Mixed Species and Agroforestry System
Interactions in Solomon Islands

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Informal agroforestry is a traditional practice in Solomon Islands, mostly intercropping food crops with fruit trees. Agroforestry systems that intercrop food crops with rows of hardwood species for the purposes of timber production have not been practiced. In response to the common problem that growers of valuable hardwood species such as teak (*Tectona grandis*) are reluctant to thin their trees, the Australian Centre for International Agricultural Research (ACIAR) established project FST/2007/020 to develop novel silvicultural systems to overcome this problem. *Flueggea flexuosa* (flueggea) is a local hardwood species that is widely utilized for housing and fencing applications. The project team established several agroforestry trials testing the hypothesis that teak and flueggea could be successfully grown together with the local tree being progressively harvested for local use, effectively thinning the plantation and allowing the teak to develop through to harvestable size. The trees could be intercropped with food crops allowing for multiple land use and income generating opportunities whilst the trees grow through to maturity.

The model was based on the assumption that trees and crops, when properly managed, complement each other rather than compete in the capture and efficient use of available growth resources. This system is a hybrid of the informal agroforestry traditionally practiced in Solomon Islands and the silvicultural management techniques applied to production forestry. However, teak and flueggea have not been previously grown together under an agroforestry regime and little is known of the species interaction or of the effect of growing different food and cash crops in the interrow. Traditional practices for growing food crops in Solomon Islands begin with forest clearance and burning of debris, a slash and burn system. Mounds are made using man-made hoes or picks to give crops better growing spot away from competing weeds.
and surface water flow during rainy seasons. Most root crops and vegetables are planted in their own blocks and kept separate from other crops. Mixing of food crops is not a usual practice in most parts of the Solomon Islands. Other crops and trees are usually planted at the boundaries of each crop’s patch or along the boundary. Most food crops reach harvesting age after 3 months. When crops are harvested, the whole plant is uprooted, plant parts and debris are piled at a location and are burnt when dry. Where the area available for gardening area is large, the harvested plot is left to fallow but if the available area is small, crops are replanted straight after harvest, leaving no time for the soil to be replenished with nutrients through decomposition of plant materials.

Amongst several silvicultural trials established in Solomon Islands, this study focuses on trials established at Ringgi and Poitete which are located at the southern and northern parts of Kolombangara Island in Western Province. These silvicultural trials were established for the purpose of examining the effect of stocking rate and species mix on teak and flueggea growth and on their potential influence over the hybrid agroforestry system. Two mixed species spacing trials and one hybrid agroforestry trial of teak and flueggea were established to test the hybrid model. The two main mixed species spacing trials have 5 treatments with 4 replicates each, treatments are a combination of stocking rate and species mix. The five different treatments include teak being grown as a monoculture (Treatment 1); and then in rows interspersed with 2 rows of flueggea at different stocking rates (Treatments 2, 3, and 4); and alternating rows of teak and flueggea at standard spacing (Treatment 5). The hybrid agroforestry trial was based on the standard 4 x 3 m spacing (Treatment 5) and further intercropped with food crops. Only Treatment 3 (4 x4m) and Treatment 4 (4 x 6m) have wider planting spaces. Standard stocking is 833 stems per hectare for Treatments 1, 2 and 5, and 625 and 416 stems per hectare for Treatments 3 and 4.
This research examined the interactions occurring between teak and flueggea, and between teak, flueggea and food crops grown in the inter-row with respect to competition for nitrogen (N), light and water, resource access, changes in system interactions with the development of the canopy, nutrient loss and issues of sustainability related to harvesting of food crops, biogeochemical cycling of carbon (C) and N, root architecture and growth and yield. Total carbon (TC), total nitrogen (TN) and stable isotope δ^{13}C and δ^{15}N, and ^{15}N-labelled tracer were analyzed using field sampled soil, foliage, branch, stem, root and litterfall from the stands to examine soil nutrient uptake, biomass content and cycling as a result of the intraspecific and interspecific interactions with relation to tree growth and productivity of the hybrid system over time and space. Root architecture, tree mean total height (THt) and diameter at breast height (DBH) were measured and assessed over the study period.

We investigated the competition between teak and flueggea for N using a ^{15}N-labelled tracer in a field trial in a 2 year old and a 4 year old mixed species stand. The study also reports the acquisition and allocation of TC and C isotope composition (δ^{13}C) in different tree components of teak and flueggea. Seven pairs of trees, one of each species, were isolated using an impermeable membrane 60 cm deep and ^{15}N-labelled tracer was applied to the soil surface. The first four plots were sampled for a period of 18 months and the age of the trees at final excavation was 4 years. The final three plots were sampled for 12 months and the age of the trees at final excavation was 2 years. Each tree was measured, felled and roots excavated, divided into the components: roots, stem, branch and foliage, and then weighed for biomass, samples of each component were oven dried at 60° C to constant weight, ground to a fine powder and analysed for TN, TC, ^{15}N enrichment, and δ^{13}C. There was no significant difference in component ^{15}N enrichment between teak and flueggea at both ages, suggesting that there could be equal uptake of added ^{15}N-labelled tracer by both species.
The $^{15}\text{N}$-labelled tracer concentration was greater in the foliage followed by the root, stem and branch for teak and flueggea. However, stem had significantly greater biomass and therefore had greater $^{15}\text{N}$ enrichment mass (kg) than other components of teak in the 2 years trial and with teak and flueggea at 4 years trial. Approximately 55% of added $^{15}\text{N}$ tracer was recovered in the 4 years trial and 43% was recovered in the 2 years trial, suggesting that higher uptake is possible with well-established root structure with age. Although teak had significant growth, $^{15}\text{N}$ tracer uptake and enrichment were not statistically different to those of flueggea which may mean that competition in growth resources was still at minimum stage and growth rates were species specific. TN was not significantly different between teak and flueggea components at age 2 and 4 years and may indicate equal access to available N belowground and with similar allocations. TC was not significantly different between components of teak and flueggea in either age and may indicate equal access to atmospheric C and similar allocations of photosynthates. Higher $\delta^{13}\text{C}$ in teak components than those of flueggea indicated that teak has higher water use efficiency per kg of tree and does not discriminate against $^{13}\text{C}$ as strongly as flueggea during photosynthesis. Similar $^{13}\text{C}$ values in tree components within the species may be the result of subsequent partitioning of the photosynthates synthesized during photosynthesis.

The litter production and C and N cycling in both teak monoculture and teak and flueggea mixed species plantings in the two trials were studied over 18 months period. Leaf litter samples were collected monthly from the five treatments. Monthly litterfall production ranged from 250.51 to 541.61 kg ha$^{-1}$ depending on treatment and trial. Treatment 1 produced significantly higher total litter than Treatment 4 at Ringgi but this difference will have been due to stocking rates. When based on individual tree productivity, teak in Treatment 4 at both trials produced significantly higher litter per tree than the teak in Treatments 3, 2, 5 and 1 while
there was no significant difference with flueggea productivity. Although teak and flueggea TC and TN, and $\delta^{13}$C and $\delta^{15}$N varied over the study period, their mean values were not statistically different except for teak in T4 having significantly lower values at Ringgi. Teak and flueggea C/N ratios were not statistically different at both trials except for flueggea in Treatment 2 at Ringgi which was significantly higher. The highest annual TC and TN returned to the soil from total litterfall were observed in Treatment 1 followed by Treatments 3, 5, 2 and 4 for Ringgi. The highest at Poitete was Treatment 5 followed by Treatments 1, 3, 2 and 4. When comparing each treatment and using individual tree productivity, Treatment 4 produced and returned the significantly highest litter and nutrient than Treatments 3, 2, 5 and 1. Overall, individual tree productivity demonstrated that mixed species stands have significant potential for cycling higher rates of C and N than monoculture teak stand, therefore establishment of mixed species stands especially using the stocking rates of Treatment 3 and Treatment 4 is recommended as a practical measure in forest rehabilitation and agroforestry systems to realize sustainable development of community forestry in the Solomon Islands.

The spatial distribution of the root systems of teak and flueggea were examined by excavating pairs of trees of each species that had been grown in isolation plots for 2 (3 pairs) and 4 (4 pairs) years. Additional trees grown without a barrier were partly excavated to ensure that the effect of the barrier on root architecture was not significant. The root architecture of both species had similar patterns of development but showed a different topology and distribution. Teak had extensive horizontal and vertical roots and occupied a larger portion of the soil volume than flueggea. Both species had similar root biomass increment of 87 % between 2 and 4 years and roots made up 20-22 % of total tree biomass at both ages. Teak and flueggea roots occupied different depths within the soil volume, which would promote nutrient uptake efficiency and therefore minimize competition.
The study evaluated the effects of stocking rate and species mix on early growth of teak in a mixed species system. Intercropping with flueggea promoted diameter, height and form of teak. Teak diameter and basal area growth significantly increased with wider planting spacing though height was not statistically different to teak in single-species stands. Intercropping with flueggea resulted in teak developing smaller branches which facilitated a self-pruning habit that promoted clear wood production. Differences in teak height between all treatments were not significant though it is interesting to note that sixty months after planting, teak in T1 at Ringgi and teak in T5 at Poitete had the greatest height as had Flueggea in T5 at Ringgi though again differences in height of flueggea was not significantly throughout the treatments. Diameter and basal area were greatest at the lower stocking than at the higher stocking for teak and flueggea. Teak of T4 had the significant diameter and basal area growth than other treatments at age 60 months. Teak form was best at the pure and mixed species stands due to self-pruning while larger crown and big branches occurred at lower stocking rates. While this can be corrected with timely silviculture, a 4 x 3 m spacing would seem to optimise the benefits of higher stocking and lower maintenance.

Overall, mixed species and agroforestry systems promoted reduction and delay of competition for growth resources in the early phase of the systems compared to monocultures. Both single and mixed species systems promoted similar C and N cycling in the plantation establishment phase. Growth in basal area was significantly higher at the mixed species stands at the lowest stocking rate, which also enable longer period of intercropping of food crops. However, as the present investigation was confined to the first 5 years, which is considered as establishment phase for teak, more studies are needed as the systems mature to fully understand the systems development and interactions to maturity.
Dedication

To my parents who worked hard to give me an impulse in my professional and personal life.

To my wife Victoria Varoro Vigulu and our beloved children Lesley Sayok Vigulu, Patrick Lonnie Vigulu, Vannisaria Syrine Vigulu and Wayne Utah Vigulu for their love, patience, and support in this phase of our lives. Without your understanding, I would not be able to finish this thesis.

To my sisters, brothers, nephews and nieces for their assistance during my field work.

To Solomon Islands, I hope we can stop the unsustainable exploitation of our natural forests and rehabilitate the degraded and deforested landscapes with mixed species and agroforestry systems as our means of sustaining our livelihood.
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Declarations of Originality

The experimentation, analyses, presentation and interpretation of results in this thesis represent original work that has not previously been submitted for a degree or diploma in any University. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made within the thesis itself.

Vaeno Wayne Vigulu

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<td>$\delta^{13}$C</td>
<td>Natural abundance of stable isotope $^{13}$C</td>
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<tr>
<td>$\delta^{15}$N</td>
<td>Natural abundance of stable isotope $^{15}$N</td>
</tr>
<tr>
<td>$^{15}$N-labelled</td>
<td>Enrichment $^{15}$N</td>
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<tr>
<td>ACIAR</td>
<td>Australian Centre for International Agricultural Research</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
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<tr>
<td>a.s.l</td>
<td>Above sea level</td>
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BA Basal area
C Carbon
C:N Carbon-nitrogen ratio
cm Centimeter
DBH Diameter at breast height
EPPL Eagon Pacific Plantation Limited
FTE Fixed Term Estate
h Tap root depth
ha Hectare
KFPL Kolombangara Forest Products Limited
kg Kilo-gram
LLS Londumoe Land System
LS Land System
m Meter
MAI Mean annual increment
mg Milligram
N Nitrogen
N2O Nitrogen dioxide
NO Nitrogen oxide
NRE Nutrient retranslocation efficiency
NUE Nutrient use efficiency
PICT Pacific Island Countries and Territories
PNG Papua New Guinea
r Maximum horizontal lateral root length
RLS Ringgi Land System
Paper submitted for publication from this thesis

Part of this thesis that has been published by the Australian Forestry Journal:

1. Competition for nitrogen between trees in a mixed-species plantation in Solomon Islands (Derived from Chapter 4)
Part of this thesis that has been re-submitted to the Agroforestry System Journal for publication after being peer reviewed:

1. Root architecture of teak and flueggea in mixed species systems in the Solomon Islands (Derived from Chapter 6).
Chapter 1 Introduction

1.1 Background

Trees extract its nutrient requirement from the soil after planting. Trees in general, are known for their capability to utilize nutrients available from both organic and inorganic sources of the soil (Boddey et al., 2000; Bhardwaj et al., 2005). However, at certain stage in the forest development, part of the trees nutrient requirement is supplied by the nutrient cycling process. Under this nutrient cycling process, there are various processes that link different compartments of plant, forest floor and soil components which facilitate movement of nutrients between plant and soil (Khanna, 1997). For example, nutrients move between foliage, twigs, wood, bark, coarse roots and fine roots to the litter and humus layers of the forest floor through the abscission and senescing process, then to the soil organic matter, the soil solution and the sorptive surfaces of soil minerals through decomposition, mineralisation and immobilisation.

Trees play an important role in maintaining and improving soil fertility through input of organic matter via litterfall, a pathway of nutrient cycling (Nair, 1984; Nair, 1985; Binkley et al., 1992; Nair, 1993; Palm, 1995; Young, 1997; Chander et al., 1998; Verheij, 2003; Boley et al., 2009). Nutrient fluxes especially carbon (C) and nitrogen (N) input into the cycling process occur through atmospheric sequestration and fixation. For example, intercropped common legumes such as *leucaena, gliricidia* and *calliandra* can sequestrate and fix atmospheric C and N and make them available through litterfall (Clarke and Thaman, 1993; Verheij, 2003). Generally, C does not have direct effect on tree growth, however, it has effects on soil structure and the release of N and other nutrients from soil organic matter. Therefore, the N levels in the soil is highly dependent on C levels. After decomposition process, when organic matter breaks down, processes of N mineralisation and immobilisation follow. Both processes entirely determine...
the amount of N released or cycled back into the soil compartment (Cowie et al., 2006). The available nitrogen maintains and improves soil fertility and enhances tree growth (Ong et al., 1991; Clarke and Thaman, 1993; Mugwe et al., 1994; Rhoades and Binkley, 1995; Parrotta, 1999; Nair, 2007; Bouillet et al., 2008). A favorable nutrient cycle therefore can maintain soil nutrient supply and reduce competition of nutrients that could lead to soil degradation and reduction of growth of individuals in a forest stand.

In forest stands, trees compete for the aboveground resource (light) and belowground resources (nutrient and water). However, plants compete more for the soil resources than light. Therefore, belowground competition can have negative impacts on growth, survival, and productivity of plants growing in proximity (Casper and Jackson, 1997). When belowground resources are limited, competition occurs when a competitor reduces the soil resources available to its neighbour of the same species (intraspecific) or of another species (interspecific) through its root network (Casper and Jackson, 1997; Nan et al., 2013). The nature of competitive interactions within and between species demonstrates the ability of a plant to influence its environment. Plants and trees directly change their environment by addition or subtraction of nutrients and water or indirectly by favouring or hindering pests and diseases. When competition is at peak, growth and development of both trees or one of them growing in proximity can be negatively affected (Xu et al., 1995a; Casper and Jackson, 1997).

An alternative to single species plantation in tropical regions is the use of mixed-species systems. Growing trees in mixed species stands and further intercropping food crops in agroforestry systems are becoming common practices to address competition, promote and achieve diverse livelihood products and ecosystem services (Olsthorn et al., 1999; Nichols et al., 2006). Intercropping trees and food crops may guarantee access and utilization of nutrients
from different soil depths (Kelty and Cameron, 1995; Sanchez, 1995; Rao et al., 1998) and therefore may reduce competition of nutrients belowground (De Costa and Chandrapala, 2000; Kelty, 2006). In an ideal system, each component would have differing phenological characteristics that guarantees competition reduction in crowns and roots at a temporal scale (Forrester et al., 2004; Kelty, 2006; Nichols et al., 2006) and promotes nutrient and water use efficiency and nutrient cycling (Parrotta, 1999; Kelty, 2006).

In recent years there has been an increase in community interest in growing teak as a high value timber in Solomon Islands. Issues of land use planning were not always considered and the best farm land was often used for teak plantations. The high stocking rate required for timber production precluded intercropping with food crops, unlike the traditional use of lower density fruit trees such as canarium, artocarpus, barringtonia and coconuts which allows for food cropping. Teak wood is a high value commodity with the potential to earn substantial income in the future for the growers. However, the traditional design and silvicultural management of plantations meant that income earning opportunities from excess food production has been lost and for many rural communities this is a major source of cash to buy essentials and pay for school and hospital fees.

A further problem that is not specific to Solomon Islands but experienced widely in smallholder forestry is a reluctance for growers to thin. This is particularly the case with non-commercial thinning or ‘thinning to waste’. The lack of infrastructure and therefore access to markets has increased this problem in Solomon Islands as the opportunity to even undertake the later commercial thin is not available. The Australian Centre for International Agriculture Research (ACIAR) established Project FST/2007/020 with the aim of improving the income of communities by developing an alternate system that would overcome the reluctance to thin and
also promote the use of agroforestry for growing high value timbers. This involved the establishment of hybrid systems that draw upon conventional production forestry techniques and traditional food gardens to develop new plantation regimes. It was hoped that interplanting teak with a local fast growing hardwood species *Flueggea flexuosa* (flueggea) would overcome the problem of thinning as flueggea is widely used for construction and fencing. Utilising the flueggea would effectively thin the plantation, eventually leaving the teak to grow through to maturity. The Project established mixed species spacing and hybrid agroforestry trials, intercropping food crops between tree rows, to examine the growth and interactions of teak and flueggea and the interactions of the trees with food crops and the overall system effect on soil quality. This study examines the intraspecific interactions between same species individuals and interspecific interactions between two different tree species and between tree species and crop components of the system on growth resources and their development vertically and horizontally above- and below-ground over time.

The main focus of this research has been located on Kolombangara Island in the Western Province, Solomon Islands (Map 3.1). Teak was grown with flueggea at four different stocking rates and species ratios, and further intercropped with food crops such as bean, capsicum, peanut, sweet potato and taro when the light was not the limiting factor. There is no prior knowledge of how these systems work or of the interactions between timber species and between timber and non-timber crops in relation to competition for nutrients, light and water or of potential allelopathic relations between species. Moreover, the longer term effects of this system on soil fertility and nutrient loss due to harvesting and food cropping is also unknown. Therefore this research examined the interactions over time and space between teak and flueggea and between teak, flueggea and food crops grown in the inter-row with respect to: competition for nutrients, light and water; changes in system interactions with the development
of the canopy; nutrient loss and issues of sustainability related to harvesting of food crops; the biogeochemical cycling of carbon and nutrients, especially nitrogen and root architecture (Figure 1.1).
Figure 1-1.1: Flow chart of productivity and sustainability in a hybrid agroforestry system encompassing the interactions
Hypotheses, research questions and objectives

Plants growing in proximity to each other interact in positive ways (complementarity) or in negative ways (competition) in their capture of growth resources. Species interactions in mixed-species stands can influence the supply, capture and efficiency of use of resources. These include: growth resource availability, including soil nutrient mineralization; \( \text{N}_2 \) fixation; litter decomposition; root spatial stratification effects on nutrient uptake; and resource-use efficiency. Mixed species and agroforestry systems are based on the assumption that when trees and crops are collectively established they complement each other rather than compete in their capture of available growth resources.

Based on a review of the literature, it is hypothesized in this study that growing teak and flueggea in mixed species and agroforestry systems are alternatives in growing teak that would promote root spatial stratification effects on nutrient uptake and resource use efficiency, which would enable complementarity and competition reduction between species in the systems. It is also hypothesized that stocking and mixed species ratio would have a developing impact on tree nutrition, biomass, growth and yield over time as system interactions changes with the development of canopy. These hypotheses are linked as illustrated by the conceptual model in Figure 1.1. Based on the above general hypotheses the questions and objectives derived were as follows.

The research questions of this study are:

1. What level of N uptake occurs between teak and flueggea in mixed species system and between teak, flueggea and food crop when grown together in agroforestry system?
2. What effect does mixed species stands have on litter production and biogeochemical cycling of C and N compared to single species stands?

3. What effect does mixed species and agroforestry systems have on teak and flueggea above- and below-ground biomass and their allocation and storage of C and N dynamics?

4. What effect does mixed species and spacing have on root development and architecture of teak and flueggea when grown together in mixed species and agroforestry systems?

5. What impact does spacing, species mix and intercropping ratios have on teak and flueggea growth, yield and form over time?

The specific objectives pursued are:

1. To determine the N uptake of teak and flueggea in mixed species system and teak, flueggea and food crops in agroforestry system

2. To determine single- and mixed-species systems litterfall production and biogeochemical cycling of C and N

3. To examine teak and flueggea above- and below-ground biomass and their allocation and storage of C and N dynamics
4. To examine the root architecture of teak and flueggea growing in mixed species systems.

5. To examine the growth and yield of teak and flueggea above- and below-ground when grown together in mixed species spacing and monoculture spacing trials.

This research was undertaken to enable the development of science based management regimes for hybrid agroforestry systems in order to maximize benefits and endorse better land use in the Solomon Islands and the wider Pacific which are facing land shortage due to increasing dynamic population, rising water, salt spray and climate change.

1.2 Overview of the thesis

The research reported in this thesis was carried out within the mixed species and agroforestry trials established on Kolombangara Island in the Western Province of Solomon Islands (Map 3.1). The four papers introduced below form the data chapters of this thesis. Chapter 6 was submitted for publication in Agroforestry Systems Journal and was accepted but returned for minor corrections before resubmitted for publication. As each data chapter was designed to be self-contained, some repetition of site descriptions, methodology and referencing has been unavoidable. A more detailed review of the literature relevant to this thesis formed Chapter 2 and pertinent literature review relevant to each research topic has formed part of each data chapter and consequently has not been presented elsewhere within this thesis. The thesis therefore consists of this introductory chapter (Chapter 1), the literature review chapter (Chapter 2), the site description and methodology chapter (Chapter 3), and the four data
chapters presented as research papers: Competition interaction (Chapter 4), Nutrient cycling (Chapter 5), Root development and architecture (Chapter 6), and Growth and yield (Chapter 7) and a general conclusions chapter (Chapter 8).

1.2.1 Competitive interaction

The sustainable management of growth resources requires an understanding of the nature of the competition for available resources between species growing in mixed species stands and agroforestry systems. In tropical areas, where growth and decomposition may be rapid, nutrient uptake and cycling in short rotation plantation may lead to early soil nutrient degradation due to intraspecific competition. Short rotation plantations are often established with fast growing commercial species with individuals having higher demand for soil nutrients for growth. Most of the nutrients taken up by the fast growing trees are stored in their biomass for growth and development and are lost through harvesting and removal of the tree parts. There have been many studies examining the nutrient uptake in single species stands (Sharma and Pande, 1989), but nutrient uptake especially N movement into the soil-plant system in mixed species stands in tropical Pacific region has received less attention.

The stable isotope $^{15}$N has been used in tracer studies to follow and examine the movement of N from soil into the plant. Several studies had used N fertilizer with known quantities of $^{15}$N to follow the N movement from litter into the soil-plant system (Blumfield and Xu, 2006) and from the soil into the plant (Pu et al., 2001; Robinson, 2001; He et al., 2009). Using this technique, the N movement from soil-plant system as the result of the interactions between teak and flueggea and between teak, flueggea and food crops could be examined over space and time. Furthermore, where in the plant N is stored and at what amount or concentrations could be determined. The report on the 12 and 18 months tracer labelled-$^{15}$N experiment at the
mixed species and hybrid agroforestry trials examining the movement of N forms the fourth chapter of this thesis (Chapter 4: Competition for resources between components of mixed-species forestry system in Solomon Islands).

1.2.2 Nutrient cycling

In agroforestry systems, the maintenance and improvement of soil fertility is essential for sustaining the growth and productivity of the current and subsequent food cropping and the health of the timber trees. Loss of nutrients may occur via timber and crop harvesting and therefore nutrient cycling is important because it is a major pathway in which soil fertility is maintained. In order for the system to be successful it should encourage nutrient cycling of C and N. Several studies (Ola-Adams, 1993; Takahashi et al., 2012) had reported C and N cycling of teak litter but litterfall studies of teak growing at the tropical Pacific countries at the establishment period is lacking. Establishing teak in mixed species systems is an alternative to teak monoculture establishments and may have higher potential to promote nutrient cycling via mixed species litterfall. The system would have the advantage of cycling various concentrations of C and N and other nutrients and therefore may ensure maintenance and improvements of soil fertility. This system would promote cycling of leached nutrients through deep rooted trees. In order to examine the cycling of C and N, teak and flueggea litterfall of all treatments in mixed species trials at Ringgi and Poitete were studied between age 2 and 3½ years to examine the C and N dynamics concentration and cycling in the establishment period. This study is reported in the fifth chapter forming this thesis (Chapter 5: Nitrogen and carbon cycling associated with litterfall production in monoculture teak and mixed species teak and flueggea stands in Solomon Islands).
1.2.3 Root development and architecture

Root architecture, the spatial configuration of root systems, is an important factor in the acquisition of essential soil resources (Lynch, 1995; Ho et al., 2005). Roots are the supply lines of plants for water and minerals, stores carbohydrate, produces essential nitrogenous compounds and a structural anchor to support the shoot (Perry, 1982; Jourdan et al., 2000; Nibau et al., 2008). However, research on teak root system architecture (RSA) growing in plantation are lacking or not publicly available to farmers although RSA is responsible for nutrient uptake which ensure teak’s growth and development and having direct impacts on the final yield (Gregory et al., 2009). One of the major causes is the difficulty to access the root structure as it proliferates from the root collar belowground and requires much time and effort as it involves intensive labor on soil excavation (Lyford and Wilson, 1964; Tatarinov et al., 2008). Some work has been carried out on root biomass and root growth of teak growing in monoculture stands in India and Thailand (Srivastava et al., 1986; Takahashi et al., 2012), however, these studies only investigated the biomass and root growth dynamics of teak at 3, 7 and 15 years following establishment. The development of root topology and distribution of teak in the early establishment phase of the plantation cycle in monoculture and mixed species systems has not been examined. Understanding the development of teak RSA is important to guide growers and decision makers in making decisions on the nurse species, spacing and silvicultural regime to apply in mixed species and agroforestry systems (Schroth, 1995). In order to examine the development of teak and flueggea root architecture, teak and flueggea that grew 4 m apart in a hybrid agroforestry and mixed species systems were excavated to examine their root development at ages 2 and 4 years. This study is reported in the sixth chapter forming this thesis (Chapter 6: Root architecture of teak and flueggea in mixed species systems in the Solomon Islands).
1.2.4 Growth and yield

Trees provide various products including timber which can generate income especially for smallholder farmers. However, farmers usually lack the knowledge to understand their trees growth and yield. The need to determine information to manage woodlots and to plan its harvesting at the peak of growth presents the need to bridge the gap between science and management to make strategic decisions based on total height and diameter at breast height (DBH). This has escalated the demand for examining the growth and yield of forests using models (Subasinghe, 2008). Establishing growth and yield models allow farmers to understand the productivity of their stands and can assist them in projecting silvicultural operations and wood flow using basal area (BA) and volume models for future forecasts.

