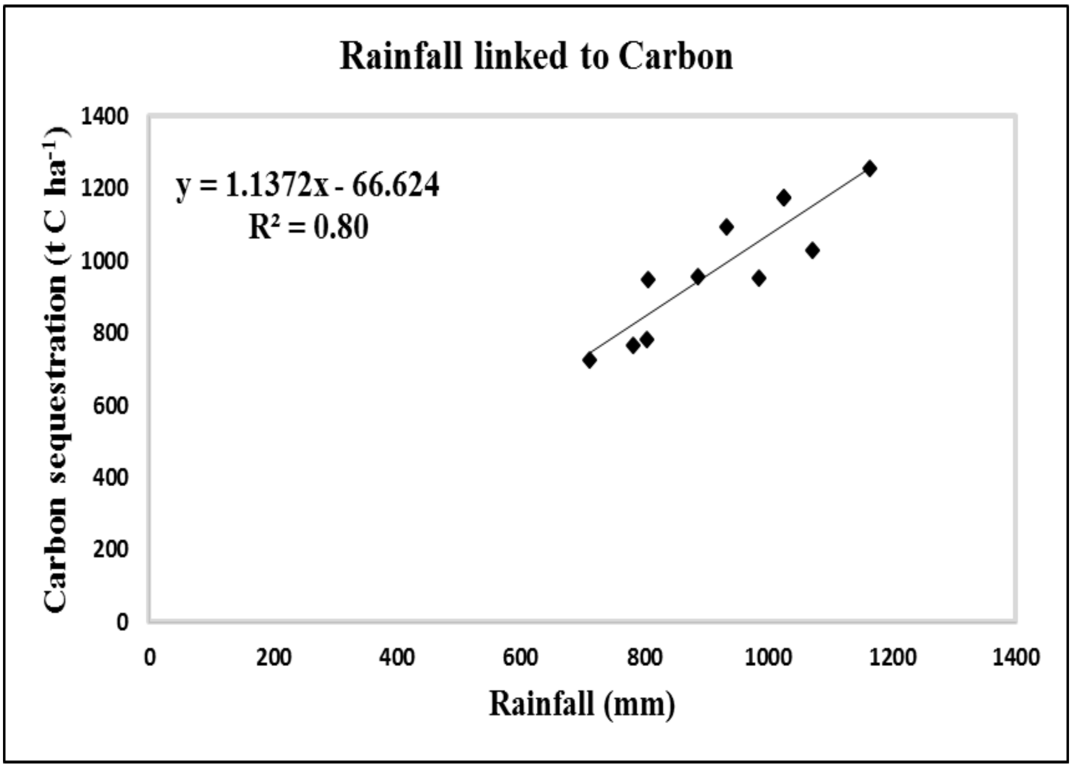

Figure 5.8 Correlation between the carbon sequestration potential and rainfall on different sub-regions of SEQ

5.4.4.3 Spotted gum biomass accumulation

The mean annual increment of the Great Sandy sub-region provides the highest potential level of production. This is brought about by the complex dynamics of geography particularly the latitudinal location, climate, biological processes and the geological formations of the site. The area is located at latitude 25.788° South and normally receives a mean annual rainfall of 1257 mm which provides abundant water to the plantation. The mean temperature of 21.84 °C is also conducive to the growth of the trees where frost is non-occurring. Furthermore, the plantation in the area normally experiences an average of 19.51 MJ m^{-2} yr^{-1} of solar radiation, thereby providing an environment conducive to growth of trees. The high growth can be attributed to the presence of rainfall. This was concluded through the result of the regression analysis showing the relationships between the rainfall and the mean annual increment (MAI). A strong positive correlation was found to exist between rainfall and MAI (R^2 = 0.89) (Figure 5.9).

However, the correlation for rainfall may not be true for all the climatic variables as one has to understand the relationship existing between the biomass production and the factors limiting its growth. For instance, spotted gum grows in high rainfall area but will not grow well in waterlogged conditions. Therefore, under high rainfall area a soil type with good drainage is more appropriate compared to clayey texture that tends to soak the roots. Moreover, this species is drought resistant but can thrive well and attain its optimum growth at 20°C and can survive in poor-nutrient soil conditions. It is relatively frost tolerant but severe frost condition may cause death to seedlings particularly during its early year. The absence of frost in Great Sandy sub-region coupled with high rainfall provides a better growth in comparison with other neighbouring sub-regions.

The combination of different climatic parameters coupled with the intrinsic edaphic condition of the site gives rise to varying production levels. By merely looking at the previous table presented (Table 5.15), one might deduce that a higher level of rainfall and temperature would automatically provide a higher biomass production such as the case of Great Sandy, Burnett Curtis Coastal (SEQ8a), Gympie block (SEQ 7a & b) and South East Hills and Ranges. However, a critical analysis of the production incorporating the dynamics of the physiological and biological processes with climatic parameters could provide a better answer. Comparatively, the Gympie Block receives higher rainfall and temperature compared to South East Hills and Ranges but accumulates lower biomass. This can be attributed to the more regular occurrence of frost in Gympie Block. The case of South Burnett (both areas) produced the lowest biomass being located in a low rainfall despite reception of a favourable mean temperature of 21 °C. Notably, this sub-region has the highest frost occurrence between April to October posing growth impediments to trees which could cause decline in plantation production.

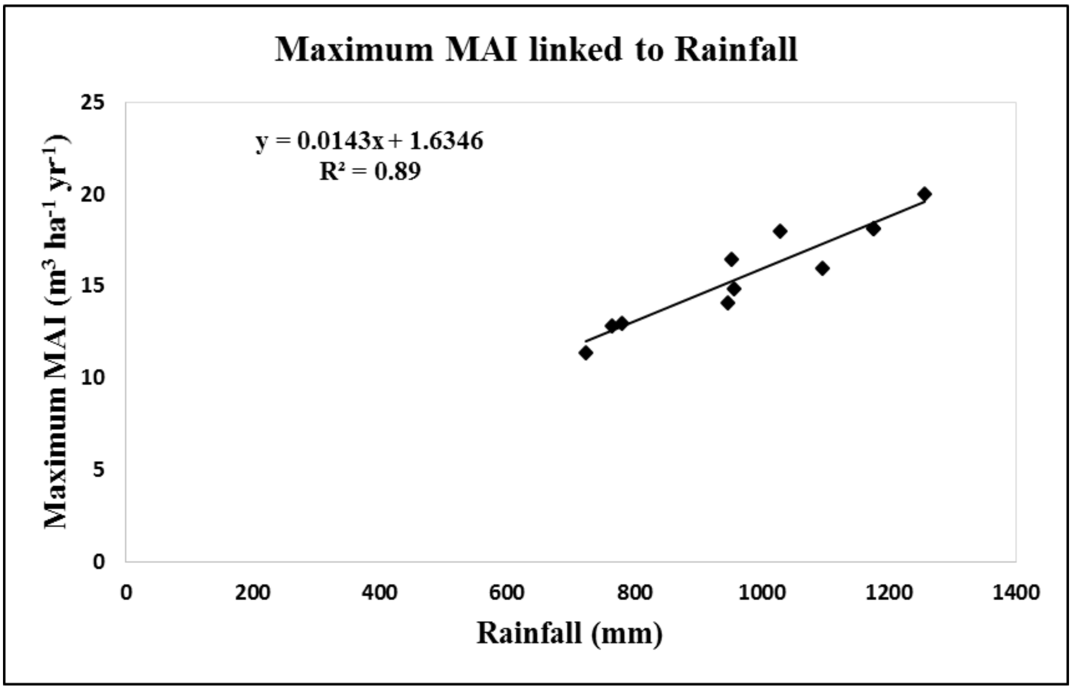

Figure 5.9 Effect of rainfall in relation to mean annual increment

The mean annual increment at a maximum sustained yield (MAI_{MSY}) indicated in table 5.15 was compared with the result of Maraseni's (2007) research. The table result shows good agreement values in particular, those sampled in the South Burnett areas. Maraseni's (2007) result showed an MAI of 12.57 m^3 ha^{-1} at year 66 whereas this study generated a result of 11.40 m^3 ha^{-1} and 12.86 m^3 ha^{-1} both at year 65 in SEQ 6 and SEQ 6a, consecutively. When the mean MAI_{MSY} of these two results (12.13 m^3 ha^{-1} yr^{-1}) were compared with Maraseni's work, a difference of 0.44 m^3 ha^{-1} yr^{-1} was observed.

The maximum total biomass (above ground and below ground) recorded in this study indicated a value of 2329 tDM ha^{-1} in a rotation period of 100 years. It contains a carbon stock of 1,164.50 tC ha^{-1}. This value is lower when compared to the results of field measurements and calculations of biomass found in the Mountain Ash (*Eucalyptus regnans*) located in Victoria, southeastern Australia. The Mountain Ash forest contains an average of 1,867 tC ha^{-1} total biomass (living plus dead) in stands with > 100 years old. Whereas, the maximum biomass carbon stock was 2,844 tC ha^{-1} with the oldest age cohort of >250 years old (Keith et al. 2009). The Keith et al. (2009) study provided a high result despite the exclusion of root biomass in the measurement and calculations of total biomass.

Preece et al. (2012) determined the biomass in the rainforest of North eastern Queensland using several carbon accounting tools. FullCAM was utilised which projected a carbon density with a standard deviation (SD) of 63.5 Mg C ha^{-1} (± 5.8 SD) equivalent to a biomass of 127 tDM ha^{-1} (± 5.8 SD). The highest results were estimated using Brown's (1997) allometry with 93.3 Mg C ha^{-1} (± 11.2 SD) equivalent to 186.6 tDM ha^{-1} (± 11.2 SD) of biomass. These values when compared to this study were very low. Discrepancies between the results of Preece et al. (2012) and this study was primarily brought about by several factors. The Preece et al. (2012) study is for plantings with less than 20 year rotation period and was concentrated on stem biomass only whereas this study focused on total biomass of plantations with a 100-year rotation period. Similarly, Bradford et al. (2014) concluded with a significant findings in aboveground biomass (AGB) at the Wet Tropics of Northern Queensland. The field measurement provided a mean AGB of 418.5 Mg ha^{-1} (± 59.7 SD). The AGB measurements included other vascular plants (e.g. figs, ferns, lianas, etc.) with <1 cm diameter. Bradford et al. (2014) results when compared to this study indicated deviations. These variations were due to the coverage of the study as Bradford et al. (2014) incorporated the vascular plants with focus on the above ground biomass. In summary, such deviations can be attributed to the applications of different accounting tools, area of coverage, measurement techniques, age, forest type and geographical locations.

5.4.5 Sensitivity Analysis and validation

The results of sensitivity analysis for spotted gum growth in relation to rainfall variations are presented in table 5.16. An approximate change in yield of 3% to 23% in its mean annual increment is evident and is due to occur within the study site when subjected to a 100 mm increase in rainfall change. A marked increase in the mean annual increment is evident as rainfall amount increases. Biomass, however, responds differently as shown by the table. The biomass increased continuously until it reached a maximum dry matter of approximately 1500 m^3 ha^{-1} yr^{-1} with 900 mm rainfall. It then starts to drop when subjected to 1000 mm rainfall. The percent changes in biomass manifest a different trend as negative values are evident when the rainfall amount is increased to more than 900 mm.

Table 5.16 Difference of biomass with 100-milimetre rainfall interval.

RAIN FALL (mm)	MAI (m^3 ha^{-1} yr^{-1})	Change (%) (MAI)	DM_{MSY} (m^3 ha^{-1} yr^{-1})	Change (%) (DM_{MSY})	DM_{100} (ton ha^{-1} yr^{-1})
400	7.29577	-	930.068	-	930.068
500	8.98785	23.19	1141.98	22.78	1141.98
600	10.7253	19.33	1330.51	16.51	1354.74
700	12.1998	13.75	1419.57	6.69	1524.09
800	13.5107	10.74	1499.92	5.66	1658.19
900	14.17	4.89	1499.93	0.00	1718.29
1000	15.2959	7.93	1463.75	-2.41	1811.18
1100	15.6973	2.62	1442.15	-1.48	1839.79
1200	16.4071	4.52	1383.33	-4.08	1885.71

The biomass was fitted on a line to see how it responded to the increasing rainfall and the graph (Figure 5.10) showed its behaviour with high accuracy. There was a positive high correlation between the two with an R^2=0.985.

The validation of the results is in most cases difficult for process based modelling in particular for biomass and carbon sequestration. Accuracy of the results of this study was primarily based on the available parameter inputs specific for the spotted gum. The most efficient and conventional way is to directly measure the biometrics of the spotted gum plantation. However, this requires a lot of time, effort and resources and may not be possible in varied situations (with temporal and financial constraints), particularly as the extent of this study site is regional. Usually, the most practical way and scientific approach is to utilize information from the previous studies as found in the literature and match parameterised variables in the modelling process. These were applied in the above mentioned process in particular the acquired secondary dataset and available parameterised inputs used were coupled with field sampling in the validation of the results.

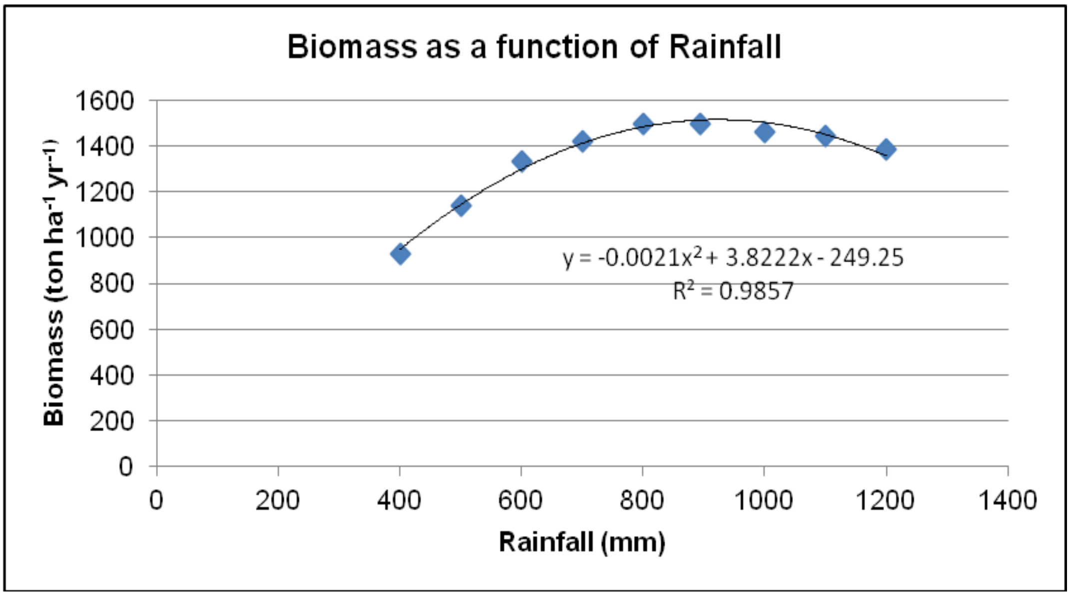

Figure 5.10 Biomass behaviour under varying rainfall amount

The results of the model validation present a goodness of fit of the developed model. The efficiency of the model when fitted with the CSIRO's biomass for *E. maculata* provides a good agreement. The model estimated the biomass (*Scenario* 1) with the coefficient of determination (CD), $r^2 = 0.87$. The CSIRO's biomass estimation was conducted on a national scale, therefore the meteorological datasets were low in spatial resolution. The comparison has limitations including: (1) the scale is different (local vs national), and (2) although both simulations are for eucalypt plantations, species used were different as this study was specific for spotted gum (CCV). However, there is no existing similar study on regional scale to compare this study.

5.5 Conclusion

The highest biomass (dry weight) of 2329 tDm ha^{-1} was estimated at the Great Sandy area with carbon dioxide equivalent of 4157 t ha^{-1} at the end of the 100-year rotation period. The lowest biomass and carbon dioxide equivalent during the same rotation period was estimated to occur at the South Burnett with values of 1422 tDm ha^{-1} and 2539 t ha^{-1}, respectively. Similarly, the MAI of the plantation at its MSY level was greatest in the Great Sandy sub-region with a value of 19.98 m^3 ha^{-1}. In contrast, the lowest value was found in one of the two sites of South Burnett sub-region estimated at 11.40 m^3 ha^{-1}. As expected, there was a strong correlation ($R^2 = 0.80$) between the rainfall and the potential carbon sequestration rates.

The biomass productions of spotted gum plantation provided a different growth trend when estimated in a local area and deviations were expected when compared with the results from a regional projections. These were attributed to local variations of bio-physical and climatic factors. Whilst trees continuously depend on solar radiation and rainfall for photosynthetic activities of the canopy, other physiological processes have to be maintained to ensure tree health and sustenance. Roots also play a major role in the nourishment of the trees and therefore fertilization must be performed during the life cycle of the plantation. It is common knowledge that high soil fertility provides higher productivity. Further details of the soil characteristics of the study area would be included such as the integration of salinity will be discussed in detail in the next chapter.

In the context of Australian Government CFIs, the results of this research can be a guide to those who would like to engage in the carbon sequestration enterprise. Care is advisable in the use of these data as they are specific to SEQ sub-regions.

CHAPTER 6

Soil Amelioration Value Estimate and Carbon Sequestration of Spotted Gum in Saline Affected Areas of SEQ

"By His knowledge the depths were broken up,
And clouds drop down the dew"

Jedidiah, *Book of Wisdom*, 970 – 928 BCE

6.1 Introduction

Salinity is an environmental issue that can affect the capability of soil to provide a good yield and hence affect the capability of a plantation to accumulate biomass. It is important that its impact be incorporated to determine the carbon sequestration capability and the financial benefits the stakeholders may derive. The benefits the stakeholders can derive is dependent on the net value of the plantation's conventional products and its soil amelioration services.

The objective of this chapter is to estimate the soil amelioration value of spotted gum plantations under saline affected areas. It also discusses the impact of salinity on the growth of spotted gum of forest plantations in the South East Queensland (SEQ). Salinity modelling was performed to determine the salt credit as part of the intangible benefits derived from the plantation on top of the conventional timber benefits. It is envisaged that salinity may potentially reduce the biomass production, whilst in the long term, the plantation established could ameliorate the saline affected areas within the region.

This chapter is sub-divided into six sections. Section 6.1 presents the chapter's context, whilst section 6.2 discusses the impact of soil salinity on carbon sequestration potential of the spotted gum plantation. It also discussed how salinity affects biomass accumulation in plants via changes in seedlings and tree mortality. Section 6.3 reviews past studies and shows the gaps in the financial estimate derived from a plantation's ability to ameliorate soil under saline conditions. Section 6.4 discusses the methodology whereas section 6.5 contains the results and discussion. The last section 6.6 concludes and discusses the need for detailed site suitability assessment with financial implications.

6.2 Impact of salinity in plantations

Previous reports such as that released by the NLWRA (2001) provided information on the alarming presence of dryland salinity in Queensland. Its impact can be significant when changes in plant health and their ability to survive are at stake. Salinity is one of the major environmental problems causing reduction of plant growth and development, leading to a loss of crop productivity of more than 50% worldwide (Parida & Das 2005). This also poses potential threat in carbon sequestration of forest plantations.