Growing trees in mixed species systems has caused concerns regarding the effect each component has on each other’s growth and productivity. Mixed species system therefore has implications for growth as each species has different phenology. However, studies on mixed species systems has determined that different species phenology has contributed to positive growth of trees growing in proximity through nutrient use efficiency (NUE) and water use efficiency. Trees source nutrients and water using their roots genetic ability at different depths. Some trees have deeper roots while others have shallow roots and combination of such species with different root architectural development have facilitated favorable growth and yield in mixed species systems. Competition for light was also reduced in mixed species stands as canopy developments vertically and horizontally are different for different species allowing for different canopy heights which make gaps for sunlight to reach sub-canopies. There have been few studies looking on teak growth and yield in mixed species systems (Kumar et al., 1998; Mutanal et al., 2001; Mutanal et al., 2009; Sharma et al., 2011). The studies have reported that teak growth have improved significantly compared to teak growing in monoculture stands. The
effects of flueggea on teak and vice versa in a mixed species system in the tropics has not been
studied. In April 2009, ACIAR Project FST 2007/020 in collaboration with KFPL and SIG
MOFR established two long-term scientific trials at Ringgi and Poitete to identify the optimum
spacing and mixture of species that promotes best tree form, rapid growth and productivity of
teak and flueggea. The report on the 60 months growth and yield of the single and mixed
species treatments within the two scientific trials forms the seventh chapter of this thesis
(Chapter 7: Growth and yield of five years old teak and flueggea in single- and mixed-species
forestry systems in the Solomon Islands).

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Chapter 2  Literature Review

2.1 Introduction

This chapter reviews literature on mixed species and agroforestry systems and interactions that occur in both systems when various species of trees and crops are intercropped. It also covers the biogeochemical cycles of carbon (C) and nitrogen (N), $^{15}$N-labelled enrichment, teak ($Tectona grandis$), flueggea ($Flueggea flexuosa$) and findings and opportunities of research in mixed species and agroforestry systems.

2.1 Mixed species system

Growing interest in mixed species forest stands has resulted in an increase in mixed species plantations being established over the recent decades (Olsthoorn et al., 1999), although this development has not been well informed by rigorous research on growth and yield (Vanclay, 2006). Literature suggests the use of mixed species plantings may be driven by considerations of: soil nutrient improvement; resource use efficiency; diversification of timber and non-timber products; biodiversity; pest and disease control; better growth (Piotto et al., 2003); and marketing opportunities (Szott et al., 1991; Sanchez, 1995; Vanclay, 2006). Rao (1998) and Sanchez (1995) further suggest that out of all of these, soil nutrient improvement and resource use efficiency are the prime reasons for the interest through input of atmospheric nitrogen with inclusion of legume crops and partitioning of nutrients by the component species from various soil zones.
As mixed species plantations involve interactions between the same species (intraspecific) and between different species (interspecific), understanding the consequences of these interactions is essential for attaining the desired outcomes such as timber production (Vanclay, 2006). Interactions in mixed species planting are complex when compared to monocultures and may have effect on nutrient inputs, litterfall, soil nutrient supply and rooting patterns (Rothe and Binkley, 2001). Tilman (1999), and Rothe and Binkley (2001) further state that such interactions are important to know in order to understand the nutritional needs of the systems components and their roles in mixed species ecosystem. Several authors claim that mixed species communities promote reduced competition for nutrients because of effective resource use and nutrient uptake facilitation (Rao et al., 1998; Tilman, 1999; Forrester et al., 2006; Forrester et al., 2010). However, Rothe and Binkley (2001) underline that although empirical studies address nutritional interactions in mixed species forest, they are comparably scarce. Most studies were from temperate environment such as in Netherlands (Hendriks and Bianchi, 1995), Sweden (Brandberg et al., 2000) and in sub-tropical to tropical environment like India (Sharma et al., 2011a; Sharma et al., 2011b; Yadav et al., 2011). Mixed species systems in the tropics are less studied and therefore this thesis will contribute to the ongoing studies of mixed species and agroforestry systems in a tropical environment.

2.2 Agroforestry systems

Agroforestry is a traditional practice (Nair, 1993; Sanchez, 1995), in use for at least 1300 years (Brookfield and Padoch, 1994) and a collective term for land use systems in which trees are grown in association with food crops in a spatial arrangement, temporal sequence or both (Young, 1985; Swift, 1988; Van Noordwijk and Purnomosidhi, 1995) to achieve higher productivity through temporal sharing of physical resources (Ong et al., 1991). Approximately
1.2 billion people (24% of the world’s population) depend directly on agroforestry’s diverse products and services in rural and urban areas of developing countries (Leakey and Sanchez, 1997). These diverse products include food, medicine, fuelwood, animal fodder, poles and timber, and the perceived services include enhancing soil fertility, nutrient cycling, nutrient and water use efficiencies, reduced nutrient leaching to groundwater and improved soil physical and biological properties (Weinstock, 1985; Swift, 1988; Jose et al., 2004). Further, because agroforestry systems involve diverse products they have the potential to reduce pest and disease risks. Among the ecosystem functions, the most important is certainly that of maintenance of soil fertility because it promotes sustainability of production (Swift, 1988). Hence, agroforestry is classified as a low-input system and an alternative to intensive cropping systems (Young, 1985), which rely heavily on inputs of inorganic fertilizers and other external inputs to sustain production. Using leguminous or actinorhizal trees growing in association with food crops may further enhance nutrient availability because they have the capacity to fix atmospheric nitrogen (Atta-Krah, 1990). This fixed nitrogen can be made available and taken up by the associate trees, food crops or stored in the soil. The optimum utilization of nitrogen by the components depends on the type of agroforestry system design, species choice and the management employed (Tiarks et al., 1998).

Although agroforestry systems have been classified in many different ways (Nair, 1993), there are only two functionally different types, simultaneous and sequential (Palm, 1995; Sanchez, 1995). Simultaneous agroforestry is where the tree and the crop components grow at the same time and in close proximity, examples would be alley cropping or hedgerow intercropping (Young, 1985; Sanchez, 1995) or agrosilviculture (Nair, 1984; Bhardwaj et al., 2005). Sequential agroforestry is where trees and crops are grown in rotation like traditional shifting cultivation (Nair, 1984; Weinstock, 1985; Brookfield and Padoch, 1994; Kass and Sanchez,
In the simultaneous system both ecological and economic interactions between the tree and food crop components exist (Young, 1985; Nair, 1993; Sanchez, 1995) over time and space.

### 2.2.1 Simultaneous agroforestry systems

Alley cropping (Atta-Krah, 1990; Sanchez, 1995) or agrosilviculture (Bhardwaj et al., 2005) is a common simultaneous agroforestry practice of growing food crops along with trees for maintaining and improving soil fertility (Swift, 1988; Xu et al., 1992; Palm, 1995) and promoting resource use efficiency. Leguminous trees are grown in hedges between alleys of specified width where short-cycle food crops are grown (Young, 1985; Xu et al., 1993; Sanchez, 1995) and have the ability to fix nitrogen, to reclaim lost nutrients from deeper layers of soil and to supply nitrogen-rich foliage. The foliage may be used as a mulch to suppress weeds and as green manure for soil fertility maintenance, obtained via periodical pruning (Atta-Krah, 1990; Sanchez, 1995; Okogun et al., 2001). The spatial patterns in the system, coupled with planned tree pruning allows the intercropped food crops to capture the fixed atmospheric nitrogen and gain sufficient solar radiation, hence promoting site resource use efficiency (Wojtkowski, 2008). The essential characteristic of the system is the design of tree rows and the management of the canopy to allow an open space above the strips of light-seeking alley crops or trees for them to grow in an environment where competition is minimized (Kelty and Cameron, 1995).

In simultaneous agroforestry systems, interactions between the tree and the crop components are maximized by the spatial arrangement (Young, 1985; Sanchez, 1995). These ecological interactions take place through microclimate actions on soil and fauna, both above- and below-
ground through shading, mutual effects on soil moisture, plant nutrient cycling or competition, and suppression of pests (Swift, 1988). Swift (1988) further states that, within these systems, the effects can be of the tree upon the food crops or of the food crops upon the trees, and can be positive (beneficial) or negative (adverse). Such intercropping has the possibility to increase the soil moisture available to crops through reduction in evapo-transpiration (Scott, 1990), or conversely to reduce soil moisture through root competition.

In the Pacific, agroforestry provides most of the food, medicines, construction materials, firewood, tools and countless other products or services that would either be impossible, or too expensive with imported substitutes (ESCAP, 2010). The common practice in most of the Pacific Island Countries and Territories is agrosilviculture which is combining tree crops and nitrogen fixing trees with tuber food crops (Nair, 1984; Vergara and Nair, 1985; Richard 2009), although silvopastoral and agrosilvopastoral activities are practiced (Nair, 1984; Vergara and Nair, 1985).

The common tree crops in agrosilviculture are coffee, coconut and cacao including nitrogen fixing trees such as casuarina, gliricidia and leucaena and alley crops such as sweet potato, cassava, yam and taro (Vergara and Nair, 1985; Clarke and Thaman, 1993; Nevenimo et al., 2007; Richard 2009). Some of the common practices in Solomon Islands under agrosilviculture are intercropping food crops with gliricidia, erythrina and cacao; and integrated production of plantation crops such as cacao and coconut or coffee and coconut with gliricidia or leucaena in mixed, dense associations with subsistence food crops such as tubers, cereals, banana, vegetables and sweet potato (Nair, 1984; Vergara and Nair, 1985; Clarke and Thaman, 1993; Richard 2009). Canarium (Canarium indicum) and artocarpus (Artocarpus altilis) are important agroforestry components interplanted with cocoa, coconuts, bananas (Yen, 1994;
Nevenimo et al., 2007; Ragone, 2011) and root crops at wider spacing. Canarium and artocarpus kernel and fruits are traditionally important food in Solomon Islands (Vergara and Nair, 1985; Ragone, 2011). The canarium kernel is high in demand as a staple food (Clarke and Thaman, 1993) thus can be sold or used in barter system country wide while artocarpus has similar importance but is specific to the eastern Solomon Islands. The Improved Temotu Traditional Agriculture system is a unique and local practice practiced by the inhabitants of Temotu Province in the far east of Solomon Islands. Under this system, canarium is one of the species interplanted at a complex agroforestry design encompassing wider spacing of 10 × 10 m squares with ten other species (Nevenimo et al., 2007). In this system, fruit trees are planted interchangeably along a tree row. The same fruit trees are planted along the next tree rows at 10m spacing but similar species are not planted adjacent/opposite to each other. For instance, Canarium indicum or Canarium salomonensis begins the first row, second Barringtonia racemosa (wild cut nut), Syzygium onesima (Pacific local apple), Spondias cytherea while Pometia pinnata begins the second row, then Artocarpus altilis (Breadfruit), then Inocarpus fagifer (Tahitian nut tree), Mango tree etc. This system of planting fruit trees is currently practiced by the Temotuans.

The silvopastoral practice has coconut, various grass pastures, cattle and goats as its components and is mostly practiced in Solomon Islands, Papua New Guinea (PNG) and Fiji, while the PNG agrosilvopastoral system has casuarina and coconuts as tree components interplanted with food crops and support for livestock such as pigs and cattle (Vergara and Nair, 1985; Richrd 2009).

2.2.2 Sequential agroforestry systems
The sequential system is similar to the traditional shifting cultivation practice (Vergara and Nair, 1985; Weinstock, 1985; Atta-Krah, 1990), but often involves planting or retention of selected regenerated tree or herbaceous species with the primary purpose of replenishing soil fertility to support succeeding short duration food crop production and, in the longer term, to ameliorate degraded and abandoned land (Clarke and Thaman, 1993; Rao et al., 1998). During the rotation system, three distinct phases occur to allow for soil fertility enhancement. The first phase involves accumulation of nutrient stocks by the standing biomass via biological nitrogen fixation and recovery of leached nutrients from deeper layers by tree roots, the second phase involves nutrient transfer from the vegetation to the soil upon fallow clearance via decomposition, and the final phase is nutrient uptake and removal via food crop harvests (Atta-Krah, 1990). The cycle repeats once site fertility has deteriorated and needs replenishment via fallow process again to sustain production of the next food crop (Clarke and Thaman, 1993).

Shifting cultivation is a traditional practice in the Pacific including Solomon Islands. It is practiced widely and is still the mainstay of subsistence farming of the rural population (Vergara and Nair, 1985). Cassava, sweet potato, taro and yams are the main crops (Clarke and Thaman, 1993). When harvests are below expected yield, the site is planted with banana and areca (Areca catechu) and left to fallow through natural regeneration (Clarke and Thaman, 1993) or planted with nitrogen fixing casuarina (PNG) and traditionally left for at least 25 years but practically less in more populated areas (Vergara and Nair, 1985; Sunderlin, 1997). This may be as low as 2 years in the densely populated province of Malaita in Solomon Islands (Clarke and Thaman, 1993). As deforestation and soil degradation escalates with shifting cultivation, the practice is claimed to be destructive (ESCAP, 2010) especially when the fallow period is too short to allow for the natural regeneration of the vegetation. As a result in many of the Island Countries, anti-shifting policies were being formulated (Vergara and Nair, 1985).
Traditional shifting cultivation which involved slash and burn, gardening and fallowing is often viewed as one of the main cause of deforestation in the Tropics (Christanty, 1975; Brown and Kathrin, 1998; Seidenberg et al., 2003; Mertz et al., 2008). Shifting cultivation practices are estimated to support the livelihoods of about 300-500 million people across the world (Nyle C, 1996) and millions of farmers in the tropics (Mertz et al., 2008). The exact figure on areas under shifting cultivation worldwide is difficult to measure (Mertz et al., 2008) however, the FAO estimated it to be around 350 million hectares of exploitable land (Nair, 1993). Nyle (1996) and Sunderlin (1997) claimed that shifting cultivation was strongly criticized because knowledge was lacking in understanding and differentiating the wide variety of practices, such as clearance, burning and short fallow period, that were lumped together under the system. If shifting cultivation involves gardening and fallowing on secondary regrowth and no further clearance of the forest, then it is preventing further deforestation compared to agricultural land development (Seidenberg et al., 2003; Mertz et al., 2008).

2.3 Research findings

One of the underlying principles of agroforestry is that trees help maintain soil fertility and support the growth of the associated and succeeding crops (Nair, 1984; Schroeder, 1993; Szott and Kass, 1993; Bhardwaj et al., 2005). Various hypotheses combined with field studies continue to test the concept under different environments (Young, 1997; Kho, 2000), as a result of these and later studies (Vergara and Nair, 1985; Lundgren, 1987; Lal, 1989; Rao et al., 1998) there has been an accumulation of a significant wealth of scientific knowledge on agroforestry (Young, 1985; Nair, 1993; Sanchez, 1995; Akinnifesi et al., 2008; Rahman et al., 2011).
Many authors confirm that alternate cycle (Weinstock, 1985; Schroeder, 1993) or sequential growing of trees along with crops (Swift, 1988; Sanchez, 1995; Rao et al., 1998; Sanchez, 1999; Yadav et al., 2011) has been proven to enhance crop yields, improve and preserve soil properties and recycle nutrients while producing fuelwood, livestock fodder, fruits, medicines, poles and timber (Young, 1985; Jose et al., 2004). However, simultaneous systems offer better potential in areas where population density is high (Weinstock, 1985) and arable land is in short supply such as the Pacific Island Countries (Vergara and Nair, 1985). Moreover, regeneration and maintenance of soil fertility, vital for sustaining crop growth and production, that is spatially and temporally separated under the sequential system is brought together under a simultaneous system, hence the latter is an alternative to the former (Atta-Krah, 1990).

Though agroforestry is a traditional practice, it is only since the 1980s that it has been widely promoted when it was regarded as a panacea for solving land-use problems in the tropics (Lundgren, 1987; Sanchez, 1995; Coe, 1997; Sanchez, 1999; García-Barrios and Ong, 2004; Scherr, 2004). Agroforestry research was mostly a collection of largely descriptive and empirical studies in the 1990s, however, since then it has gradually transformed with a more scientific approach based on process-oriented research (Sanchez, 1995; Young, 1997; Yadav et al., 2011).

Exploitation of interactions between tree and food crop components is important to manage because it can cause either a positive or negative response in plant function and growth (Ong and Leakey, 1999; Reyes, 2008), hence the need for better understanding of the interactions bring about a strong desire for the improvement of traditional, as well as evolving systems (Nair, 1993; Rao et al., 1998). The two major principles in mixed species and agroforestry systems are competition and complexity (Sanchez, 1995). Both competition and complexity in
turn determine the productivity and sustainability of the agroforestry systems (Vergara and Nair, 1985; Sanchez, 1995; Reyes, 2008).

In considering the overall productivity of mix species and agroforestry systems, it is essential to investigate and measure quantitatively the changes in soil fertility and the interactions that unfold by competition or complementarity in the capture and partitioning of growth resources between tree and crop components (IAEA, 2008). This is especially true for nutrients and water, usually the two most limiting factors influencing crop growth due to site, locality and competition over time.

**2.4 Interactions in mixed species and agroforestry systems**

The literature emphasises the fact that the success of mixed species and agroforestry systems relies heavily on the exploitation of the way the system components interact (Monteith *et al.*, 1991; Nair, 1993; Ong and Leakey, 1999; Reyes, 2008). Nair (1993) defined component interactions as the effect of one component of the system on the performance of another component and on the overall system. To better understand these interdependent interactions, the examination of a number of complex processes is necessary including the biogeochemical cycle of nutrients, system components biomass nutrient content, soil fertility, competition, microclimate, pests and diseases, soil conservation and allelopathy (Rao *et al.*, 1998).

Several studies (Schroeder, 1993; Forrester *et al.*, 2006) in agronomy, agroforestry, forestry and ecology have identified the importance of intraspecific and interspecific interactions. However, knowledge of the underlying mechanisms is limited because few have explored the theoretical and experimental aspects of these interactions (Nair, 1993). Nair (1993) further
emphasises that, due to the complexity and lifespan of agroforestry systems, both investigations of mechanisms and processes are extremely difficult thus making it impossible to generalize and extrapolate results from one study to another. Component interactions, especially intraspecific, represent a critical aspect of mixed species and agroforestry systems that need further examination to realize their full potential (Nair, 1993; Nicotra and Rodenhouse, 1995).

Interspecific competition under different resource availability regimes and its effects on community structure have been investigated by numerous researchers (Wilson, 1988; Aerts et al., 1991; Reader et al., 1994; Nicotra and Rodenhouse, 1995; Vanclay, 2006).

2.4.1 Intraspecific and interspecific interactions

Competition generally refers to the use of a limiting resource when it falls below the combined demands of plants (Went, 1973), and one exerts a negative effect on the other (Forrester et al., 2006). Went (1973) emphasises that plants can be in close proximity and yet not competing as long as the water, nutrients and light are in excess of their needs. Intraspecific competition occurs when individuals of the same species compete for the same resource for food or living space in mixed species and agroforestry systems and interspecific competition involves individuals of different species (Narwal and Haouala, 2013; Amb and Ahluwalia, 2016). The existence of both intraspecific and interspecific competition leads to more complex interactions in plantation mixtures than monoculture (Forrester et al., 2006). Forrester (2006) underlines that the net effect of the system is the parameter commonly measured as the product of both intra- and inter-specific interactions. The product of both interactions may have negative or positive effects on the system components (trees) and may result in their substitution, reduction or increased yields.
Intraspecific competition can be critical to the growth, survival and reproductive success of individual components in mixed species and agroforestry systems (Monteith et al., 1991). Nicotra (1995) experimentally discovered that intraspecific competition significantly affected plant growth. For instance, intraspecific competition intensity increased with increasing resource availability and with increasing plant productivity (Nicotra and Rodenhouse, 1995). In their findings, Nicotra and Rodenhouse (1995) reported that competition was most intense at high light and high nitrogen than at intermediate availability of light and nitrogen and that where both or either resources were limited; the response of the plants to intraspecific competition was reduced.

### 2.4.2 Simultaneous interactions

Simultaneous agroforestry combines trees with crops in various arrangements. The parallel establishment and close proximity of tree and crop components initiates the interaction (Sanchez, 1995) with competition for resources above- and belowground (Ong et al., 1991; De Costa and Chandrapala, 2000) building gradually over time and space (Scott, 1990).

Forrester (2006), observed the following on his examination of the interactions in a mixed species stand. (1) If intra- and interspecific competition are the same (or the density is too low for plants to interact) then the average plant size and overall size inequality should be the same in mixtures and monocultures. In this case it is just as beneficial to plant monocultures of each species. (2) Where the interspecific competition is greater than intraspecific competition for one species and vice versa for the other, the species receiving the greater share of resources will be larger in mixed plantings than in monoculture, while the species receiving a lower supply of resources will be correspondingly smaller. (3) Where interspecific competition is
greater than intraspecific competition for both species, the average size of both species in mixed
plantings will be smaller than in monoculture and finally (4) when interspecific competition is
lower than intraspecific competition for both species the average size of both species in a mixed
planting will be greater than in a monoculture and the yield of the mixed plantings will be
greater than that of monocultures. The compensatory effect described in situation three was
also confirmed in a separate study using mixtures of herbaceous species (Trenbath, 1974).

Minimizing resource competition between trees and crops, whilst maximizing the use of
available resources, is fundamental to improving yields and overall productivity in mixed
species and agroforestry systems (Schroeder, 1993; Livesley et al., 2000). Given the
knowledge of intraspecific and interspecific interactions, both could be managed or exploited
towards sustaining the overall productivity of the agroforestry systems. Both intra- and
interspecific competition should be examined concurrently (Forrester et al., 2006) because
studies of intraspecific competition may reveal patterns of competition intensity that cannot be
identified by studies of interspecific competition alone (Nicotra and Rodenhouse, 1995). In our
study, the five treatments in the mixed species spacing trials can accommodate such lines of
investigation for teak only as no mono-species flueggea treatment was established

2.4.3 Sequential interactions

In a sequential arrangement, leguminous trees and plants are usually planted or allowed to
regenerate after food crop harvest to allow for replenishment of nutrients (Vergara and Nair,
1985; Young, 1985). The food crops planted following clearance of fallow are expected to
benefit from improved soil conditions (Clarke and Thaman, 1993; Sanchez, 1999). The fallow
trees or vegetation can be planted (Vergara and Nair, 1985) as either single or mixed stands, or
regeneration of a mixture of species from the soil seed banks. The interactions that occur during
the fallow period are often between the fallow trees and the weeds and usually the weed
populations are negatively affected (Rao et al., 1998) as determined by growth and abundance
assessments which occurred simultaneously with the closing of the canopy over time. One of
the interactions that interest researchers is the effects that fallow plants have on the subsequent
cropping which may be caused by residual allelopathic chemicals (Nakafeero, 2007).
Allelopathic chemicals are the chemical compounds released via leaf litter and root litter during
the decomposition process or root secretion into the soil (Nakafeero, 2007; Arbogen, 2008).

2.4.4 Allelopathic interactions

Allelopathy is best defined as the effects of one plant on another, both harmful and beneficial
through the release of metabolic chemicals by processes such as leaching, root exudation and
volatilization (Rabotnov, 1974; Gonzales et al., 1995; Nakafeero, 2007). The basic concept of
mixed species and agroforestry systems is combining trees with crops in various arrangements;
however, the concept of allelopathy may limit the range of tree and crop species that can be
used (Nakafeero et al., 2007). Allelopathic interactions are certain to exist in mixed species
and agroforestry systems because they involve combinations of trees (Nakafeero et al., 2007)
and food crop species. Allelopathic phenomena have been observed in many agricultural crops
and weeds (Rice, 1974; Kunz et al., 2016), and tree species (Coder, 1998; Chen and Wang,
2012) but may be highly variable due to site, climate, species and individual situations
(Nakafeero et al., 2007). Research has shown that some weeds and tree crops release some
allelochemicals into the soil which adversely affect the germination, growth and yield of crops
and weeds (Bhatt and Todaria, 1990; Einhellig, 1996; Kunz et al., 2016). For example, in a
laboratory and field research, Nandan and Dhillon (2005) reported that leaf extracts of poplar
(Populus deltoides Bartr Ex Marsh) at lower concentrations had stimulatory effects on root length of ten wheat varieties and higher concentrations adversely affect germination and seedling growth of some of the varieties tested. Rizvi (1987) also confirmed that mimosine an allelochemical produced by leucaena is toxic for rice and wheat because, it affects their seed germination, radical and plumule length at 1 to 5 ml concentrations. Recognizing the effects of allelopathy is important in simultaneous systems because of the longer retention period of trees and direct exposure of crops to the continuous release of chemical compounds (Rice, 1974; Rao et al., 1998; Nandal and Dhillon, 2005) that may interfere with food crop growth (Smith, 1990). Nevertheless, such released chemical compounds via leaf litter or root secretion may have temporary or no effect at all in humid environments due to leaching and rapid removal by the microorganisms (Rao et al., 1998) during the decomposition process.

Not all allelochemicals released have negative effects, studies have begun to identify that some were identified as having beneficial, neutral, or selective effects on companion and neighboring crop plants (Rizvi and Rizvi, 1987; ArborGen, 2008). Considerable progress on allelopathy research has been made in pursuit of understanding the nature of allelochemicals (Chen and Wang, 2012) and the extent of their negative effects and potential benefits in annual cropping systems (Rao et al., 1998; Amb and Ahluwalia, 2016; Kunz et al., 2016). However, most studies were done under laboratory conditions and their practical value is not clear (Rao et al., 1998; ArborGen, 2008). Thus, when intercropping or alley cropping systems are conducted, caution must be taken as it is prudent to be aware that allelopathic interactions may exist and may be the cause of unexpected or unexplained failures of the mixed species system. When noticed, such situation could be avoided or minimized via spacing adjustments, irrigation, application of inorganic fertilizer, review of intercropping systems and change of tree species (Einhellig, 1996; ArborGen, 2008; Kato-Noguchi and Salam, 2013; Ali et al., 2014).
It is evident from the research that allelopathic interactions among plants are generalized and not plant specific (ArborGen, 2008). Allelopathic influences can vary greatly depending upon the tree, crop species and conditions under which they grow (Stowe, 1979; Chen and Wang, 2012). Further, it can be very complex when the interaction involves several other factors including different classes of chemical compounds, soil types, rate of decomposition of soil residue, cropping systems, and competition for nutrients, moisture, light and other growth resources (Stowe, 1979; Nakafeero et al., 2007; ArborGen, 2008; Kato-Noguchi and Salam, 2013; Ali et al., 2014). Although implications of allelopathic interactions on crop production are still uncertain, farmers are reminded to be cautious when intercropping tree species with food crops.

2.5 Tree species and food crop intercropping in agroforestry systems

Trees improve soil fertility and modify the microclimate under their canopies (Young, 1985) both favorably and unfavorably. Thus success in utilising agroforestry systems involves careful consideration of several factors including the choice of tree species with reference to their canopy, root structure (Rao et al., 1998; Schroth, 1999; Nair, 2007), crop species, alley width, biomass production, straight bole, number of crop cycles, survival, pruning frequency, tillage, fertilization, weed dynamics (Sanchez, 1995), and adaptation to local climate and soil.