Forestation of recharge areas in marginalised lands such as salinity affected areas are recognised under CFI as a mechanisms to ameliorate the soil while storing carbon and thereby earning carbon credits. However, doubts exist about the effectiveness of establishing trees to ameliorate and manage dryland salinity due to the poor growth and survival of the trees (Archibald et al. 2006). These were disproved by previous studies of Hill (2004) and Pannell (2001). Though results were optimistic, salinity impact on growth and survival of trees must be understood. Similarly, the present benefits must be determined to provide land holders with information for land use decision-making and perhaps also enabling production over previously saline areas. Overall, the success of this strategy relies on the capability of trees to sequester carbon efficiently on a saline environment.

6.2.1 Salinity impact on the growth and development of spotted gum

Little quantitative data are available on the relationship between the growth rates of eucalypt species and soil salinity (Feikema & Baker 2011). There was no long series data found for the relationship of carbon sequestration of mature spotted gum species (CCV) located in southeast Queensland affected with salinity. Most of the studies conducted were for eucalypt seedlings or juveniles in pots under controlled conditions. Others were conducted for other eucalypt species at older stages but continuity of experiments for certain species throughout its rotation period is lacking. For instance, research on effect of variations of salinity in several tree species (e.g. *C. citriodora, Grevillea robusta, etc.*) conducted by Sun and Dickinson (1993) was significant.

Sun and Dickinson (1993) determined the impact of different salinity levels on biomass of spotted gum seedlings however, the focus was for five months-old spotted gum seedlings. Benyon et al. (1999) studied a 7-year old *E. camaldulensis* and 6-year old *E. occidentalis* on a saline discharge site in New South Wales. Whilst the study of Feikema and Baker (2011) conducted in New South Wales examined the growth of three eucalypt species (*E. camaldulensis, E. globulus* and *E. grandis*) in relation to soil salinity and was up to age 10 only. In south east Australia, a study of *E. grandis* and *C. maculata* in degraded saline soils (Falkiner et al. 2006) was at age 3.8 to 4.8 years old which studied the impact of salinity on its root distribution rather than the biomass. All these studies found that salinity affects the growth and development of eucalypts from root to shoot, affecting the overall biomass.

From a physiological perspective, salinity is one of the major stressors in plants (Wei 2002). Luttge (2004) studied the ecophysiology of Crassulacean Acid Metabolism (CAM) and some C3 plants and found out that salinity first affects the acquisition of CO_2 through resistance of the stomata and mesophyll. This could inhibit the photosynthetic activity of the plants leading to irreversible impacts that could result in death (Loreto & Centritto 2008) though species tolerance and response to salinity may vary as found in several studies.

For instance, *E. camaldulensis* and *E. occidentalis* reached a 26 m^2 mean leaf area in a non-salt media. Whilst under moderate salinity, mean leaf area of *E. camaldulensis* was reduced by 38.5% whereas *E. occidentalis* mean leaf area remained unchanged (Benyon et al. 1999). Moreover, a separate study on impact of salinity on various eucalypt species revealed a promising performance as the result showed *E. citriodora* took more time to manifest signs of stress and was more tolerant in comparison with other species such as *E. cloeziana*. *E. cloeziana* however died at 100 mM NaCl and had the lowest value of biomass whilst *E. citriodora* survived but died at 200 mM NaCl (Sun and Dickinson 1993). Albeit being more salt tolerant than other species, *E. citriodora* has a low salt tolerance at 180+ mM based on 50% seedling mortality (Lambert & Turner 2000). Though physiology is inclusive of this study's limitations, the above literature was deemed worth mentioning to show how tree growth is affected by salinity and could serve as the basis to determine the coefficient salinity impact.

The impact of salinity on eucalypt growth and survival may manifest depending on its level and provenances. For instance, a laboratory experiment in Thailand showed discrepancies in survival rate of *E. camaldulensis* seedlings (10 months) based on varying salt concentrations with 30%, 16% and 14% survival for 13.3 dS m^{-1}, 13.4 dS m^{-1} and 16.1 dS m^{-1}, respectively (Cha-um & Kirdmanee 2010). In Australia particularly in the Central Queensland, Madsen and Mulligan (2006) showed the effects of NaCl on emergence and growth of a range of provenances of *E. citriodora*. The result revealed a mean plant survival of 100% for both 0 and 100 mM (11 dS m^{-1}), 98.61% survival for 200 mM (20 dS m^{-1}), 70.83% for 300 mM (28 dS m^{-1}) whilst 13.89% survival was observed for 400 mM (36 dS m^{-1}) salinity level. Mean dry weight recorded was 9.19 (g/plant) (100%) under 0 mM (1dS m^{-1}), 4.32 (g/plant) (47.32%) with 200 mM (20 dS m^{-1}), and 0.57 (g/plant) (6.39%) under 400 mM (36 dS m^{-1}). On another provenance range, Eucalypt trees of *E. occidentalis* and *E. camaldulensis* at 7 years old were found to have a mean survival of 78% and 68% under saline (4.5 dS m^{-1}) conditions (Benyon et al. 1999). Though salinity could impact the growth of eucalypts in particular spotted gum (*C. citriodora*), planting this species in problem affected sites could provide potential benefit in the long run.

Planting eucalypts on recharge areas has been recommended as a viable management strategy that could increase groundwater discharge (Schofield 1992; Greenwood et al. 1985) and eventually ameliorate soil. This is possible as eucalypt has the ability to extract groundwater direct from the water table while excluding the salts from the roots. Benyon et al. (2001) showed a significant difference in water use by eucalypt species planted in a saline discharge areas, ranging from about 50 litres per day in *E. occidentalis* to 270 litres per day in *E. spathulata*. The tree roots' absorptive capacity is viewed to be beneficial to affected areas as this absorption mechanism could lead to soil amelioration and alleviate soil salinity condition.

6.2.2 Spotted gum plantation for site amelioration

Planting of eucalypts in recharge zones could provide substantial amelioration in saline affected areas (DNR 1997). Recharge areas can often be found in irrigated areas. On the other end are the saline discharge zones where it usually develops in the lower parts of the landscape in most cases on foot slopes and bases of the catchments.

The occurrence of discharge zones are complex interactions between several factors such as geological formation, edaphic and climatic factors. However, these are normally found in areas with heavier clay soils on drainage depressions where water movement is restricted and tend to impede drainage of water (Murphy et al. 2001). As reported, salts are stored in thick clay horizons within the regolith and in some instances, coarse materials may serve as conduits for salt transport to adjacent water channels and the nearby land surfaces (Cresswell et al. 2004). This geologic process can be directly linked with some situations in this study where plantations are located in clayey soils. Salts can be absorbed by the trees established in the clayey areas whilst experiencing water logging. Water logged areas are associated with saline problematic soils (Murphy et al. 2001), leading to growth impediment as expressed in most of the sub-regions in this study.

As mentioned previously, DNR (1997) stated that in general, areas receiving rainfall with a mean of more than 700 mm yr^{-1} and less than 1,100 mm yr^{-1} are considered at the highest risk of water table salinisation. Below this amount is considered not at risk as less water is received and is insufficient to provide the plants water needs and ground recharge. Likewise, amounts above this is also not at risk as more water can flush the salt through the soil profile via leaching (DNR 1997). However this may not be true in all instances as measurement of root zone salinity demonstrated that salinity at a given depth may rise and fall by 10 dS m^{-1} or more over a period of several months. This was attributed to mechanisms that exist in plants for rapid redistribution and accumulation of salt (Morris & Collopy 1999). Risk of salinity occurrence is also attributed to factors such as temperature, topography, soil type and geological formation.

For instance 6, 20 and 100 year old eucalypts planted on recharge sites were shown to consume 100, 160 and 450 litres each per day during summer when ample amount of soil moisture is available (Clinton & Perry 1999). Planting of trees in hillslope areas was found to be successful in particular where recharge and discharge zones are in close proximity (Daamen et al. 2002) whilst planting trees on recharge areas along a ridgeline was found to reduce groundwater levels in discharge areas at the base of the catchment by about 2.5 metres in 11 years (Reid 1995). Whereas, Otto (1993) contended that tree planting of 25% between the recharge and discharge areas is considered to be sufficient to control salinity whilst reforestation of recharge areas could affect the deep aquifers.

It was concluded that water levels confined in aquifers can be lowered to as much as 1 to 3 metres within the radius of 1 to 2 kilometres depending on the rate the water is extracted from the ground. Furthermore, studies in the Murray-Darling Basin concluded that recharge decreases more or less in proportion to the plantations occupying 15%, 30% and 60% of the catchment. It was estimated that a steady-state drainage rate of 10 - 20 mm yr^{-1} (> 1.0 – 1.5% of rain) under woodland is required to keep the soil chloride less than 20 mg kg^{-1} (Tolmie et al. 2003). Whilst 60% of chloride was lost from the upper 1.5 m of soil as observed from the Brigalow Catchment area during the 16 years of study (1981-1997). Nevertheless, at least 15-50% of the affected area must be revegetated to impact the ground water table level as found out in the studies conducted by Tolmie et al. (2003), Kuginis and Daly (2001), Campbell et al. (2000) and Stauffacher et al. (2000).

Reforestation could prove to be of benefit as studies showed evapotranspiration as a mechanism which aids in drawing out water from discharge areas. For example, annual evaporation from *E. maculata* trees in upslope areas was estimated to be 2300 mm at age 7 (Greenwood et al. 1985) with an average monthly evaporation of 27.38 mm. This finding varies as it found that in midslope areas exhibited lower evaporation ability whereas, *E. globulus* has a value of 2700 mm in upslope and only 2200 mm in midslope areas (Greenwood et al. 1985). This could provide opportunities and benefits for stakeholders to ameliorate soil and could potentially increase the benefits from the plantation.

6.3 Net present value of forest plantation

Costs from dryland salinity can be incurred from interventions and mitigation to further prevent the spread and/or remediation. In Western Australia for example, costs can come from engineering methods such as shallow surface drainage on farms (Campbell et al. 2000), pumping groundwater (Pannell 2001) and other remediation to protect infrastructure and assets. Remediation could come in the form of plantation establishments in discharge areas but also entails costs. Though reforestation is deemed a viable option, its monetary returns must also be determined.

Despite forest plantation's capability to ameliorate soil is reassuring as previous studies had shown, its financial benefit is seldom given importance specifically, when considering the biomass accumulation under saline conditions. Perhaps, the lack of studies which accurately incorporate salinity in the forest plantation's financial return inhibited this. In fact, there is lack of consistency in valuation of forest plantation and its benefits as shown by the literature review.

The result of a study that estimated the net present benefit of tree planting on a saline affected areas in New South Wales with a discount rate of 7% was positive. In particular, the block and alley planting pattern could provide net present benefits of AU\$3,621 ha^{-1} and AU\$4,457 ha^{-1}, respectively over a 30 year period. Not surprisingly, the inconsistence in carbon price estimates was also found. The carbon prices estimates in the literature showed significant variations.

In Victoria, Connor et al. (2008) adopted a value of AU\$12.96 per tonne CO_2-e which was based on European Union carbon exchange market trading of €8.00 per tonne CO_2-e at that time. Other studies such as that by Burns et al. (1999), Eono (2001), and Benitez and Obersteiner (2006) adopted a carbon price estimate of AU\$20 $tonne^{-1}$ or AU\$5.45 per tonne CO_2-e. Whilst the Australian government adopted a price of AU\$23 $tonne^{-1}$ which was applied in determining carbon price in this study. To assure success in spotted gum plantations, salinity impact on carbon sequestration and the forestation's financial benefits should also be determined.

6.4 Methodology

6.4.1 Mortality modelling for 3-PG

Mortality and salinity modelling was necessary to determine the extent of annual stem loss which would be incurred in a spotted gum plantation given various ranges of salt concentrations in different sub-regions. Similarly, this was indicative of the impact of the plantation to ameliorate saline problematic areas *vis a vis* its impact on biomass production. The results of previous research in salinity impacts in eucalypt growth were instrumental in the development of a mortality model for this study. The first experiment conducted by Sun and Dickinson (1993) investigates a salinity level of 0 - 200 mM NaCl concentration (0 – 18 dS m^{-1}) while the study conducted by Madsen and Mulligan (2006) applied a salinity level of 0 – 400 mM NaCl concentration (0 – 36 dS m^{-1}). These two different datasets were combined and the survival rate of spotted gum in various salinity level from 0 – 400 mM NaCl (0 – 37 dS m^{-1}) for eleven (11) spotted gum provenances in Queensland and New South Wales (Table 6.1) were analysed to arrive at a percent mortality. The same datasets from the experiment conducted by Sun and Dickinson (1993) with 5 months-old spotted gum in Queensland and by Madsen and Mulligan's (2006) 6 months-old eucalypt seedlings were modelled to determine how spotted gum behaves under varying salinity levels.

Limited datasets for spotted gum seedlings under saline conditions were found, so this dataset was considered most appropriate to be incorporated in the biomass simulation. Those dataset were chosen due to the following reasons: (1) different salinity levels were captured in various areas within Queensland, (2) spotted gum was one of the studied eucalypt species, and (3) the focus was on seedlings rather than mature trees.

Table 6.1 Percent survival of 18 spotted gum provenances subjected to different salt concentrations derived from two separate experiments (source: Madsen and Mulligan 2006; Sun and Dickinson 1993).

Species/ (Age)	Total Provenances	Salt Concentration in mM NaCl (dS m^{-1}) 0 (0.5)	50 (5.0)	100 (11.0)	150 (14.0)	200 (20.0)	300 (28.0)	400 (36.0)
Various Eucalypt species including E. citriodora and E. maculata (5 months)	9	100	85	78	52	0	-	-
E. citriodora and E. maculata (6 months)	2	100	-	100	-	98.61	70.83	13.89

The percent mortality equations fitted for a 5-month and 6-month old spotted gum seedlings were then manipulated to create a mortality equation for young spotted gum grown in varied salinity levels. The total biomass change given specific mortality and salinity in Table 6.2 was used to recalibrate the impact of salinity on biomass of spotted gum.

As the units are in milliMolar salt (mM NaCl), conversion to deciSiemen per metre (dS m^{-1}) was necessary to match the model equation with the salinity datasets acquired from DERM. The developed general mortality model was statistically analysed for accuracy and became instrumental in the calculation of the percent seedling mortality.

Table 6.2 Total biomass change of spotted gum (g cm^{-2}) subjected to different salt concentrations derived from the two experiments (Source: Madsen and Mulligan 2006; Sun and Dickinson 1993).

		Salt Concentration in mM NaCl (dS m^{-1})						
Species/ (Age)	**Provenance**	**0 (0.5)**	**50 (5.0)**	**100 (11.0)**	**150 (14.0)**	**200 (20.0)**	**300 (28.0)**	**400 (36.0)**
E. citriodora/ (5 months)	Gibbs Ck.	7.62	6.40	6.00	3.97	0	-	-
E. maculata/ (5 months)	Pur. of Dunmore	8.90	5.40	4.10	2.35	1.92	-	-
E. citriodora/ (6 months)	Duaringa	9.22	-	6.40	-	4.74	4.81	0
E. citriodora/ (6 months)	Hughenden	7.94	-	6.16	-	4.74	2.65	1.33
E. citriodora/ (6 months)	Mt. Carbine	10.24	-	6.06	-	4.45	2.87	0
E. citriodora/ (6 months)	SW Mt. Garnet	8.90	-	5.74	-	4.01	3.91	0.65
E. citriodora/ (6 mos)	Kennedy	9.12	-	5.80	-	3.99	2.93	0
E. citriodora/ (6 months)	Irvinebank	9.01	-	5.71	-	5.54	2.09	0.6
E. citriodora/ (6 months)	Mt. Garnet	9.83	-	6.26	-	3.34	3.06	0.75
E. citriodora/ (6 months)	Mareeba	9.24	-	7.02	-	4.14	2.75	0
E. citriodora/ (6 months)	Expedition R.	9.20	-	6.80	-	3.89	3.23	1.76

To visualise the study area's spotted gum mortality as affected by salinity, GIS modelling was performed. The developed equation model was overlaid with the salinity thematic layer using an appropriate raster algorithm in the ArcGIS software. This process generated a continuous value of spotted gum mortality in varying saline conditions throughout the study site. The outcome was used with the extracted salinity level of each sub-region to come up with mortality value for each sampled site. The percent mortality was utilized as input in the 3-PG as a seedling mortality rate per year prior to biomass simulation. This provided the simulation on how much loss would be incurred in the plantation on an annual basis given the salinity level.

The result was then used as input for seedling mortality (*gammaN0*) parameter in the 3-PG biomass simulation. A single mature tree mortality (*gammaNx*) value of 1% was used in this study based from the result of mortality model for a 25 year old spotted gum under salinity range of 0.06 dS m^{-1} to 0.2 dS m^{-1} whereas a *gammaNx* value of 27% was used on a 4.5 dS m^{-1} salinity level based from the studies of Benyon et al. (1999). Given the absence of mortality data for mature trees of spotted gum under saline conditions, this was deemed most appropriate figure to be used as Benyon et al. (1999) study was focused on a 25 year old eucalypt trees growing in a saline soil with 4.5 dS m^{-1}. This mortality figure was also comparable to the results of the study conducted by Archibald et al. (2006) on the mean survival of a 25-years old eucalypt species as estimated to be more than 70%. Additionally, the parameter value for maximum canopy quantum efficiency, α_c, used in this study was 0.06 mol C mol PAR^{-1} which was based on the previous studies of (Landsberg & Waring 1997).

6.4.2 Soil Salinity modelling

Soil salinity point datasets requested from the Department of Environment and Resource Management (DERM, 2010) were used to visualize the extent of salinity in the study site. Points (*n=655*) in the vector layer were interpolated in the same manner as that of the soil nutrients, using the kriging method. The krigged soil salinity values generated from the DERM datasets were used to extract soil salinity information. During the processing and analysis of the data set it was noticed that the datasets are concentrated on the northern and southern part of the study site. It posed questions on the statistical distribution of the samples in which this study acknowledges as a shortcoming.

Ordinary kriging was the best interpolation technique for salinity from among the tested geostatistical method with an *RMSE* equal to 2.50 and *MSE* of 0.57. The process made use of the distance as against the geographical distribution of each value on the plane using the variogram. This procedure was indispensable to generate a continuous salinity values within the plane particularly in areas of unknown points. The created salinity map is named *EC* map which was reclassified into five levels that corresponds to the five (5) salinity categories developed by Bruce and Rayment (1982) namely: very low (<0.15 dS m^{-1}), low (0.15 – 0.45 dS m^{-1}), medium (0.45 – 0.90 dS m^{-1}), high (0.90 – 2.0 dS m^{-1}) and very high (>2.0 dS m^{-1}). Though there are other salinity classifications available (Appendix D), this classification was adopted as it was designed specifically for Queensland.

Extraction of values to points eventually followed after generation of the salinity thematic map. Values of salinity per sub-region were extracted using the spatial analyst tools in the ArcMap *v*.10 (ESRI ArcGIS package). The generated salinity map was instrumental in the calculation of the mortality for the varied salinity concentration of the sampled points, which became one of the parameter inputs to biomass modelling.

Later, the salinity thematic layer, *EC* map was beneficial in suitability modelling where the salt reduction level, (*EC_Loss* map) was visualised and soil amelioration value of the sub-regions was finally calculated.