Establishing woodlots using a mixture of tree species having different growth habits, rooting patterns and quality of leaf residues may lead to higher biomass productivity by enhancing complementary use of growth resources and promoting greater synchrony in the release of nutrients from residues in relation to crop requirements (Rao et al., 1998; Kazakou, 2009;
Rahman, 2011). Rao (1998) further stressed that in agroforestry systems, the timing of release of nutrients from tree litter can be influenced by choice of tree species, especially in their decomposition timing. Moreover, existence of belowground competition is limited to the choice of tree species. However, identifying and matching such species, site suitability and whether they have potential in an economic sense and would be accepted by farmers remains an issue (Schroth, 1999).

Although the number of tree species explored in agroforestry research has increased substantially (Maclean et al., 1992), much remains to be done and little interest has been given to income generating or high-value tree species (Rao et al., 1998).

Intercropping teak with leucaena in India, in a simulated taungya system, a temporary association of annual crops in juvenile tree plantations, promoted height and diameter growth of teak and improved soil fertility (Kumar et al., 1998). However, little is known on teak intercropping interactions and growth performance in the humid tropics. Flueggea was only recently intercropped in coconut plantations and food gardens for local housing material and firewood in Samoa (Thomson, 2006), Vanuatu, Fiji and the Solomon Islands. Growing teak and flueggea together with further intercropping with food crops is currently being examined in the Solomon Islands and forms the basis for the experimental work undertaken through this project.

2.6 Agroforestry tree species components

Several exotic but important hardwood tree species such as teak and mahogany (*Swietenia macrophylla*) had been introduced into Solomon Islands at trial level (Pandey and Brown,
Teak and mahogany make up portions of the only two major commercial plantations in Solomon Islands, namely Kolombangara Forest Products Limited (KFPL) and Eagon Pacific Plantation Limited (EPPL) and are almost exclusively used for community plantings. Teak has been a choice of intercropped tree species in agroforestry systems in several tropical and sub-tropical countries, including India (Kumar et al., 1998; Depommier, 2003; Mutanal et al., 2009; Sharma et al., 2011a; Sharma et al., 2011b), Thailand (Samek and Skole, 2011), Indonesia (Rohadi, 2009) and Malaysia (Taman Negara Article, 2000). Mixed species plantings of teak and flueggea further intercropped with food plants is currently being researched by a project for the Australian Centre for International Agricultural Research (ACIAR) in Solomon Islands. These plantings are the sites for the experimental work described in this thesis.

### 2.6.1 Tectona grandis

*Tectona grandis*, Teak, is a 30-35m tall deciduous tree of the family Verbenaceae and grows well in well drained sites in moist, warm tropical climate. The tree has a straight stem and often fluted at base with buttress. It has a spreading crown with large simple leaves in opposite arrangement with elliptic shape. Has flowers that are like terminal cymose panicles and flowering season occurs between June and September. Fruit a drupe, brown, densely floccose hairy, covered by inflated calyx with seeds 1-4. Bark is thick, fibrous with rough surface and light brown to greyish colour (Kaosa-ard, 1986; Peter, 1993; Pandey and Brown, 2000).

Teak, a species of fine dark wood, highly durable, easily worked, attractive, strong and relatively light (Australian Agribusiness Group, 2007; Forwood, 2008; Miranda et al., 2011) is originally from an area encompassing parts of India, Thailand, Myanmar and Laos (Goh and
Monteuuis, 2005; Midgley et al., 2007; Fofana et al., 2008). However, in the last century it has been cultivated widely across the semi and humid Tropics (Evans, 1992; Forwood, 2008) such as Sri Lanka (Ball et al., 1999), Laos (Midgley et al., 2007), Malaysia (Abod and Muhammad, 2002), East Timor (Miranda et al., 2011), Tanzania (Zyl, 2005), Nigeria (Akindele, 1991), Costa Rica (Ivan et al., 2004; Viquez and Prz, 2005; Boley et al., 2009), other American countries (Pandey and Brown, 2000) and the Oceania (Ladrach, 2009) including Solomon Islands (Pandey and Brown, 2000). Teak has been traded as a commodity and used for around 2000 years (Australian Agribusiness Group, 2007).

High demand and premium prices for teak combined with declining stocks from the natural resource has led to strong conservation measures being put in place within the countries where it is indigenous, with, until recently, the exception of Myanmar (Ball et al., 1999; Goh and Monteuuis, 2005). Myanmar has recently (April 2014) instigated a ban on the export of round logs and slashed its export quota for lumber in a bid to boost local manufacture of teak goods and improve the countries’ foreign exchange earnings. This has resulted in a drastic reduction in the availability of teak wood supply from natural forests, thus focus has changed to plantations which are currently an increasingly important source of timber to meet the steady and increasing demand (Midgley et al., 2007; Forwood, 2008).

Today, teak is one of the most economically and socially important tropical timber tree species (Fofana et al., 2008). Its fine dark and quality aesthetic wood are the reasons for positioning itself well on high demand for making of premium fine furniture (Ladrach, 2009), shipbuilding, flooring, paneling and fixtures (Australian Agribusiness Group, 2007). Competing singly as a fine dark wood in the white wood international market, makes teak remains one of the world’s
most valuable timber and as a result, interest in growing and investing in teak remains high (Forwood, 2008).

Teak has been mostly cultivated in monoculture plantations with 80 to 100 years rotation length like in Thailand, (pers, comm. Thai growers 2013; William, 2009) due to a prolonged annual dry season. However, with the recent establishment of management techniques, improved planting materials and teak planted in better growing conditions, for example, like in the Solomon Islands, rotation length has been reduced to 20 or 25 years (Ladrach, 2009) with MAI (mean annual increment) of 15 - 18 m³/ha per year. In the last decade, teak has been a species of choice in agroforestry systems in India (Kumar et al., 1998; Sharma et al., 2011a; Sharma et al., 2011b). Teak has been intercropped with legume crops and food crops to enhance its growth and productivity and the overall land productivity to generate sustainable income for communities. Teak benefits from soil nutrient improvement especially nitrogen input via biological nitrogen fixation (Kumar et al., 1998). Legume crop residues such as stems, roots and leaves are used as organic fertilizer.

There is little information on the performance of teak in mixed species and agroforestry systems in areas, including Solomon Islands that are outside its natural distribution. Thus the economic and ecological implications of integrating teak into mixed species and agroforestry systems especially when intercropped with flueggea need better understanding in Solomon Islands. The dynamic interactions need to be understood as teak may have either negative or positive effects on flueggea and crop yield, or flueggea and the agricultural crops may have effect on teak productivity. Examining the interactions effect via studies on soil properties, nutrient cycles, and possible impacts on productivity may provide much needed information to determine the best management regime for mixed species and agroforestry systems.
2.6.2  Flueggea flexuosa

*Flueggea flexuosa*, Flueggea, is a small to medium tree typically 10-16 m tall of the family Euphorbiaceae and grows on lowland, humid tropics with rainfall of up to 5000 mm. It occurs naturally in the Philippines, eastern Indonesia, the Solomon Islands, and northern Vanuatu (Thomson, 2006). The tree has a straight stem with clear bole and sometimes with buttresses. The crown is narrowly columnar to conical shape with radiating small branches and that are horizontal. The leaves are simple, alternate with oblong-elliptic shape. Flueggea has male and female flowers that are borne on separate trees and are arranged in short axillary clusters. Flueggea bears fruits of small, green globose berries and turned dark purple-black at full maturity with 4-6 angular seeds in each fruit. The bark is thin and light brown in colour (Thomson, 2006; Orwa et al., 2009).

Flueggea is traditionally an important source of durable, round timber throughout the Solomon Islands and the Pacific for local uses in house building, fencing, crafts and gardening (Wilkinson et al., 2000). However, it was classified as one of the lesser-known species in need of promoting in the timber market (Wilkinson et al., 2000). The species is well suited for planting in various agroforestry systems including boundary plantings for property demarcation, planted fallows, and in plantations mixed with other tree and food crops because it is a short rotation species allowing thinning at an early stage, and it provides shade, wood and other environmental services such as improving soil organic matter (Wilkinson et al., 2000; Thomson, 2006). According to Thomson (2006), flueggea usually have well developed, near surface, lateral root system; grows well on coastal areas with mean annual rainfall of 1800-4500 mm and at temperature ranging between 22°-32° C. It prefers full sunlight but can grow satisfactorily with up to about 30% shade and grows well at neutral to acid soils of pH 4.0-7.7 (Thomson, 2006).
Establishing mixed species plantations using flueggea, a native species, and teak, an introduced species is a novel approach to growing high value timber within Solomon Islands. The interactions, growth, yield, nutrient uptake and cycling need better understanding to establish the optimum growth management regime. Moreover, integrating food crops within a mixed flueggea and teak agroforestry system further warrants the study of the effect of the emerging interactions, nutrient cycling and loss via harvesting on their growth and productivity.

2.7 Biogeochemical cycling of carbon and nitrogen

Teak is a species that is commonly established in industrial plantations and as a component of agroforestry systems in the semi-humid and humid tropics (Evans, 1992; Kumar et al., 1998; Sharma et al., 2011a). Teak grows well in monoculture plantations and therefore its rotation has been reduced to 20 or 25 years (Ladrach, 2009). However, the rapid turnover in relatively short rotation plantations, including teak, has raised concern about the long-term sustainability and the effects on site quality for succeeding rotations (Khanna, 1997a). Repeated loss of nutrients through the harvesting of crops within agroforestry systems may adversely affect soil fertility (Palm, 1995). Nitrogen is a limiting nutrient in the tropics and its loss via biomass harvest and during site preparation is a concern (Khanna, 1997b). Intercropping nitrogen fixing species in an agroforestry system is one way to mitigate soil nutrient loss in monocultures (Clarke and Thaman, 1993; Mugwe et al., 1994; Khanna, 1997b). Intercropping legumes in a mixed species system can improve plant growth and productivity and soil N dynamics (Young, 1985; Khanna, 1997b).
Biogeochemical cycling of carbon and nutrients especially nitrogen is pivotal to the success of any reforestation, afforestation and agroforestry systems in degraded, deforested land or grassland. Biogeochemical cycles encompass soil-plant relationships, including the gains to the soil via the natural processes such as biological nitrogen fixation (Palm, 1995; Khanna, 1997b), organic matter decomposition and nutrient losses by plant uptake (Landsberg and Sands, 2011). Trees and crops tap those nutrients, use them and make them available to the system again via litterfall pathways (Yadava and Thoudam, 1995; Dutta and Agrawal, 2001) after being decomposed by the soil microorganisms and at their death. Landsberg and Sands (2011) further stated that soil enrichment with nutrients via organic matter decomposition pathway is very much dependent on the quality of the litter (Rao et al., 1998) and their mass.

When trees and food crops are intercropped, nutrient loss is expected from the system and nutrient sustainability is a concern for succeeding food crop production (Khanna, 1997b; Tiarks et al., 1998). Nutrients may leave the system via timber, fodder and food crop harvests (Szott and Kass, 1993; Khanna, 1997b; Tiarks et al., 1998). Nutrient loss may also occur naturally through soil erosion, leaching, gas volatilization and surface runoff (Szott et al., 1991).

For the agroforestry system to be successful with progressive food crop production, the nutrient balance and cycling of the system must be understood (Mathuva et al., 1998). Nutrient cycling can be determined through foliar, litterfall and soil nutrient characterization (Tiarks et al., 1998). For successful agroforestry, nutrient inputs and outputs must either be balanced or the former be superior via the biogeochemical cycling of nutrients (Rao et al., 1998) or corrected with human intervention via organic fertilizer through availability and application of mulching and litterfalls or inorganic fertilizer application (Mathuva et al., 1998) when soil nutrient improvement is desperately required to boost growth and yield. The nutrient reserves of
agroforestry systems are in the foliage, bark and branches, sapwood and heartwood of the trees, in the soil (Khanna, 1997b) and in the food crops, however, progressive nutrient loss via fodder and crop harvests (Szott and Kass, 1993; Mathuva et al., 1998) may reduce the soil’s capability to supply future crops with essential nutrients. Thus understanding the dynamics of nutrient outputs or inputs from or to the system via biogeochemical cycling is an essential prerequisite for understanding and predicting the effects of nutrition on trees and food crops growth and productivity in mix species and agroforestry systems. Further, nutrient cycling differs between stands of monoculture and mixed species because the former only has one species while the latter have more than one component, each having different turnover times (Young, 1985; Khanna, 1997b) and needing careful understanding of the effect of each component on the system as a whole.

2.8 Growth and yield

The need for bridging the gap between science and management in order to make strategic decisions based on specific information was one of the reasons that heightened the demand for forest models (Subasinghe, 2008). Growth and yield models are important tools used by Forest Managers and woodlot owners to make strategic decisions on their forest resource. Both are used for site evaluation, testing hypotheses of growth, estimating expected yields, examining variability of yield, exploring silvicultural options and establishing optimal management regimes (Vanclay, 1994) which are science based (Nair, 2007).

This study will examine growth and yield based on teak and flueggea mixed species spacing trials at two sites on the island of Kolombangara in Western Province of Solomon Islands. These sites at Ringgi and Poitete were used to identify the optimum species mix and spacing
for higher survival, rapid growth, best form, high productivity, and resistance to wind throw. It also included a hybrid agroforestry trial to examine nitrogen competition between the system’s components.

Growth and yield data are available for teak plantations for different sites and countries across the tropics and subtropics. This study developed growth and yield data using the growth parameters from the mixed species trials. There are several means of analysis of various parameters to develop a growth and yield models in the literature (Akindele, 1991; Vanclay, 1994; Piotto et al., 2003; Ivan et al., 2004; Petit and Montagnini, 2004; Zyl, 2005; Subasinghe, 2008; Breugel et al., 2011; Hall et al., 2011), however, only diameter or height or basal area or volume relationship with time would be pursued to determine the outcome of this study. A summary of frequency, the number of assessments and diameter information of a stand is an important measure of competition. Basal area is an important parameter for tree growth modeling over time. Growth models encompass frequency of basal area over time and can be used to monitor the growth of an individual or a stand to analyze how an individual growth varies or performs with different levels of competition interactions (Rivas et al., 2005). Further, growth and yield models are significant tools to examine the effect between human intervention on competition via thinning and pruning over the past management and the current stand dynamics (Castagneri et al., 2008).

### 2.9 Further research opportunities

Previous studies have assessed the advantages agroforestry has over monoculture agriculture practices (Price, 1995; Jolliffe and Wanjau, 1999; Nair, 2007; Rahman, 2011). It has been determined that intercropping tree species improved growth, soil nutrients, enhanced resource
utilization and offered diverse products to the farmers at all levels (Mutanal et al., 2009; Sharma et al., 2011a). However, according to Rothe and Binkley (2001) although empirical studies are addressing the nutritional interactions in mixed species forests over time, they are comparably scarce. Moreover, limited attention has been given to biophysical processes (Sanchez, 1995; Young, 1997) and growth modelling needs to be continuously pursued (Subasinghe, 2008) for mixed species stand (Bartelink, 2000; Vanclay, 2006).

Growing teak outside its natural range may be difficult when faced with lack of its growth and yield characteristics (Ivan et al., 2004) including lack of local soil fertility status. Teak has been mostly planted in monoculture plantation for timber (Ivan et al., 2004); however, intercropping with legume trees and crops has been investigated over the last two decades (Kumar et al., 1998; Mutanal et al., 2009; Sharma et al., 2011a; Sharma et al., 2011b). Studies reported that teak growth and soil properties improved when intercropped with legume and food crops (Kumar et al., 1998; Mutanal et al., 2009; Sharma et al., 2011a; Sharma et al., 2011b). These studies confirmed that under science-based agroforestry systems, teak and food crop growth and soil fertility can be enhanced and improved.

Teak was first introduced in the Solomon Islands in 1956 (Raomae, 2010). Its rapid growth, and the demands it makes on the local environment has not been well evaluated. Intercropping teak and flueggea within an agroforestry system has not been tried and little is known of the species interaction or of the effect of growing different food and cash crops in the interrow, or about the potential for increasing or limiting productivity.

Data on teak’s growth and yield characteristics in the Solomon Islands is still lacking and in some cases the available information shows unrealistic figures and may not be applicable in
the long term. Local knowledge on flueggea grown in plantations is limited and non-existent in mixed species stands.

Mixed species planting involving teak and flueggea and further intercropped with food plants presents an opportunity to establish high yielding and short rotation wood stands to meet community food and timber needs for local and commercial use. However, gaps exist in knowledge about their environmental effects and hence the need to examine their competitive interactions for growth resources, evaluate and model early growth and yields within the agroforestry system.

Thus the main aim of this study is to examine the dynamic of the systems components during the early stages of plantation development and to develop provisional growth and yield data for mixed species teak and flueggea stands at various stocking and species ratios in the Solomon Islands. The outcome will serve as a basis for growth and yield predictions and future studies on silvicultural models for teak and flueggea in agroforestry systems in the country and other Pacific Island Countries and Territories (PICT) that share many common ecological zones.

Many authors agree that there is still more to discover in agroforestry systems, especially when agroforestry is practiced across sites with a wide variety of environmental factors (Young, 1985; Nair, 2007). Recent research work examined mixed species and agroforestry systems especially in tree and crop nutrition and nutrient uptake (Korner, 2005; Piotto, 2008; Seyed et al., 2011). Studies are ongoing to investigate the impacts of mixed species and various arrangements to determine the best regime that will promote and enhance growth and productivity whilst maintaining or improving the soil quality (Bristow et al., 2006; Nair, 2009;
This thesis will contribute to the empirical studies on agroforestry systems in the tropics especially with mixed species plantings of teak and flueggea and further intercropped with food crops. Understanding and managing the dynamic and evolving intraspecific and interspecific interactions of the agroforestry systems is the prime goal of this research.
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Chapter 3  Site Description and Methodology

3.1 Introduction

This chapter describes the study sites, experimental designs, and field sampling and analytical procedures used in this research programme. While the methodologies are also described in the following result chapters, this chapter provides more detailed information on the methodologies, their background and the reasons why they were used. All experiments were field-based with the intention to determine uptake and allocation of C and N in tree biomass, carbon (C) and nitrogen (N) cycling, root architecture and growth and yield.

3.2 General Site Descriptions

The experimental trials were located at Ringgi and Poitete within Kolombangara Forest Products Limited (KFPL) Fixed Term Estate (FTE) on Kolombangara Island, Western Province, Solomon Islands (Map 3.1).

Kolombangara Island is circular in shape with an approximate total area of 685 km² with diameter of 30 km and is a typical example of an extinct cone shaped volcano (Stratovolcano) and by far the biggest in Solomon Islands (Vigulu, 2007). Kolombangara is part of the New Georgia Group of Islands that was formed by the coalescing and periodic uplift of several volcanic cones and their fringing reefs in the past (Hansell and Wall, 1975). Consequently, volcanic ash has had an important effect on soil formation throughout the group in addition to the parent material.
Map: 3-1: Map of (a) Pacific Ocean (b) Solomon Islands and Western Province, and (c) Kolombangara Island and the experimental trials (c)
The parent material of the soils on Kolombangara is olivine, basalt, breccias and lavas (Anon, 1984). With reference to the US Soil Classification, both trial sites are located on soil order Oxisol and under the great group known as Haplorthox. However, each site has different Land System (LS). A land system is basically identified by its land form, geology, soils, vegetation and potential land use (Hansell and Wall, 1975). Detailed descriptions of the land systems and soils are given by Hansell and Wall (1975) in their study of Kolombangara’s soils and structure.

There are ten land systems on Kolombangara (Map 3.2); however, the two main mixed species and hybrid agroforestry trials are located only on two land systems. The Ringgi site which has a mixed species and an agroforestry trial is located on the Londumoe LS (LLS) and the soil was described as having “dark brown, dark yellowish brown or strong brown clay”. The Poitete site which has a mixed species trial is located on the Ringgi LS (RLS) and the soil type was described as “deep, yellowish red or reddish brown clay with a deep, dark brown or dark reddish brown topsoil”. There is general agreement by Hansell and Wall (1975), and Bowkett (Bowkett, 1979) on the suitability of the soils for plantation development on Kolombangara.

Kolombangara’s climate is humid tropical. The mean temperatures at sea level are 28° C during the day and 22° C at night with humidity ranging from 60 to 90 % (Speed, 1993). The rainfall is fairly evenly distributed throughout the year with a mean annual rainfall of 3,430 mm. The mean monthly rainfall and temperature for Kolombangara Island are shown in Figure 3.1. There is often a drier period around August and September and wet period between December and March for the Island (Vigulu, 2007). Further, Kolombangara is located on the northern limit of the tropical cyclone belt and therefore subject to occasional cyclones (Whitmore, 1974). Rainfall data was determined with KFPL’s assistance for the trials around Ringgi and Poitete sites.
Map: 3-2: Kolombangara Island Land System (Vigulu 2007)
Figure 3-1: Ringgi (a) and Poitete (b) rainfall and temperature over 5 years period (2007 – 2011)

### 3.3 Ringgi Site Description

The site (8° 05’ 16.33’’ S and 157° 08’ 46.62’’ E) was established on an area of secondary forest mainly dominated by *Macaranga* species, *Euphorbiaceae* species, *Trema orientalis*, *Endospermum medullosum* and variety of *Ficus* species. It is on flat land with a gentle slope of 1 degree. The soil is loamy sand with medium to heavy clay horizon and is part of the Londumoe Land System (LLS). The majority of LLS is located at the south east sector of the Island (Ringgi plain), in a fan of fluvial deposits and recent alluvial valleys originating from
eroded volcanic material. The LLS is the smallest of the two land systems and most fertile, however, according to Hansell and Wall (1975), oil palm (*Elaeis guineensis*) trials on LLS at Ringgi Cove illustrated a deficiency in phosphate, a major nutritional problem. It is therefore known that the fertility is mainly restricted to the humus-rich topsoil. The chemical and physical properties of the soil at Ringgi site is tabulated in Table 3.1.

Table 3-1: Chemical and physical properties of soil of Ringgi trial (Site 1)

<table>
<thead>
<tr>
<th>Soil physical and chemical properties</th>
<th>0-10 cm</th>
<th>10-20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (g cm(^{-3}))</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>pH</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Cation Exchange Capacity (cmol(+) kg(^{-1}))</td>
<td>12.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Total carbon (TC) (%)</td>
<td>6.23</td>
<td>4.30</td>
</tr>
<tr>
<td>Total nitrogen (TN) (%)</td>
<td>0.73</td>
<td>0.48</td>
</tr>
<tr>
<td>δ(^{13})C (%)</td>
<td>-27.10</td>
<td>-26.57</td>
</tr>
<tr>
<td>δ(^{15})N (%)</td>
<td>7.37</td>
<td>8.30</td>
</tr>
</tbody>
</table>

3.4 Poitete Site Description

The site (7° 52´ 34.39´´ S and 157° 07´ 46.78´´ E) was logged in the early 1980’s and formerly a secondary forest and the land is undulating with a gentle slope of 4-5 degrees. The soil is mostly loamy clay with medium to heavy clay horizon and is within the Ringgi Land System which spreads from the coastline up to the 400m contour, and covers more than 90% of the area considered suitable for reforestation on Kolombangara. The soils have a high moisture holding capacity, a good structure and are extremely stable. Although recommended as very
suitable for plantation forestry, available nutrients tend to be confined to shallow layers of top
soil. RLS has very low subsoil fertility, a feature that can be remedied by fertilizer application
(Hansell and Wall, 1975). The chemical and physical soil properties of the soil at Poitete are
tabulated in Table 3.2.

Table 3-2: Chemical and physical properties of soil of Poitete trial (Site 2)

<table>
<thead>
<tr>
<th>Soil physical and chemical properties</th>
<th>0-10 cm</th>
<th>10-20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (g cm$^{-3}$)</td>
<td>0.80</td>
<td>0.82</td>
</tr>
<tr>
<td>pH</td>
<td>5.1</td>
<td>4.8</td>
</tr>
<tr>
<td>Cation Exchange Capacity (cmol (+) kg$^{-1}$)</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Total Carbon (TC) (%)</td>
<td>6.75</td>
<td>5.35</td>
</tr>
<tr>
<td>Total Nitrogen (TN) (%)</td>
<td>0.76</td>
<td>0.58</td>
</tr>
<tr>
<td>δ13C (‰)</td>
<td>-27.25</td>
<td>-26.99</td>
</tr>
<tr>
<td>δ15N (‰)</td>
<td>6.96</td>
<td>7.52</td>
</tr>
</tbody>
</table>

3.5 Common Details to both Trials

3.5.1 Genetic Material

The plant material used in this study are teak and flueggea. Solomon Land Race teak has been
improved over several progeny trials since it was first introduced in Solomon Islands in the
early 1950’s from Papua New Guinea. Teak seeds were collected from an improved clonal teak
stand planted around 1984 near Poitete on Kolombangara Island and is the only seed orchard
in the country. Seeds were germinated, transferred to standout beds and planted. At age 4-5
months, the seedlings were harvested by total removal from the ground, lateral roots trimmed
and the stem was cut off at 20-25 mm above the first root to produce a stump. The stump is capable of being stored for several weeks prior to planting and produces vigorous growth once planted.

Plate 3-1 Two (2) months old teak seedlings growing in standout bed

Plate 3-2: Four to five (5) months old teak seedlings ready for stump preparation
Plate 3-3: Teak stumps ready to be uprooted (4-5 years old)

Plate 3-4 Uprooted teak stump with lateral roots
Plate 3-5: Teak stump, after all lateral roots were trimmed

Plate 3-6 Prepared teak stumps. They are going to be kept in a moist bag or spread out in a standout bed for at least 3 weeks. The stumps are ready for planting when new roots and shoots are seen growing from the stump.
There has been no formal attempt to improve flueggea. Seeds were therefore collected in various flueggea locations around Munda area from selected mother trees of satisfactory growth characteristic, germinated and raised in root trainers for at least 3 months to a height of 25-30 cm.

Plate 3-7: Three weeks old flueggea seedlings raised in poly bags

3.6 Experimental Design

3.6.1 Mixed Species Trial

Mixed species trials were established at both the Ringgi and Poitete sites. Each trial was established in April 2009 on a 2 ha area and consisted of a randomized complete block design with five treatments and four blocks, allowing for spatial variation across the trial site. The trial was established to examine optimal spacing for teak and flueggea in a mixed species system and compare with monoculture teak. There were 5 treatments characterized by species ratio
and stems per hectare (sph) or planting spacing (Table 3.3). The 5 treatments represented 5 plots in a block and with 4 blocks; there are a total of 20 plots. In each plot, there were 6 lines planted with 8 trees. Each plot is buffered by the 1st and the 6th lines and the 1st and the 8th trees of each line. Each plot has a total of 24 measured trees of which T1 had 100 % teak and mixed stands comprised of T5 having 50 % teak and 50 % flueggea, and T2, T3 and T4 have 33 % teak and 67 % flueggea.