6.4.3 Net present value of spotted gum plantation

The result of the biomass simulations for both scenarios were used in this specific process. Initially, a worksheet in Microsoft Excel was designed specifically for the present value of forestry system costs and revenues to facilitate calculations of the net present value. This served as a template for costs and benefits input for each of the sampled sites where equations were written for automatic calculations. Costs for plantations were calculated first followed by the revenues. The net present value was determined using the formula (Eq. 6.1) with *PVc* as the present value of forestry system costs, *Ct* as the cost incurred at a specific time *t*, *r* is the discount rate, and $1/(1+r)^t$ as the discount factor.

$$PV_C = \sum_t \left(\frac{Ct}{(1+r)^t}\right) \qquad \text{(Eq. 6.1)}$$

Costs of establishment, thinning, marking and harvesting were identified and are tabulated (Table 6.3). These were set in appropriate cells of the template for automatic calculations.

Table 6.3 Activities that incurred costs for spotted gum plantation.

Activities	Costs (AU$ ha^{-1})	Author/ Source
One-off cost		
Establishment cost in year 1	1800	(Polglase et al. 2008)
Thinning	300	(Polglase et al. 2008)
Marking	100	(Polglase et al. 2008)
Annual cost		
Maintenance cost	AU$40 ha^{-1}	(Polglase et al. 2008)

An annual maintenance cost of AU$40 ha^{-1} was also applied. As maintenance cost is an annual recurring costs, it was calculated using annuity to arrive at its present cost. The present value on annual costs, PV_{AC} (Eq. 6.2) was specifically used for this purpose where, AC_t is an annualised cost, and *T* also represents time.

$$PV_{AC} = AC_t\left(\frac{1}{r} - \left(\frac{1}{r(1+r)^T}\right)\right) \qquad \text{(Eq. 6.2)}$$

This step was followed by the calculations of the revenues from thinning and harvesting activities. The tabulated prices (Table 6.4) for Queensland were found from the review of literature and were utilised.

The volume and biomass were derived from the biomass modelling. The 253 sampled sites with biomass, volume and carbon for year 1 to year 100 was entered in the worksheet to determine the revenue of each specific points. Timber revenues were calculated from the volume accumulated in year 100 whereas sawlog revenues were gained from the volume in year 4 and year 12. The present value for revenue (Eq. 6.3) was calculated from the given equation below:

$$PV_R = \sum_t \left(\frac{Rt}{(1+r)^t}\right) \qquad \text{(Eq. 6.3)}$$

where, PV_R stands for present value for revenue and *Rt* is the revenue at a specified time *t*. Revenue was determined from the sawlogs as a result of thinning. Thinning is normally conducted on the 4th and 12th year (Polglase et al. 2008) which was also applied during the simulation process. The tangible benefits derived from thinning are pulpwood and sawlogs of different grades and composition. These were adopted from the literature as reported by Polglase et al. (2008) and Venn (2005). The composition of each derived products and its corresponding stumpage prices is indicated in Table 6.4 below.

Annual carbon and soil amelioration or salt revenues were finally added. Prices of these intangible benefits were also incorporated in the same table. The carbon revenue was directly determined by multiplying the carbon values by the market price of AU$23 tonne^{-1} for carbon whereas the salt amelioration revenue was determined based from the 60% salinity reduction as a result of the establishment of the plantation.

Table 6.4 Prices of spotted gum products from varied sources.

Products	Price (AU$ m^{-3})	Author/ Source
Tangible Benefits		
Pulpwood in year 12 (70%)	98	(Polglase et al. 2008)
C grade sawlog in year 12 (30%)	75	(Polglase et al. 2008)
Stumpage in year 100 (compulsory – 78%)	100	Maraseni, 2007
Stumpage in year 100 (optional – 17%)	70	Maraseni, 2007
Stumpage in year 100 (landscape – 5%)	20	Maraseni, 2007
Intangible Services		
Carbon	AU$23 tonne^{-1}	Market value
Salt (salinity amelioration)	AU$23 x 60% C	This study

This process was performed spatially to create a continuous layer of values for the entire study site. The biomass map (*DM100* map) in a raster format was initially created followed by mathematical calculations where *DM100_Salinity* map was deducted from the *DM100* to get the biomass loss (*DM100_Loss*). It may have been easier to use the percent mortality map in a straight forward manner by multiplying it to the biomass map. However, the simulation process captured all the input variables and is therefore more accurate.

The data from the study conducted by Tolmie et al. (2003) found a 60% decrease of chloride during the 16 year observation as a result of brigalow revegetation. This was the longest duration study found for the impact of revegetation in reducing the salinity level and found most suitable for this process. This percentage value was adopted in determining the salt reduction level as a result of 100 year plantation rotation for spotted gum. The biomass map was spatially multiplied by 60% to determine the salt reduction level and the generated map was converted to carbon map by dividing it to 50%. This was further multiplied by the price of carbon at AU$23 per ton of carbon. This determines the price of salt amelioration.

The discount rate applied in the valuation analysis of this study was 7% as this is a real rate that incorporates net of inflation and has been commonly used for plantation forestry investments in Queensland (Wilson et al. 2003; Spencer et al. 1999). Any form of tax levies or charges relating to plantation establishments are exclusive of these analyses.

Statistical analysis was conducted to determine the goodness of fit of the developed model. The output was further subjected to validation. The mortality rating of the actual spotted gum plantation in Warril View, Queensland was used to validate the result of the modelling and to support the validity of the claim.

6.5 Results and Discussion

6.5.1 Mortality of spotted gum in saline affected areas

The result of fitting the equation created for spotted gum for the 5 month-old (Eq. 6.4) and 6 month-old (Eq. 6.5) spotted gum are presented below whereas the curve fittings of the two models were shown in Figure 6.1.

$$S_{5months} = -0.0027\,(EC_e)^2 + 0.0654\,(EC_e) + 96.314 \qquad \text{(Eq. 6.4)}$$

$$S_{6months} = -0.001\,(EC_e)^2 + 0.1994\,(EC_e) + 96.905 \qquad \text{(Eq. 6.5)}$$

Where $S_{5months}$ stands for percent survival of the 5 month-old spotted gum, $S_{6months}$ is the percent survival for the 6 month-old eucalypts and EC_e is the salinity level in dS m^{-1}. The result of statistical analysis as shown by the goodness-of-fit for the equations showed a result of 98.03% and 98.48%, respectively.

The result of mortality modelling was based on the combined datasets of Madsen and Mulligan (2006) and Sun and Dickinson (1993) for spotted gum seedlings and is shown in the equation below (Eq. 6.6). The modelling showed a range of mortality from its lowest value of 1.93% to the highest at 40.95% (R^2 = 0.981).

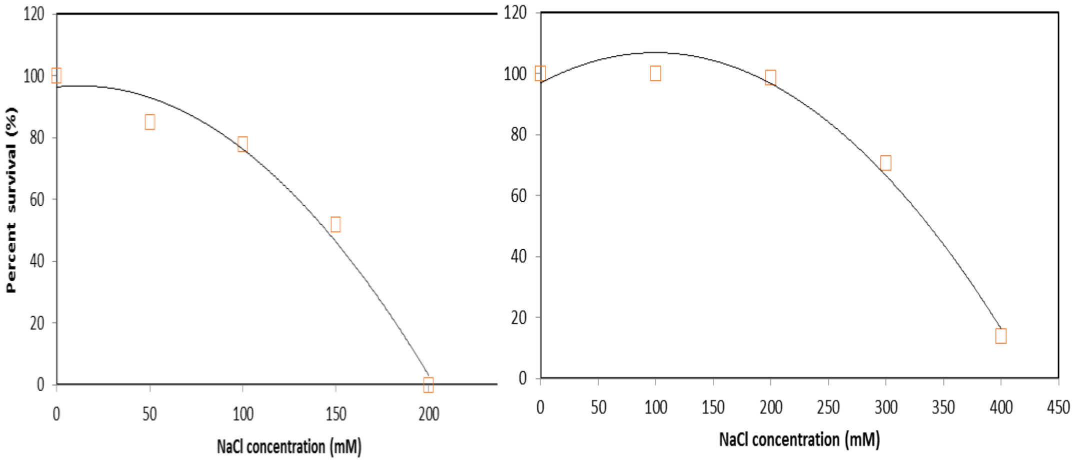

Figure 6.1 Fitted curve for two different models: Left curve (5-month old model) and Right curve (6-month old model)

The lowest percent mortality value corresponds with the locations found mostly in central and western SEQ whereas high mortality was found mostly along the coastline with the highest percent concentrated in the sub-region 4, the Southern Coastal Lowlands (Figure 6.2).

$$M_{CCV}\,(\%) = 4.435\,(EC_e)^3 - 36.579\,(EC_e)^2 + 71.548\,(EC_e) \qquad \text{(Eq. 6.6)}$$

where, M_{CCV} represents mortality of young spotted gum in percent, and EC_e is salinity in dS m^{-1}. The sample sites in sub-region 4 such as points 204 and 272 was found to have the highest mortality of 40.94% and 40.95%, respectively. This corresponds directly with the values of salinity normally found along or near the bodies of salt water. It was not surprising to find that the northern most part of the study site in particular the sub-region 1 – Burnett Curtis Hills and Ranges showed 12.45 – 18.16% mortality. Though sub-region 1 is connected with the northern inland, its eastern part is mostly coastal and its land surface from the coast is neither distant nor impossible to be reached by ocean sprays.

The result of the statistical analysis showed a high confidence in the utilisation of the developed mortality model. When the result of the model was further subjected to validation, it was found out that it was close to the actual value. The model equation estimated a comparative value of 7.59% against the actual 8% mortality of spotted gum plantation located in Warril View, Queensland.

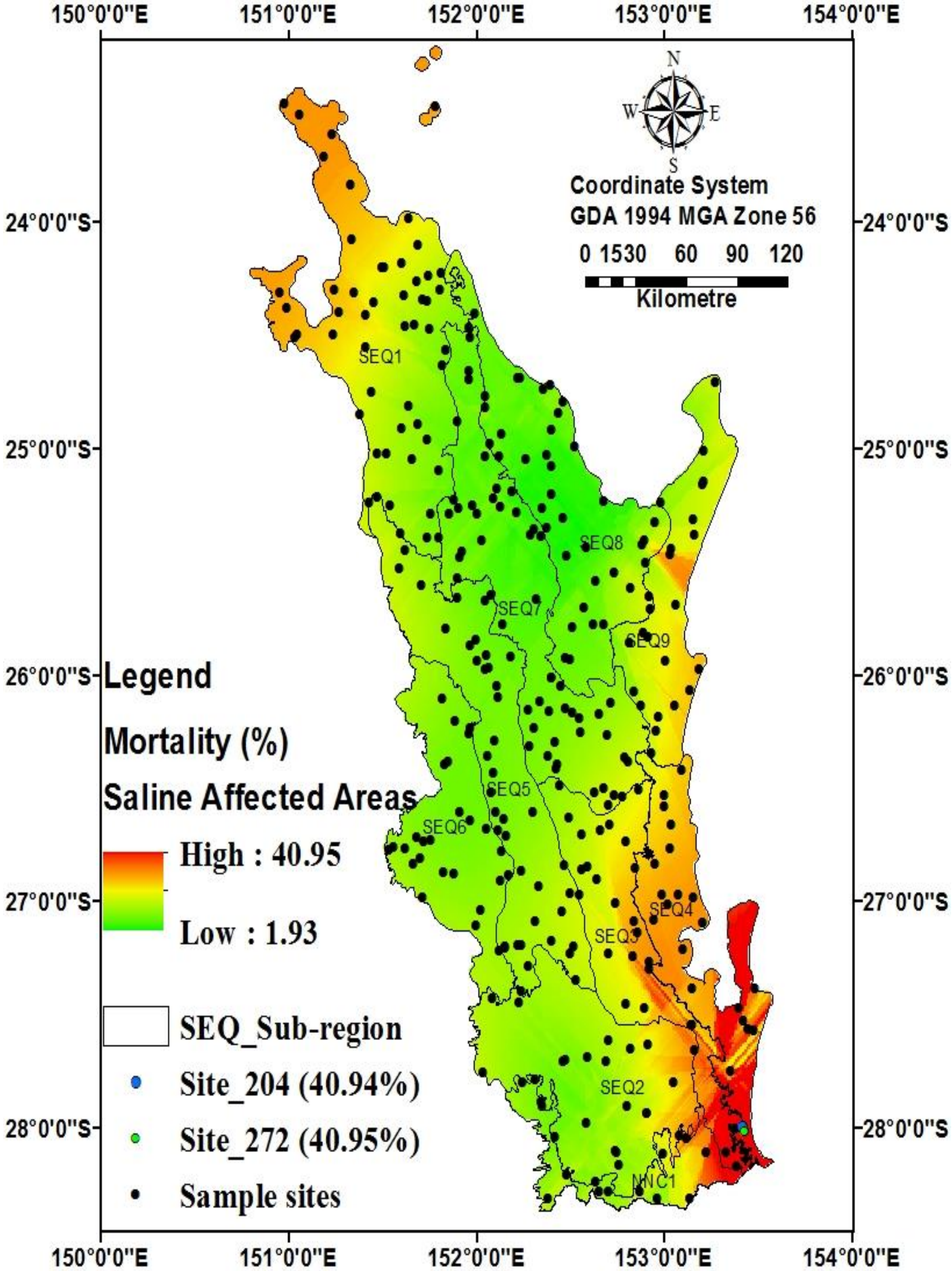

Figure 6.2 Modelled percent mortality of the spotted gum under saline conditions based on datasets from Madsen and Mulligan (2006) and Dickinson (1993)

6.5.2 Salinity modelling and salinity impact on seedlings

Ten sampled sites, except that in South Burnett resulted to a very low salinity levels that are below the concentration level tolerable for spotted gum. Results showed an estimated range of 0.02 – 2.07 dS m^{-1} with the lowest salinity concentrations found in areas away from the coast (Figure 6.3). The highest level was found in sub-region 4, in the Southern Coastal Lowlands where percent mortality including some of the areas near the coast in sub-region 8, Burnett Curtis Coastal. Sample points show the mortality and salinity level of the site and are tabulated (Table 6.5) below. It was surprising to find higher salt concentrations in one of the sampled sites in SEQ 6A, South Burnett in comparison with the rest of the sites previously presented in Table 6.2.

Table 6.5 Salinity level in selected sampled sites with the corresponding percent mortality.

SEQ (Sub-Regions)	Salinity level (dS m^{-1})	Mortality (%)
SEQ 9 – Great Sandy	0.14	9.72
SEQ 8 – Burnett Curtis Coastal	0.07	5.25
SEQ 8A – Burnett Curtis Coastal	0.09	6.03
SEQ 7 – Gympie Block	0.08	5.57
SEQ 7A - Gympie Block	0.12	7.97
SEQ 7B - Gympie Block	0.14	9.59
SEQ 6 – South Burnett	0.12	8.33
SEQ 6A – South Burnett	0.16	5.61
SEQ 3 – Southeast Hill and Ranges	0.13	10.26
SEQ 2 - Moreton Basin	0.12	8.39
SEQ 2A - Moreton Basin	0.09	6.60

This can be attributed to the complex interactions of soil types and climatic variability though this was not investigated in this study. This may be one of the factors why spotted gum production in the area is low as observed by Maraseni (2007) and also as shown in the result of this study.

Generally, the study site has a very low to low salinity level as shown in the map (Figure 6.3). A very low level of salinity (0.02 – 0.15 dS m^{-1}) nearly covers the entire region which are found in sub-regions 3, 5, 6, 7, and 8 traversing from the north east to the south west part of the study site.

Moderate levels ranging from 0.45 - 0.90 dS m^{-1} are found along the coastal area of sub-region 4 down to its southern boundary. The eleven sampled sites had salinity levels below the concentration level tolerable for spotted gum. Nevertheless, the result of statistical analysis showed significant salinity variations ($P<0.05$) within the study site ranging from 0.02 – 2.07 dS m^{-1}.

It was found that salinity was lowest in one of the South Burnett areas and highest at the Southern Coastal Lowlands. This can be attributed to several factors such as geographical location and soil type. Southern Coastal Lowlands although characterised with sandy soil but being near the coast could experience salt sprays coming from the ocean and ground water can experience salt water intrusion. The inland areas would have less of an exposure by the sea sprays though climatic conditions and other land practices may affect salinity as well.

Majority of the sub-regions do not exceed the highest level of 2 dS m^{-1}, with the exception of Sub-region 4 with a moderate level of salt concentrations. Sites located in this sub-region could pose detriment to the growth of spotted gum. Areas with a very low level, such as that found in the central part of Sub-regions 7 and 8, could potentially provide good tree growth and biomass yield. However, this scenario may change when rainfall, climate and human interventions interplay. As shown in the map, the salinity distribution should not be of concern in nearly all the sub-regions. This may be viewed as not detrimental to the growth of the spotted gum as the result of modelling did not reach nor exceed the limit of salt tolerance in most cases and therefore, may not be sufficient to impact the yield.

However, the result of the modelling proved otherwise as changes in estimated biomass was observed when mortality was incorporated. For example, the results showed that a 0.14 level of salinity in Great Sandy can incur an approximate 10% mortality in the plantation due to salt stress. It must be borne in mind that salt affects mainly the food production area of trees and thereby affect the supply of food necessary for cell growth.

6.5.3 Biomass and carbon sequestration under saline conditions

Several scenarios were set during the biomass simulation. The rotation period was set to 100 years with the intention to sequester carbon and reduce emission for a long period of time. Two scenarios were created in the simulation. The first scenario was termed as *Scenario 1* in this study with specific mortality (Mortality = varied) corresponding to salinity level of each sub-region. The fertility rating was varied (FR = varied) with the assumption that fertilization will be performed despite the salinity condition. This further assumes that fertilization can alleviate nutrient deficiency but cannot eliminate the salinity of the affected soil. *Scenario 2* was created for marginal areas having 4.5 dS m^{-1} salinity with an assumption that the intention of the land owner is to reforest the area without any fertilization.

The table below (Table 6.6) provides a summary of the estimated biomass accumulation and carbon sequestration at a maximum sustained yield (MSY) in two different salinity scenarios. The tabulated results demonstrate significant variances in the spotted gum biomass as affected by salinity. Biomass accumulation from all the sites in *Scenario 1* ranged from 263.54 to 1239.09 tDm ha^{-1} whilst *Scenario 2* accumulated a biomass from 101.86 to 295.22 tDm ha^{-1}.

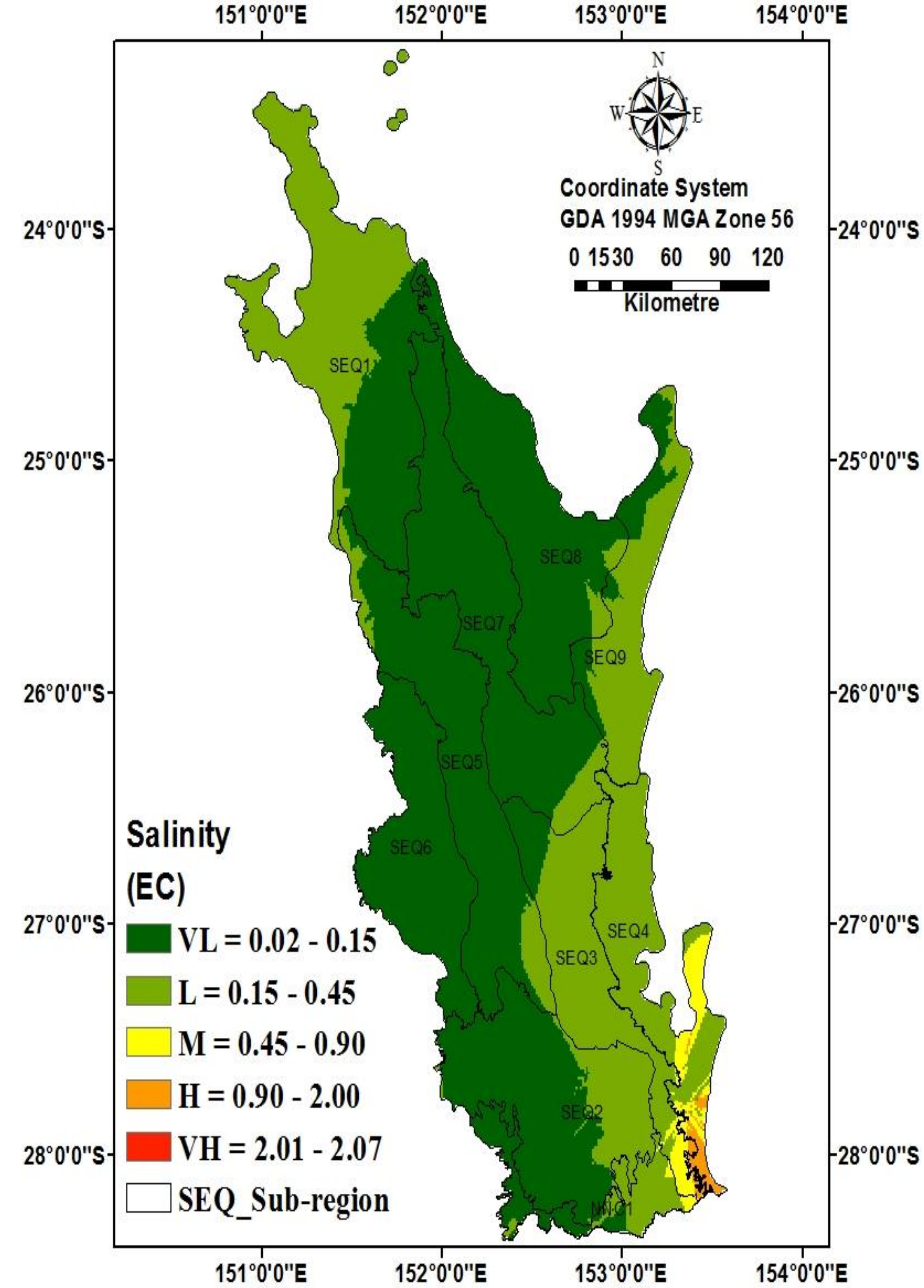

Figure 6. 3 Salinity distribution (dS m^{-1}) in the study site.

This maximum sustained yield can be attained within 38 to 49 years for *Scenario 1* whereas it takes 14 years for *Scenario 2* to attain its peak yield from all the sampled sites except in sub-region 9 which can be attained within 13 years. This can be attributed to the presence of salt as it affects the survival of spotted gum in areas such as this. It also indicates that the efficiency of spotted gum to sequester carbon dioxide in the atmosphere becomes limited as it experiences salt stress. The results also convey information on the duration where this species can function optimally. In the case of *Scenario 1*, trees can be expected to continuously increase in growth up to 49 years whilst *Scenario 2* was estimated to gradually decrease its maximum yield beyond year 14.

Table 6.6 Maximum biomass accumulation and carbon sequestered under two different salinity scenarios in selected sampled sites.

	Scenario 1 **Salinity level = 0.02 – 0.22 (dS m^{-1})**		***Scenario 2*** **Salinity level = 4.5 (dS m^{-1})**	
Sub-region (SEQ)	***Biomass$_{MSY}$ (*tDM ha^{-1}*)**	****Carbon (*t C ha^{-1}*)**	***Biomass$_{MSY}$ (*tDM ha^{-1}*)**	****Carbon (*t C ha^{-1}*)**
SEQ 9 – Great Sandy	1232.09	616.04	295.22	147.61
SEQ 8 – Burnett Curtis Coastal	710.23	355.12	200.66	100.33
SEQ 8A – Burnett Curtis Coastal	610.02	305.01	173.57	86.79
SEQ 7 – Gympie Block	457.53	228.77	160.66	80.33
SEQ 7AB - Gympie Block	684.85	342.42	207.78	103.89
SEQ 6 – South Burnett	263.54	131.77	101.86	50.93
SEQ 6A – South Burnett	438.44	219.22	142.03	71.02
SEQ 3 – Southeast Hill and Ranges	526.84	263.42	165.60	82.80
SEQ 2 - Moreton Basin	513.65	256.82	152.52	76.26
SEQ 2A - Moreton Basin	667.57	333.79	189.80	94.90

*Biomass$_{MSY}$ = biomass at maximum sustained yield; *tDM ha^{-1}* = ton dry matter per hectare; ***t C ha^{-1}* = ton carbon per hectare

Variances are also noticeable between the mean annual increments (MAI) of both scenarios. MAI range for *Scenario 1* was estimated at 4.62 to 19.68 m^3 ha^{-1} yr^{-1} with the lower range found at SEQ 6 in South Burnett and the upper range at SEQ 9 in Great Sandy. There is a substantial reduction in the MAI range found in *Scenario 2* estimated at 3.21 to 13.66 m^3 ha^{-1} yr^{-1}, with its minimum and maximum attained in South Burnett and Great Sandy, respectively.

6.5.3.1 Scenario 1 - Biomass and carbon sequestered under low salinity areas

In the first glance, it would appear that there is no salinity problem in the study site as it ranges from 0.027 – 2.064 dS m^{-1}. This could be attributed to the small number of samples collected which may not be able to capture the local variations of salinity in the whole region which occurred in small patches of land. However, when the biomass change (Table 6.7) was determined between that attained from the non-saline areas to the low saline areas, the change was found to be significant. Non-saline areas (0 dS m^{-1}) used in this sub-chapter is the estimated biomass simulated in chapter 5 of this study. Simulated MAI and biomass value of non-saline area became the base value by which the two scenarios (Scenario 1 and 2) were compared. The table 6.7 shows the results of plantation biomass change exposed to low saline areas versus the non-saline sites.

Table 6.7 Biomass difference accumulated between non-saline and low saline (0.2 - 2.0 dS m^{-1}) areas in selected sampled sites.

Sub-Region	Non-Saline Areas (0 dS m^{-1})		Low Saline Areas (0.2 – 2.0 dS m^{-1})		Change (difference) (%)	
	MAI_{MSY} (m^3 ha^{-1} yr^{-1})	Total DM_{100} (tDM ha^{-1})	MAI_{MSY} (m^3 ha^{-1} yr^{-1})	Total DM_{100} (tDM ha^{-1})	MAI_{MSY}	Total DM_{100}
SEQ9 – Great Sandy	19.98	2329.00	19.68	2291.26	-2	-2
SEQ8 – Burnett Curtis	15.98	1867.00	11.69	1342.24	-27	-28
SEQ8a – Burnett Curtis	17.95	2142.00	10.69	1238.94	-40	-42
SEQ7 – Gympie Block	14.87	1774.00	7.43	921.78	-50	-48
SEQ7 a & b – Gympie Block	18.15	2051.00	11.15	1300.98	-39	-37
SEQ6 – South Burnett	11.40	1422.00	4.62	618.58	-59	-56
SEQ6a – South Burnett	12.86	1566.00	7.61	902.24	-41	-42
SEQ3 – South East Hills & Ranges	16.43	1971.00	8.98	1083.46	-45	-45
SEQ2 – Moreton	12.99	1607.00	9.10	1059.69	-30	-34
SEQ2a – Moreton	14.08	1611.00	11.32	1299.14	-20	-19

The biomass change was highest in the South Burnett region whereas the lowest change was located in the Great Sandy Region. This information suggests that rainfall plays a vital role in saline areas. The initial modelling under non-saline soil showed the Great Sandy Region provided the best growth for spotted gum. Under low saline conditions, growth simulated showed that this same area was least affected and provided the least change of only 2% for MAI and biomass. In contrast, the South Burnett (SEQ 6) under non saline condition has a limited sequestration capacity as a result of its lowest MAI. When this area was exposed to the low saline scenario, the simulation result reflected the highest impact both on its MAI and biomass. Under this scenario the plantation is expected to experience a 59% reduction in MAI and 56% difference in both biomass and carbon sequestration capacity. This can be attributed to the amount of rainfall occurring in the two contrasting sites. As Great Sandy region is located in high rainfall zone, the presence of low salt concentrations may not significantly affect the spotted gum's capability to absorb water and sequester carbon. It is possible that the limited amount of rainfall in South Burnett may present limited capability for spotted gum as salt serves as a barrier in the hydraulic conductivity of the soil, thereby, hindering water movement. In this context, the salinity impact on biomass accumulation and carbon sequestration could be explained in relation to the rainfall. This study also acknowledges the interplay with other significant variables as explained in the previous chapters.

As mentioned previously, the extracted salinity values of the eleven sampled sites from the processed salinity map suggested that there was no salinity problems in the area if based primarily on Queensland salinity classes. However, when salinity level was assumed to be maintained until the end of the 100-year rotation period, the biomass production of spotted gum plantation in the South Burnett resulted in a maximum of 59% change as estimated by the model. Salt concentrations greater than 2.00 dS m^{-1} were found mainly concentrated at the lower southeast portion of the study site. However, the results of this sampling were not included in this discussion as this was part of the simulation setting in *Scenario 2* which is explained in the next sub-topic.

6.5.3.2 Scenario 2 - Biomass and carbon sequestered under high salinity areas

The information provided by the results of increased sampling was instrumental in justifying the level of salinity used in setting *Scenario 2*. The choice of 4.5 dS m^{-1} salinity level applied under *Scenario 2* was justified. The 27% *gamma Nx* based from Benyon et al. (2006) study was considered most appropriate in this case. This salinity level was classified as moderately saline, however for the purpose of comparison in this study, this was considered as high salinity.

Table 6.8 shows the estimated biomass accumulation and carbon sequestration for *Scenario 2*. Information is implicit in the extent of salinity impact on spotted gum as shown by this simulation run. The biomass change suggested a significant impact of the salt concentrations on spotted gum for a long period of exposure. This salinity level as shown by the simulation can significantly reduce the MAI and biomass of the plantation to 72% and 99%, respectively. The 72% MAI reduction is expected to be experienced by the plantation as early as the 14th year whilst the 99% biomass reduction is expected to occur at the end of its rotation in 100 years.

The simulated carbon sequestration on all the sites was significantly different ($P <$ 0.05) spatially both within and between the two scenarios. These differences were explained by the variations in rainfall, temperature and other environmental factors including salinity causing mortality in spotted gum. This information is very relevant in the plantation establishment for carbon sequestration under the CFI compliance as it has implications in biomass production when implemented under salinity affected areas. This result also indicates that spotted gum plantations can be considered capable to sequester atmospheric carbon dioxide in saline environment for a longer period of time.

Table 6.8 Biomass difference accumulated between non-saline and high saline (4.5 dS m^{-1}) areas in selected sampled sites.

Sub-Region	Non-Saline Areas (0 dS m^{-1})		High Saline Areas (4.5 dS m^{-1})		Change (difference) (%)	
	MAI_{MSY} (m^3 ha^{-1} yr^{-1})	**Total DM_{100} (tDM ha^{-1})**	**MAI_{MSY} (m^3 ha^{-1} yr^{-1})**	**Total DM_{100} (tDM ha^{-1})**	**MAI_{MSY}**	**Total DM_{100}**
SEQ9 – Great Sandy	19.98	2329.00	13.66	52.33	-32	-98
SEQ8 – Burnett Curtis	15.98	1867.00	8.05	31.93	-50	-98
SEQ8a – Burnett Curtis	17.95	2142.00	7.37	35.96	-59	-98
SEQ7 – Gympie Block	14.87	1774.00	5.13	18.88	-66	-99
SEQ7 a & b – Gympie Block	18.15	2051.00	7.69	28.19	-58	-99
SEQ6 – South Burnett	11.40	1422.00	3.21	14.37	-72	-99
SEQ6a – South Burnett	12.86	1566.00	5.26	22.31	-59	-99
SEQ3 – South East Hills & Ranges	16.43	1971.00	6.19	26.81	-62	-99
SEQ2 – Moreton	12.99	1607.00	6.28	30.12	-52	-98
SEQ2a – Moreton	14.08	1611.00	7.81	31.19	-45	-98

It may appear that the MAI and carbon sequestration values in saline areas are low and below commercial profitability threshold, however these values are preferred to avoid overestimation as per IPCC principle of conservativeness. Financial benefits must be considered when considering commercial plantation as reflected by the results on its maximum sustained yield.

6.5.4 Carbon sequestration and financial benefits of spotted gum

From the results, it is evident that significant variations in the maximum sustained yield and carbon sequestration capability in all the sub-regions are brought about by the complex interactions of the local climatic and biophysical predictors. Taking a closer look at the result of the simulations on the productivity of the different sites provides information on the location of potential suitable sites for carbon enterprises. For easier identification, the range of estimated values for the maximum sustained yield in the study site was classified into three categories of low, medium and high (Table 6.9).

Table 6.9 Categories of spotted gum productivity in selected sampled sites located in various sub-regions.

Sub-region in SEQ	MAI_{MSY} (m^3 ha^{-1} yr^{-1})	Category
SEQ9 – Great Sandy	19.98	High
SEQ8 – Burnett Curtis Coastal	15.98	Medium
SEQ8 a – Burnett Curtis Coastal	17.95	Medium
SEQ7 – Gympie Block	14.87	Medium
SEQ7 a & b – Gympie Block	18.15	Medium
SEQ6 – South Burnett	11.40	Low
SEQ6 a – South Burnett	12.86	Low
SEQ3 – South East Hills and Ranges	16.43	Medium
SEQ2 – Moreton Basin	12.99	Low
SEQ2 a – Moreton Basin	14.08	Low

The total revenue of the plantation alone without considering the land value ranges from AU$28,000 ha^{-1} yr^{-1} to AU$57,000 ha^{-1} yr^{-1} within the region depending on the productivity. However, its total costs are estimated to be at AU$29,000 ha^{-1} yr^{-1} (Table 6.10). The annual revenue however varies from a loss of - AU$10.41 ha^{-1} yr^{-1} to a maximum financial benefit of AU$278 ha^{-1} yr^{-1} under the timber, carbon and salt scenario. Under the timber, carbon and salt scenario, only one sub-region is negative in revenue whereas under the scenario of timber and carbon, sub-regions 6 and 2 have negative returns. It is estimated that under the conventional timber alone scenario, all the sites are not financially viable.

Table 6.10 Net present value of 100-year plantations based on total cost and revenue only without land value or opportunity cost.

Sub-region	Year 100	Total Revenue (AU$)	Total Cost (AU$)	NPV Timber (AU$)	NPV Timber+ Carbon (AU$)	NPV Timber + Carbon + Salt (AU$)
9	100	56,930	29,108	-252	221	278
8	100	42,913	29,108	-265	95	138
8a	100	47,309	29,108	-261	135	182
7	100	38,436	29,108	-269	54	93
7a	100	53,428	29,108	-255	190	243
7b	100	53,428	29,108	-255	190	243
6	100	28,068	29,108	-276	-39	-10
6a	100	36,273	29,108	-267	35	72
3	100	42,282	29,108	-265	89	132
2	100	31,491	29,108	-274	-8	24
2a	100	38,371	29,108	-268	54	93

Values from approximately 11 to 14 m^3 ha^{-1} were considered low growth values and are not commercially viable. Medium values ranged from 15 to 18 m^3 ha^{-1} of commercial value, while high value of 20 m^3 ha^{-1} was classified as commercially profitable. However, economic viability could only be achieved if the land values or the opportunity cost of land is considered. In areas where the opportunity cost of land is very high (for example, urban development area) even a high range of growth rate may not be competitive. Alternative land uses (e.g. housing) could be more attractive.

As concluded by Venn (2005), plantations with high growth values of 20 to 25 m^3 ha^{-1} yr^{-1} are profitable or commercially viable in some parts of the Queensland hardwood region if the rural land values are less than AU$2,300 ha^{-1} while 15 m^3 ha^{-1} yr^{-1} can be viable if land values were less than AU$1,600 ha^{-1}. As per the author's estimate, carbon sequestration of plantations in Queensland regions are valued at AU$630 ha^{-1} in 30 years with 10 m^3 ha^{-1} yr^{-1}. Another study conducted by Maraseni (2007) found out a value of AU$794 for Kingaroy in 34 years with an MAI of 9.7 m^3 ha^{-1} yr^{-1}.

It is noted that four sites, all located in South Burnett and Moreton Basin have marginal productivity (11 - 14 m^3 ha^{-1}). The sub-regions located in Burnett Curtis Coastal, Gympie Block and South East Hills and Ranges have medium potential with values ranging from 15 – 18 m^3 ha^{-1}. Whilst only one site located at Great Sandy sub-region reached a high commercially viable growth of 20 m^3 ha^{-1}. The result of this study is comparable with the growth prediction of *E. maculata* estimated by the CSIRO (Polglase et al. 2008) for agroforestry hardwood opportunities that ranged from 7 to 31 m^3 ha^{-1}.

Similarly, the results of studies conducted by Paul et al. (2008) identified MAI value of 6.59 m^3 ha^{-1} $year^{-1}$ at age 30 for areas with low precipitation of 755 mm. This value is lower in comparison to the results of this study, considering they are both located in a low rainfall areas. One simulated site in this study located in South Burnett has an average annual rainfall of 765 mm, accumulating an MAI of 8.84 m^3 ha^{-1} $year^{-1}$ (age 30). Deviations of the values between the two studies may seem significant, however as latitudinal variations and geographical locations may affect solar radiation, temperature and occurrence of frost, a deduction cannot be presented on the basis of rainfall alone. Likewise, landscape scale must be considered as a small piece of land may contain variation in one site attribute that could arise to yield variation.

Additionally, a spotted gum plantation at Kingaroy area receiving an average annual precipitation of 781 mm has MAI of 12.65 m^3 ha^{-1} yr^{-1} attained at year 66 with a stocking density of 250 sph (Maraseni 2007). For purposes of comparison, similar stocking density was applied in one of the sites of South Burnett in this study with 765 mm rainfall. Results of this modelling for the same plantation of 250 sph at age 66 shows a mean annual increment of 11.65 m^3 ha^{-1}. This value is 1 m^3 ha^{-1} lower than the projected value at Maraseni's Kingaroy growth projection. Maraseni's modelling was based on the best performing stocking density (250 sph) that would provide the maximum potential productivity whereas this study considered the conservative stocking density of 200 sph. Significant is the incorporation of spacing in Maraseni's work whereas this study includes the biophysical processes and climate in carbon accumulation. As spacing is not incorporated in the carbon modelling of this study, it would be interesting to consider this component in the future. Furthermore, the results of this study included the mortality of the plantations which may have contributed to a lower MAI in comparison with that of Maraseni (2007). Mortality was based from the actual inventory of experimental plantation at Warrill view (Lee 2010a). Comparatively, the Maraseni (2007) study made use of regression modelling whilst this study is more of a process-based modelling.