Table 3-3: Detail of each treatment replicated in 4 blocks at the Ringgi and Poitete trials.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Species ratio</th>
<th>Stems per Hectare (sph)</th>
<th>Planting space (m × m)</th>
<th>Treatment plot area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teak</td>
<td>1 : 0</td>
<td>833</td>
<td>4 × 3</td>
<td>0.058</td>
</tr>
<tr>
<td>2</td>
<td>Teak and flueggea</td>
<td>1 : 2</td>
<td>833</td>
<td>4 × 3</td>
<td>0.058</td>
</tr>
<tr>
<td>3</td>
<td>Teak and flueggea</td>
<td>1 : 2</td>
<td>625</td>
<td>4 × 4</td>
<td>0.077</td>
</tr>
<tr>
<td>4</td>
<td>Teak and flueggea</td>
<td>1 : 2</td>
<td>416</td>
<td>4 × 6</td>
<td>0.115</td>
</tr>
<tr>
<td>5</td>
<td>Teak and flueggea</td>
<td>1 : 1</td>
<td>833</td>
<td>4 × 3</td>
<td>0.058</td>
</tr>
</tbody>
</table>
Figure 3-2: Design of the mix species trial at Ringgi (a) and Poitete (b) (2009 – 2014)
3.6.2 Hybrid agroforestry trial

The trial was located at Ringgi with a similar layout to Treatment 5 having 833 stems per hectare at 1:1 ratio of teak and flueggea. This trial was intercropped with food crops including legume crops (beans and peanuts) and non-legume crops (potato, capsicum and taro). Food crop intercropping was conducted between December 2011 and April 2012 when the trees were 2-5 months old. Crops, especially bean and peanut were planted at a planting space of 30 cm x 30 cm in the 8m x 3m 15N tracer experiment plot under a teak and flueggea tree. Total of 200 bean plants were planted in Plot 1 and total of 200 peanut plants were planted in Plot 3. Capsicum plants were planted in Plot 2 at a planting space of 50 cm x 50 cm with a total of 96...
crops. Potato plants were spaced at 1m x 1m and therefore a total of 24 crops were planted across Plot 4. There were also 2 taro plants planted in between the teak and flueggea tree in Plot 4. The crops were managed for only 1 rotation within the 5 months study period. The bean and capsicum fruits were harvested by hand picking between the second and the fifth month; potato, taro and peanut were totally uprooted by hand at the fifth month to harvest their edible tuber and groundnuts. The trial was used to examine the competition of N between components of agroforestry and the effect of food cropping and food crops harvesting on growth of the system’s components and nutrient cycling.

3.6.3 Tracer $^{15}$N experiment

The $^{15}$N tracer study was located at Ringgi site and aimed to investigate the N uptake and movement in teak and flueggea growing in enclosed system over 12 and 18 months period in 2 and 4 years mixed species stands. The method used was that described by Blumfield et al. (2004) and Blumfield and Xu (2006) on the study of fluxes of soil mineral N using $^{15}$N-labelled ammonium sulphate in isolation plots.

Eight isolation plots were established, each containing one teak and one flueggea that had been planted at 4 m x 3 m spacing (Figure 3.4) and enclosing a total soil volume of 14.40 m³. The plots were isolated by excavating a trench to a depth of 60 cm and installing a barrier of double-layered building-grade plastic film (Plates 3.8 - 3.11). The trenches were then firmly back-filled (Plate 3.12). The barriers were established at the midpoint between the adjacent trees and represented the maximum free area available to the trees. Each tree had a maximum growing surface area of 12 m² or a growing space of soil volume of 7.20 m³.
Figure 3-4: Schematic design of the $^{15}$N tracer experiment

Plate 3-8: Plot 2 area marking.
Plate 3-9: Plot 2 trench digging

Plate 3-10: Plot 2 perimeter trench completion.
Plate 3-11: Placing of double-layered building-grade plastic film in the trench to form barrier at Plot 2.

Plate 3-12: Back filling of the plot trench to firmly hold the double-layered building-grade plastic film in position at Plot 2.
Of the total of eight isolation plots, four plots (plots 1 - 4) were established in August 2011 when the Ringgi mixed species trial planted in April 2009 turned 2½ years. These plots had undergrowth of weeds and creepers during the period. The other four isolation plots (plots 5 – 8) were established in February 2012 when the agroforestry trial planted in November 2011 turned 3 months. These plots had undergrowth of legume and non-legume crops, weeds and creepers during the period.

All the isolation plots were applied with a tracer containing $^{15}$N-labelled ammonium sulphate at a rate of 0.825 kg N ha$^{-1}$ with 10.24 atom % $^{15}$N. Approximately 7.0323 g of ammonium sulphate with content of 1.90 g of $^{15}$N-labelled tracer was dissolved in 8 litres of tap water (Plate 3.13). Each plot soil surface was divided into 8 blocks, and the solution was applied with care taken to ensure an even coverage of each plot soil surface (Plate 3.14). Each plot had enriched $^{15}$N ammonium sulphate solution applied being 237.50 mg of $^{15}$N per m$^2$. The age of teak and flueggea when excavation work was undertaken were 2 (agroforestry trial plot) and 4 years (Ringgi mixed species trial plot). The specific growth characteristics of both species are presented in Table 3.1. Teak and flueggea grew at 4m x 3m planting spacing at both trial plots.
Plate 3-13: Preparation of enriched $^{15}$N ammonium sulphate solution in the field at Plot 3

Plate 3-14: Application of enriched $^{15}$N ammonium sulphate solution in equally spaced 2 inch depth and 1 inch wide holes in a meter square
3.7 Field sampling and measurement methods

3.7.1 Soil sampling

At the Ringgi and Poitete mixed species trials, and agroforestry trial, soil sampling was carried out at 0, 24, 36 and 48 months following planting of the trials. Each sampling was carried out at 0-10 and 10-20 cm depth. For each treatment (plot), a composite sample was obtained from 5 cores (ca diameter 10 cm), each of which was collected randomly within the plot (Plate 3.15). These positions were at least 1.0 m from the plot boundary demarcated by either teak or flueggea in the first and the sixth lines and the first and the eight trees, to avoid edge effects.

Plate 3-15: Soil sampling at 2 years old Poitete mixed teak and flueggea trial

At the $^{15}$N-labelled tracer experiment, soil sampling was carried out at the end of the study period after 12 and 18 months of $^{15}$N applications at the 2 and 4 years plots. Before excavation of the trees, three transects were demarcated at equal distance to each other in parallel to the
longest side of each plot. Soil samples were taken from 4 cores in equal distance to each other along each transects within the tracer $^{15}$N plots at depths 0-10 and 10-20 cm depths. For each transect and depth, a composite sample was taken from the 4 cores (ca. diameter 10 cm). The samples were used to examine if surface flow had impacted on the distribution of the enriched $^{15}$N application over time. The soil samples were marked as north (mountain side), centre (middle) and south (seaward side).

As all the soil samples were taken for subsequent chemical analysis, they were passed through a 2 mm sieve before air-drying for at least 3 to 4 weeks under room temperature and grinding in a Rocklab puck and ring grinder prior to storage in polyethylene vials for chemical analysis.

3.7.2 Foliar Sampling

Foliar samples were collected within each trial annually for 3 years beginning 2011. Foliage was sampled from 3 to 4 branches fully exposed to the sunlight around the crown of four average trees of teak (Plate 3.16) and flueggea (Plate 3.17) in each treatment at the mixed species trials at Ringgi and Poitete. Eighteen leaves of flueggea and twelve leaves of teak were collected within a treatment and bulked separately by species. Flueggea leaf size is small compared to teak and therefore collecting 6 leaves per branch increases representation of the crown.
Plate 3-16: Foliar sampling of 2 years old teak using ladder

Plate 3-17: Foliar sampling of 2 years old flueggea using ladder
At plots 1-4 of the $^{15}$N-labelled tracer experiment (Ringgi mixed species trial), foliar samples were taken from each teak and flueggea within each plot and control at 6, 12, and 18 months after the application of the enriched $^{15}$N-labelled ammonium sulphate solution. At plots 5-8 of the $^{15}$N-labelled experiment (Agroforestry trial), foliar samples were taken from teak and flueggea at 6 and 12 months after the application of the enriched $^{15}$N-labelled ammonium sulphate solution. Foliar samples of each species were sampled from upper branches and second or third order of leaves and packed in labelled paper bags. Additional samples of mature leaves and old leaves (middle and lower leaves from shoots) were taken from both trees in each plot when each tree was harvested.

All foliar samples were dried at 60 °C to constant mass, each sample dried mass was then determined. Dried foliar samples were ground to a fine homogenous powder using Puck and ring mill (Rocklabs, New Zealand) and sub-samples stored in polyethylene sterile vials until chemical analysis. For the $^{15}$N enriched samples, $^{15}$N cross-contamination was prevented through thoroughly washing of grinding vessel under running warm water between each grinding operation.

### 3.7.3 Litterfall sampling

Litterfall sampling began in March 2011 when the Ringgi and Poitete mixed species trials turned 2 years and the trees were of sufficient height and canopy development and continued until September 2012, at age of 3½ years. Each trial had a total of 60 litter traps (15 litter traps per block). Each treatment had 3 litter traps positioned at random locations at the midway point between lines and away from the boundary trees to avoid edge effects. Traps were made of wooden squares holding nets made from shade cloth and mounted on wooden stakes 1 m above the forest floor (Plates 3.18). Each trap had a catchment area of 0.50 m² (0.71 m × 0.71 m) with a 30 cm depth (Plate 3.19). Over the study period, each month’s collection showed 99% of the litterfall were leaves and therefore only leaf litterfall production was measured and reported.
Plate 3-18: Litterfall trap under 2 years old mixed teak and flueggea plantation

Plate 3-19: Leaf litter trapped in the litterfall trap.

At the $^{15}\text{N}$-labelled experimental plots at the Ringgi mixed species trial, monthly litterfall measurement began in September 2011 after the application of $^{15}\text{N}$-labelled solution in August.
until September 2012 when litterfall measurement at Ringgi and Poitete mixed species trials ended. Litterfall sampling was not conducted at the agroforestry trial because litterfall production was very low due to young and small crowns and open canopy.

Monthly leaf litter collected from each trap in each treatment were separated by species and pooled into two paper bags and were oven dried at 60° C to constant weight and weighed separately. Dried leaf litterfall samples were ground to a fine homogenous powder using Puck and ring mill (Rocklabs, New Zealand) and sub samples were stored in polyethylene sterile vials until chemical analysis.

3.7.4 Root architecture assessment

Root architecture assessment was conducted using similar method used by Archer and Strauss (1985). Only 7 plots of pairs of teak and flueggea growing at Ringgi site were manually excavated in March 2013, of which four plots (Plots 1-4) were of age 4 years and three plots (Plots 5, 6 and 8) were of age 2 years. A fluegea in Plot 7 in 2 years trial died during the study period and was therefore excluded from the analysis. Root architecture, especially topology and distribution, were assessed using tape measure and protractor (Plates 3.20 and 3.21).
Plate 3-20: Flueggea tap root and anchorage structure. Tap root structure at age 31/2 years old.

Plate 3-21: Flueggea lateral root distribution at age 2 years old.

The root follow technique (Archer and Strauss, 1985) was used to measure the root length starting from the trunk (Plate 3.21). Exposed roots were maintained at their position using...
sticks and wire for support during assessment. Total root system length (cm) with root diameter were measured using measuring and diameter tapes or rope to follow their angle (Román-Avilés et al., 2004) before aligning with tapes for calibration. Root growth angles were assessed using thin flexible wire to copy or take the shape of the root angle by bending and then measured using protractor. Root samples were taken from lateral roots at 10, 30, 50, 70, 90, 110 and 130 cm from the stem base. Similar sampling was conducted on the main tap roots or support root when tap root did not exist. Additional trees, a pair of teak and flueggea growing without a barrier, were partly excavated to ensure that the effect of the barrier on free root architecture was not significant.

3.7.5 Biomass assessment and sampling

Biomass assessment was conducted on the same seven pairs of teak and flueggea excavated in March 2013 at Ringgi site for root architecture assessment. Before felling of the trees, diameter at breast height (DBH) and crown radius were measured. When felled, each tree’s total fall height, crown height (from ground level to the first living branch) and the crown length (first branch to crown tip) were measured. The stem was cut into 1 m sections for ease of weighing and stump and roots were excavated. Excavations of soils were done manually using crowbar, mattock, spades and shovels, starting from the boundary of the enclosed plot and moving inward. Encountered lateral roots were supported with pegs and all root cut-offs were stored in a safe place. When the soils were all removed and only the ones that stick to the tap roots were left, both trees were then felled using a chainsaw.

Three stem discs were sampled from each tree at 20 cm aboveground level, middle of the stem length (at 2.5 and 5.5 m for teak of 2 and 4 years and 1.5 and 3.5 m for flueggea) and 5 m below each tree’s stem’s tip. Eighteen leaves of flueggea and nine leaves of teak were sampled from
three top branches exposed to sunlight, mid of middle branches and base of bottom branches (top, middle and bottom). Tree parts were distributed into compartments of foliage, branches, stem wood and roots and weighed in the field for fresh weights using a Golden Lark 200 kg hanging scale. Each teak and flueggea biomass component was sub-sampled and dried in paper bags at 60 °C to constant mass; each sample dried mass was then determined. Dried component biomass were ground to a fine homogenous powder using Puck and ring mill (Rocklabs, New Zealand) and sub-samples stored in sterile, airtight containers until elemental analysis. Each stem disc was sliced into 5-10 mm width with disc diameter length and grounded. Branches of teak and flueggea were not sampled at 4 years for both species and therefore their dry mass and nutrient content were not reported.

Plate 3-22: Stem fresh weight assessment using Golden Lark 200 Kg scale and shed cloth to bundle stem pieces together
Plate 3-23: Tap and lateral roots ready for fresh weight assessment

Plate 3-24: Removal of leaves from the branches in preparation for foliage fresh weight assessment
Plate 3-25: Stem samples, sampled as stem disks from top (5 m from the stem tip), middle (midway between stem top and bottom) and bottom (10 cm above ground level)

3.7.6 Food crop and weed sampling

Grass and shrubs growing under Plots 1-4 and crops and grass growing under Plots 5, 6 and 8 of the $^{15}$N labelled experiment were also harvested, weighed and sampled. Sub samples were oven dried at 60 °C to constant mass and subject to the same process as the foliar and litter samples. Dry and fresh weight ratio was determined after achieving constant weights of the crops and weeds.

Food crop harvests from the agroforestry trial were sampled for fresh weight and sub-samples undergo oven drying for the determination of nutrients in each class of biomass. The information was essential for the determination of each crop’s dry weight and nutrients removed by their harvest.
Plate 3-26: Potato leaf sample after incubation

Plate 3-27: Potato root (tuber) sample after incubation
Plate 3-28: Weed sample after incubation

3.7.7 Tree growth measurement

At the mixed species trials at Ringgi and Poitete, tree total height (TH) and diameter at breast height over bark (DBHOB) were measured for each tree within the net plots of each treatment. The TH was measured every six month after planting with a measuring pole for the first one and a half year (Plate 3.29) and later Suunto Clinometer was used, while the DBH was measured with a diameter tape at 1.3 m (Plate 3.30) above ground level every six months from 12 month-old. Using clinometer, total tree heights were measured from 15 m distance by taking the % reading of the tree base at ground level and the trees highest stem tip. In each treatment, the mean of TH, DBH, basal area (BA) and volume (V) for all trees within each net plot was calculated, and expressed as growth index for each treatment replicate.
Plate 3-29: Height assessment of teak using measuring pole

Plate 3-30: Diameter at breast height over bark assessment using diameter tape
Crown assessment

Crown assessment was only conducted for the teak and flueggea trees growing in the $^{15}$N-labelled tracer plots. Before felling of the trees, diameter at breast height (DBH) and crown radius were measured (Plate 3.31). When felled, each tree’s total fall height, crown height (from ground level to the first living branch) and the crown length (first branch to crown tip) were measured. The assessment was done to capture the growth characteristics of both species in a mixed species system.

Plate 3-31: Crown radius assessment of 18 months old teak using measuring pole

Laboratory analytical procedure

This study aimed at determining and examining the carbon and nitrogen contents and dynamics in the plant and soil. Amongst the most used methods of determining TC, TN, stable isotopes $^{13}$C, $^{15}$N and atomic $^{15}$N, dry combustion using CN analyser coupled to a mass spectrometer was recommended to be the most accurate (Sollins et al., 1999). This method can
simultaneously measure the carbon and nitrogen dynamics in either soil or plant sample. Thus, plant and soil TC, TN, stable isotopes $^{13}$C, $^{15}$N and atomic $^{15}$N were analysed using a Eurovector 3000 elemental analyser (Milan, Italy) coupled to a GVI Isoprime mass spectrometer (Manchester, UK). Samples of air dried and ground soil (approximately 15-16 mg), foliage, branch, stem wood, root and crop (5-6 mg) and litterfall (8-9 mg) were packed into tin capsules that were pelletised and loaded into the auto-sampler, which dropped the capsule and sample into the combustion column. To ensure the results were accurate, a 10% replication was performed. Samples were determined for TC, TN and the $^{13}$C/$^{12}$C ratio and $^{14}$N/$^{15}$N ratio, which were used to calculate the $\delta^{13}$C (‰) and $\delta^{15}$N (‰) following the equation:

$$\delta^{13}C (‰) = \frac{R_{\text{sample}} - 1 \times 1000}{R_{\text{std}}}$$

where $R_{\text{sample}}$ is $^{13}$C/$^{12}$C ratio of a sample and $R_{\text{std}}$ is $^{13}$C/$^{12}$C ratio of the international PeeDee Belemnite (PDB) standard (Cadisch et al., 1996; Xu et al., 2000).

$$\delta^{15}N (‰) = \frac{R_{\text{sample}} - 1 \times 1000}{R_{\text{std}}}$$

where $R_{\text{sample}}$ is $^{14}$N/$^{15}$N ratio of a sample and $R_{\text{std}}$ is $^{14}$N/$^{15}$N ratio of the international PeeDee Belemnite (PDB) standard (Cadisch et al., 1996; Xu et al., 2000).

3.8.1 Mass spectrometer and operational conditions

The isotope ratio mass spectrometer used for this analysis was a Mass Spectrometer Sercon Hydra 20-22, connected to Inlet Sercon Europa EA-GSL Elemental Analyser (Plate 3.32). The reference standards were prepared using the ammonium sulphate (δ0.5) and sucrose (δ12.2). Because samples usually have intrinsic variation during the analysis, a reference series of each
Sample type (plant components and soil) was included as part of the analysis. This reference series, ranging from 40-180% of the reference standard, was included prior to the analysis of each sample type. Reference standards were analysed before and after each twelve samples and one of these was treated as a standard for internal calibration while the rest were treated as a sample. This made it possible to re-designate the conditional and reference standards and redo the run should any of the standards give an inconsistent reading.

Operational conditions were:

Manufacturer: Micromass
Mass Spectrometer: Isoprime Sercon Hydra 20-22
Preparation System: EurovectorEA 3000
Primary Standards: ¹⁵N: IAEA-N1, IAEA-N2
Primary Standard: ¹³C: IAEA-CH-6
Elemental Standard: KHP, (NH₄)₂SO₄
Working Standards: SPT
Inlet: Sercon Europa EA-GSL
Combustion Furnace Temperature: 1020 °C
Reduction Furnace Temperature: 600 °C
Gas Chromatography Oven Temperature: 44 °C
Carrier Gas: Helium 5.0
Helium Flow Rate: 100 ml/min
Plate 3.2 – Mass spectrometer Sercon Hydra 20-22, connected to Sercon Europa EA-GSL Inlet Elemental Analyser. In the tube is the leaf litter sample after being processed in the mass spec machine. Notice the carbon in dark colour
3.9 References


Chapter 4  Competition for resources between components of a mixed-species forestry system in Solomon Islands

4.1 Abstract

Mixed-species plantings of teak (*Tectona grandis* L. f.) and flueggea (*Flueggea flexuosa* Muell. Arg) were being trialled to overcome the reluctance of growers to thin mono-culture stands of teak (as each tree is perceived to be highly valuable) in Solomon Islands. Using $^{15}$N-labelled tracer, we investigated the competition between species for nitrogen (N) and $^{15}$N recovery in a field trial in 2 and 4 years mixed species stands. The study also investigated the acquisition of carbon (C) and carbon isotope composition ($\delta^{13}$C) of both species in 2 and 4 years stands. Pairs of trees, one of each species, were isolated by an impermeable membrane 60 cm deep and $^{15}$N-labelled tracer was applied to the soil surface. Four pairs of teak and flueggea from the 4 years trial and three pairs of teak and flueggea from the 2 years trial were measured and harvested, divided into the components: roots, stem, branch and foliage, and then weighed for biomass and analysed for total N (TN), total C (TC), $^{15}$N enrichment, and $\delta^{13}$C. Teak had significantly greater growth in height and diameter at breast height (DBHOB) than flueggea at age 4 years. There was no significant difference in component $^{15}$N enrichment between teak and flueggea at both ages, suggesting that there could be equal uptake of added $^{15}$N-labelled tracer by both species. The $^{15}$N concentration was greater in the foliage followed by the root, stem and branch for teak and flueggea. However, stem had significantly greater biomass and therefore had greater $^{15}$N mass (kg) than other teak components in the 2 and 4 years trial and with flueggea in the 4 years trial. Although not significant, approximately 55% of added $^{15}$N tracer was recovered from the plot’s components in the 4 years trial and 43% was recovered in the 2 years trial, suggesting that higher uptake is possible with well-established root structure and increase
of litter production with age. TC and TN content were not significantly different between teak and flueggea components at age 2 and 4 years and may indicate equal access to growth resources and with similar allocations. Less negative values of $\delta^{13}$C in teak components than those of flueggea indicated that teak has lower water use efficiency. Although teak had significant stem growth (height, basal area and volume) in the 4 year plots, $^{15}$N uptake and enrichment were similar to those of flueggea which may mean that competition for growth resources was still at minimal or access to the resources was equal and growth rates were species specific.

**Key words:** *Tectona grandis, Flueggea flexuosa*, carbon, nitrogen, $^{15}$N recovery, $\delta^{13}$C

### 4.2 Introduction

A greater interest in the benefits of mixed species systems has resulted in increase in mixed species plantings being established over the recent decades (Olsthoorn et al., 1999). However, empirical studies addressing nutrient cycling and nutritional interactions among different components of these mixed species systems are scarce (Nair and Souvannavong, 2000; Rothe and Binkley, 2001).

Teak (*Tectona grandis* L. f.) is a commercially important exotic hardwood species usually grown in mono-species systems in Solomon Islands, mainly for export as round logs. Flueggea (*Flueggea flexuosa* Muell. Arg) is an important local natural lowland forest hardwood species much in demand for house timbers in large dimensions and often used for traditional houses and fence construction in small dimensions. Growing teak in mixed species stands with flueggea was seen as a way to address the reluctance of growers to thin mono-species stands
of teak. Reluctance to thin (due to the perceived high value of each teak tree) is the greatest barrier to correct silvicultural management of smallholder plantations. However, prior to introducing this mixed species system into local communities, trials were established to understand the nature of the competition for available resources between teak and flueggea. The work reported here is part of that longer-term trial established to examine the mono-species system and the mixed species system effect on teak and flueggea growth and nutrient uptake and cycling. In this chapter, we examine the interactions between teak and flueggea, and between teak, flueggea and food crops grown in the inter-row with respect to competition for nutrients especially N, light and water. The uptake of N and allocation to biomass components by teak and flueggea of different ages growing in a closed system were examined using a $^{15}$N-labelled tracer method and mass balance technique. The water use efficiency (WUE) of teak and flueggea were examined using C isotope composition ($\delta^{13}$C) (Arndt et al., 2000; Xu et al., 2000; Ibell et al., 2013).

The study of N dynamics in plants has been conducted for other plant species using $^{15}$N-labelled material (Blumfield et al., 2004) and $^{15}$N-labelled solution (Barea et al., 1989; Blumfield and Xu, 2006; Gill et al., 2012) to examine N uptake, N movement and competition. Nitrogen uptake and C accumulation studies have been reported to provide insights into ecological and physiological processes (Dijkstra et al., 2003; Xu et al., 2009; Ibell et al., 2013). In terms of nutrient cycling, quantifying biomass and nutrient allocation in different tree and plant components is helpful for estimating tree nutrient uptake and nutrient removal through harvesting in a forest ecosystem (Bergman, 1992; Stefan et al., 1997). Quantifying above-ground biomass over time is important to evaluate forest ecosystem productivity, nutrient and carbon cycle. Though a lot of information is available in the literature regarding nutrient cycling dynamics in different forest ecosystems and plantations, little information is available
with respect to teak forests and plantations (Kraenzel et al., 2003; Fernandez-Moya et al., 2013).

The objective of this study was to determine N uptake and movement in teak and flueggea biomass using a $^{15}$N-labelled tracer and to determine $^{15}$N recovery as the result of competition in the enclosed soil-plant system. The study also reports the allocation of total C (TC), total N (TN) and C stable isotope composition ($\delta^{13}$C) in different tree components of teak and flueggea.

4.3 Materials and Method

4.3.1 Site description

The trials were conducted at Ringgi, on Kolombangara island (8° 05´ 16.33´´ S and 157° 08´ 46.62´´ E, 84 m a.s.l), Western Province, Solomon Islands. Trial plots were established on land formerly covered with regenerated secondary forests, on an Oxisol soil (Hansell and Wall, 1975). Ringgi has a monthly rainfall range of 229-396 mm with humid tropical climate and temperature is consistent all year with a yearly mean of 28 °C. Although the rainfall is fairly evenly distributed throughout the year, there is often a drier period around August and September and wetter period between December and March. Soil physical and chemical properties are presented in Table 4.1.

Table 4-1: Soil physical and chemical properties of the two mixed species trial at Ringgi site
### Soil physical and chemical properties

<table>
<thead>
<tr>
<th></th>
<th>Trial 1 0-10 cm</th>
<th>Trial 1 10-20 cm</th>
<th>Trial 2 0-10 cm</th>
<th>Trial 2 10-20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (g cm(^{-3}))</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>pH</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Cation Exchange Capacity (cmol(+) kg(^{-1}))</td>
<td>12.0</td>
<td>7.0</td>
<td>12.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Total carbon (TC) ( % )</td>
<td>6.23</td>
<td>4.30</td>
<td>7.57</td>
<td>4.30</td>
</tr>
<tr>
<td>Total nitrogen (TN) ( % )</td>
<td>0.73</td>
<td>0.48</td>
<td>0.75</td>
<td>0.44</td>
</tr>
<tr>
<td>(\delta^{13}\text{C} (%o))</td>
<td>-27.10</td>
<td>-26.57</td>
<td>-27.83</td>
<td>-26.85</td>
</tr>
<tr>
<td>(\delta^{15}\text{N} (%o))</td>
<td>7.37</td>
<td>8.30</td>
<td>6.49</td>
<td>7.78</td>
</tr>
</tbody>
</table>

### 4.3.2 Experimental design

The \(^{15}\text{N}\)-labelled tracer study was conducted within a larger study looking into optimal spacing for teak and flueggea in a mixed species system. This \(^{15}\text{N}\)-labelled tracer study investigated N uptake and movement in teak and flueggea growing in an enclosed system at 2- and 4- year old mixed species stands. The method used was that described by Blumfield and Xu (2004, 2006) on the study of fluxes of soil mineral N using \(^{15}\text{N}\)-labelled ammonium sulphate in isolated plots and total \(^{15}\text{N}\) recovery in the trees and soil.