6.5.5 Financial benefits from spotted gum plantation in saline areas

The results of benefit and costs analysis provided the information for the determination of net present benefit of spotted gum plantation under business-as-usual scenario and in areas confronted with saline issues. As plantations normally incur costs during the initial phase of its establishment and at specific stages where maintenance and thinning is required, these costs were included. The expenditures for the spotted gum forestry establishment was AU$1,800 ha^{-1} which included land preparation and other labour involved whilst marking and thinning for years 4 and 12 were AU$100 ha^{-1} and AU$300 ha^{-1}, respectively. An annual maintenance cost of AU$40 ha^{-1} was allowed for fertiliser and pesticide as was determined by experts such as Polglase et al. (2008). Revenues gained from the plantations were from the 12th year of thinning where a revenue of AU$75 m^{-3} for C grade sawlog was derived while AU$98 m^{-3} was gained from pulpwood in year 12. No revenue was gained in year 4 as thinned trees has no commercial value during this year. Timber benefit was not gained during the optimal growth stage of the plantation, as CFI does not allow harvesting within the duration of the rotation, to ensure continuous carbon sequestration. After the end of the rotation, plantings are allowed to be harvested. This provided a revenue for timber gained by selling stumpage at AU$100 m^{-3} for compulsory logs (78%), AU$70 m^{-3} for optional logs (17%) and AU$20 m^{-3} for landscape logs (15%). The intangible benefits came from carbon sequestered at a market price of AU$23 $tonne^{-1}$ annually and recharge benefit of 60% of the carbon accumulated throughout the rotation period multiplied by the carbon cost of AU$23 $tonne^{-1}$ which was gained from year 25 until the rotation ends. This was on the basis that plantation is capable of lowering soil salinity from year 25 and onwards as stated by several experts such as Hill (2004).

The net present value of spotted gum plantation for soil amelioration was estimated to vary from AU$2,845 ha^{-1} yr^{-1} to AU$3,866 ha^{-1} yr^{-1}. Timber benefit was AU$1,516 ha^{-1} yr^{-1} to AU$5,685 ha^{-1} yr^{-1} from two thinning activities and harvesting the plantings at the end of 100 years. The bulk of the benefit was from the incorporation of carbon sequestration and soil amelioration benefit. The total costs and total revenue without considering land values or opportunity costs is estimated to be at AU$29,108 ha^{-1} yr^{-1} whilst revenue varied from AU$28,068 ha^{-1} yr^{-1} to AU$28,068 ha^{-1} yr^{-1}.

Plantation established in low saline areas particularly in the Great Sandy sub-regions provides a financial benefit only when the maintenance is up to 12 years right after the second thinning. The assumption is that at this stage the plantations has to be left undisturbed to sequester carbon and allow the regeneration to develop for a higher biomass accumulation. With this scenario, a net profit of AU$27,822 can possibly be derived from the plantation with timber, carbon and salt amelioration. Though the understorey growth was not considered in this study, it was further assumed that floor vegetation could help enhance the soil salinity condition of the area.

A different scenario was created when the carbon price was increased to AU$41 $tonne^{-1}$ under a 7% discount rate. Spotted gum plantations in the Great Sandy sub-region can provide an estimated total financial profit of AU$98,455 ha^{-1} with timber, carbon and soil amelioration benefits.

Financial loss was estimated to be incurred when the current market price of AU$23 per ton carbon was applied unless this was complemented by a higher soil amelioration revenue or a higher stumpage price. The scenario for increased soil amelioration revenue and increased stumpage price was not included in this study.

The common harvesting age of spotted gum plantation in Australia is 25 to 30 years with thinning normally done on the 4th and 12th year where benefits could be derived. As Carbon Farming Initiative (CFI) does not allow for harvesting during this period, the spotted gum plantation benefits were allocated mainly from intangible services such as carbon and salt credits. With harvesting allowed at the maturity of the 100-year rotation period that was the only period where timber benefit was included.

6.6 Conclusions

Forestation for carbon sequestration is one of the mitigating measures that could offset emissions whilst potential suitable sites needs to be established to secure financial profitability. However carbon accounting for specific species needs to be implemented to assure accuracy in crediting. Similarly, soil amelioration benefits (e.g. salinity) from plantation that could increase the forestation profitability need to be incorporated. It is believed that with an appropriate model that could integrate significant components affecting spotted gum growth could assist in addressing the issues in carbon accounting and crediting. Available established tools such as net present value and GIS could be used to identify potential suitable sites where carbon sequestration through forestation can be implemented successfully.

Nevertheless, as the threshold level for spotted gum is not reached, this is not expected to impact on the yield of spotted gum in the whole study area except for localised pockets that may exceed the limit of its salt tolerance. The salinity level and extent of the problem during the conduct of the study is not concerning, however as salinity is a complex phenomenon we cannot discount the possibility of it being a problem in the near future. It should be borne in mind that the localised pockets of salinity may occur that could pose risks to the establishment of the plantation and therefore these results should be used carefully.

Soil salinity is one of the major environmental problems causing reduction of plant growth and development, leading to a loss of crop productivity of more than 50% and is recommended to be prioritised for soil amelioration. Though salinity affects the growth of spotted gum plantations, it can also aid in soil amelioration process in the long term and eventually could create a positive financial benefit. Soil amelioration could also increase the benefits derived from the plantation on top of its conventional benefit if the maintenance cost would only be up until year 12 or when price per ton of carbon is increased.

The plantation in SEQ is estimated to provide carbon credits of 2609 to 4441 ton ha^{-1} at least within a 100 year under non saline conditions. Spotted gum can be expected to continuously sequester carbon for a long period of time and is appropriate for CFI environmental planting. This can offset a conservative maximum estimate of 4441 ton carbon emission of ha^{-1} in the study site alone without consideration of leaching and other risks.

Forestation may provide financial benefits even if established under high salinity level zones. MAI of approximately 5 to 20 m^3 ha^{-1} can be produced in plantations with low salinity levels (0.2 - 0.22 dS m^{-1}) whereas MAI of 3 to 14 m^3 ha^{-1} was estimated by forestation activities in high salinity zones (4.5 dS m^{-1}) within the study site. Moreover, other benefits can be derived from forest plantations in saline affected areas even when exclusive of its tangible goods and services. These may include environmental benefits in saline affected areas for 100 years through carbon reduction emission and soil amelioration. However, when commercial plantations are established in low rainfall zone with salinity problems, these may result in financial loss. Though the spotted gum could survive, its profitability is not guaranteed.

As the time of writing of this dissertation, areas where rainfall exceeds 600 mm cannot be subjected as eligible for CFI projects. It should be realised that these areas, particularly areas with 700 mm up to 1100 mm rainfall are where salinity occurs. If the Direct Action Plan of the current Australian Government was to expand the eligible CFI projects, incorporating areas over 600 mm rainfall especially those with salinity problems may be socially and environmentally profitable in the long run.

In reality the scenario is not always favourable for forestry in any one sub-region. The analysis would be different if site suitability of the study site is visualized as land uses are not homogeneous throughout the landscape. In this case, GIS mapping is found to be indispensable and could potentially visualize the suitable sites where forestation is favourable to implement. This will be discussed further in the next chapter.

CHAPTER 7

Site Suitability Analysis of Spotted Gum Plantation for SEQ

*"**Wisdom** strengtheneth the wise more than*
Ten mighty men which are in the city"

Jedidiah, *Book of Ecclesiastes*, 970 – 928 BCE

7.1 Introduction

Establishment of spotted gum plantations for forestation investments have potential in southeast Queensland and may be feasible for soil amelioration and GHG offsetting but, site suitability for the desired purpose is the key. This chapter will focus on the integration of the identified climatic and biophysical factors as a result of biomass modelling and integration to come up with the suitable sites. Sites suitable for forestation will be determined for biomass production and carbon sequestration. The net present value of spotted gum plantation as affected by various environmental conditions, in particular the impact of soil fertility and salinity, was incorporated for added financial benefits. Suitable sites will be modelled and visualised with the use of the ESRI GIS spatial and statistical tools.

This chapter is sub-divided into five sections. The first section 7.1 is an overview of the content followed by the second section 7.2 that provides background information and gaps that need to be addressed in the suitability of spotted gum plantation establishments for carbon sequestration under saline conditions. Section 7.3 discusses the site suitability methodology whereas section 7.4 presented the results and discussion. Finally, section 7.5 ends with the conclusions.

7.2 Background Information

7.2.1 Spatial interpolation in GIS

Among the spatial interpolation techniques reviewed in the literature, kriging was favoured as this is the most appropriate and suitable for the soil nutrient parameters under study. Kriging is a method of calculating estimates of a regionalized variable at a point, over the region of study, and uses a criterion for the minimization of an estimation variance (Divi 2004). In kriging, the predictions are based on the model that the unknown value $Z(x)$ to be estimated which represents both global trend $m(x)$ of the data and local variation $\dot{e}(x)$ (Xuan & Xuan 2004) given by the equation below (Eq. 7.1).

$$Z(x) = m(x) + \dot{e}(x) \qquad \text{(Eq. 7.1)}$$

In the case of *n* observation points with values $Z(x_1), Z(x_2),\ldots, Z(x_n)$ at points $x_1, x_2\ldots, x_n$ distributed in the neighbourhood of X_0, the best estimator at X_0 is given by the following equation (Eq. 7.2):

$$Z^* (x_0) = \sum_{i=1}^{N} \lambda_i \, Z(x_i) \text{ where } i = 1,\ldots, n \qquad \text{(Eq. 7.2)}$$

λ_i is the vector of kriging weights and *N* is the number of sampled locations. Further innovation on interpolation and analysis methods were developed by Matheron (1963) and Gandin (1963) as cited by Hengl (2007). In their development work, the derivation and plotting of semi-variances was introduced. This is the difference between two neighbouring values termed as a variogram and defined in a mathematical expression given by equation (Eq. 7.3):

$$\gamma (h) = \tfrac{1}{2} (Z(x) - Z(x+h)]^2 \qquad \text{(Eq. 7.3)}$$

where $\gamma (h)$ is the experimental variogram model, $Z(x)$ and $Z(x + h)$ are two known values with separation distance *h*. The normality around this theory is that the semi-variances are smaller at shorter distances but stabilize at certain distance to levels that are more or less equal to global variance. This is known as the spatial auto-correlation effect (Hengl 2007). Calculation of semi-variances through this process produces an experimental variogram which necessitates transfer of or fitting of such values to the theoretical variogram model. There are number of variogram models that are available for choice such as linear, spherical, exponential, circular, Gaussian, Bessel, power, etc. Fitting of variogram to a certain model is an iterative method and is important for deriving semi-variances for all locations and solves kriging weights. The fitting of the theoretical model for the observed variogram is guided by the following features of consideration (Divi 2004):

(1) Presence or absence of sill (*c*), which is indicated by the levelling off of the variogram once *h* increases beyond some distance (range);
(2) Behaviour (shape) of the variogram at the origin; and
(3) Presence or absence of nugget effect (*c0*), indicated by an intercept of the variogram on the y-axis of the model graph. The nugget effect implies abrupt changes in the regionalized variable over small distances, variability at spatial scales finer than sample spacing.

This method has advantages over other means as the variogram helps in the understanding of the extent, characteristics and structure of the variation of the parameters under study. It also provides information on the behaviour of the parameters (e.g. isotropy or anisotropy) prior to fitting decision. Lastly, it helps in determining the kind of suitable kriging method that could generate best estimates (Xuan & Xuan 2004). Having these benefits in mind, geostatistical analysis were preferred in particular the kriging method in the spatial interpolation of soil nutrients.

7.2.2 Site suitability modelling using multiple criteria decision analysis

Many spatial decision support tools have been developed for suitability analysis. For instance, multi-criteria analysis that makes use of several criteria or elements interacting with each other that mimics the functionality of a system. The components are either added or multiplied, with or without weights to simulate the effects or impacts of a phenomena or system (Hill et al. 2003). The effects of each component may be influenced by the frequency of rainfall, temperature changes, soil fertility and other significant bio-geophysical changes of the target ecosystem.

Site suitability analysis require input datasets or variables to determine the best possible sites depending on the purpose of the study. The conventional practice involves weighted linear combination (WLC) of variables pre-standardised to fit the demand (Basnet et al. 2001). Variables may come from environmental factors such as soil fertility, temperature, rainfall and other relevant factors. These can be easily incorporated in a GIS environment with appropriate modelling tools even with the presence of multiple variables. These then require standardisation and classification according to the requirements and purpose. Given the multiple parameters, an appropriate multiple criteria analysis is desired where GIS-MCDA (multiple criteria decision analysis) is of high importance. The absence of scientifically proven weighting appropriate for carbon estimation and costly field collection dictated other techniques and spatial mapping with Analytical Hierarchy Process was determined as the best option. Likewise, AHP can also combine attributes by a weighted additive approach and end up with a decision despite large number of parameter attributes. It is user friendly and can be easily executed with the mathematical operations and cartographic modelling. As such, sites suitable for forestation are possible to be determined through overlays of different thematic layers generated from GIS modelling.

The Analytical Hierarchy Process (AHP) was developed by Saaty (2000) based on a pairwise comparison matrix. This technique can determine factor weights (*wi*) for areas of relative importance under study. However, physiological variables and their dynamic interaction in tree processes may pose a difficult challenges when modelled using GIS alone. For instance, the biomass production and carbon sequestration capability of a spotted gum plantation. It is therefore necessary that process modelling be implemented before integration in GIS to come up with suitable sites. This is the case in this study where process modelling in particular biomass simulation and other processes were initially conducted prior to site suitability modelling.

7.3 Methodology

7.3.1 Biomass GIS visualization

Firstly, a total of 315 randomly generated points were generated across all the sub-regions of the area. The specific locations (e.g. longitude and latitude) of all the points were identified for the purpose of determining their corresponding physical data from the local datasets available. The datasets that were collected for each of the points were then used as input in 3-PG physiological process modelling. After biomass simulation, the total carbon was calculated. The detailed procedure on fertility rating, biomass simulation and carbon sequestration was discussed in Chapter 5. The results were organised in a tabulated format and exported to a GIS format for the 315 sample sites. The populated sample points holding all the bio-physical information were then interpolated.

The combination of parameter values used as input in the growth and biomass simulation in 3-PG were generated to create layers of variables that enabled biomass visualization using ArcMap *v*.10. All of the important variables/parameters (temperature, rainfall, frost, mortality, evaporation, FR, etc.) used for biomass simulation were transformed into individual thematic layers and were further classified.

Potential biomass production zones were spatially created as a result of the biomass modelling. Four zones were created including very low, low, moderate, and high. Each zones correspond with the suitable ranges of the mean annual increment (MAI) of the spotted gum. The thematic layer for biomass, *DM100* map was then used to create the *NPV* map where costs and revenues from the calculated net present value were integrated using a mathematical algorithm in ArcGIS. The tabulated results from chapter 6 were instrumental in this process. The NPV map was then classified into three zones e.g. low, medium and high. The same process was completed for saline conditions.

7.3.2 Salinity modelling and visualization

Chapter 6 provided details of the salinity modelling. As mentioned earlier, the soil salinity point datasets requested from the Department of Environment and Resource Management (DERM 2010) were used to visualize the extent of salinity in the study site. Points ($n=655$) in vector layer were interpolated in the same manner as that of the soil nutrients, using a kriging method. The generated salinity map, which was named *EC* Map was spatially transformed into another thematic layer that provided the loss of biomass in the spotted gum plantation under salinity conditions. This was possible with the integration of the developed spotted gum mortality equation. With the use of mathematical algorithm in ArcGIS, the developed mortality equation was mathematically incorporated with the salinity map. This process was conducted to calculate the spotted gum plantation biomass loss under different salinity concentrations. The generated map was named *Mort_Salt Map*.

After these procedures, extraction of values to points eventually followed using the spatial analyst tools in the ArcMap *v*.10 (ESRI ArcGIS package). The 315 sampled points were used for extraction of spotted gum mortality under different salinity levels from the named *Mort_Salt Map,* which became one of the parameter inputs to biomass modelling.

Finally, the biomass data relating to biomass and salinity were assumed to be normal and homoscedastic. Results generated on fertile conditions (Scenario 1) were compared with that of the results estimated from saline affected areas (Scenario 2) and analysed by ANOVA to determine the variations between the two scenarios.

7.3.3 Net present value

The net present value (NPV) of spotted gum plantation system revenue and costs were developed using the excel software. The detailed procedure was discussed in Chapter 6. The calculated costs and revenues were used as input in modelling the financial benefits derived from both the fertile and saline areas. The values on costs and revenues were spatially integrated using the mathematical algorithm available in ArcGIS. All the thematic layers for these values were overlaid with the biomass maps (*DM100 Map* and *DM100_Salinity Map*) and created a visualised NPV maps for both scenarios (*Scenario 1* and *Scenario 2*).

7.3.4 Integration for site suitability using GIS

Homogenous geographical zones were created via a rasterized biomass and carbon map. These zones were further reclassified for suitability purposes such that classes were based on the biomass production viability e.g. 0 - 1000 tDM m^3 ha^{-1} yr^{-1}, 1,000.01 – 1,600 tDm m^3 ha^{-1} yr^{-1}, 1,600 – 2,200 tDm m^3 ha^{-1} yr^{-1} and > 2,200 tDM m^3 ha^{-1} yr^{-1}. Non-forested areas such as infrastructure, built-up areas, bodies of water, natural heritage and parks were excluded from the land use map. Agricultural areas particularly irrigated cropping, seasonal horticultural areas and other perennial horticulture areas were excluded for forestation. Reclassification resulted in two zones of 1 and 0 for production and non-production area, respectively. This was necessary to comply with the forestation requirements on land use allocations and to avoid the conflicting issues in forestry as against agricultural production. The generated salinity map was also reclassified into five zones based from the Queensland salinity categories as was discussed in chapter 6. The categories used to classify the thematic layers were shown in the table 7.1.

After the reclassification, all the reclassified thematic layers were weighted using the spatial analyst tool. The resulting map was standardised where an index of site suitability was developed. Five homogenous zones of site suitability index were created as very low, low, moderate, high and very high site indices.

Finally, the rainfall areas with mean annual rainfall of less than 700 and more than 1100 mm were excluded. This provided for the eligibility of this project for the CFI which falls under saline areas that normally occurs in sites receiving a mean annual rainfall of 700-1100 mm.

Table 7.1 Categories and classification of variables used.

Variable	Categories	Classification
Biomass (tDM ha^{-1} yr^{-1})	0 – 1,000.00 1,000.01 – 1,600.00 1,600.01 – 2,200.00 > 2200.00	1 2 3 4
Land use (Types)	Non-Production areas (e.g. forest reserve, native forests, parks and heritage, built-up areas, water bodies, prime agricultural areas)	0
	Production areas (e.g. pasture area, non-agricultural areas, forest plantation, barren lands, grasslands)	1
Salinity (EC_e in dS m^{-1})	0 – 0.15 0.15 – 0.45 0.45 – 0.90 0.90 – 2.00 > 2.00	1 2 3 4 5
Net present value (AU$)	0 – 50.00 51.00 – 100.00 > 100.00	1 2 3

7. 4 Results and discussions

7.4.1 Biomass mapping

Results of biomass mapping from *Scenario 1* modelling showed the distribution of potential suitable sites for carbon sequestration (Figure 7.1). Most of the suitable sites are located along the coastal areas as indicated by the red and orange shaded areas. As the distance increases from the coastal to the inland areas, suitability for carbon sequestration decreases. Marginal production is expected mostly in the western areas along the boundary of the study site.