Eight isolation plots were established in the mixed species trials, each containing one teak and one flueggea tree that had been planted at 4 m x 3 m spacing (Figure 4.1) and enclosing a total soil volume of 14.40 m\(^3\). The plots were isolated by excavating a trench to a depth of 60 cm and installing a barrier of double-layered building-grade plastic film. The trenches were then
firmly back-filled. The barriers were established at the midpoint between the adjacent trees and represented the maximum free area available to the trees. Each tree had a maximum growing surface area of 12 m² and an enclosed soil volume of 7.20 m³. Of the total of eight isolation plots, four plots (plots 1-4) were established in August 2011 when the first mixed species trial planted in April 2009 turned 2½ years. The other four isolation plots (plots 5-8) were established in February 2012 when the second mixed species trial planted in November 2011 turned 3 months.

A tracer containing $^{15}$N-labelled ammonium sulphate was applied to all plots at a rate of 0.825 kg N ha$^{-1}$ with 10.24 atom % $^{15}$N. Approximately 7.0323 g of ammonium sulphate with content of 1.90 g of $^{15}$N-labelled tracer was dissolved in 8 litres of tap water. Each plot soil surface was divided into 8 blocks, and the solution was applied with care taken to ensure an even coverage of each plot soil surface. The first four plots (plots 1 – 4) were sampled for a period of 18 months and the age of the trees at final excavation was 4 years, these will be referred to as the 4 year plots. The 4 year plots had undergrowth of grass and shrubs. The final three plots were sampled for 12 months and the age of the trees at final excavation was 2 years, these will be referred to as the 2 year plots. The 2 year plots had undergrowth of grass and crops (bean, capsicum, peanut, potato and taro) during the period but potato and taro were the only crops growing when the excavation work was undertaken. Four teak and four flueggea trees in areas adjacent to the isolation plots were selected for foliar sampling over the study period and were treated as control trees.
Figure 4-1: Schematic design of the $^{15}$N tracer experiment

### 4.3.3 Foliar and litterfall sampling

Foliar samples were taken from each plot at 6, 12, and 18 months after the application of $^{15}$N-labelled tracer in the 4 year plots and at 6 and 12 months in the 2 year plots. Foliar samples of each species were taken from upper branches and second or third order of leaves and packed in labelled paper bags. Additional samples of mature leaves and old leaves (middle and lower leaves from shoots) were taken from both trees in each plot when harvested. Young leaves were not sampled. Foliar samples were dried at 60 °C to constant mass, the mass of each dried sample was then determined. Dried foliar samples were ground to a fine homogenous powder using Puck and ring mill (Rocklabs, New Zealand) and sub-samples stored in sterile, airtight containers until elemental analysis. As samples were $^{15}$N enriched, $^{15}$N cross-contamination was prevented through thoroughly washing of grinding vessel under running warm water between the grinding operations.
Litterfall, especially leaves were collected over 12-month period after the application of $^{15}$N-labelled tracer in the 4 year plots. Over the 12-month litterfall collection period, dead branches and twigs did not fall into the traps. Monthly litterfall samples were collected and separated into labelled paper bags by species. There was no significant litterfall production in the 2 year plots and therefore collection was not done. Litterfall samples were dried at 60 °C to constant mass, each sample dried mass was then determined. Dried litterfall samples were ground to a fine homogenous powder using Puck and ring mill (Rocklabs, New Zealand) and sub-samples stored in sterile, airtight containers until elemental analysis.

### 4.3.4 Crop and weed sampling

Grasses and shrubs growing in the 4 year plots and crops and grass growing in the 2 year plots were also harvested and sampled. Sub samples were oven dried at 60 °C to constant mass and subject to the same process as the foliar and litter samples. The grasses, weeds, shrubs and crops that grew in the plots were sampled for the mass balance of $^{15}$N-labelled tracer applied.

### 4.3.5 Measurement of above- and below-ground biomass

Only 7 plots were manually excavated, 3 plots from the 2 years and 4 plots from the 4 years 12 and 18 months after $^{15}$N-labelled ammonium sulphate application. A flueggea in Plot 7 in the 2 years trial died during the study period and this plot was therefore excluded from the analysis. Before felling of the trees, diameter at breast height over bark (DBHOB) and crown radius were measured. When felled, each tree’s total fall height, crown height (from ground level to the first living branch) and the crown length (first branch to crown tip) were measured. The stem was cut into 1 m sections for ease of weighing and stump and roots were excavated. Three
stem discs were sampled from each tree at 20 cm aboveground level, middle of the stem length (at 2.5 and 5.5 m for teak of 2 and 4 years and 1.5 and 3.5 m for flueggea) and 5 m below each tree’s stem’s tip. Eighteen leaves of flueggea and nine leaves of teak were sampled from three top branches exposed to sunlight, mid of middle branches and base of bottom branches (top, middle and bottom). Tree parts were distributed into compartments of foliage, branches, stem wood and roots and weighed in the field for fresh weights using a Golden Lark 200 kg hanging scale. Each teak and flueggea biomass component was sub-sampled and dried in paper bags at 60 °C to constant mass; each sample dried mass was then determined. Dried component biomass samples were ground to a fine homogenous powder using Puck and ring mill (Rocklabs, New Zealand) and sub-samples stored in sterile, airtight containers until elemental analysis. A 5-10 mm disc was taken from each of the stem sections and similarly dried to constant weight and ground to a fine, homogenised powder. Branches of teak and flueggea were overlooked and were not sampled at 4 years plot for both species and therefore their nutrient contents are not reported.

4.3.6 Soil sampling

The 15N enrichment of soil was determined on soil samples taken after 12- and 18-months following 15N-labelled tracer applications at the 2 and 4 years plots. Before excavation of the trees, three transects were demarcated at equal distance to each other in parallel to the longest side of each plot. Soil samples were taken from 4 cores at equal distance to each other along each transect within the tracer 15N plots at depths of 0-10 and 10-20 cm. The 4 soil samples from each depth in each transect were mixed separately in 6 zip bags. The samples were used to examine if surface flow had impacted on the distribution of the 15N-labelled tracer application over time. The soil samples were marked as north (mountain side), centre (middle)
and south (seaward side). The soil samples for each transect and depth of each plot were air
dried for at least 3 weeks, sieved <2 mm and processed the same as the foliar and litter samples.

4.3.7 Chemical analyses

About 6 mg of root, stem wood, branch, foliage and crop, 9 mg of litterfall or 16 mg of soil
homogenised powder were weighed in to tin capsules and analysed on an Isoprime isotope ratio
mass spectrometer (Cheshire, UK) with an Europa Elemental Analyser GSL, (Cheshire, UK
CWI 6JT). Samples were analysed for total N, total C, δ\(^{13}\)C, δ\(^{15}\)N, and \(^{15}\)N enrichment as
reported previously (Ibell et al., 2013). All analyses were carried out at Griffith University,
Nathan, Queensland.

4.3.8 Calculation of TC, TN and \(^{15}\)N

Data analysis followed the method used by Rowe et al. and Ibell et al. (2001, 2013). Samples
of leaf, branch, stem and root were sub-sampled, weighed, oven-dried and reweighed, to obtain
dry weight conversion factors for each component of teak and flueggea of 2 and 4 years. Dry
weights of each part from each age were calculated. The TC, TN (%) and \(^{15}\)N enrichment (atom
%) were measured in subsamples of tree components from each species and age. Teak and
flueggea TC, TN and \(^{15}\)N-labelled tracer uptake and allocation in each tree part and total were
calculated for each age. \(^{15}\)N recovery from the enclosed system was determined using the mass
balance technique (Blumfield and Xu, 2006).

The amount of TC and TN in each plant component was calculated as follows:

\[
\text{TC or TN (kg)} = \text{Dried biomass sample (Kg)} \times (\text{TC or TN % / 100})
\]
The amount of $^{15}$N in each plant component was calculated as follows:

$$^{15}\text{N content (g)} = \text{biomass (g)} \times \text{N concentration (\%)} \times \text{atom \% excess }^{15}\text{N}$$  (2)

Recovery of added N was calculated as a percent:

$$\text{Recovery of added }^{15}\text{N (\%)} = \left(\frac{^{15}\text{N recovered (g)}}{^{15}\text{N applied (g)}}\right) \times 100$$  (3)

where $^{15}$N recovered and $^{15}$N applied were calculated as excess over the background natural abundance.

Annual litterfall production was calculated following the method used by Oladoye et al. (2010). Total litter collected over the study period for teak and fluegga was divided by the total number of months to determine the monthly mean production and annual production of either species. The monthly litterfall TN (kg), TC (kg) and enriched $^{15}$N content (kg) for either species were obtained by multiplying the TN (%), TC (%) and enriched $^{15}$N (%) with the monthly total litter biomass (kg) for each species. The annual inputs of TN, TC and $^{15}$N to the forest floor for each species were determined by multiplying each species annual litter biomass with the mean TN, TC, $^{15}$N (Chapter 5). Potential return to soil of TN, TC and enriched $^{15}$N of teak and fluegga were compared using individual tree TN, TC and $^{15}$N production.

### 4.3.9 Statistical analysis

The SPSS Statistics 22 software was used for statistical analyses. Normality of variables was tested using Shapiro-Wilk test and homogeneity of variance was tested with Levene’s test. The data were further analysed using multiple univariate ANOVA and Tukey post hoc test where necessary to investigate pairwise significant differences in tree parts and leaf litter biomass and...
TN, TC, δ^{13}C and ^{15}N within the species and across the species, and across the treatments. If not stated otherwise, all reported values are given as arithmetic means ± standard errors.

4.4 Results

4.4.1 Tree growth and biomass

Within species, teak had a significant difference in the height (p<0.0001) and DBHOB (p<0.001) between the 2-year plots and the 4-year plots (Table 4.2). Similarly, flueggea had significant difference in the height (p<0.0001) and DBHOB (p<0.0001) between the 2-year plots and the 4-year plots. The mean height of teak was significantly greater than flueggea in both age groups (p<0.01). However, the difference in DBHOB between the species only occurred at the 4 year plots when teak was significantly greater than flueggea (p<0.001). Teak had significantly greater basal area (BA) (p<0.005) and volume (p<0.005) than flueggea at the 4-year plots though neither was significantly different at the 2-year plots. There was no significant difference in crown radius and crown height between teak and flueggea at either age. Teak had significantly greater crown length than flueggea (p<0.05) at the 4-year plots but no significant difference was observed at the 2-year plots. Teak had significantly greater mean annual increment (MAI) of tree height and DBHOB than flueggea at the 4-year plots (p<0.01) and had significantly greater MAI of tree height than flueggea at the 2-year plots (p<0.0001).

Table 4-2: Growth characteristics (mean±SE) of destructively sampled teak and flueggea

<table>
<thead>
<tr>
<th>Growth characteristics</th>
<th>2 year plots</th>
<th>4 year plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Teak</td>
<td>Flueggea</td>
</tr>
<tr>
<td></td>
<td>Teak</td>
<td>Flueggea</td>
</tr>
</tbody>
</table>
Tree height (m) | 8.39±0.20^a | 4.76±0.71^b | 15.63±0.88^a | 11.78±0.55^b
---|---|---|---|---
Diameter at breast height (DBHOB) (cm) | 8.47±1.57^a | 5.40±0.95^a | 19.35±1.04^a | 12.70±0.58^b
Basal area (BA) (cm²/tree) * | 60.0±20.0^a | 20.0±10.0^a | 290.0±30.0^a | 130.0±10.0^b
Volume (m³/tree) ** | 0.025±0.01^a | 0.006±0.002^a | 0.235±0.04^a | 0.076±0.01^b
Crown height (m) | 4.37±1.28^a | 1.57±0.07^a | 6.07±0.09^a | 6.20±0.41^a
Crown radius (m) | 1.11±0.53^a | 2.03±0.26^a | 3.33±0.32^a | 2.70±0.22^a
Crown depth (m) | 4.02±1.31^a | 3.19±0.64^a | 9.56±0.93^a | 5.58±0.78^b

Values followed by the same letter within rows under each age are not significantly different at p<0.05 (Tukey post hoc test).

* Basal area (BA) = (D/200)^2 x π. Where: π = 3.142; D = DBHOB

** Volume = BA x Height x 0.5

There was no significant difference in dry mass of foliage, branch, stem and root between teak and flueggea at the 2 year plots (Table 4.3). However, teak had significantly greater stem biomass than flueggea at the 4 year plots (p<0.05) though there was no significant difference in foliage, branch and root biomass. The greatest proportion of biomass, either fresh or dry, was found in the stem, followed by root, branch and foliage for both species at both ages.

Table 4-3: Above- and below-ground biomass dry matter (mean±SE) of teak and flueggea

<table>
<thead>
<tr>
<th></th>
<th>2 year plots</th>
<th>4 year plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter at breast height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crown height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crown radius</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crown depth</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### 4.4.2 Biomass total C and total N

When comparison was done within the species, teak stem had significantly greater C content than branch (p<0.05), whereas no significant difference was detected for foliage and root C content at the 2 year plots (Table 4.4). However, stem had significantly greater C content than foliage (p<0.001) and root (p<0.01) at the 4 year plots. There was no significant difference in C content between components of flueggea at the 2 year plots; however, stem had significantly greater C content than foliage (p<0.0001) and root (p<0.005) at the 4 year plots. There was no significant difference in C content of each component between teak and flueggea at either age.

Table 4-4: Above- and below-ground biomass C (kg) (mean±SE) of teak and flueggea at the 2 year and 4 year plots

<table>
<thead>
<tr>
<th>Biomass parts</th>
<th>Teak</th>
<th>Flueggea</th>
<th>Teak</th>
<th>Flueggea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foliage (kg)</td>
<td>2.76±1.06\textsuperscript{a}</td>
<td>2.15±0.67\textsuperscript{a}</td>
<td>10.84±1.02\textsuperscript{a}</td>
<td>10.46±1.05\textsuperscript{a}</td>
</tr>
<tr>
<td>Branch (kg)</td>
<td>1.90±1.54\textsuperscript{a}</td>
<td>2.33±0.93\textsuperscript{a}</td>
<td>16.25±1.24\textsuperscript{a}</td>
<td>14.13±1.97\textsuperscript{a}</td>
</tr>
<tr>
<td>Stem (kg)</td>
<td>8.72±1.90\textsuperscript{a}</td>
<td>4.43±1.58\textsuperscript{a}</td>
<td>67.60±10.78\textsuperscript{a}</td>
<td>42.76±5.04\textsuperscript{b}</td>
</tr>
<tr>
<td>Root (kg)</td>
<td>3.76±0.89\textsuperscript{a}</td>
<td>2.66±0.92\textsuperscript{a}</td>
<td>29.32±3.90\textsuperscript{a}</td>
<td>20.62±1.91\textsuperscript{a}</td>
</tr>
</tbody>
</table>

Values followed by the same letter within rows under each age are not significantly different at p<0.05 (Tukey post hoc test)
Values followed by the same capital letter within column are not significantly different at p<0.05 (Tukey post hoc test).

Values followed by the same letter (lower case) within rows under each age are not significantly different at p<0.05 (Tukey post hoc test).

The N content was not significantly different between teak components at either age (Table 4.5). Nitrogen content was significantly greater in stem than in foliage of flueggea at the 4 year plots (p<0.01) whereas no significant differences were detected between flueggea components at the 2 year plots. There was no significant difference in N content in foliage, branch, stem and root between teak and flueggea at the 2 year plots and among foliage, stem and root at the 4 year plots.

Table 4-5: Above- and below-ground biomass N (mean±SE) of teak and flueggea at the 2 year and 4 year plots

<table>
<thead>
<tr>
<th>Biomass parts</th>
<th>2 year plots</th>
<th>4 year plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Teak</td>
<td>Flueggea</td>
</tr>
<tr>
<td>Foliage (kg)</td>
<td>0.0079±0.003^Aa</td>
<td>0.0044±0.001^Aa</td>
</tr>
</tbody>
</table>
Branch (kg)  0.0056±0.004\textsuperscript{Aa}  0.0115±0.004\textsuperscript{Aa}

Stem (kg)  0.0150±0.003\textsuperscript{Aa}  0.0108±0.004\textsuperscript{Aa}  0.0868±0.02\textsuperscript{Aa}  0.0776±0.01\textsuperscript{Aa}

Root (kg)  0.0148±0.001\textsuperscript{Aa}  0.0103±0.003\textsuperscript{Aa}  0.1597±0.05\textsuperscript{Aa}  0.0473±0.01\textsuperscript{ABa}

Values followed by the same capital letter within column are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns under each age are not significantly different at p<0.05 (Tukey post hoc test)

4.4.3 Biomass $\delta^{13}$C

The $\delta^{13}$C values in stem and branch were not significantly different in teak at the 2 year plots and were significantly greater than $\delta^{13}$C in foliage (p<0.01, p<0.05) (Table 4.6). There was no significant difference in $\delta^{13}$C among the components of teak at the 4 year plots. There was no significant difference in $\delta^{13}$C values among the foliage, branch and root of flueggea at the 2 year and 4 year plots. However, across age, only $\delta^{13}$C value of root for flueggea at the 2 year plots was significantly higher than the $\delta^{13}$C of root at the 4 year plots (p<0.05). There were significant interspecies differences in $\delta^{13}$C values of teak and flueggea biomass components within age. Teak had higher $\delta^{13}$C values of foliage (p<0.01), stem (p<0.0001) and branch (p<0.0001) than flueggea at the 4 year plots but only in stem $\delta^{13}$C at the 2 year plots (p<0.01)

Table 4-6: Above- and below-ground biomass $\delta^{13}$C (mean±SE) of teak and flueggea at the 2 year and 4 year plots

<table>
<thead>
<tr>
<th></th>
<th>2 year plots</th>
<th>4 year plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branch (kg)</td>
<td>0.0056±0.004</td>
<td>0.0115±0.004</td>
</tr>
<tr>
<td>Stem (kg)</td>
<td>0.0150±0.003</td>
<td>0.0108±0.004</td>
</tr>
<tr>
<td>Root (kg)</td>
<td>0.0148±0.001</td>
<td>0.0103±0.003</td>
</tr>
</tbody>
</table>
### 4.4.4 Biomass $^{15}$N enrichment

The $^{15}$N enrichment was significantly greater in stem than in the root, branch and foliage of teak at the 2 year plots (p<0.0001) (Table 4.7). Enrichment of $^{15}$N in stem of teak was significantly greater than in the root (p<0.0001) and foliage (p<0.0001) while teak root was significantly more enriched in $^{15}$N than the foliage at the 4 year plots (p<0.01). Similar pattern was also observed in flueggea where the stem was significantly enriched in $^{15}$N compared with the foliage (p<0.05) while no differences in $^{15}$N enrichment were found between flueggea foliage and root at the 4 year plots. There were no significant differences found in $^{15}$N enrichment between components of flueggea at the 2 year plots. There were no significant interspecies differences in $^{15}$N enrichment between teak and flueggea components at either age.

<table>
<thead>
<tr>
<th>Biomass parts</th>
<th>Teak</th>
<th>Flueggea</th>
<th>Teak</th>
<th>Flueggea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foliage (%)</td>
<td>-28.51±0.11&lt;sup&gt;Ab&lt;/sup&gt;*</td>
<td>-28.93±0.22&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-27.69±0.40&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-29.00±0.45&lt;sup&gt;Ba&lt;/sup&gt;*</td>
</tr>
<tr>
<td>Branch (%)</td>
<td>-27.80±0.12&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-28.37±0.03&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-27.37±0.10&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-29.41±0.14&lt;sup&gt;Ba&lt;/sup&gt;*</td>
</tr>
<tr>
<td>Stem (%)</td>
<td>-27.56±0.05&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-28.50±0.16&lt;sup&gt;Ba&lt;/sup&gt;*</td>
<td>-27.79±0.16&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-29.94±0.10&lt;sup&gt;Ba&lt;/sup&gt;*</td>
</tr>
<tr>
<td>Root (%)</td>
<td>-27.88±0.09&lt;sup&gt;Aab&lt;/sup&gt;*</td>
<td>-28.71±0.36&lt;sup&gt;Aa**&lt;/sup&gt;</td>
<td>-27.79±0.16&lt;sup&gt;Aa&lt;/sup&gt;*</td>
<td>-29.94±0.10&lt;sup&gt;Ba&lt;/sup&gt;*</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within rows under each age are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within column are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same number of asterisk (*) within the rows and within the species are not significantly different at p<0.05 (Tukey post hoc test)
Table 4-7: Above- and below-ground biomass component $^{15}$N enrichment (mean±SE) of teak and flueggea at the 2 year and 4 year plots

<table>
<thead>
<tr>
<th>Biomass parts</th>
<th>2 year plots</th>
<th>4 year plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Teak</td>
<td>Flueggea</td>
</tr>
<tr>
<td>Foliage (g)</td>
<td>0.089±0.02$^{Ab}$</td>
<td>0.086±0.02$^{Aa}$</td>
</tr>
<tr>
<td>Branch (g)</td>
<td>0.036±0.03$^{Ab}$</td>
<td>0.067±0.03$^{Aa}$</td>
</tr>
<tr>
<td>Stem (g)</td>
<td>0.63±0.05$^{Aa}$</td>
<td>0.39±0.11$^{Aa}$</td>
</tr>
<tr>
<td>Root (g)</td>
<td>0.18±0.05$^{Ab}$</td>
<td>0.29±0.18$^{Aa}$</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within rows under each age are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within column are not significantly different at p<0.05 (Tukey post hoc test)

4.4.5 Litterfall $^{15}$N enrichment

There was no significant difference in litterfall production between teak and flueggea over the 12 month study period when litters in the 4 year plots were measured (Table 4.8). Although TC, TN, $^{15}$N (mg) and $^{15}$N (%) values were greater in teak than in flueggea, these differences were not significantly different (p>0.05). Approximately monthly mean of 0.049 and 0.037 mg of $^{15}$N-labelled tracer was cycled by teak and flueggea over the period of 12 month litter measurement. About 16 % of $^{15}$N-labelled tracer was released monthly in teak litterfall and about 36 % was released in flueggea litterfall monthly.

Table 4-8: Litterfall production, TC, TN and $^{15}$N enrichment of the 12 months litterfall measurement in the 4 year plots
<table>
<thead>
<tr>
<th></th>
<th>Teak</th>
<th>Flueggea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly litterfall (kg ha(^{-1}))</td>
<td>77.392±14.10(^a)</td>
<td>52.88±3.73(^a)</td>
</tr>
<tr>
<td>Total Carbon (g)</td>
<td>38.240±6.63(^a)</td>
<td>24.479±1.69(^a)</td>
</tr>
<tr>
<td>Total Nitrogen (g)</td>
<td>1.319±0.27(^a)</td>
<td>0.761±0.07(^a)</td>
</tr>
<tr>
<td>% (^{15})N (mg)</td>
<td>0.587±0.17(^a)</td>
<td>0.438±0.12(^a)</td>
</tr>
<tr>
<td>% (^{15})N (%)</td>
<td>0.0309±0.0093(^a)</td>
<td>0.023±0.01(^a)</td>
</tr>
</tbody>
</table>

Values followed by the same letter within the rows are not significantly different at p<0.05 (Tukey post hoc test)

4.4.6 Tree \(^{15}\)N recovery

The \(^{15}\)N recovery in teak stem was significantly greater than in teak root (p<0.05) and branch and foliage (p<0.0001) at the 2 year plots (Table 4.9). Teak root had significantly greater \(^{15}\)N recovery than in teak branch (p<0.05) and foliage (p<0.005). Recovery of \(^{15}\)N in the root of teak was significantly greater than the recovery of \(^{15}\)N in the foliage (p<0.05) at the 4 year plots. There were no significant differences in \(^{15}\)N recovery between biomass components of flueggea at either age. There were no significant species difference in the mass of \(^{15}\)N recovered between components of teak and flueggea, despite the difference in biomass at either the 2- or 4- year plots. Tree recovery of \(^{15}\)N (as a percentage of added \(^{15}\)N) followed the order: stem>root>foliage>branch for teak and root<stem<branch<foliage for flueggea at the 2 year plots. There were no significant differences between teak and flueggea total \(^{15}\)N recovery at either age.
Table 4-9: Biomass $^{15}$N recovery (%) (mean±SE) of teak and flueggea at the 2 year and 4 year plots

<table>
<thead>
<tr>
<th>Biomass parts</th>
<th>2 year plots</th>
<th>4 year plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 months following $^{15}$N application</td>
<td>18 months following $^{15}$N application</td>
</tr>
<tr>
<td></td>
<td>12 months following $^{15}$N application</td>
<td>18 months following $^{15}$N application</td>
</tr>
<tr>
<td>Foliage (%)</td>
<td>0.14±0.04$^{Ac}$</td>
<td>0.094±0.02$^{Aa}$</td>
</tr>
<tr>
<td>Branch (%)</td>
<td>0.059±0.04$^{Ac}$</td>
<td>0.17±0.07$^{Aa}$</td>
</tr>
<tr>
<td>Stem (%)</td>
<td>0.58±0.04$^{Aa}$</td>
<td>0.50±0.16$^{Aa}$</td>
</tr>
<tr>
<td>Root (%)</td>
<td>0.38±0.05$^{Ab}$</td>
<td>0.61±0.34$^{Aa}$</td>
</tr>
<tr>
<td>Total (%)</td>
<td>1.159±0.17$^{A}$</td>
<td>1.374±0.59$^{A}$</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within rows under each age are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns are not significantly different at p<0.05 (Tukey post hoc test)

4.4.7 Total $^{15}$N recovery in the soil-plant system

There was no significant difference in the amount of $^{15}$N recovered in terms of mass (Table 4.10) or percentage (Table 4.11) for both periods of $^{15}$N-labelled tracer applications (p>0.05).

There was significant difference in the total amount of $^{15}$N recovered in the soil than in the total amount of $^{15}$N recovered in teak, flueggea and weed/shrub at the 2 year plots though the amount of $^{15}$N recovered in the soil and in the crop were not significantly different. There was significant recovery in the amount of $^{15}$N in the soil than in teak, flueggea and weed/shrub at...
the 4 year plots. The total $^{15}$N recovered (mg) was not significantly different between the ages.

Approximately 39-76 % and 27-64 % of the added $^{15}$N-labelled tracer was apparently lost from the soil-plant system at the 2 year and 4 year plots. However, the total amount of $^{15}$N-labelled recovered from both plant and soil was around 24-73 % at the 2 year and 4 year old $^{15}$N-labelled study trials.