The highest biomass production level of more than 18 m^3 ha^{-1} yr^{-1} was located in *Zone 4* which was highlighted by red patches. This composed the potential highly suitable sites within a minimal area of 178,710 hectares. It was estimated that a biomass of more than 2200 tDM ha^{-1} can be produced in this zone. As shown in the map, these sites were concentrated in the south eastern part of the study area that were found mostly in Sub-region 4 with a small portion scatted in Sub-regions 9 and 3. Only 2.68% is composed of highly suitable sites for spotted gum carbon sequestration whilst the majority of the site was classified as low in suitability, located in *Zone 2* which comprised of 62.22% of the total area (Table 7.2).

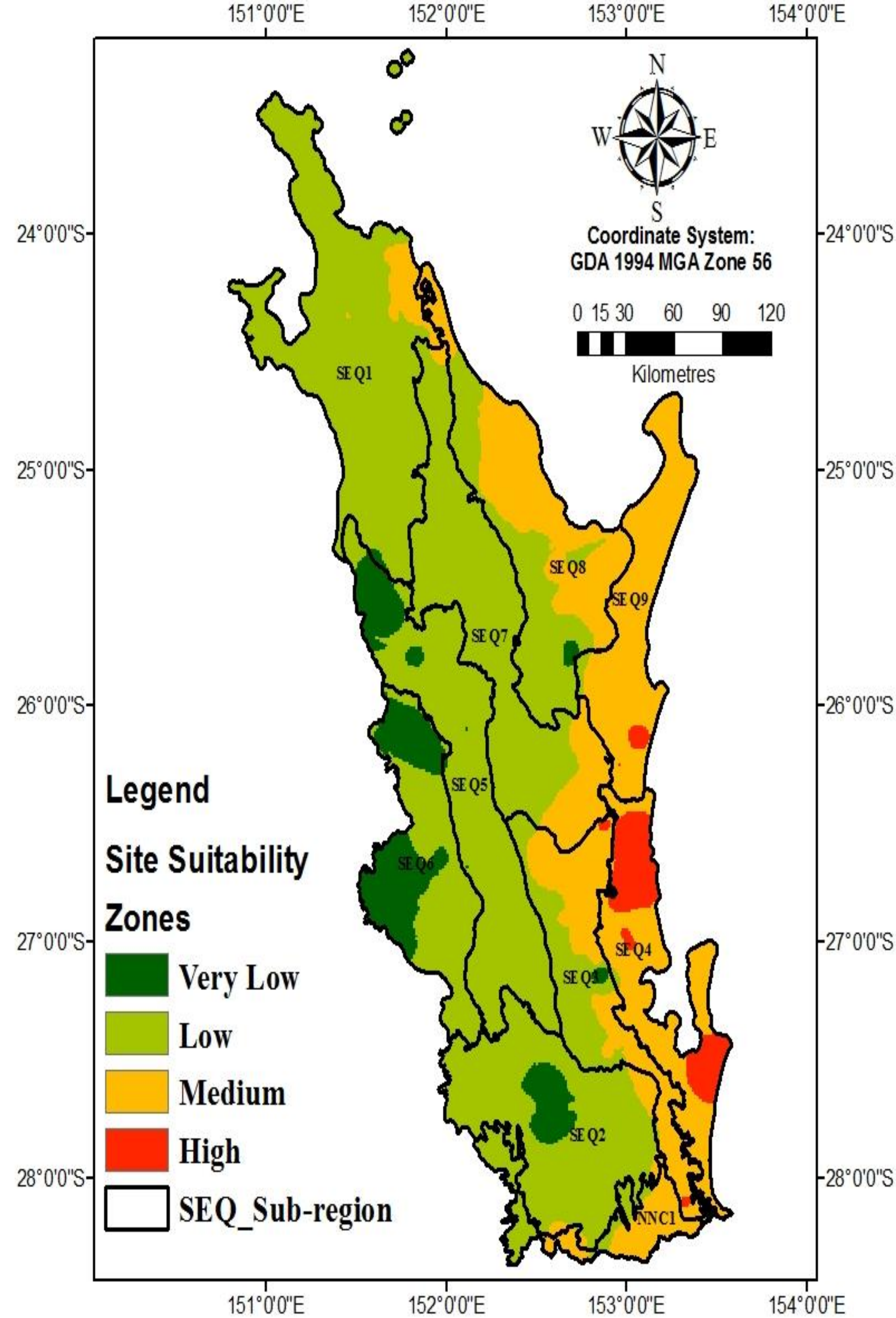

Figure 7.1 Geographical locations of suitable production zones

Table 7.2 Potential areas for spotted gum forestation in south east Queensland under fertile soil condition.

Zones	Biomass potential	Total DM_{100} ($tDM\ ha^{-1}$)	MAI ($m^3\ ha^{-1}\ yr^{-1}$)	Area ('000 ha)	Percent (%)
1	Very Low	0 – 1000	0 – 10	432.10	6.48
2	Low	1000.01 – 1600	10.01 – 14	4,148.94	62.22
3	Medium	1600.01 – 2200	14.01 – 18	1,908.43	28.62
4	High	> 2200	> 18	178.71	2.68

Zone 2 with low suitability can produce at a level of 10.01 – 14.00 $m^3\ ha^{-1}\ yr^{-1}$. A maximum biomass of 1600 tDm ha^{-1} is expected to be reached when the plantation matures in this zone. This zone included the northern to the southern portion of the site and formed part of all the sub-regions. However, the lowest producing areas estimated were found in *Zone 1* which was highlighted in dark green and is composed of a very low site suitability for biomass production. It was estimated to accumulate up to a maximum of 1000 tDm ha^{-1} with 10 $m^3\ ha^{-1}\ yr^{-1}$ MAI. Sub-regions located at the western and southern part in particular the Sub-regions 6 and 2, respectively were composed of sites in this class. On the other hand, *Zone 3* which is capable of accumulating biomass at a rate of 14.01 – 18.0 $m^3\ ha^{-1}\ yr^{-1}$ was found mainly in the easterly sub-regions. Areas in this zone were expected to accumulate a maximum of 2200 tDm ha^{-1} with 18 $m^3\ ha^{-1}\ yr^{-1}$.

Table 7.3 shows the result of the distribution of the suitable sites within in each sub-region. Results indicated the bulk of the area with high suitability for carbon sequestration is located in the Southern Coastal Lowlands (SEQ 4), and some portions in Great Sandy (SEQ 9) and SE Hills and Ranges (SEQ 3). In contrast, the very low suitability areas were mainly situated in South Burnett composing more than 84% of its total land area.

Areas in Brisbane-Barambah Volcanics (SEQ 5) had most of its areas with a marginal production and are very low in suitability for forestation purposes comprising of more than 66% of its area. This was followed by Burnett-Curtis Hills and Ranges with more than half of its total area of a very low to low biomass production shown by the area percentage. Overall, the Southern Coastal Lowlands (SEQ 4) is viewed to have areas highly suitable for this endeavour whilst South Burnett (SEQ 6) is the least suitable.

After masking the ineligible forestation sites (e.g. built-up areas, reservation and natural heritage, parks, intensive agricultural areas, water bodies, etc.) only the production areas were left. These production areas were mainly located in sub-regions that are potentially eligible for CFI such as those with 700-1100 mm mean annual rainfall.

Table 7.3 Distribution of potential suitable areas in each sub-regions.

Sub-regions in SEQ	Area (%)			
	Very Low	Low	Medium	High
SEQ 9 - Great Sandy	-	69.11	25.92	4.97
SEQ 8 - Burnett Curtis Coastal	46.96	28.18	24.86	-
SEQ 7 - Gympie Block	-	73.49	26.51	-
SEQ 6 - South Burnett	84.63	15.37	-	-
SEQ 5 – Brisbane-Barambah Volcanics	66.66	33.34	-	-
SEQ 4 – Southern Coastal Lowlands	-	62.12	23.30	14.58
SEQ 3 – South East Hills and Ranges	43.93	26.36	26.35	3.36
SEQ 2 - Moreton Basin	54.51	32.71	12.78	-
SEQ 1 – Burnett-Curtis Hills and Ranges	57.72	34.64	7.64	-
NNC1 – Scenic Rim	-	72.93	27.07	-

The generated map indicated reduction in areas for spotted gum plantation. The masking procedure resulted to an estimated 50% reduction in the biomass production area with a total area of only 3,328,803 hectares as shown in the Figure 7.2. The extent of production areas was significantly reduced which led to a loss of highly suitable areas. These production areas were comprised of *Zone 1* with 5.28% (352,158 ha), *Zone 2* with 43.01% (2,867,698 ha) and *Zone 3* left with 1.63% (108,946 ha) out of the total study area. Though highly suitable sites for carbon sequestration seem to be limited in its extent, this is acceptable. This is considered to provide opportunity for other land use and avoids allocation conflict with other important uses such as agricultural crop production. However, these zones were further reduced when salinity modelling was incorporated, limiting the extent for carbon sequestration activities in the inland west regions.

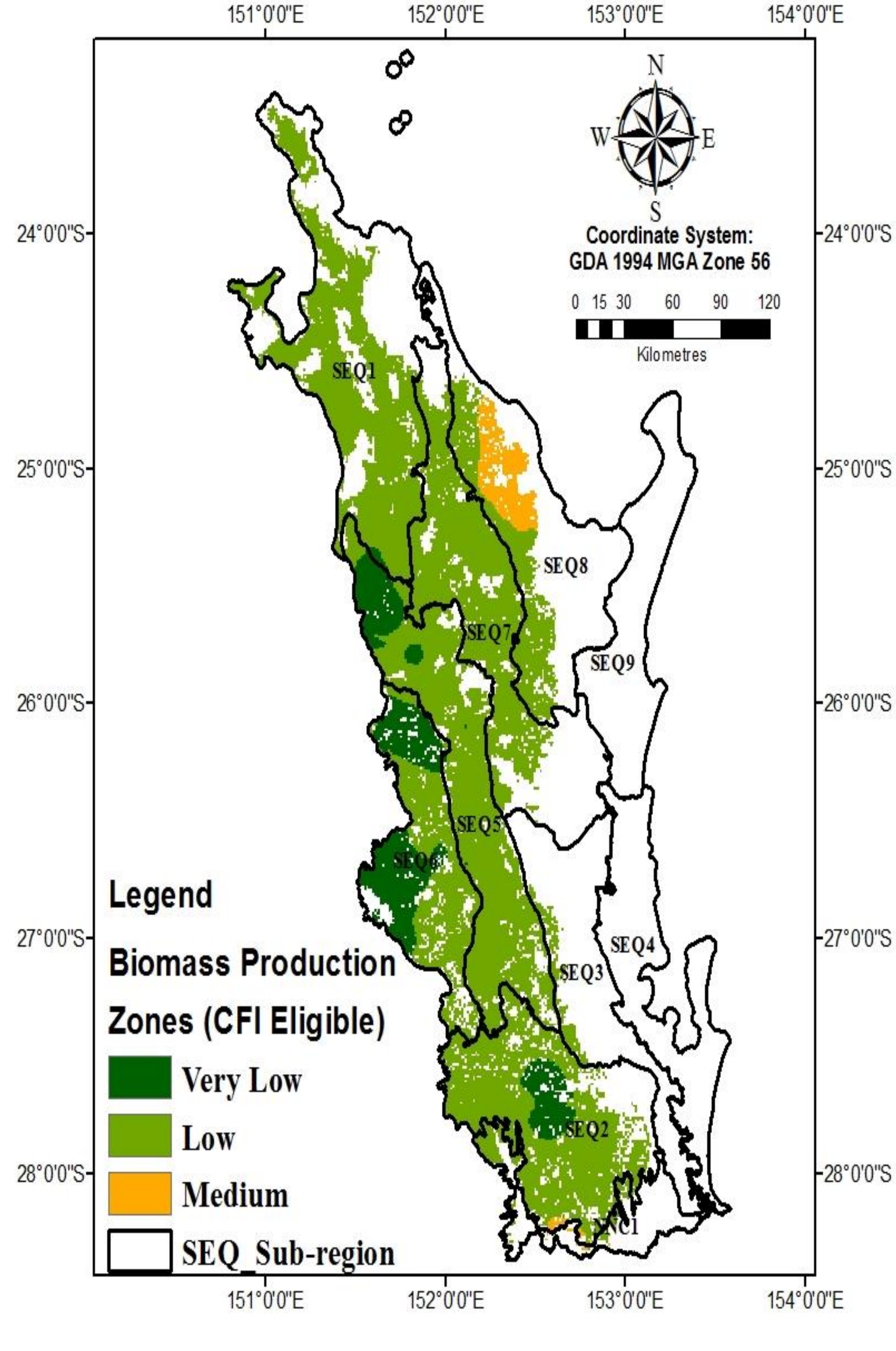

Figure 7.2 Potential biomass production zones for spotted gum

7.4.2 Suitable sites influenced with salinity

Results of site suitability modelling for carbon sequestration under various salinity levels (Figure 7.3) provided the extent of reduction in the productive areas. Biomass production was reduced to a significant extent from the presence of all zones to a two zone level with a very low to low suitability.

Almost a hundred percent (99.78%) of the site is comprised of a very low productive areas belonging to *Zone 1* with a very low suitability as reflected in the tabulated results (Table 7.4). An insignificant percentage (0.22%) of scattered patches of *Zone 2* were found in Burnett-Curtis Coastal and Great Sandy sub-regions.

Table 7.4 Potential areas for spotted gum carbon sequestration in south east Queensland under saline conditions.

Zones	Biomass potential	Total DM_{100} (tDM ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	Area ('000 ha)	Percent (%)
1	Very Low	0 – 1000	0 – 10	6,653.51	99.78
2	Low	1000.01 – 1600	10.01 – 14	14.67	0.22
3	Medium	1600.01 – 2200	14.01 – 18	0	0
4	High	> 2200	> 18	0	0

With salinity persisting in the area, the sites are expected to produce as much as 1600 tDm ha^{-1} at a maximum mean annual increment of 14 m^3 ha^{-1} yr^{-1}. The result of excluding ineligible sites reduced the sites to half as shown in the generated map of production area (Figure 7.4.)

Nearly all the production sites are composed of *Zone 1* (99.24%) with only a very small patch for *Zone 2* which is less than a percent (0.76%). A total area of 3,303,504 hectares was of a very low production zone that has potential biomass accumulation of 1,000 tDm ha^{-1} at a maximum rate of 10 m^3 ha^{-1} yr^{-1} MAI. *Zone 2* on the other hand is expected to have a full production level of 1367 tDm ha^{-1} within the designated area of 25,298 hectares.

The result of site suitability index modelling made use of several variables that provided the suitable sites for the whole study site (Figure 7.5 and 7.6). The maps indicated the locations of the highly suitable sites for carbon sequestration that are reflected by the highest site index (SI) of 0.62 to 1.0. These highly suitable areas are concentrated in the sub-regions 9 and 4.

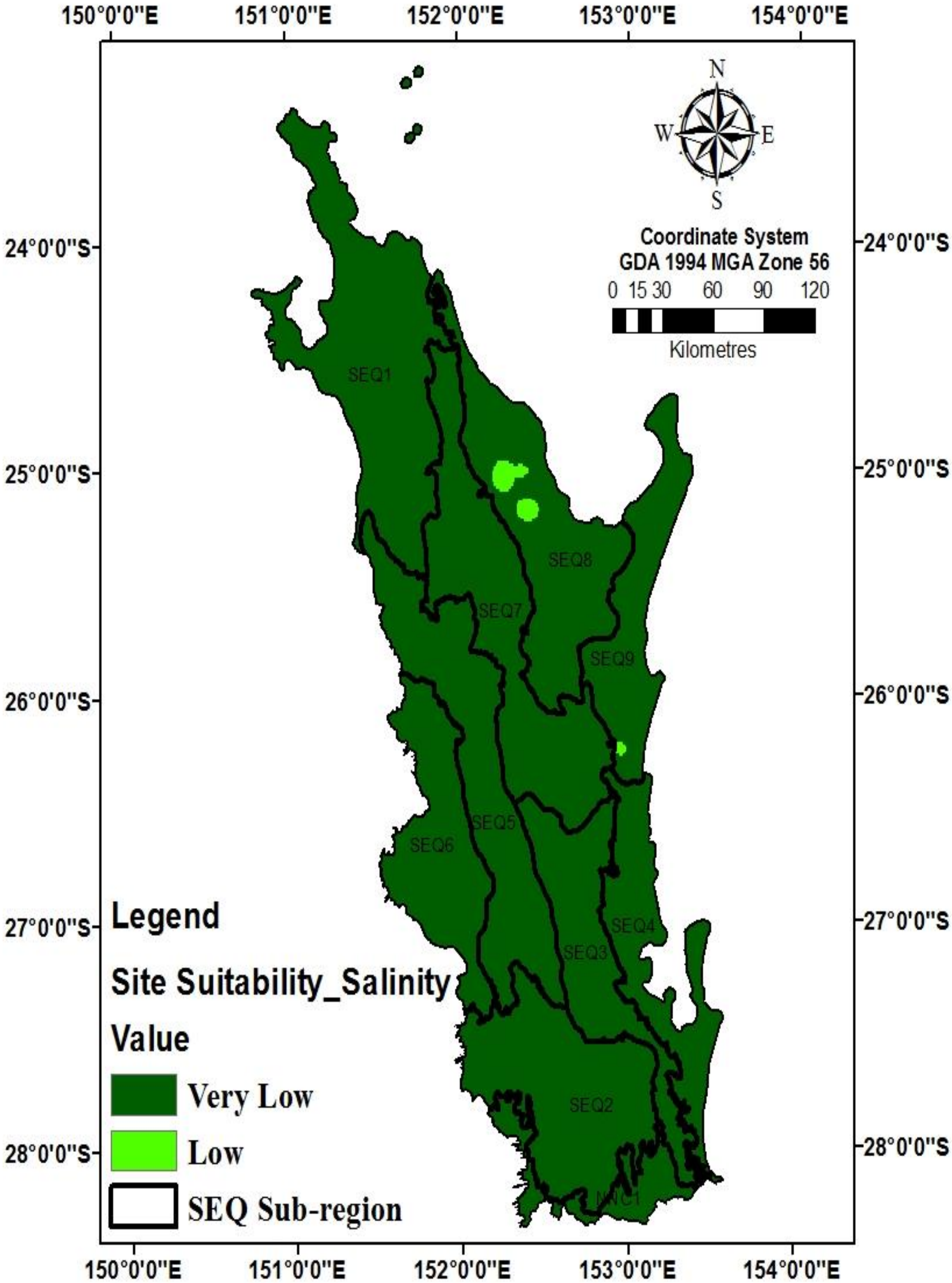

Figure 7.3 Location of potential suitable production sites for carbon sequestration under varied salinity levels

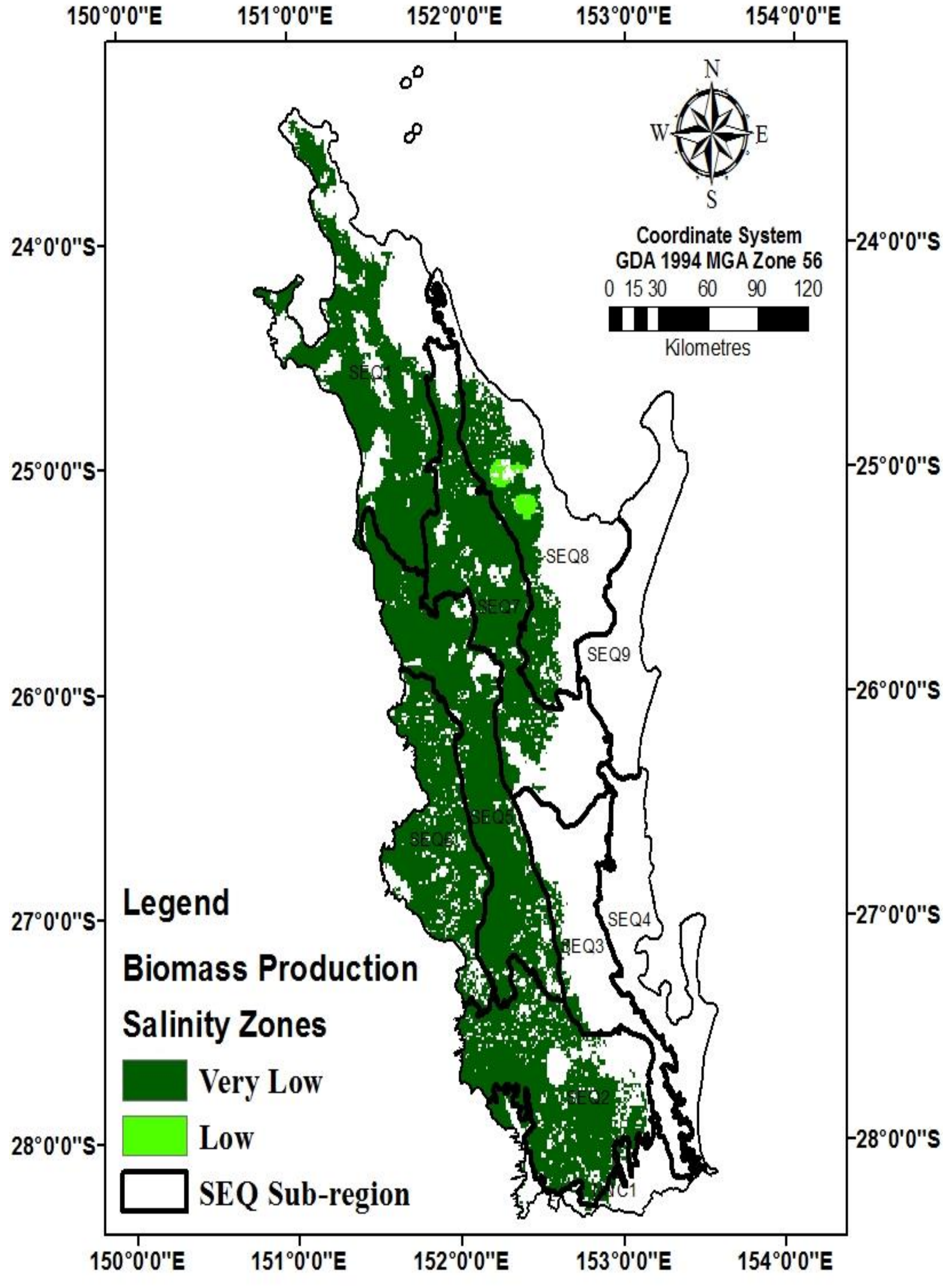

Figure 7.4 Potential biomass production sites for carbon sequestration under varied salt concentrations

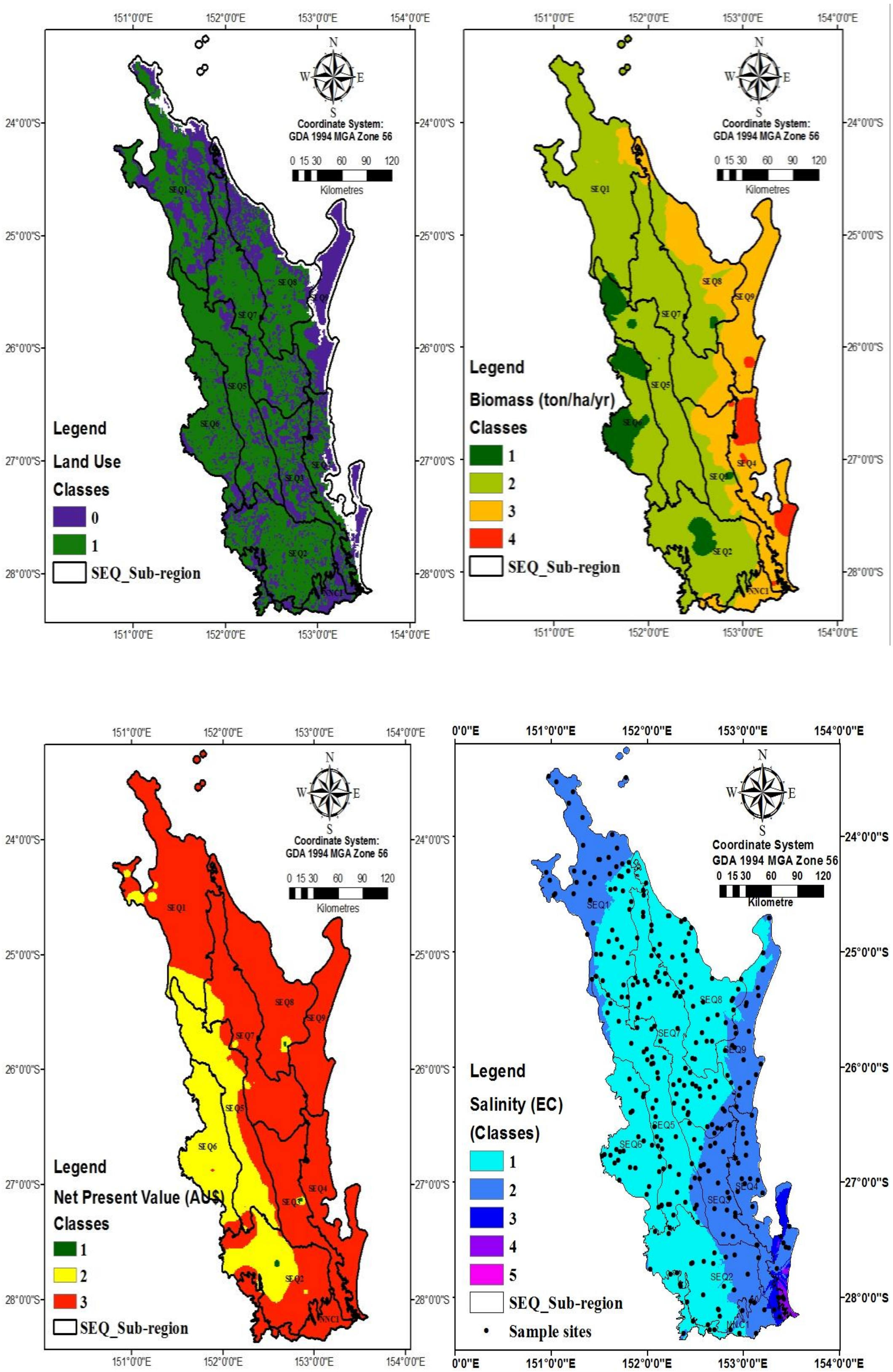

Figure 7.5 Variables used in the site suitability modelling: land use classes (top left), biomass classes (top right), NPV classes (bottom left) and salinity classes (bottom right).

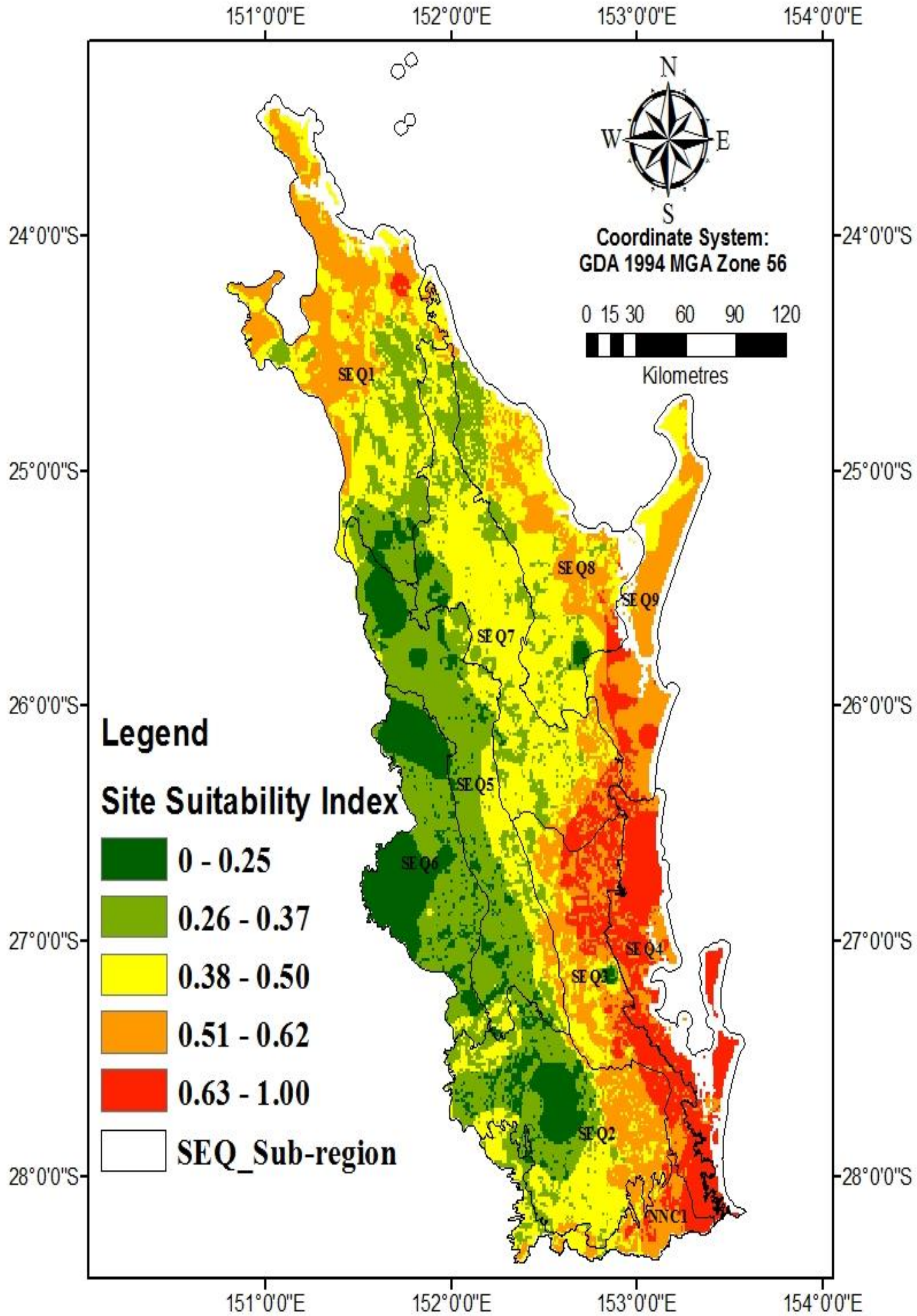

Figure 7.6 Estimated site suitability index for carbon sequestration

The very low site suitability index ranging from a value of 0 - 0.25 were found in sub-regions 6 (South Burnett), 5 (Brisbane-Barambah Volcanics) and 2 (Moreton Basin). These areas are concentrated along the western areas of the study site, extending from the northern to the southern part. It is expected that tree production in these areas are possible but would be a challenge. However, most of the central part of the SEQ region provides a moderate to high suitability index ranging from 0.37 – 0.62 and can provide better options with little intervention such as silvicultural management.

The exclusion of ineligible sites, to fulfil the requirements that will suit for the CFI eligibility, greatly reduced the suitable sites (Figure 7.7). The majority of the CFI eligible sites are moderately suitable as shown by the yellow highlighted areas. The high suitability sites can be found in the northern part of the region at sub-region 1, which includes patches of lands in sub-regions 8 and 2 highlighted by the orange shades.

7.5 Conclusions

Forestation in southeast Queensland is suitable for carbon sequestration activities when established in suitable sites of medium to high rainfall areas. It is expected that benefits from the timber, carbon and soil amelioration capacity in high rainfall areas will remain financially beneficial. However when timber only was accounted in high rainfall areas, benefits were negative. The financial feasibility can be potentially achieved both in non-saline and low saline environment, however the financial returns of the plantation under high saline environment is questionable given the current carbon price.

The inclusion of the saline risk areas provides eligibility of the spotted gum plantation for sequestration and carbon offsetting under the CFI guidelines.

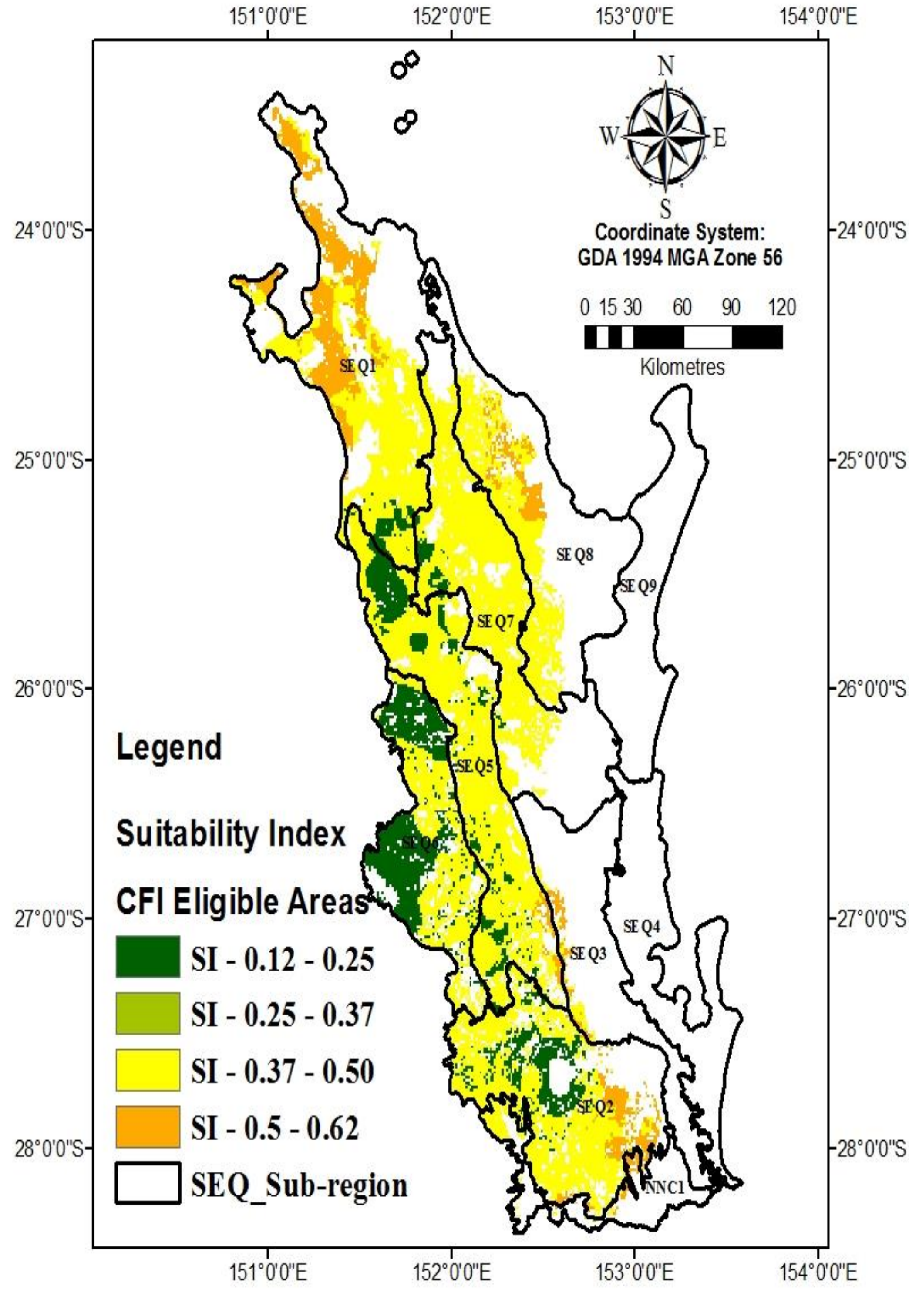

Figure 7.7 CFI eligible areas showing the site suitability index

CHAPTER 8

Conclusions and Recommendations

"Walk in wisdom toward them that are without,
redeeming the time"

Paul, *Book of Colossians 80 AD*

8.1 Introduction

This study identified several issues and concerns related to forestation for carbon sequestration particularly in marginalised areas with salinity problems. This was addressed by modelling the biomass accumulation determined via process based modelling and use of variables specific for spotted gum. Suitable sites were assessed with the consideration of financial returns from the conventional timber revenue plus the carbon sequestration and soil amelioration benefits derived from the plantation. It gives consideration also to the establishment of plantation in saline affected soils. Although related studies have been conducted in the past, most were at a national scale, not specific to sub regions and not species specific. Due to financial and temporal constraints during the implementation of this study, ground truthing was not possible and the validation was concentrated on parameterised variables and the result of data mining from the literature. The overarching aim of this study was to present the conclusions on the potential suitable sites for carbon sequestration in the southeast Queensland with recommendations drawn from the results of the previous chapters.

This chapter is subdivided into three major sections; section 8.1 provides the general overview of this study, section 8.2 discusses the achievement of the objectives and 8.3 provides the recommendations derived from the result of the whole study.

8.2 Carbon sequestration potential in different SEQ sub-regions

This study successfully achieved its objectives 1 and 2 which is to review current literature pertaining to issues on carbon sequestration; and to determine the carbon sequestration capability of spotted gum plantation. This study showed that high potential for spotted gum plantation is available in SEQ though its productivity may vary from different sub-regions. Under the varying bio-physical and climatic conditions in different sub-regions of SEQ, analysis showed that spotted gum plantations have high potential for carbon sequestration particularly in Great Sandy region where high rainfall occurs. Overall, the potential for this species to be used for forestation is high but may remain questionable when established in marginal areas especially with salinity problems.

Chapter five demonstrated that there are large areas where stakeholders could venture into carbon sequestration enterprises. The current high rates of biomass and carbon sequestration in Eucalyptus plantation depend on soil fertility and climatic parameters. Few areas would be capable of supplying the required nutrient demands of spotted gum for a long rotation period. In particular, high soil fertility rating must be achieved to come up with improved carbon sequestration. Additionally, spotted gum is frost susceptible during the juvenile stage and could lead to mortality in areas with very high frost days. Consequently, this could provide an excellent opportunity for its establishment in warmer areas and therefore, an advantage in the event of increasing temperature brought about by climate change.

8.2.1 Carbon sequestration potential under saline conditions

Forestation using spotted gum could ameliorate problematic sites while generating profit out of its products, both tangible and intangible. Carbon and salt credit estimated could provide opportunities to increase profitability of plantation forestry particularly in areas with high salinity. Chapter six showed that inclusion of salinity as benefits will provide increased opportunities in forestation and perhaps other intangible benefits of the forest would also come into play to assure better financial outcomes. Salinity in SEQ is not prevalent, however there are patches of land where high salt concentrations are found. Despite the absence of salinity problems in the area as per limited samples, SEQ should be monitored for any early indications of dryland salinity. On top of this, the complex changing climatic conditions and its dynamic interaction with the site attributes may lead to dryland salinity and therefore, this region cannot be guaranteed to be saline-free in the near future.