Table 4-10: Tracer $^{15}$N recovery (mean±SE) for biomass (teak, flueggea and grass or shrubs or crops), soil (0-10 and 10-20 cm) and total system at the 2 year and 4 year plots

<table>
<thead>
<tr>
<th>Plot Component</th>
<th>12 months following $^{15}$N application</th>
<th>18 months following $^{15}$N application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teak (mg)</td>
<td>21.923±1.30$^{Ab}$</td>
<td>81.671±18.67$^{Ab}$</td>
</tr>
<tr>
<td>Flueggea (mg)</td>
<td>26.224±7.45$^{Ab}$</td>
<td>61.703±14.87$^{Ab}$</td>
</tr>
<tr>
<td>Crop (mg)</td>
<td>32.550±8.99$^{ab}$</td>
<td></td>
</tr>
<tr>
<td>Weed/Shrub (mg)</td>
<td>17.192±10.90$^{Ab}$</td>
<td>4.128±2.96$^{Ab}$</td>
</tr>
<tr>
<td>Soil (mg)</td>
<td>705.448±315.46$^{Aa}$</td>
<td>894.14±293.69$^{Aa}$</td>
</tr>
<tr>
<td>Total system (mg)</td>
<td>803.337±344.11$^{A}$</td>
<td>1041.639±330.18$^{A}$</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within rows are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns are not significantly different at p<0.05 (Tukey post hoc test)

Table 4-11: Tracer $^{15}$N recovery (mean±SE) for biomass (teak, flueggea and grass or shrubs or crops), soil (0-10 and 10-20 cm) and total system at 12 and 18 months following application of $^{15}$N
## 4.5 Discussion

### 4.5.1 Growth and biomass

The high rainfall, ample sunlight and fertile soils of Solomon Islands give tree growers near perfect conditions resulting in faster growth and shorter rotation lengths. This was evident from the average total height and DBHOB of teak at both 2 year and 4 year plots in our study which were greater than those reported for teak trees of a similar age grown in a mixed species system with leucaena, under warm humid climate with mean annual rain fall of 2670 mm in Kerala,

<table>
<thead>
<tr>
<th>Plot Component</th>
<th>12 months following $^{15}$N application</th>
<th>18 months following $^{15}$N application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teak (%)</td>
<td>1.154±0.07$^{Ab}$</td>
<td>4.298±0.98$^{Ab}$</td>
</tr>
<tr>
<td>Flueggea (%)</td>
<td>1.380±0.39$^{Ab}$</td>
<td>3.247±0.78$^{Ab}$</td>
</tr>
<tr>
<td>Crop (%)</td>
<td>1.713±0.47$^{ab}$</td>
<td></td>
</tr>
<tr>
<td>Weed/Shrub (%)</td>
<td>0.905±0.57$^{Ab}$</td>
<td>0.217±0.16$^{Ab}$</td>
</tr>
<tr>
<td>Soil (%)</td>
<td>37.129±16.60$^{Aa}$</td>
<td>47.060±13.39$^{Aa}$</td>
</tr>
<tr>
<td>Total system (%)</td>
<td>42.281±18.06$^{A}$</td>
<td>54.823±17.38$^{A}$</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within rows are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns are not significantly different at p<0.05 (Tukey post hoc test)
peninsula India (Kumar et al., 1998) and 5 years teak stand, under mean annual rainfall of 4107 mm in Costa Rica (Perez and Kanninen, 2005). The reported mean height of 5 year old teak grown in a plantation in Costa Rica was 11m with a DBHOB of 10cm.

In our trial, teak was grown with a local hardwood species to promote correct form. Of single, straight and cylindrical trunk with a low prevalence of heavy branching. When growth between the two species was compared, teak was the more vigorous species with an annual incremental height gain of 3.91 m year⁻¹ compared with 2.95 m year⁻¹ for flueggea. Similarly the annual incremental gain in DBHOB for teak was 4.84 cm year⁻¹ compared to 3.18 cm year⁻¹ for flueggea.

The faster growth was also evident in the greater biomass growth of teak and flueggea at the 2 year and 4 year plots. However, teak biomass growth was only significantly higher than flueggea at the 4 year plots which indicates teak may begin developing stem biomass around age 4 years. Similarity of biomass of all tree components across species may also indicate similar allocations of C and biomass in both species and suggests that competition was still at minimum. Stem biomass reported in this study were much higher than the observed and predicted bole biomass reported for teak at age 4 years in India (Sharma et al., 2011) growing in mono-species plantation under 1200 mm annual rainfall, which emphasises the favourable growth conditions existing for teak in Solomon Islands.

### 4.5.2 Biomass TC and TN content

The concentration of TC in teak followed the order: root>stem>branch>foliar while in flueggea components followed the order stem>root>foliage>branch. The higher allocations of TC to the
root and stem in both species may indicate that stem and root biomass growth was favoured for uptake of nutrients and water and for support of the aboveground biomass. Dry mass TC followed the order stem>root>foliage>branch for teak and stem>root>branch>foliage for flueggea at the 2 year plots. Solomon teak is usually branchless at their early growth up to age of 2½ years before development of crown begins.

The TN concentration for teak at the 2 year plots followed the order: root (0.44 %) > foliage (0.44 %) > branch (0.41 %) > stem (0.17%). Similar pattern was observed in teak at the 4 year plots: root (0.51 %) > foliage (0.37 %) > stem (0.12 %); consequently, teak had greater content of TN in its root. Flueggea had allocation strategy which was slightly different to teak and changed with age and followed the order: root (0.44 %) > branch (0.43 %) > foliage (0.29 %) > stem (0.24 %) at the 2 year plots and foliage (0.30 %) > root (0.23 %) > stem (0.18 %) at the 4 year plots. The stem remained below 0.17 % at both study periods and ages. The lower concentration of TN in tree stem was also reported by Blumfield and Xu (2006) in hoop pine seedling stem and Zeller et al. (2001) in European beech. Changing concentration of TN in flueggea components over time may indicate prioritisation and allocation of N at the 2 year plots for nutrient uptake and at the 4 year plots for canopy development for photosynthesis requirements (Zeller et al., 2001). Although TN concentration among the components were different, these differences were masked by the biomass dry weight as total nutrient content of a tree or tree component is a function of nutrient concentration and biomass. The uptake, accumulation and distribution of N in the tree components are usually influenced by several factors including age, species, soil conditions, and climate (Ola-Adams, 1993).

4.5.3 Biomass δ13C
The values of δ\textsuperscript{13}C among the components of teak and flueggea at the 4 year plots were significantly different and this could be related to individual species rate of isotopic discrimination against \textsuperscript{13}C in the foliage during photosynthesis (Hogberg \textit{et al.}, 1995; Xu \textit{et al.}, 2000). Similar values in \textsuperscript{13}C of all tree components within the species may be the result of subsequent partitioning of the photosynthates or compound synthesized in photosynthesis, especially sugar to each species components (Blumfield and Xu, 2006). Teak may have higher water use efficiency (WUE) than flueggea and therefore have less negative values compared to flueggea (DeLucia and Schlesinger, 1991; Ometto \textit{et al.}, 2006). Teak maintained similar values of δ\textsuperscript{13}C at both ages, which indicates a steady WUE with increasing age than flueggea.

The study examined whether flueggea is a right species to intercrop with teak or not. WUE is one of the parameters to determine to decide on their intercropping interactions in agroforestry systems to determine if competition had already began at 2 or 4 years. If WUE was not determined using δ\textsuperscript{13}C we would not have determined and know their fate on water use when intercropped. Teak had higher WUE because it could control and reduces stomatal conductance during photosynthesis process that promoted a minor effect on canopy transpiration and an increase in carbon assimilation that gave teak an increase in growth (Phillips, 1996; Laurence \textit{et al.}, 2004; Peter \textit{et al.}, 2005) and a better capacity to assimilate CO\textsubscript{2} than flueggea. The δ\textsuperscript{13}C values of flueggea got more negative with age and may indicate lower WUE and increased rate of discrimination against \textsuperscript{13}C over time. This may also be a reflection of the different morphologies of these species and the different growth strategies.

The morphological properties assessed and growth strategies determined during the study period includes the diameter, total height, and height to crown base, crown depth, crown diameter, root development lateral and horizontal or root architecture. Teak grows faster than flueggea in height while flueggea develop crown earlier than teak. Teak develops wider crown
diameter than flueggea and Teak produces broader leaves while flueggea produces smaller leaves. Flueggea sheds more leaves under the teak canopy as a result there are more branches without leaves on flueggea crown. Teak develops deeper tap root and anchorage roots, and longer roots than flueggea, while flueggea develop lateral roots and shorter lateral roots but with dense smaller hairy roots.

4.5.4 Biomass $^{15}$N enrichment

The application and use of $^{15}$N tracer made it possible to examine the uptake and partitioning of $^{15}$N to the tree components and changes over time in both teak and flueggea. The $^{15}$N enrichment of teak and flueggea has revealed that the total uptake of $^{15}$N-labelled tracer was not significantly different between the two species, indicating that N competition within the system was at minimum or insignificant in the first 4 years. Blumfield and Xu (2006) reported that the use of $^{15}$N tracer had allowed them to follow the active partitioning of fertiliser N in the different components of hoop pine seedlings and evaluate its changes within components over the time. In our study, the $^{15}$N enrichment showed that teak and flueggea had allocated higher percentage of $^{15}$N to their foliage, followed by the root, stem and branch indicating allocation of N to the growing tissues for growth (Zeller et al., 2001). Consequently, higher $^{15}$N with consideration of mass followed the order stem $>$ root $>$ foliage $>$ branch. Greater biomass and higher $^{15}$N enrichment in teak and flueggea stem at both ages indicate higher biomass allocation to their stems as TN concentration was lowest in the stem and branch (Buchmann et al., 1996). Allocation of TN in the stem was also high for teak and flueggea at the 2 year plots and only for flueggea at the 4 year plots while teak had higher TN in the root than in the stem at the 4 year-old. Significant increase in $^{15}$N enrichment in the stem by both species may be
related to the role of the stem as a conduit between roots and shoots (Dickson, 1989; Blumfield and Xu, 2006).

4.5.5 Litterfall $^{15}$N enrichment

The $^{15}$N enrichment of litterfall allowed us to follow its cycling rate. Over the study period, litterfall collected in the $^{15}$N tracer experiment plots were analysed separately for the tracer recovery. Along that period of time, the monthly litterfall data collected showed the amount of $^{15}$N tracer released from both teak and flueggea trees through litterfall. This showed that the N cycling can be tracked using the $^{15}$N tracer over time. The concentration of $^{15}$N-labelled tracer in the litterfall was similar for both species and a similar amount was recycled monthly. However, as teak sheds more leaves and has larger surface area than flueggea, teak cycled higher content of $^{15}$N than flueggea. Zeller et al. (2001) reported that less than 30 % of litter $^{15}$N incorporated in tree biomass returned to the soil as litterfall. Our study showed that about 16 and 36 % of $^{15}$N-labelled tracer returned to the soil in teak and flueggea leaf litterfall, suggesting that greater litter N in teak was used for growth (Zeller et al., 2001). Teak uses greater N for its growth and therefore having flueggea in the mixed species stand ensure N cycling and maintain soil quality. The lower content of $^{15}$N tracer determined from teak (16%) litterfall than flueggea (36%) litterfall over time raised an important point, having flueggea intercropped with teak in mixed species and agroforestry systems ensures N cycling and maintains soil N quality, because flueggea has been shown to cycle $^{15}$N tracer at a higher rate. As both the undergrowth woody and the herbaceous species litter were not sampled and analysed over the study period, their N-cycling rates were not known and therefore cannot be compared to teak and flueggea.
The recovery of $^{15}$N tracer was greatest in the stem for teak and in the root for flueggea at the 2 year plots. At age 4 years, $^{15}$N recovery was greatest in the root for teak and stem for flueggea. The changes in $^{15}$N recovery between stem and root for teak between 2 and 4 years and from root to stem for flueggea demonstrated the partitioning strategy for growth with age, possibly prompted by the emerging competition, phenological changes and aging of physiological tissues (Blumfield and Xu, 2006). As trees grow, they may compete with the available resources and over time as above- and below-ground biomass develop, they would modify the competition to their favour. This was evident in our result as the $^{15}$N recovery was greatest at age 4 than 2 years and may indicate that well developed root structure with age enabled higher nutrient uptake rate. When trees compete, those that grow quickly dominate the growing space above through their canopy development and belowground through spread of their lateral roots. When this happens, the other plants that were slower to grow are suppressed and in this situation the rapid growing plant controls the competition for its advancement above others. Competition may play a role in the changes of N compositions in the plant biomass because as competition develops, N will be allocated to the growing part of trees especially the root and the crown. Some plant parts act as storage until there is a need to allocate to the growing part of the plant when prompted by competition, growing season and damage caused by natural disaster. Phenological changes may have some impacts because teak at age 4 years is already producing flowers and fruits. Flowering and fruiting seasons occur on certain times of the year. Some teak trees shed leaves during the year although not all showed this teak phenological character in the Solomons. Flowering and growing of new leaves may have impact on the N reallocations as teak ages.
4.5.7 Total N recovery in trees, crops, weeds and soil

Individual tree and stand productivity is enhanced when nutrients (especially N) is available. The efficiency of N uptake depends on root development of each tree and the associated microbial communities (Zeller et al., 2001; Coleman et al., 2004). The higher recovery in the 4 year plots may be due to well-developed root structure that prevented leaching and promoted $^{15}$N-labelled uptake while the canopy closure enabled lower temperature, reduces the direct fall of rain and increase forest floor biomass which may lessen the possibility of denitrification and leaching of $^{15}$N. Denitrification occurrence was anticipated to be higher in the open canopy with higher temperature and soil surface expose to high rainfall and surface flow (Davidson et al., 1993; Smart et al., 1999; Bustamante et al., 2004). The total amount of unaccounted $^{15}$N tracer was greater (57%) at the 12 month than at the 18 month (45%) period. The greater loss from the younger trees (2 years) than at the older trees (4 years) may be partly attributable to denitrification (Pu et al., 2002; Blumfield and Xu, 2006). The $^{15}$N tracer application to the younger trees was under open canopy and exposed to rain and sun which had higher chances and longer period for denitrification to occur (Xu et al., 1992). However, the harvesting of food crops during intercropping period would be the main reason for higher rates of unaccounted $^{15}$N tracer in the 2 year plots. Food crop $^{15}$N concentration recovered had statistically similar concentration with the soil $^{15}$N concentration and may indicate higher uptake and loss of $^{15}$N during harvesting. Higher $^{15}$N uptake of crop plants than that of trees would cause a greater loss of $^{15}$N through harvesting and is potentially the largest cause of the differences between the $^{15}$N recovery of the 2 year and 4 year plots. This is an important issue in agroforestry nutrient management. The loss of 30% of $^{15}$N was reported by Blumfield and Xu (2006) in the hoop pine seedling pot experiment conducted in the glass house and by Xu et al. (1992) in the field microplot experiment with maize. Our $^{15}$N-labelled tracer loss was 45-57% which was higher than 30%. The higher loss was expected as the experiment was conducted at the high
rainfall location and that climatic conditions played important roles in $^{15}$N transformations in wet season (Pu et al., 2002). Further, at the 2 year plots, crops had been harvested and weeds were removed during crop maintenance thus resulted in greater $^{15}$N loss. There was significant amount of $^{15}$N in the soil that was recovered at the end of the study period (33 % and 10 % in 0-10 and 10-20 cm at the 4 year plots and 22 % and 15 % at the 2 year plots respectively.

4.6 Conclusion

Teak growth in height and DBHOB was significantly greater than flueggea at age 4 years. However, biomass was only significantly different in the stem. This showed teak and flueggea performed at their species specific growth rate and was not affected by being grown together in the mixed species system. Teak and flueggea had similar uptake of TN and acquisition of TC and allocation to biomass components. As stem had greater biomass, it had greater partitioning of TC, TN and $^{15}$N than the root, branch and foliage and showed that under conditions of high N uptake, resources are stored in the stem for future requirements. Teak maintained a higher WUE as indicated by higher $\delta^{13}$C than flueggea at the two ages and cycled approximately 16 % of monthly $^{15}$N through leaf litterfall. Teak and flueggea had similar enrichment of biomass components at 12 and 18 months study period which indicated similar uptake of $^{15}$N. Recovery of $^{15}$N between teak and flueggea were not significantly different at either age, which indicated similar rate of uptake at both ages. Older stand had higher recovery of $^{15}$N in the soil-plant system than the younger stand and root structure is directly responsible for the uptake of $^{15}$N. At the younger stand, crop had greater uptake of $^{15}$N than teak and flueggea and their harvests and burning of weeds during maintenance may have contributed to higher loss of $^{15}$N within the system. Although teak had significant growth, $^{15}$N uptake and
enrichment were similar to flueggea which may mean that competition in growth resources, especially N, was still at minimum stage.

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4.8 Pictures of Teak and Flueggea Growth over Time
Plate 4-1: Three (3) months old teak

Plate 4-2: Three (3) months old flueggea
Plate 4-3: Three (3) months old teak and flueggea prior to being isolated to become Plot 8 of the $^{15}$N-labelled experiment.

Plate 4-4: Three (3) months old teak and flueggea of Plot 8 $^{15}$N-labelled experiment. They were isolated by excavating a trench to a depth of 60 cm.
Plate 4-5: Installation of the barrier of double-layered building-grade plastic film in Plot 8.

Plate 4-6: Application of the $^{15}$N-labelled solution after the trench was back filled in Plot 8.
Plate 4-7: One and a half years old teak and flueggea in Plot 8 of the $^{15}$N enrichment experiment

Plate 4-8: Two (2) years old teak and flueggea in Plot 8 of $^{15}$N enrichment experiment before excavation
Plate 4-9: Two (2) years old teak and flueggea in Plot 5 of $^{15}$N enrichment experiment before excavation.
Chapter 5  Nitrogen and carbon cycling associated with litterfall production in monoculture teak and mixed species teak and flueggea stands in Solomon Islands

5.1 Abstract

High demand for teak (*Tectona grandis* L.f.), a species of economic importance, was the reason Solomon Islands experienced a surge in community-wide planting of monoculture teak stands in the last two decades. Mixed species planting of teak and flueggea (*Flueggea flexuosa* Muell. Arg.) was introduced to overcome the reluctance of growers to thin their stands. However, there is lack of information on the effect of changing from monoculture to mixed species plantings on the cycling of nutrients especially carbon (C) and nitrogen (N). This study assessed litter production and C and N cycling in both teak monoculture and teak and flueggea mixed species plantings over 18 months. Leaf litter samples were collected from two trials established with five different treatments (T) located at Ringgi and Poitete sites: teak planted at 833 stems per hectare (sph) (T1), teak planted in rows with 2 rows of flueggea at 833 sph (T2), 625 sph (T3) and 416 sph (T4), and teak planted in alternating rows with flueggea at 833 sph (T5). Monthly litterfall production ranged from 250.51 to 541.61 kg ha\(^{-1}\) depending on treatment and trial. Treatment 1 produced significantly higher total litter than T4 at Ringgi. Based on individual tree litterfall production, teak in T4 (lowest stocking rate) at both trials produced significantly higher litter per tree than the teak in T3, T2, T5 and T1 while there was no significant difference with flueggea productivity. Although teak and flueggea species total carbon (TC) and total nitrogen (TN), and \(\delta^{13}C\) and \(\delta^{15}N\) vary over the study period, their mean values were statistically similar except for teak in T4 having significantly lower values at Ringgi. Teak and flueggea C:N ratios were statistically similar at both trials except for flueggea in T2 at Ringgi which was significantly higher. The highest annual TC and TN returned to the
soil from total litterfall were observed in T1 followed by T3, T5, T2 and T4 for Ringgi. The highest at Poitete was T5 followed by T1, T3, T2 and T4. When comparing each treatment and using individual tree productivity, T4 significantly produced and returned the highest litter and nutrient than T3, T2, T5 and T1. Overall, individual tree productivity demonstrated that mixed species stands have significant potential for cycling higher rates of C and N than monoculture teak stands, therefore establishment of mixed species stands, especially T4 and T3 is recommended as a practical measure to address the widely experienced problem of reluctance by growers to thin high value trees while preserving the balance of nutrient input into the ground. Adopting such measures is another step to realising sustainable development of community forestry in the Solomon Islands.

Key words: *Tectona grandis*, *Flueggea flexuosa*, mixed species, monoculture, litterfall production, carbon and nitrogen cycling

5.2 Introduction

The increased demand for teak (*Tectona grandis* L.f.) due to its excellent wood quality and wide range of end-uses resulted in increased areas of teak monoculture plantations (Jha, 2003; Fofana *et al.*, 2008) and agroforestry systems (Mutanal *et al.*, 2009; Sharma *et al.*, 2011) across the tropics. A report from 2014 acknowledged that teak plantations account for at least 75 % of the tropical hardwood plantations but only 3 % of the world’s forest plantations (Chandrasekhara Pillai *et al.*, 2014). The Solomon Islands experienced a surge in community monocultural planting of teak in the last two decades as people began to appreciate the potential export value but also to rehabilitate the rainforest areas degraded by logging. Mixed species
stand of teak and flueggea (*Flueggea flexuosa* Muell. Arg.), a local tree species, is a system
developed to overcome the reluctance of growers to thin pure teak stands. However, little is
known regarding how the transition from monoculture to mixed species systems affects
nutrient cycling, particularly C and N, and system sustainability.

The biogeochemical cycling of C and N via litterfall contributes to the maintenance and
eventual improvement of soil quality (Hansen *et al.*, 2009; Leon and Osorio, 2014) over time
when leached nutrients are captured by deeper roots and recycled through litter. The production
of litterfall is the major pathway for the return of organic matter from plants to the soil surface
(Veneklaas, 1991; Bubb *et al.*, 1998; Oladoye *et al.*, 2010). The quantity and quality of litterfall
fractions varies between species and forest ecosystems (Rothe and Binkley, 2001), depending
on stand age and development, and is influenced by water and soil nutrient availability
(Polglase and Attiwill, 1992; Bubb *et al.*, 1998). Nutrients are made available from litterfall
during the decomposition process which is highly dependent on the influence of climate,
litterfall physico-chemical properties (lignin content, other phenolic compounds, lignin/N ratio,
C:N ratios, physical leaf toughness and physical leaf surface barriers) and the decomposer
organisms (Attiwill and Adams, 1993; Bubb *et al.*, 1998; Lorenzen *et al.*, 2007). Among the
nutrients, N deserves attention as it is a limiting nutrient in the tropics (Khanna, 1997).

Other studies have been conducted on C and N cycling associated with litterfall in the tropics,
however, they were mostly on natural forests (Vitousek and Sanford, 1986; Hermansah *et al*.,
2002; Yang *et al*., 2005) and plantations outside of the Pacific region (Bernhard-Reversat,
1996; Ma *et al*., 2007; Oladoye *et al*., 2010) or both (Ashagrie and Zech, 2013). Teak litterfall
studies had been conducted in monoculture plantations in South Asia (Sharma and Pande,
1989; Pande *et al*., 2002; Jha, 2003; Takahashi *et al*., 2012), Africa (Egunjobi, 1974) and Latin
America (Kraenzel et al., 2003); however, their results are not applicable in projecting C and N cycling to manage teak plantations in the Solomon Islands due to differences in soil and environmental conditions.

Therefore the main objective of this study was to gain an understanding of the litterfall production and litter C and N dynamics in monoculture teak and mixed species teak and flueggea plantings. The study also examines the litterfall C:N ratio as it is generally regarded as an indicator of litter quality as it influences the litter decomposition and cycling of mineral nutrients (Hobbie, 1992; Wolf et al., 2011). This information will guide the management and establishment protocols of these stands to maintain site productivity and sustainability in Solomon Islands.

5.3 Materials and methods

5.3.1 Site description

The study was conducted from 1st March 2011 to 30th September 2012 on trials located at Ringgi (8° 05´ 16.33´´ S and 157° 08´ 46.62´´ E) and Poitete (7° 52´ 34.39´´ S and 157° 07´ 46.78´´ E) on Kolombangara Island, Western Province, Solomon Islands. Both trials were planted in April 2009 on land formerly covered with regenerated secondary forests and located on Oxisol soil (Hansell and Wall, 1975). Ringgi and Poitete scientific trials are situated at the coastal region at an altitude of 84 m and 27 m a.s.l, where the slope is flat for Ringgi and slightly undulating for Poitete. The climate is humid tropical and temperature is consistent all year with a yearly mean of 28° C. Ringgi has a monthly rainfall range of 229-396 mm and Poitete 220-367 mm (Figure 5.1). Although the rainfall is fairly evenly distributed throughout...
the year, there is often a drier period around August and September and wetter period between December and March for both Sites. Soil physical and chemical properties are presented in Table 5.1.

Figure 5-1: Rainfall and temperature of Ringgi (a) and Poitete (b) trial sites

Table 5-1: Soil physical and chemical properties for Ringgi and Poitete trial sites
### Soil physical and chemical properties

<table>
<thead>
<tr>
<th></th>
<th>Trial 1 (Ringgi)</th>
<th>Trial 2 (Poitete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (g cm⁻³)</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>pH</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Cation Exchange Capacity (cmol (+) kg⁻¹)</td>
<td>12.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Total Carbon (TC) (%)</td>
<td>6.23</td>
<td>4.30</td>
</tr>
<tr>
<td>Total Nitrogen (TN) (%)</td>
<td>0.73</td>
<td>0.48</td>
</tr>
<tr>
<td>δ¹³C (‰)</td>
<td>-27.10</td>
<td>-26.57</td>
</tr>
<tr>
<td>δ¹⁵N (‰)</td>
<td>7.37</td>
<td>8.30</td>
</tr>
</tbody>
</table>

### 5.3.2 Experimental design

Each trial was established on a 2 ha area and consisted of the same randomized complete block design with five treatments and four blocks, allowing for spatial variation across both trial sites. The trials were established to examine optimal spacing for teak and flueggea in a mixed species system and compare with monoculture teak. There were 5 treatments characterised by species ratio and stems per hectare (sph) or planting spacing (Table 5.2). The 5 treatments represented 5 plots in a block and with 4 blocks; a trial should have 20 plots. In each plot, there were 6 lines planted with 8 trees. Each plot is buffered by the 1st and the 6th lines and the 1st and the 8th trees of each line. Each plot had a total of 24 measured trees of which T1 had 100 % teak and mixed stands comprised of T5 having 50 % teak and 50 % flueggea, and T2, T3 and T4 have 33 % teak and 67 % flueggea. Tree growth assessed at the end of litterfall study at both trials is presented in Table 5.3a and b. The undergrowth was rich with shrub layer and...
herbaceous community. During the study period, two pruning operations were conducted at the
Ringgi trial and only one was conducted at the Poitete trial. Both trials were treated with manual
clear weeding annually.

Table 5-2: Detail of each treatment replicated in 4 blocks at the Ringgi and Poitete trials.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Species ratio</th>
<th>Stems per hectare (sph)</th>
<th>Planting space (m × m)</th>
<th>Treatment plot area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teak</td>
<td>1 : 0</td>
<td>833</td>
<td>4 m × 3m</td>
<td>0.058</td>
</tr>
<tr>
<td>2</td>
<td>Teak and flueggea</td>
<td>1 : 2</td>
<td>833</td>
<td>4 m × 3m</td>
<td>0.058</td>
</tr>
<tr>
<td>3</td>
<td>Teak and flueggea</td>
<td>1 : 2</td>
<td>625</td>
<td>4 m × 4m</td>
<td>0.077</td>
</tr>
<tr>
<td>4</td>
<td>Teak and flueggea</td>
<td>1 : 2</td>
<td>416</td>
<td>4 m × 6m</td>
<td>0.115</td>
</tr>
<tr>
<td>5</td>
<td>Teak and flueggea</td>
<td>1 : 1</td>
<td>833</td>
<td>4 m × 3m</td>
<td>0.058</td>
</tr>
</tbody>
</table>
5.3.3 Litterfall sampling

Litterfall was sampled using litter traps. Sampling began in March 2011 when both trials turned 2 years and the trees were of sufficient height and canopy development and continued until September 2012, at age of 3½ years. Each trial had a total of 60 litter traps (15 litter traps per block). Each treatment had 3 litter traps positioned at random locations at the midway point between lines. Traps were made of wooden squares holding nets made from shade cloth and mounted on wooden stakes 1 m above the forest floor. Each trap had a catchment area of 0.50 m² (0.71 m × 0.71 m) with a 30 cm depth. Over the study period, each month’s collection showed 99% of the litterfall were leaves and therefore only leaf litterfall production was studied. Leaf litter collected from each trap in each treatment were separated by species and pooled into two paper bags and were oven dried at 60° C to constant weight and weighed separately. Dried leaf litterfall samples were ground to a fine homogenous powder using Puck and ring mill (Rocklabs, New Zealand) and samples stored in sterile, airtight containers until elemental analysis.