Similarly, spotted gum can be favoured as against mixed or natural revegetation as spotted gum plantation sequester faster and store more carbon in the long term. It is in the stakeholders' advantage if plantations will be incorporated in the carbon sequestration projects under CFI.

Use of 3-PG with GIS is more applicable and practical in the sense that it can assess suitable sites with suitable parameters to facilitate biomass estimation of local and regional areas accurately. The process performed aided in attainment of objective 3 in this study. The result of this study however should be used with care as the results are appropriate for the south east Queensland only and specific for spotted gum plantations.

8.2.2 Potential financial benefits from carbon sequestration

It is concluded in this study that areas where mean annual growth of spotted gum is from 11 to 14 m^3 ha^{-1} are not suitable sites and are not profitable commercially. Though this will provide environmental benefits in the form of soil amelioration and carbon sequestration the long term impact is beneficial. Areas where mean growth is 15 m^3 ha^{-1} and above are potentially suitable for carbon sequestration however, financial viability depends on land values. Commercial profitability could only be achieved if the opportunity cost of land is less than approximately AU$1,600 ha^{-1}. In areas where future potential urban development is highly feasible, plantation may not be an option. Similarly, it may also be beneficial when maintenance of plantations is foregone after year 12 and plantation is left to regenerate itself for understorey vegetation.

It was concluded that when the current market carbon price is incorporated in timber revenue, the profitability is questionable. In particular, areas with MAI below 15 m^3 ha^{-1}. Positive returns could be gained when added benefits of plantation are incorporated with its conventional timber value. The plantation's additionality such as carbon sequestration and soil amelioration could enhance the value of this venture. However, financial profitability is only attained when the carbon price was increased to more than AU$23. Despite the limitation to be commercial and financially viable in saline affected areas, the spotted gum has good potential to alleviate salinity via soil amelioration.

During the writing of this thesis, the prescribed price of carbon was AU$ 23/ton. However, when this thesis was finalised, the carbon price mechanism (CPM) was repealed but the CFI was reinforced. The CPM prescribed a fixed price of AU$23/ton will cease to take effect on 2 February 2015 and this will leave a vacuum for carbon price (Australian Government 2015). Once this price ceases, there will be no fixed price for ACCUs and price will be determined through the negotiations of the buyers and the sellers (Australian Government 2015). At this stage, the absence of carbon price provides an opportunity for re-evaluation and assessment of the carbon price under climate change.

The financial benefit analysis showed that financial gain is positive in suitable areas located in various sub-regions of south east Queensland. This can provide financial gains which are an advantage for stakeholders in particular on marginal agricultural lands. Soil amelioration is also a possibility when plantations are established in saline risk areas.

Though biomass and carbon was shown to be affected by salinity concentrations at early stages, in the long term it could be more profitable in terms of social services and other conventional tangible benefits. It is concluded that soil amelioration alone could provide a benefit of AU$1,191 ha^{-1} yr^{-1} with the assumption that maintenance is forgone from year 12, after the second thinning is conducted. As shown by this study, there are potential opportunities to bundle other marketable value added externalities of forest plantations for international and domestic markets. On top of its tangible benefits, such as wood, food, fodder and fibre, there are clearly identified benefits such as protective and ecological services that could be accounted. These can come in the form of enhanced biodiversity, ecosystem functions, clean water production, balance of climate, regulations of the hydrological cycle, conservation and alleviation of desertification (Harrison et al. 2003; Brockerhoff et al. 2013). These intangible benefits could increase profitability when incorporated into forest valuations. There are increasing interests in the accounting of these services and it is likely that future markets will be developed.

8.2.3 Potential suitable sites for carbon sequestration in saline areas

The CFI guidelines allow planting of trees in saline affected areas where credit can be earned. Suitable sites were found to be located in several regions of the study site ranging from a site suitability index of 0 to 1 in all the areas. However, when subjected to CFI eligibility with the addition of salinity risk areas potential suitable sites for the project were greatly reduced and the suitability index also decreases. The CFI eligible areas for carbon sequestration provide site suitability index of 0.125 to 0.62. Areas with suitability index of 0.25 may pose challenges in instances where rainfall and fertility is low whilst it is expected that plantation can thrive in sites with a suitability index of 0.37 to 1.0.

The planting of trees in the project areas should contribute to the mitigation of dryland salinity to be approved by the government under CFI. Similarly, mixed planting is favoured more than plantations. This study corresponds with the CFI activities except that the focus is on plantation. However, the result of this study can be used to compare the capability of spotted gum plantations against that of mixed vegetation and perhaps could provide information for other policy and decision makers to allow plantation establishment in the future as it has potential for soil amelioration. The spotted gum plantation provides opportunities to control groundwater recharge as it can effectively prevent the rising of the water table.

This study has therefore met its fourth objective in determining suitable sites for carbon sequestration activities and the generated spatial maps can provide benefits if CFI eligible areas shown in the suitability mapping under potential saline sites are considered for carbon offsetting.

8.3 Recommendations

Forestation would be more beneficial when established in saline areas however, a more detailed understanding and analysis on the formation and extent of salinity in varying geographical locations and its relationship with environmental and climatic parameters is necessary. Soil nutrient concentrations vary with soil depth and soil type. It would be more appropriate if a depth of soil samples on a tree root zone would be conducted in the future to estimate the role of nutrient cycling in relation to biomass accumulation and the carbon cycle within trees. It is recommended that spotted gum established in saline areas be promoted as eligible for environmental plantings under the CFI projects. As shown in this study, the plantation's soil amelioration and carbon sequestration capability could potentially provide environmental and social benefits in the long term.

It is also recommended that further research be conducted to address salinity and plantation productivity with relation to the changing climate. Furthermore, accurate estimates proved to be helpful in accounting for atmospheric carbon dioxide sequestered by spotted gum, however, it would be beneficial if the future study could focus on low and medium rainfall zones of SEQ.

Monitoring of salinity indications is recommended. In particular, areas near the coastal areas are susceptible to salinity as cyclic salt from ocean spray or rainwater can be deposited at up to 15 to 30 kg ha^{-1} yr^{-1} along these areas as found by experts such as Johnson et al. (2009). Accumulation of salt is associated with reductions in growth rate brought about by detraction of its canopy from the productive biomass accumulation and carbon sequestration.

As this study is site and species specific, caution is urged when using the results. The results can serve as benchmark during the finalisation of RFA in SEQ. Information embodied in this study will also aid as a decision support tool for stakeholders who would like to embark on a carbon sequestration enterprise in particular those in SEQ areas.

As the scope of this study is just a small portion of the Queensland state, it is recommended that research be conducted to identify and quantify suitable sites and conduct valuations on the benefits of other ecological services provided by the tree plantations in Queensland. Despite the presence of abundant land, suitable areas must not only be identified but considerations on allocation and silvicultural practices brought about by a stakeholder’s choice of land use must be taken into account. As profitability is dependent on productivity and suitability, it is important that research activities on the development of a scaled down spatially explicit biomass sequestration models be conducted. Opportunities to design research that will capture carbon sequestration including other environmental benefits such as biodiversity would be highly beneficial. Further research is necessary that will tackle issues in the accuracy and precision of the parameters used in 3-PG in particular the soil variables. It is suggested that the impact of the changing climate in carbon sequestration be given focus particularly in saline areas.

Finally, it is recommended that modelling that captures all the factors affecting salinity must be conducted. Modelling must be performed in conjunction with the use of the most accurate tools available to accurately measure the salt level such as the electromagnetic devices. Large area maps should be downscaled with the use of an appropriate mapping techniques such as remote sensing and GIS to improve accuracy. Similarly, choice of species and provenance must be undertaken with care and salt tolerant species must be planted in areas with salinity problems for amelioration.

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APPENDICES

Appendix A. Summary of models showing the result for twelve Australian continental NPP estimates (NPP values were adopted from Roxburgh et al. 2004).

Model	Author/Developer	Parameters	Timeframe which estimate calculated	Continental NPP (Gt Cy-1)
1. RFBN	(Roderick et al. 2001)	Average annual climate data, radiation, efficiency use,	Based on 9 years (1982-1990) satellite data	3.31
2. DLdP	(Graetz 1988)	Averaged annual precipitation	Average annual precipitation, based on 74y of records (1921-1995)	3.22
3. Olson	(Olson et al. 1983)	N/A	N/A	2.86
4. Miami	(Pittock & Nix 1986)	Averaged annual precipitation and temperature	Average annual precipitation and temperature, based on 74y of records (1921-1995)	2.46
5. Century	(Parton et al. 1988)	Monthly time series climate data	Monthly time series climate data from global climate database	1.81
6. CenW	(Kirschbaum 1999)	Monthly average minimum, maximum temperature, rainfall, radiation amount and turn-over rates of soil organic matter, $C0_2$ uptake, water use, and nitrogen cycling.	Monthly average minimum, maximum temperature, rainfall and radiation derived from ESOCLIM (1921-1995)	1.76
7. Aussie GRASS	(Rickert et al. 2000)	Daily climate data, rainfall, temperature, solar radiation, pan evaporation, VPD, Grazing	Utilises interpolated daily climate data, estimated daily, for the period 1957-2000, daily rainfall, temperature, solar radiation, pan evaporation, VPD, grazing	1.66
8. TMS	Berry and Roderick Unpublished data	NDVI, net radiation	1982-1990 satellite data (NDVI), Net radiation	1.61
9. Miami-OZ	(Roxburgh & Davies 2006)	Average annual precipitation and temperature	Average annual precipitation and temperature, based on 74y of records (1921-1995)	1.17

Appendix A. Cont...

Model	Author/Developer	Parameters	Timeframe which estimate calculated	Continental NPP (Gt Cy-1)
10. Bios Equil	(Raupach et al. 2003)	Climate variables (precipitation, solar radiation, temperature, humidity, NDVI data for calculating tree LAI,	Climate variables – precipitation, solar radiation, temperature, humidity (1980-1999) NOAA/NASA pathfinder data for calculating grass and tree LAI (1984-1994)	0.93
11. 3-PG	(Landsberg & Waring 1997)	Precipitation/climate data, Min and Max temperature, frost days, Solar radiation, VPD, LAI, soil water storage, soil fertility rating, initial conditions of biomass and stocking rates, silvicultural management conditions (e.g. irrigation and thinning) carbon fraction in plant components.	Precipitation, min and max temperature, frost days, solar radiation, VPD, Frost days (1970-2000)	0.93
12. VAST	(Barrett 2003)	Monthly composite NDVI, surface radiation budget data, min and max air temperature, precipitation	Monthly composite NOAA/NASA pathfinder NDVI (1981-1994) continental cells with observation in undisturbed vegetation isolated, and values extracted. NASA Langley surface radiation budget data – monthly averaged (1983-1991), monthly average min and max air temperature (1972-1997), monthly average precipitation (1890-1997)	0.65

Appendix B. Summary of area of all sub-regions as per IBRA.

IBRA Sub Region Code	IBRA Sub Region Name	Area (km^2)	Area (ha)
NNC1	Scenic Rim	2,302	230,230
SEQ1	Burnett - Curtis Hills and Ranges	11,175	1,117,492
SEQ2	Moreton Basin	7,844	784,387
SEQ3	Southeast Hills and Ranges	5,333	533,330
SEQ4	Southern Coastal Lowlands	5,095	509,478
SEQ5	Brisbane - Barambah Volcanics	8,063	806,317
SEQ6	South Burnett	5,636	563,594
SEQ7	Gympie Block	8,585	858,468
SEQ8	Burnett - Curtis Coastal Lowlands	7,873	787,251
SEQ9	Great Sandy	4,770	477,050
	Total Area	66,676	6,667,596

Appendix C. Input variables for spotted gum used in the 3-PG model.

Meaning/comments	Name	Units	CCV	Source
Biomass partitioning and turnover				
Allometric relationships & partitioning				
Foliage:stem partitioning ratio @ D=2 cm	pFS2	-	(1)	Sands & Landsberg (2002)
Foliage:stem partitioning ratio @ D=20 cm	pFS20	-	(0.15)	Sands & Landsberg (2002)
Constant in the stem mass v. diam. Relationship	aS	-	0.184	Paul et al. (2007)
Power in the stem mass v. diam. relationship	nS	-	2.32	Paul et al. (2007)
Maximum fraction of NPP to roots	pRx	-	(0.8)	Sands & Landsberg (2002)
Minimum fraction of NPP to roots	pRn	-	(0.25)	Sands & Landsberg (2002)
Litterfall & root turnover				
Maximum litterfall rate	gammaFx	1/month	0.008	Paul et al. (2007)
Litterfall rate at t = 0	gammaF0	1/month	0.001	Landsberg & Waring (1997) Default
Age at which litterfall rate has median value	tgammaF	months	12	Landsberg & Waring (1997) Default
Average monthly root turnover rate	gammaR	1/month	0.015	Landsberg & Waring (1997) Default
NPP & conductance modifiers				
Temperature modifier (fT)				
Minimum temperature for growth	Tmin	deg. C	17	(Nursery 2010)
Optimum temperature for growth	Topt	deg. C	20	Paul et al. (2007)
Maximum temperature for growth	Tmax	deg. C	86	(Nursery 2010)
Frost modifier (fFRost)				
Days production lost per frost day	kF	days	2	Paul et al. (2007)
Soil water modifier (fSW)				
Moisture ratio deficit for $f_q = 0.5$	SWconst	-	0.7	Landsberg & Waring (1997) Default

Appendix C. Cont…

Meaning/comments	Name	Units	CCV	Source
Power of moisture ratio deficit	SWpower	-	(9)	Sands & Landsberg (2002)
Fertility effects				
Value of 'm' when FR = 0	m0	-	(0)	Sands & Landsberg (2002)
Value of 'fNutr' when FR = 0	fN0	-	(1)	Sands & Landsberg (2002)
Power of (1-FR) in 'fNutr'	fNn	-	(0)	Sands & Landsberg (2002)
Age modifier (fAge)				
Maximum stand age used in age modifier	MaxAge	years	(50)	Sands & Landsberg (2002)
Power of relative age in function for fAge	nAge	-	(4)	Sands & Landsberg (2002)
Relative age to give fAge = 0.5	rAge	-	(0.95)	Sands & Landsberg (2002)
Stem mortality & self-thinning				
Mortality rate for large t	gammaNx	%/year	0	Landsberg & Waring (1997) Default
Seedling mortality rate (t = 0)	gammaN0	%/year	0	Landsberg & Waring (1997) Default
Age at which mortality rate has median value	tgammaN	years	0	Landsberg & Waring (1997) Default
Shape of mortality response	ngammaN	-	1	Landsberg & Waring (1997) Default
Max. stem mass per tree @ 1000 trees/hectare	wSx1000	kg/tree	(300)	Sands & Landsberg (2002)
Power in self-thinning rule	thinPower	-	1.5	Landsberg & Waring (1997) Default
Fraction mean single-tree foliage biomass lost per dead tree	mF	-	0	Landsberg & Waring (1997) Default
Fraction mean single-tree root biomass lost per dead tree	mR	-	0.2	Landsberg & Waring (1997) Default

Appendix C. Cont…

Meaning/comments	Name	Units	CCV	Source
Fraction mean single-tree stem biomass lost per dead tree	mS	-	0.2	Landsberg & Waring (1997) Default
Canopy structure and processes				
Specific leaf area				
Specific leaf area at age 0	SLA0	m^2/kg	6.01	Paul et al. (2007)
Specific leaf area for mature leaves	SLA1	m^2/kg	6.01	Paul et al. (2007)
Age at which specific leaf area = (SLA0+SLA1)/2	tSLA	years	(2.5)	Sands & Landsberg (2002)
Light interception				
Extinction coefficient for absorption of PAR by canopy	K	-	0.5	Landsberg & Waring (1997) Default
Age at canopy cover	fullCanAge	years	(0)	Sands & Landsberg (2002)
Maximum proportion of rainfall evaporated from canopy	MaxIntcptn	-	0.15	Landsberg & Waring (1997) Default
LAI for maximum rainfall interception	LAImaxIntcptn	-	(0)	Sands & Landsberg (2002)
Production and respiration				
Canopy quantum efficiency	alpha	molC/molPAR	(0.06)	Sands & Landsberg (2002)
Ratio NPP/GPP	Y	-	0.47	Landsberg & Waring (1997) Default
Conductance				
Maximum canopy conductance	MaxCond	m/s	0.02	Landsberg & Waring (1997) Default
LAI for maximum canopy conductance	LAIgcx	-	3.33	Landsberg & Waring (1997) Default
Defines stomatal response to VPD	CoeffCond	1/mBar	0.05	Landsberg & Waring (1997) Default
Canopy boundary layer conductance	BLcond	m/s	0.2	Landsberg & Waring (1997) Default

Appendix C. Cont…

Meaning/comments	Name	Units	CCV	Source
Wood and stand properties				
Branch and bark fraction (fracBB)				
Branch and bark fraction at age 0	fracBB0	-	0.56	Paul et al. (2007)
Branch and bark fraction for mature stands	fracBB1	-	0.35	Paul et al. (2007)
Age at which fracBB = (fracBB0+fracBB1)/2	tBB	Years	9	Paul et al. (2007)
Basic Density				
Minimum basic density - for young trees	rhoMin	t/m3	0.654	Paul et al. (2007)
Maximum basic density - for older trees	rhoMax	t/m3	0.654	Paul et al. (2007)
Age at which rho = (rhoMin+rhoMax)/2	tRho	years	4	Landsberg & Waring (1997) Default
Stem height				
Constant in the stem height relationship	aH	-	0	Landsberg & Waring (1997) Default
Power of DBH in the stem height relationship	nHB	-	0	Landsberg & Waring (1997) Default
Power of stocking in the stem height relationship	nHN	-	0	Landsberg & Waring (1997) Default
Stem volume				
Constant in the stem volume relationship	aV	-	0	Landsberg & Waring (1997) Default
Power of DBH in the stem volume relationship	nVB	-	0	Landsberg & Waring (1997) Default
Power of stocking in the stem volume relationship	nVN	-	0	Landsberg & Waring (1997) Default
Conversion factors				
Intercept of net v. solar radiation relationship	Qa	W/m2	-90	Landsberg & Waring (1997) Default
Slope of net v. solar radiation relationship	Qb	-	0.8	Landsberg & Waring (1997) Default

Appendix C. Cont…

Meaning/comments	Name	Units	CCV	Source
Molecular weight of dry matter	gDM_mol	gDM/mol	24	Landsberg & Waring (1997) Default
Conversion of solar radiation to PAR	molPAR_MJ	mol/MJ	2.3	Landsberg & Waring (1997) Default
Note: Sands & Landsberg (2002) values are derived for *E. globulus;* Landsberg & Waring (1997) values are the default for pine and eucalypt species; Paul et al. (2007) are for *E. maculata/C. maculata* (spotted gum)				

Appendix D. EC values of soil salinity classes used in Australia.

EC_e (dS m^{-1})	**Salinity Class**	**EC_e (dS m^{-1})**	**Salinity Class**
Bruce & Rayment (1982)	Bruce & Rayment (1982)	(USSL 1954)	(USSL 1954)
< 0.15	Very Low (VL)	< 2	Non- saline (0)
0.15 - 0.45	Low (L)	2 – 4	Slightly saline (1)
0.45 - 0.90	Medium (M)	4 – 8	Moderately saline (2)
0.90 – 2.0	High (H)	8 – 16	Very saline (3)
> 2.0	Very High (VH)	> 16	Highly saline (4)