5.3.4 Chemical analysis

Approximately 9 mg of leaf litterfall homogenised powder were weighed into tin capsules and analysed for total C, total N, and C and N isotope composition (δ¹³C and δ¹⁵N) using Isoprime isotope ratio mass spectrometer (Cheshire, UK) with an Europa Elemental Analyser GSL (Cheshire, UK). All analyses were carried out at Griffith University, Nathan, Queensland.

Table 5-3: Teak and flueggea growth data (mean ± SE) at (a) Ringgi and (b) Poitete trials at the end of leaf litterfall study period (age 3½ yrs) presented in total height, diameter at breast
height (DBH), crown height (distance from ground to first live branch), crown radius and
crown depth (from first live branch to the tree tip).

(a)

<table>
<thead>
<tr>
<th>Treatment (No.)</th>
<th>Species</th>
<th>Height (total) (m)</th>
<th>Diameter at breast height (cm)</th>
<th>Crown height (m)</th>
<th>Crown radius (m)</th>
<th>Crown depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teak</td>
<td>16.47±0.25</td>
<td>16.95±0.60</td>
<td>6.08±0.13</td>
<td>3.09±0.05</td>
<td>11.22±0.49</td>
</tr>
<tr>
<td>2</td>
<td>Teak</td>
<td>13.80±0.64</td>
<td>17.76±0.65</td>
<td>5.92±0.14</td>
<td>3.44±0.23</td>
<td>10.01±0.64</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>10.99±0.67</td>
<td>11.16±0.36</td>
<td>5.78±0.49</td>
<td>2.96±0.03</td>
<td>6.92±0.30</td>
</tr>
<tr>
<td>3</td>
<td>Teak</td>
<td>14.93±0.50</td>
<td>19.57±1.78</td>
<td>5.52±0.24</td>
<td>3.17±0.18</td>
<td>10.48±1.05</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>11.44±0.94</td>
<td>11.79±0.42</td>
<td>5.35±0.59</td>
<td>3.03±0.07</td>
<td>6.80±0.36</td>
</tr>
<tr>
<td>4</td>
<td>Teak</td>
<td>14.35±0.26</td>
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<td>3.43±0.16</td>
<td>10.88±0.19</td>
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<tr>
<td></td>
<td>Flueggea</td>
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<td>12.26±0.16</td>
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<td>3.07±0.10</td>
<td>6.94±0.19</td>
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<td>5</td>
<td>Teak</td>
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<td>3.33±0.14</td>
<td>10.92±0.49</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
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<td>5.33±0.59</td>
<td>3.11±0.11</td>
<td>7.40±0.49</td>
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</table>

(b)

<table>
<thead>
<tr>
<th>Treatment (No.)</th>
<th>Species</th>
<th>Height (total) (m)</th>
<th>Diameter at breast height (cm)</th>
<th>Crown height (m)</th>
<th>Crown radius (m)</th>
<th>Crown depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teak</td>
<td>14.72±0.81</td>
<td>15.41±0.51</td>
<td>5.41±0.33</td>
<td>3.39±0.19</td>
<td>9.31±0.52</td>
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<tr>
<td>2</td>
<td>Teak</td>
<td>15.04±0.32</td>
<td>17.21±0.23</td>
<td>5.85±0.48</td>
<td>3.76±0.23</td>
<td>9.19±0.24</td>
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<tr>
<td></td>
<td>Flueggea</td>
<td>11.07±0.65</td>
<td>10.70±0.55</td>
<td>5.14±0.39</td>
<td>3.32±0.07</td>
<td>5.93±0.30</td>
</tr>
<tr>
<td>3</td>
<td>Teak</td>
<td>14.73±0.67</td>
<td>18.56±0.43</td>
<td>5.74±0.55</td>
<td>3.72±0.27</td>
<td>9.00±0.33</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>10.19±0.49</td>
<td>12.58±0.31</td>
<td>5.08±0.19</td>
<td>3.22±0.19</td>
<td>5.12±0.32</td>
</tr>
<tr>
<td>4</td>
<td>Teak</td>
<td>14.98±0.38</td>
<td>21.37±0.19</td>
<td>5.30±0.49</td>
<td>4.10±0.07</td>
<td>9.68±0.54</td>
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<tr>
<td></td>
<td>Flueggea</td>
<td>10.68±0.30</td>
<td>12.49±0.71</td>
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<td>5.75±0.12</td>
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<td>Teak</td>
<td>15.30±0.41</td>
<td>18.99±0.45</td>
<td>5.79±0.28</td>
<td>3.78±0.10</td>
<td>9.52±0.39</td>
</tr>
<tr>
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<td>Flueggea</td>
<td>11.38±0.78</td>
<td>11.15±0.61</td>
<td>5.02±0.27</td>
<td>3.10±0.09</td>
<td>6.36±0.54</td>
</tr>
</tbody>
</table>
5.3.5 Data and statistical analysis

Annual litterfall production was calculated following the method used by Oladoye et al. (2010). Total litter collected over the study period for each treatment was divided by the total number of months to determine the monthly mean production and annual production per treatment (Figure 5.2). To compare how treatments affected litter production, we calculated litter production on an individual tree basis for each species (Figure 5.3). Individual tree annual production was determined by dividing each treatment’s annual production by its density. The monthly litterfall C and N content for each treatment were obtained by multiplying the total C (TC) and total N (TN) with the monthly total litter biomass for each treatment. The annual inputs of C and N to the forest floor for each treatment were determined by multiplying each treatment’s annual litter biomass with the mean C and N percentages (Tutua et al., 2008).

Potential return to soil of TC and TN of teak and flueggea within species and across treatments were compared using individual tree TC and TN production.

The SPSS Statistics 22 software was used for statistical analyses. Normality of variables was tested using Shapiro-Wilk test and homogeneity of variance was tested with Levene’s test. The data was further analysed using multiple univariate ANOVA and Tukey post hoc test where necessary to investigate pairwise significant differences in leaf litterfall production and litterfall C and N dynamics within species across treatments. Origin pro 8.5 was used to plot graphs. If not stated otherwise, all reported values are given as the mean ± standard error.
5.4 Results

5.4.1 Litterfall production

The annual litterfall (Mg ha\(^{-1}\) yr\(^{-1}\)) production was not significantly different between treatments for T1, T2, T3 and T5 at Ringgi trial, though T1 was significantly higher than T4 (p<0.05) (Figure 5.2). There was no significant difference in litterfall production between treatments at the Poitete trial. When calculated on an individual tree basis, there were no significant differences due to spacing. No significant difference in litterfall production per tree was observed for flueggea (Figure 5.3a and b). At Poitete, teak litterfall production per tree was only significantly different between T1 and T4 (p<0.001). As with the Ringgi site, there was no significant difference in flueggea litter production between treatments (Figure 5.2c and d).

Figure 5-2: Annual total production of leaf litter by treatment at (a) Ringgi and (b) Poitete
Figure 5-3: Individual tree mean annual leaf litter (kg ha$^{-1}$ year$^{-1}$) by species and treatment at Ringgi (a and b) and Poitete (c and d).

As a general rule, litterfall peaked in the warmer, wetter months (December to March) of the southern hemisphere summer at both Ringgi and Poitete. There was no significant difference between months on litter production at Ringgi though it was significant across months for Poitete. The litterfall was significantly greater on January 2012 than other treatments and was significantly greater on August 2011 than July and September 2012 at Poitete (Figure 5.4). The highest monthly litterfall occurred at Ringgi in December 2011 (1,506 kg ha$^{-1}$) and the lowest litterfall occurred in July 2011 (776 kg ha$^{-1}$). Poitete litterfall peaked in January 2012 (2,275 kg ha$^{-1}$) and was lowest in July 2012 (746 kg ha$^{-1}$). Teak contributed a higher proportion of biomass to the total litterfall production in the mixed species systems than flueggea and followed the following order: 74 (T5) > 64 (T2) > 62 (T4) > 60 (T3) % for Ringgi and 70 (T4) > 69 (T5) > 63 (T2) > 60 (T3) % for Poitete (Figure 5.3). Greater litter production was associated with higher rainfall at December 2011 and January 2012.
There was no significant difference in TC between treatments for litterfall of either species at the Ringgi site while teak at T4 had significantly lower TC than other treatments at Poitete (p<0.01) (Table 5.4). No significant differences were observed in teak litterfall TN among treatments at both sites. Flueggea litterfall TN was significantly lower for T2 than for the other treatments at Ringgi (p<0.05), but was not significantly different among treatments at Poitete. There was no significant difference in either litterfall $\delta^{13}$C or $\delta^{15}$N for either species at the Poitete site. Teak litter $\delta^{13}$C was significantly lower at T1 (p<0.05) than other treatments at the Ringgi site while flueggea litter $\delta^{15}$N was lower for T2 at the same site (p<0.05). There was no significant difference between the other treatments.
Table 5-4: Leaf litterfall TC, TN, δ¹³C and δ¹⁵N for teak and flueggea at (a) Ringgi and (b) Poitete.

### (a)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Total Carbon (TC) %</th>
<th>Total Nitrogen (TN) %</th>
<th>δ¹³C (%)</th>
<th>δ¹⁵N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teak</td>
<td>48.48±0.37 a</td>
<td>1.59±0.05 a</td>
<td>-29.18±0.11 b</td>
<td>2.76±0.15 a</td>
</tr>
<tr>
<td>2</td>
<td>Teak</td>
<td>48.23±0.41 a</td>
<td>1.58±0.06 a</td>
<td>-28.86±0.12 ab</td>
<td>2.45±0.19 a</td>
</tr>
<tr>
<td>3</td>
<td>Teak</td>
<td>48.74±0.32 a</td>
<td>1.54±0.06 a</td>
<td>-28.75±0.09 a</td>
<td>2.63±0.25 a</td>
</tr>
<tr>
<td>4</td>
<td>Teak</td>
<td>48.15±0.56 a</td>
<td>1.42±0.06 a</td>
<td>-28.73±0.07 a</td>
<td>2.75±0.27 a</td>
</tr>
<tr>
<td>5</td>
<td>Teak</td>
<td>48.47±0.41 a</td>
<td>1.46±0.04 a</td>
<td>-29.01±0.12 ab</td>
<td>2.73±0.21 a</td>
</tr>
</tbody>
</table>

### (b)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Total Carbon (TC) %</th>
<th>Total Nitrogen (TN) %</th>
<th>δ¹³C (%)</th>
<th>δ¹⁵N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teak</td>
<td>48.08±0.34 a</td>
<td>1.56±0.04 a</td>
<td>-28.98±0.09 a</td>
<td>2.44±0.38 a</td>
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<tr>
<td>2</td>
<td>Teak</td>
<td>47.96±0.39 a</td>
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<td>Teak</td>
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<td>2.69±0.30 a</td>
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<td>4</td>
<td>Teak</td>
<td>46.29±0.42 b</td>
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<td>-28.57±0.15 a</td>
<td>2.95±0.33 a</td>
</tr>
<tr>
<td>5</td>
<td>Teak</td>
<td>48.56±0.41 a</td>
<td>1.55±0.06 a</td>
<td>-28.73±0.10 a</td>
<td>2.56±0.26 a</td>
</tr>
</tbody>
</table>

Values represent means ± standard errors. Different letters within column and species indicate significant differences at \( P<0.05 \).
As treatment effect was not significant on the chemical parameters of litterfall from both species at both sites, the aggregated means of litterfall TC, TN, δ^{13}C and δ^{15}N of all treatments were determined to detect potential differences over the study period. The monthly mean of teak litterfall TC in either trial (Ringgi, Poitete) was significantly higher in December 2011 (p<0.0001, p<0.01) and January 2012 (p<0.0001, p<0.05), and February 2012 (p<0.0001) for Ringgi than March and August 2011 and June 2012 (Figure 5.5). The teak litterfall TC in June 2012 for Ringgi was significantly higher than in March and August 2011 (p<0.0001) while litterfall TC in August 2011 was significantly lower than January and February 2012 for Poitete (p<0.001). Flueggea litterfall TC was significantly higher in either trial in December 2011 (p<0.0001, p<0.01), and January (p<0.01) and February 2012 (p<0.001, p<0.05) than March and August 2011, and February and June 2012 for Poitete. Flueggea litterfall TC in June 2012 was significantly lower than in March and August 2011 and February 2012 (p<0.05) at Poitete.

Figure 5-5: Teak and flueggea leaf litter TC (%) mean pattern between March 2011 and June 2012 at Ringgi (a) and Poitete (b) trials. The letters represent significance between months.

Monthly litterfall TN was significantly higher in August 2011 (p<0.0001) and June 2012 (p<0.01) than March 2011 for teak while flueggea TN was significantly higher in August 2011.
(p<0.05) than other months at Ringgi (Figure 5.6). Flueggea had significantly higher litterfall TN in December 2011 (p<0.01) and for either species in January (p<0.001, P<0.03) and June 2012 (p<0.005, P<0.03) than March 2011 at Poitete.

Figure 5-6: Teak and flueggea leaf litter TN (%) mean pattern between March 2011 and June 2012 at Ringgi (a) and Poitete (b) trials. The letters represent significance between months.

There was no significant difference in teak δ¹³C between months over the study period in either trial (p>0.05) though a significant decrease in δ¹³C was observed for flueggea at the final months of the study period (p<0.01) (Figure 5.7). Litter δ¹³C were more negative at Ringgi beginning on December 2011 and Poitete on February 2012 until the end of the study period.

The monthly mean litterfall δ¹⁵N of teak and flueggea was significantly higher in February 2012 than in March 2011 (P<0.0001, p<0.01) and only teak litter δ¹⁵N was significantly higher in August and December 2011 at Ringgi (p<0.001) (Figure 5.8). The litterfall δ¹⁵N of teak and flueggea was significantly higher in December 2011 (p<0.001, p<0.01) and only teak in February 2012 (p<0.01) than the other months at Poitete.
Figure 5-7: Teak and flueggea’s leaf litter $\delta^{13}$C (‰) mean pattern between March 2011 and June 2012 at Ringgi (a) and Poitete (b) trials. The letters represent significance between months.

Figure 5-8: Teak and flueggea’s leaf litter $\delta^{15}$N (‰) mean pattern between March 2011 and June 2012 at Ringgi (a) and Poitete (b) trials. The letters represent significance between months.

Litterfall C:N ratios were not significantly different in teak in either trial. Only flueggea litterfall C:N ratio was significantly higher for T2 at Ringgi ($p<0.05$) and was not significantly
different for treatments at Poitete (Table 5.5). Over the study period, monthly mean C:N ratio was significantly higher for teak in March 2011 in either trial than August 2011 and June 2012 for Ringgi (p<0.01), and January and June 2012 for Poitete (p<0.05) (Figure 5.9). The C:N ratio of flueggea of either trial was significantly higher in March 2011 and February 2012 and only Ringgi in December 2011 and January 2012 (p<0.05). The C:N ratios were lower for both species in live foliage (data not included) compared to leaf litter at each treatment of both trials. Teak live foliage had lesser C:N ratios than flueggea in each treatment of both trials. The Poitete trial had lower C:N ratios for both species live foliage than Ringgi.

Table 5-5: Leaf litter C:N ratio of Ringgi and Poitete trials over the study period

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Ringgi trial</th>
<th>Poitete trial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Teak</td>
<td>Flueggea</td>
</tr>
<tr>
<td>T1</td>
<td>31.01±1.02 a</td>
<td>31.23±0.89 a</td>
</tr>
<tr>
<td>T2</td>
<td>31.48±1.33 a</td>
<td>36.60±1.30 a</td>
</tr>
<tr>
<td>T3</td>
<td>32.66±1.20 a</td>
<td>33.06±0.87 ab</td>
</tr>
<tr>
<td>T4</td>
<td>34.95±1.35 a</td>
<td>32.29±1.10 b</td>
</tr>
<tr>
<td>T5</td>
<td>33.67±0.91 a</td>
<td>31.89±1.06 b</td>
</tr>
</tbody>
</table>

Values represent means ± standard errors. Different letters within column indicate significant differences at $P<0.05$.
Figure 5-9: Teak and flueggea leaf litter C:N ratios mean trend between March 2011 and June 2012 for Ringgi (a) and Poitete (b) trials. The letters represent significance between months.

5.4.3 Carbon and N return via litterfall

Treatment 1 at Ringgi returned significantly greater C and N (Mg ha\(^{-1}\) year\(^{-1}\)) to the soil than the mixed species treatments (p<0.0001, p<0.05) (Figure 5.10a and b). Within the mixed species treatments, T3 and T5 contributed significantly greater C and N to the soil than T2 and T4 (p<0.05) while T2 contributed significantly greater C and N to the soil than T4 (p<0.05).

There was no significant difference between T2, T3 and T5 in N contribution to the soil, however, their contribution was significantly greater than T4 (p<0.05).

Treatment 5 at Poitete contributed significantly greater C and N to the soil than other treatments (p<0.0001) except for T1 where both had no significant difference in N contribution to the soil (Figure 5.10c and d). Treatment 1 and T3 contributed significantly greater C and N to the soil than T2 and T4 (p<0.0001). Treatment 2 contributed significantly greater C to the soil than T4 (p<0.0001) but had no significant difference in contribution of N to the soil with T4.
Figure 5-10: Total leaf litter TC and TN (Mg ha\(^{-1}\) year\(^{-1}\)) for Ringgi (a and b) and Poitete (c and d).

When comparing treatments with individual tree productivity, C and N contribution to the soil significantly increased with increasing spacing in teak, although this was not significantly different for flueggea spacing in either trial. Individual teak contribution of C and N to the soil was significantly greater at T4 than the other treatments at either trial (p<0.0001) (Figure 5.11 and 5.12). Treatment 3 returned significantly higher C and N to the soil than T1, T2 and T5 in either trial (p<0.01). Treatment 2 contributed significantly higher C and N to the soil than T1 and T5 at Ringgi (p<0.05) though at Poitete, T2 and T5 contributed statistically similar C and N to the soil but was significantly higher than T1 (p<0.0001).
Figure 5-11: Individual tree TC and TN (kg ha\(^{-1}\) year\(^{-1}\)) inputs of teak (a and c) and flueggea (b and d) litterfall to the forest floor at Ringgi trial.

Figure 5-12: Individual tree TC and TN (kg ha\(^{-1}\) year\(^{-1}\)) inputs of teak (a and c) and flueggea (b and d) litterfall to the forest floor at Poitete trial.
5.5 Discussion

5.5.1 Litterfall production

Litterfall sampling was conducted over an 18 month period, sufficient to cover the local annual weather pattern. Crown development is an influential factor in litter production. Litterfall increased with canopy closure as a result of individual trees competing for radiation interception and photosynthetic surface area, which influenced the processes of senescence that govern natural litter fall. At Ringgi, two pruning operations removed the lower green branches and foliage thereby opening up the canopy and reducing senescence and abscission processes, which reduced litter fall. A delay in pruning at Poitete contributed to higher litterfall. Litterfall was higher following canopy closure due to the lower branches experienced senescence and abscission.

Litter fell throughout the year with higher rates in the wet season between December and March for both species. The peak of teak litterfall at wet season contrasts with the findings of other studies which have reported that teak litter peaks in the dry season as a result of dessication or water stress (Egunjobi, 1974; Ola-Adams and Egunjobi, 1992). This highlights one of the differences between Solomon Island grown teak and many other teak producing countries. Teak is naturally deciduous and will defoliate completely in areas where there is a prolonged dry season such as Thailand. However, in the Western Province of Solomon Islands where this study took place, teak retains its foliage year round. The fact that the peak of teak litterfall in our study was in the wetter season may relate to the high winds associated with the rainy season and diurnal temperature range (Ogunyebi et al., 2013). Teak has larger leaf surface area than flueggea and therefore was hit hard by the rainfall and wind causing it to shed more leaves than flueggea. The leaves of flueggea are typically small, approx. 15-20 sq. cm. By contrast teak
has large leaves, up to 400 sq.cm, with consequently higher wind resistance. During Cyclone Yasi in 2011 in northern Queensland, it was noted that teak survived by shedding leaves in the high wind whereas other species that held on to their leaves suffered severe damage (pers.comm. T.J. Blumfield). Teak may have an adaptive response to windy conditions by shedding leaves which may also explain the greater contribution to litterfall than flueggea. However, environmental factors that have control over the onset of senescing and abscission process and site differences must not be overlooked (Vitousek, 1984; Ogunyebi et al., 2013).

The peak of litterfall recorded for both species during wet season is comparable with other tropical species reported by studies of Ola-Adams and Egunjobi (1992) for Afara (Terminalia superba Engl. & Diels) and Leucaena leucocephala (Lam) (Oladoye et al., 2010). Despite the difference in seasonal peak period, teak litter production for all five treatments in either trial followed a similar pattern and fell within the range of teak litter production between 1.71 to 10.32 Mg ha\(^{-1}\) year\(^{-1}\) reported by Jha (2000) in trials from different climatic zones of ages 1 to 56 years. The lack of significant difference in total litterfall of teak and flueggea between treatments at both trials (except for T1 and T4 at Ringgi) suggests that litterfall is not dependent upon spacing. However, when total litter of teak and flueggea was analysed by individual tree litterfall production, significant differences were determined for teak across treatments. Total litter production per tree increases as stand density decreases because lower stocking stands have individuals with larger crowns and higher leaf mass. Teak response to available growing space around age 2 to 3 years by developing its crown horizontally and therefore increased its crown size and produces higher litterfall. In the higher density stands, teak tend to develop its crown vertically with smaller crown due to early competition for light and therefore produces lower leaf mass. The result showed that mixed stand of 416 sph (T4) has potential to promote
higher individual tree crown and litter production than single and mixed species stands of 833 sph.

On our study, litter production was mainly accounted for by species composition and density and the local weather pattern. Higher teak ratio and stocking in T1 and T5 produced greater litter than T2, T3 and T4. Treatments with the highest ratio of teak to flueggea produced higher litterfall during wet and windy season because teak canopy are much higher than the flueggea canopy and therefore exposes more to the hit of the rainfall and the strength of the wind. Flueggea crown is often 2 to 3 metres lower than teak crown and therefore is sheltered from the wind although its crown is exposed to the rain. Further, flueggea is a shade tolerant species and therefore it does not compete for light in response to teak canopy shade. In the higher density, teak compete for light and concentrated its crown growth vertically. It was observed that, as teak grow taller, lower branches experience senescing process, as a result there was an increase in litterfall production. Teak individuals experience the senescing process in response to competition to supply and concentrate nutrients in the growing crown.

5.5.2 Leaf litter TC, TN, δ^{13}C and δ^{15}N

5.5.2.1 Litterfall TC

Litterfall TC for both species was lower in all treatments at both trials in March and August 2011 and June 2012 when litter fall was least. The TC was higher in December 2011, January and February 2012 when litter fall was highest. Litter TC at Ringgi suggested that most of the litter that shed around August at Ringgi were mostly green leaves that fell from mechanical damage caused by strong wind after pruning took place, when canopy was opened. Litter that fell in December to February during wet season were combination of mature and brown leaves.
The Poiteute trial was not pruned and therefore most litter fall would be from senescing and abscission process. There was no significant difference found between the TC of green leaves and that of litterfall for both species in our study. Teak young leaves average TC of our study (46.48 %) is similar to the young and medium teak leaves TC (46.4 and 46.5 %) of 20 years old teak plantation in Panama (Kraenzel et al., 2003). However, teak litter average TC was greater (48.57 %) for Solomon teak than for Panama teak litter (43.30) (Kraenzel et al., 2003) which may indicate that Solomon teak has greater C input to the soil system than Panama teak through litter. The difference may be due to site and provenance differences.

5.5.2.2 Litterfall TN

The higher litterfall TN of teak and flueggea from March to August at Ringgi could also be explained by the larger proportion of green litter in the traps during that time. Although we did not find significant differences between the TN of green leaves and litterfall for both species, N concentrations have been reported to be higher in green leaves than in senescent litter due to the retranslocation of N from senescing leaves to the growing zone for growth (Vitousek, 1984). Egunjobi (1974) also reported that increases in N concentrations in litterfall could be attributed to either aborted or mechanically damaged green leaves and not from senescing litterfall.

Teak showed significantly greater litter TN than flueggea at Ringgi after December 2011. The difference in litter TN of teak and flueggea at Ringgi over the study period may indicate higher leaching of N at Ringgi as Ringgi trial was pruned twice during the study period. Pruning opened the canopy twice and rain could have direct impact on nutrient leaching as soil surface was exposed to high rainfall which could cause downward flow. As teak has much deeper roots
than flueggea, it may access available N beyond flueggea’s reach. However, at Poitete, teak and flueggea had no significant difference in litter TN. A possible reason could be, soil N is available in soil depths accessible to both species. As Poitete topography is undulating, it is better drained than Ringgi and may prevent N leaching downwards. Surface flow was prevented by undergrowth grass, creepers and shrubs and therefore soil N was available to both species. The higher litter TN of flueggea than teak although not significantly different was related to flueggea’s root development and distribution as observed during root excavation. Flueggea have higher percentage of fine roots in the 0-5 cm soil depth (where decomposition takes place) than teak at age 4 years. Further, the fact that flueggea maintains higher litter TN than teak over the study period at Poitete trial, may also relate to the retranslocation process (Vitousek, 1984; Ogunyebi et al., 2013). According to our Lab analysis, we discovered that flueggea has greater TN than teak in leaf litterfall. According to Bisawas et al (2012), lower nutrient content found in litterfall indicates the nutrient use efficiency (NUE) capability of a species. Therefore, in our study, teak can be classified to have higher or increased NUE capability than flueggea in the uptake and use of N in its development. This may mean that teak have higher nutrient retranslocation efficiency (NRE) and therefore recovers more TN to supply the growing crown than flueggea during the retranslocation process before abscission takes place. These results were confirmed by the pattern of TN in green foliage analysis. Teak has higher TN in its green foliage than flueggea but has lower TN in its leaf litter than flueggea and therefore, flueggea cycled greater N through litterfall than teak which makes sense in growing both species in a mixed species system to complement lack of N cycling through litterfall in monoculture system.

Our results also showed that the amount of N returned to the soil was increasing over time for both sites. The higher TN in litter over the study period is a good indication of higher N uptake
and cycling which may reflect the rapid development of tree canopy of both species (Blumfield et al., 2004; Ibell et al., 2013). There was similar potential for uptake and cycle of N through litterfall by both species at Poitete and Ringgi as both species have ideal growth rates in the Solomon Islands. The higher litter TN in the months following the execution of the study may indicate higher photosynthesis and more accumulated growth for both sites (Blumfield et al., 2004; Ibell et al., 2013). The mean TN of teak and flueggea litter (Table 5.4) were within the range of TN reported for teak litter (Egunjobi, 1974) and similar to the study of Ola-Adams and Egunjobi (1992).

5.5.2.3 Litter δ¹³C

Despite growing in the same soils, teak had significantly greater litter TC and δ¹³C than flueggea which may indicate species differences (Hogberg et al., 1995; Bassiri Rad et al., 2003; Charles et al., 2011). This has also been reported in a study conducted by Arndt (2000) which showed difference in foliar δ¹³C of ziziphus (Ziziphus mauritiana Lamk) and peach (Prunus persica L.). He reported that, the higher values of peach foliar δ¹³C than ziziphus showed that peach does not discriminate against ¹³C as strongly as ziziphus and also indicated that peach had higher water use efficiency than ziziphus. Higher teak litter δ¹³C compared to flueggea may indicate that teak has higher water use efficiency (WUE) than flueggea (DeLucia and Schlesinger, 1991; Ometto et al., 2006) and teak may not discriminate against ¹³C as strongly as flueggea during photosynthesis (DeLucia and Schlesinger, 1991; Arndt, et al., 2000; Kristiansen et al., 2005; Huang et al., 2008; Ibell et al., 2013). Moreover, lower flueggea δ¹³C compared to teak was also found in live foliage for Ringgi (teak, -27.81 and flueggea, -28.75) and Poitete (teak, -27.61 and flueggea, -28.46). The result may explain that teak experienced water stress at canopy closure and because soil moisture mostly might be available at the soil
surface, flueggea having surface root network showed a less conservative water-use strategy 
($\delta^{13}$C becomes more negative) than teak (Cullen et al., 2008), and forcing teak to engage a 
higher WUE strategy because it has a deeper root network (Chapter 4) and less fine roots at the 
same depth as the flueggea root network. When roots and stumps of teak and flueggea were 
exposed, flueggea trees presented intensive network of finer surface roots. Presence of 
intensive fine root network in the top soils can result in higher water interception and absorption 
therefore reducing water flow vertically.

WUE is one of the variables used to determine if teak and flueggea can grow together in mixed 
species and agroforestry systems and therefore important to determine in leaf litter as well. 
Further, determination of leaf litter $\delta^{13}$C is important because one can also use the information 
to estimate the top soil $\delta^{13}$C, which has not been covered in this thesis. According to soil 
analysis both mix species trials have topsoil of similar value as teak leaf litter, possibly due to 
teak leaf litter having influenced the topsoil because of its high litterfall compared to flueggea 

Studies also reported that tree height can influence $\delta^{13}$C concentrations as a result of changes 
in hydraulic conductivity, responsible for drawing in water through the roots and pulled up 
through the tree to the tips of all branches over time (McCarroll and Loader, 2004; Ibell et al., 
2013). Teak grew rapidly during its early growth and had a dominant canopy exposed to 
sunlight than flueggea. With greater leaf evaporative area, teak may use higher amounts of 
water for cooling as transpiration than in physiological processes such as photosynthesis and 
respiration (Kocher and Harris, 2007). Higher requirement of water for transpiration may cause 
teak to experience water stress and develop higher WUE as indicated by less negative $\delta^{13}$C  
than flueggea as water potential and stomatal conductance decrease with height (Ibell et al., 
2013).
Litter $\delta^{15}N$ reflects the soil $\delta^{15}N$ which is, in turn, dependent upon the soil N source (Charles et al., 2011; Ibell et al., 2013) and reflects the isotopic composition of N that was acquired by plant roots over the entire rhizosphere (Mardegan et al., 2009; Charles et al., 2011). The general increase in litter $\delta^{15}N$ over the study period may indicate that the tree roots were accessing soil N in deeper soil zone as $\delta^{15}N$ increases with depth (Hoberg, 1997; Rowe et al., 2001; Bustamante et al., 2004; Charles et al., 2011). Both studies of Mardegan et al. (2009) and Charles et al. (2011) showed that the increase of plant root network coverage could lead to the increase of live leaf and litterfall $\delta^{15}N$ over time. An increase in $\delta^{15}N$ in our study shows an acceleration of N cycling rates on Kolombangara condition and generally, in the Solomon Islands, which means that there is higher potential for N losses through leaching or volatilisation. Leaching is associated with heavy rainfall and therefore the significant variations of $\delta^{15}N$ over time reflects the nitrate leaching which relate to increase of soil $\delta^{15}N$ with depth (Matson et al., 1987; Hoberg, 1997; Charles et al., 2011).

Present study soil result (data not included) showed that TN decreased with depth (0-10 and 10-20 cm) while $\delta^{15}N$ values increased with depth at both sites. The increasing $\delta^{15}N$ pattern with depth was similar to other studies (Hoberg, 1997; Bustamante et al., 2004) and may indicate presence of NO$_3^-$-N in deeper soils (Matson et al., 1987). TN’s decreased with depth, may suggest most nitrogen transformations by soil biota into different N forms such as ammonia (NH$_4^+$) and nitrate (NO$_3^-$) were mostly located above 10 cm while lower composition below 10 cm was the result of downward flow of NO$_3^-$-N (Matson et al., 1987; Blumfield et al., 2004) and root turnover (Palm, 1995). Ammonia has a positive charge and
stays to negatively charged soil particles while nitrate has a negative charge, which causes it
to be repelled by negatively charged soil particles and therefore readily travels through soil
profile with water (Attiwill and Leeper, 1987; Schulten and Schnitzer, 1998; Barbarick, 2013).
Bustamante (2004) also reported higher δ^{15}N with soil depth under Cerrado plants in Brazil.
The possible explanation of the increase of δ^{15}N with depth was the result of fractionation
against ^{15}N during the mineralisation of organic matter and further plant uptake, leaving behind
a decomposed organic matter with higher δ^{15}N values (Hoberg, 1997; Blumfield et al., 2004).
Furthermore, increase of δ^{15}N with depth could be related to the losses of N from soil to the
atmosphere as a result of discrimination against ^{15}N (Bustamante et al., 2004). High rainfall
sites, such as the sites we used on Kolombangara, may experience greater losses of NO and
N_{2}O (Davidson et al., 1993) through denitrification (Poth et al., 1995; Smart et al., 1999;
Bustamante et al., 2004). At an ecosystem level, teak and flueggea litter with higher δ^{15}N may
indicate high N losses (Lajtha and Michener, 1994) and higher relative rates of N cycling
(Templer et al., 2007; Ibell et al., 2013).

5.5.2.5 Litter C:N ratio

Overall, there was lack of significant difference between the C:N ratios within teak and
flueggea and across teak and flueggea in single and mixed species treatments in either sites.
Similar C:N ratios may suggest that, there was similar litter quality of teak and flueggea at both
trials. Higher C:N ratios may indicate reduced litter quality and reduced decomposition rates
(Yan et al., 2009; Wolf et al., 2011). Studies suggested that N content and C:N ratios are good
indicators of litter decomposition capabilities (Aerts, 1997; Marc, 2001; Smith and Bradford,
2003). Lack of significance on C:N ratio within and between species across treatments and at
both trials may indicate similar decomposition rates at which nutrients in the litter become
available for recycling (Lorenzen et al., 2007). Litterfall C:N ratios are reported to reflect long-
term N cycle (Robinson, 2001; Kahmen and Wanek, 2008) and are indicators of soil N status
(Gundersen et al., 1998). Our results on C:N ratios for teak and flueggea were significantly
lower than for the European and North American tree species reported by a study conducted
by Hobbie (2006) in Poland.

5.5.3 Carbon and N inputs via leaf litter

With total litter production, T1 representing single teak stands and the highest stocking rate
returned the most nutrients at Ringgi and T5 with alternating rows of teak and flueggea at
Poitete while T4 that had the lowest stocking rate returned the least at both trials. Teak litter
contained significantly greater C content than flueggea and therefore returned more C than
flueggea in all treatments and at both trials and may suggest that teak sequestered more C than
flueggea. Teak litter also contained and returned to soil significantly greater N content than
flueggea and followed similar pattern of C returned at both sites. The greater return of C and
N to the soil at T1 and T5 at both trials was associated with greater treatment litter production
and litter nutrient concentrations.

The highest individual tree annual C and N content returned to the soil was recorded for teak
and flueggea of T4 at Poitete and teak and flueggea of T4 and T3 at Ringgi, although was not
significantly different within flueggea across treatments, irrespective of sites. This might
suggest that wider spacing and least density enhanced individual trees canopy development
and as a result individual tree input of C and N to the soil were significantly greater than higher
density stands. Our result on TC returned through teak leaf litter (1.5-2.75 Mg ha⁻¹ year⁻¹) for
both trials was lower than the result reported on a study conducted by Imvitthaya et al. (2011)
in Thailand, where an estimation of 6.06 to 7.76 Mg C ha\(^{-1}\) year\(^{-1}\) was reported. The lower return of C in the present study as compared to reported elsewhere in literature for tropical forests and plantations (Pregitzer and Euskirchen, 2004; Imvitthaya et al., 2011), may be attributed to climatic conditions, species and tree fractions studied as this study only examine leaf litterfall.

Our annual result on teak litter TN from both trials (30-90 kg N ha\(^{-1}\)) was similar to the study conducted by Egunjobi (1974) in Ibadan where 72.10 kg N ha\(^{-1}\) year\(^{-1}\) from teak litter of 9,024 kg ha\(^{-1}\) year\(^{-1}\) was reported. Further, our results falls within the results reported by a study conducted by Jha (2003) in India that reported 25.86 and 90.69 kg N ha\(^{-1}\) year\(^{-1}\) for 1 and 5 years old teak plantations. The mean annual return of plant nutrients in the litterfall falls within the range reported for tropical stands of various species and ages (Vitousek, 1984; Jha, 2003).

The differences in the C and N amount returned between treatments of both trials were attributed to differences in total litter and litter C and N concentrations.

5.6 Conclusion

All treatments at both trials produced leaf litter all year round and peaked during the high rainfall season. Total litterfall was statistically similar for all treatments at both trials except for T1 and T4 at Ringgi and litter production fall within the range reported for tropical forests. The present study has determined the patterns of litterfall production, and C and N return for single and mixed stands of teak and flueggea. Overall, teak returned higher C and N than flueggea due to its greater leaf litter surface area and litterfall C and N concentrations. It was determined that local weather was partly responsible for the variations in litterfall production, nutrient concentrations and nutrient input to the forest floor. Treatment 1 representing single
teak stands returned the highest C and N through total leaf litterfall while T4 returned the least, however, individual tree litter productivity and litter C and N returned to the soil was significantly greater at T4 and T3. The results indicate that mixed species systems, especially T3 and T4 with stocking rates of 625 and 416 are alternatives to monoculture teak as individual teak and flueggea are more productive in litter production and therefore promote higher sequestration of C and return of N. Further study in the nutrient cycling of C and N in the remaining term of the rotation is recommended to fully appreciate the overall dynamics of nutrient cycling as the system matures towards full harvesting.

5.7 Acknowledgement

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5.8 References


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5.9 Photos of Litterfall Traps collecting Leaf Litter

Plate 5-1: Two and a half (2½) years old teak with litterfall trap placed in between two planting rows

Plate 5-2: Pruning opens up the canopy at two and a half (2½) years old teak and flueggea. Notice the sunlight reaches the forest floor.
Plate 5-3: Litterfall trap under teak canopy

Plate 5-4: Leaf litter collected in the trap
Chapter 6  Root architecture of teak and flueggea in mixed species systems in the Solomon Islands

6.1 Abstract

Agroforestry is an important and sustainable alternative to monocultural land uses. In mixed species systems, root architectural traits of the component plants or trees that utilize different areas of the soil volume are advantageous. It minimizes belowground competition and promotes complementarity in the capture of growth resources. To examine root spatial interaction, teak (*Tectona grandis*) and flueggea (*Flueggea flexuosa*) were grown in trial plots on Kolombangara Island, Solomon Islands. Seven pairs of trees were isolated using a plastic barrier at two different age trials, 100 m apart. Three pairs of trees at age 2 years and four pairs of trees at age 4 years were manually excavated and productivity, biomass and root architecture, especially topology and distribution, were assessed. Additional trees growing without a barrier were partly excavated to ensure that the effect of the barrier on root architecture was not significant. The root architecture of both species had similar patterns of development but showed a different topology and distribution. Teak had extensive horizontal and vertical roots and occupied a larger portion of the soil volume than flueggea which may relate to nutrient and water uptake and adaptive growth. Flueggea had a shallow root behavior with shorter horizontal and vertical roots, hence occupying a smaller portion of the soil volume compared to teak. Generally, it had an intensive network of finer, non-woody surface lateral roots, which may have shorter turnover and thus reduce the trees root biomasses. Both species had similar root biomass increment of 87% between 2 and 4 years and had 20-22% of root biomass over total tree biomass at both ages. Teak and flueggea roots occupied different depths within the soil volume, which would promote nutrient uptake efficiency and therefore minimize competition.
Key words: Root topology, distribution, biomass, productivity, *Tectona grandis, Flueggea flexuosa*

**6.2 Introduction**

Root architecture is genetically based (Van Noordwijk *et al.*, 1993; Van Noordwijk and Purnomosidhi, 1995; Xu and Chen, 2006; Das and Chaturvedi, 2008). However, nutrient status, plant vigour, soil properties (Van Noordwijk *et al.*, 1993) and wind (Nicoll and Ray, 1996) could also have influence over root development and distribution. Roots are the acquisition and supply lines for water and minerals (Schroth and Zech, 1995; Xu and Chen, 2006). Furthermore, they store carbohydrates, produce essential nitrogenous compounds and act as a structural anchor to support the shoot (Perry, 1982b; Jourdan *et al.*, 2000; Nibau *et al.*, 2008).

Belowground competition can have negative impacts on growth, survival, and productivity of plants growing in proximity (Casper and Jackson, 1997). Belowground competition occurs when a competitor reduces the soil resources available to its neighbour through its root network (Casper and Jackson, 1997; Nan *et al.*, 2013). Therefore, root architecture, the spatial configuration of root systems (Ho *et al.*, 2005; Armengaud *et al.*, 2009), is the primary factor to investigate when considering underground competition and access to soil resources (Casper and Jackson, 1997; Nan *et al.*, 2013).

Tree growth and development are limited by competition when available resources cannot meet the demand (Xu *et al.*, 1995a; Casper and Jackson, 1997). Plants have different root architecture and patterns of development to optimize soil resource acquisition (Nan *et al.*, 2013). Previous field and laboratory studies have discovered various patterns of root
development in response to the supply of soil resources (Schippers and Olf, 2000; Schenk and Jackson, 2002). However, little is known about how different plant species interact when grown in proximity. Information about how belowground plant interaction may impact on the aboveground productivity and biomass is lacking, especially for tropical tree species.

As success in the competition for nutrient uptake depends on root architecture, the latter has direct impact on each tree’s final yield (Lynch, 1995; Armengaud et al., 2009; Gregory et al., 2009). Studies of root architecture are therefore required in potentially commercially important mixed species systems. However, describing the entire root architecture is difficult. Fine roots, which are responsible for the uptake of water and nutrients in the rhizosphere, and in the volume of soil around the plant roots (Tatarinov et al., 2008; Day et al., 2010), are difficult to protect and measure during excavation. Consequently, most studies have focused on the root topology only, the network of coarse roots (Oppelt et al., 2000; Resh et al., 2003; Tatarinov et al., 2008). Determining the root exploration area (volume of soil) using root topology can help determine the approximate area of the fine root network (Nadezhdina and Cermak, 2003) and may provide information about underground coverage and interactions. Several studies have been undertaken on tree root architecture of temperate and boreal tree species using destructive (Haag et al., 1989; Ritson and Sochacki, 2003; Andis, 2009) and scanning methods (Nadezhdina and Cermak, 2003; Danjon and Reubens, 2008). However, such information on subtropical and tropical trees is still scarce.

The supply of naturally grown teak from areas encompassing parts of India, Thailand, Myanmar and Laos (Goh and Monteuiuis, 2005; Midgley et al., 2007; Fofana et al., 2008) is diminishing rapidly. Teak (*Tectona grandis* L.f.) is an economically important species and is widely planted across the tropics in monoculture plantations (Evans, 1992; Niskanen, 1998;
Kraenzel et al., 2003; Fofana et al., 2008; Forwood, 2008) and agroforestry systems (Kumar et al., 1998; Mutanal et al., 2009; Sharma et al., 2011). Teak woodlots are an important component of rural landscapes in Solomon Islands and are often grown to rehabilitate the logged-over rainforests. Growing teak with flueggea (Flueggea flexuosa Muell.-Arg.), a local tree species, in mixed species stands is a system being developed in Solomon Islands to overcome the reluctance of growers to thin pure teak stands. There is a lack of information on the root architecture and hence belowground competition and its impact on tree growth in these mixed species systems.

Therefore the aim of this study was to examine the growth, root architecture and distribution of both teak and flueggea within mixed species systems at 2- and 4-years old. The objectives were to assess growth, evaluate and describe root development and structure in terms of depth and lateral extent, soil volume exploration and root biomass. Understanding the root architecture and distribution of teak and flueggea would allow the development of a scientifically based management regime for growing high value timber species in hybrid agroforestry systems.

6.3 Materials and methods

6.3.1 Site description

The trials were conducted on Kolombangara island (8° 05´ 16.33´´ S and 157° 08´ 46.62´´ E, 84 m a.s.l), western Solomon Islands. Trial plots were established on land formerly covered with regenerated secondary forests, on an Oxisol soil (Hansell and Wall, 1975). The average annual rainfall was 3,600 mm and the average temperature 28° C. Although the rainfall is fairly evenly distributed throughout the year, there is often a drier period around August and
September and wetter period between December and March. Soil physical and chemical properties of the two trial plots are presented in Table 6.1.

Table 6-1: Soil physical and chemical properties of the two mixed species trial at Ringgi site

<table>
<thead>
<tr>
<th>Soil physical and chemical properties</th>
<th>Trial 1 (4 years)</th>
<th>Trial 2 (2 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (g cm(^{-3}))</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>pH</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Cation Exchange Capacity (cmol(+) kg(^{-1}))</td>
<td>12.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Total carbon (TC) (%)</td>
<td>7.77</td>
<td>5.53</td>
</tr>
<tr>
<td>Total nitrogen (TN) (%)</td>
<td>0.69</td>
<td>0.51</td>
</tr>
<tr>
<td>(\delta^{13}C) (%)</td>
<td>-27.10</td>
<td>-26.57</td>
</tr>
<tr>
<td>(\delta^{15}N) (%)</td>
<td>7.37</td>
<td>8.30</td>
</tr>
</tbody>
</table>

6.3.2 Experimental design and stand description

The belowground plant interaction study was conducted within a larger study looking into optimal spacing for teak and flueggea in a mixed species system. The specific growth characteristics of both species are presented in Table 6.2. The belowground plant interaction study investigated root architecture development, especially the root topology and distribution, and their nitrogen (N) uptake. The present paper focuses on root topology and distribution of both species. The method used was that described by Blumfield and Xu (2004) on the study of fluxes of soil mineral N using \(^{15}\)N-labelled ammonium sulphate in isolation plots. Eight isolation plots were established, each containing one teak and one flueggea that had been planted at 4 m x 3 m spacing (Figure 6.1) and enclosing a total soil volume of 14.40 m\(^3\). The plots were isolated by excavating a trench to a depth of 60 cm and installing a barrier of double-layered building-grade plastic film. The trenches were then firmly back-filled. The barriers
were established at the midpoint between the adjacent trees and represented the maximum free area available to the trees. Each tree had a maximum growing surface area of 12 m² or a growing space of soil volume of 7.20 m³. Of the total of eight isolation plots, four plots (plots 1 - 4) were established in August 2011 when the first mixed species trial planted in April 2009 turned 2½ years. The other four isolation plots (plots 5 – 8) were established in February 2012 when a further mixed species trial that had been established on an adjacent site in November 2011 turned 3 months. These plots had undergrowth of local weeds and creepers during the period. The age of teak and flueggea when excavation work was undertaken were 2 (second trial plot) and 4 years (first trial plot). Teak and flueggea grew at a stocking of 833 stems per hectare (sph) at both trial plots.

Table 6-2: Species description of teak and flueggea

<table>
<thead>
<tr>
<th>Species</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Tectona grandis</em> L.f.</td>
<td>An adapted exotic tree and fast growing. Light-demanding and does not tolerate shade. Tolerate acidic soils. Grow to more than 25 m. Cylindrical bole and base often buttressed. Has spreading and rounded crown with four-sided branchlets with simple, broadly elliptical or obovate leaves, usually 30-60 cm long. Wood is use for construction, boat building, indoor and outdoor furniture.</td>
</tr>
<tr>
<td>Verbenaceae</td>
<td></td>
</tr>
<tr>
<td><em>Flueggea flexuosa</em> Muell. Arg.</td>
<td>Native and fast-growing tree. Prefers sunlight and tolerate 30 % shade. Tolerate acidic soils. Grow to height of 10-16 m and DBH of 20-30 cm. Cylindrical bole. Has conical shape crown but exhibit an oblong or spreading with age. Leaves are simple, alternate, and oblong-elliptic with rounded or tapered base and prominent, pointed, often curved tip, usually 8-12 cm long. Locally valued as source of timber for house building, craft and fencing material.</td>
</tr>
<tr>
<td>Euphorbiaceae</td>
<td></td>
</tr>
</tbody>
</table>

6.3.3 Determination of the volume of soil explored by roots

According to the observed root architecture and distributions, at age 2 and 4 years, both species presented a cone root shape. Therefore, the explored volume of soil could be projected using the cone volume formula. The soil volume of root network takes into account the farthest lateral root length and the maximum depth of the tap root (Nadezhdina and Cermak, 2003).

\[ V_{ea} = \frac{1}{3} \pi r^2 h \]

Where \( V_{ea} \) is the approximate volume exploitation area, \( r \) is the maximum horizontal lateral root length and \( h \) is the tap root depth.

6.3.4 Above and below-ground productivity and biomass measurement
Only 7 plots were manually excavated, of which three plots were of age 2 years and four plots were of age 4 years. A flueggea in Plot 7 in 2 years trial died during the study period and was therefore excluded from the analysis. Tree diameter at breast height (DBH) and crown radius were measured before the trees were felled using diameter tape and tape measure while total height and crown height and depth were measured after fall using tape measure. Root architecture, especially topology and distribution, was assessed using tape measure and protractor using the root follow technique method (Archer and Strauss, 1985). Fresh foliage, branch, stem and root biomass were measured using a Golden Lark 200 kg hanging scale. Additional trees, a pair of teak and flueggea growing without a barrier, were partly excavated to ensure that the effect of the barrier on free root architecture was not significant.

6.3.5 Statistical analysis and root structure photo editing

The SPSS Statistics 22 software was used for statistical analyses. Normality of variables was tested using Shapiro-Wilk test and homogeneity of variance was tested with Levene’s test. The data was further analysed using multiple univariate ANOVA and Tukey post hoc test to investigate significant differences in tree lateral and vertical roots, explored volume of soil and root biomass between species within ages and within species across ages. Differences were considered significant at $P<0.05$. No statistics were applied to the root data measured from the open environment because of insufficient replication. Digital photos of root structures were edited and prepared using the PIXLR Express photo editing software and scale bars were inserted to each photo using ImageJ software.

6.4 Results
6.4.1 Tree growth

Growth of teak and flueggea aboveground presented as productivity (Table 6.3) and biomass (Table 6.4) reflected their species specific growth characteristics (Table 6.2). Both species had rapid growth over the first 4 years during the study period. Between 2 and 4 years, teak had an increase of total height, DBH, crown height, crown radius and crown depth of 47, 56, 28, 67 and 57 % respectively, and flueggea had an increase of 60, 57, 75, 25 and 43 % respectively.

Teak invested more in height than on crown development at age 2 years. Teak and flueggea had a similar increase of 86 and 87 % in above- and below-ground biomass across ages. Across ages, foliar, branch, stem, and root biomass of teak had an increase of 75, 89, 87 and 87 %, while flueggea had an increase of 79, 83, 90 and 87 % respectively. Aboveground biomass of flueggea is 48-49 % that of teak at 2 and 4 years.

Table 6-3: Productivity of teak and flueggea presented in height, DBH, crown height (distance from ground to first branch), crown radius and crown depth (from first live branch to the tree tip)

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Species</th>
<th>Total Height (Fall) (m)</th>
<th>Diameter at Breast Height (cm)</th>
<th>Crown Height (m)</th>
<th>Crown radius (m)</th>
<th>Crown Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Teak</td>
<td>8.39±0.20</td>
<td>8.47±1.57</td>
<td>4.37±1.28</td>
<td>1.11±0.53</td>
<td>4.02±1.31</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>4.76±0.71</td>
<td>5.40±0.95</td>
<td>1.57±0.07</td>
<td>2.03±0.26</td>
<td>3.19±0.64</td>
</tr>
<tr>
<td>4</td>
<td>Teak</td>
<td>15.63±0.88</td>
<td>19.35±1.04</td>
<td>6.07±0.09</td>
<td>3.33±0.32</td>
<td>9.56±0.93</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>11.78±0.55</td>
<td>12.70±0.58</td>
<td>6.20±0.41</td>
<td>2.70±0.22</td>
<td>5.58±0.78</td>
</tr>
</tbody>
</table>

Table 6-4: Biomass (fresh) of teak and flueggea presented in foliar, branch, stem and root
<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Species</th>
<th>Foliar (kg)</th>
<th>Branch (kg)</th>
<th>Stem (kg)</th>
<th>Root (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Teak</td>
<td>5.67±2.19</td>
<td>5.00±4.51</td>
<td>27.17±5.93</td>
<td>9.50±2.26</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>4.67±1.45</td>
<td>4.67±1.86</td>
<td>9.00±3.22</td>
<td>5.00±1.73</td>
</tr>
<tr>
<td>4</td>
<td>Teak</td>
<td>22.25±2.10</td>
<td>45.75±3.50</td>
<td>210.75±33.63</td>
<td>74.00±9.85</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>22.75±2.29</td>
<td>28.25±3.95</td>
<td>86.75±10.23</td>
<td>38.75±3.59</td>
</tr>
</tbody>
</table>

### 6.4.2 Root system development

Teak presented more extensive lateral (horizontal) and vertical (depth) root growth (Table 6.5) than flueggea within the isolation barrier at both sampling times, although this was not statistically significant. A pair of teak and flueggea growing outside the isolation barrier was assessed (Table 6.6) by having half of the root system exposed. This confirmed that even in a free growing environment, teak had more aggressive root system than flueggea in terms of depth and spread.

<table>
<thead>
<tr>
<th>Stand</th>
<th>Species</th>
<th>Age (Years)</th>
<th>Total Range (cm)</th>
<th>Root growth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed species</td>
<td>Teak</td>
<td>2</td>
<td>140-250</td>
<td>178.33±35.86 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48-80</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>2</td>
<td>78-240</td>
<td>162.67±46.91 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25-76</td>
</tr>
<tr>
<td>Mixed species</td>
<td>Teak</td>
<td>4</td>
<td>190-630</td>
<td>390.00±96.26 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80-150</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>4</td>
<td>160-270</td>
<td>237.50±26.26 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>65-84</td>
</tr>
</tbody>
</table>

Values represent means ± standard errors. Different letters within column indicate significant differences at $P<0.05$. 

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Table 6-6: Root lateral and vertical growth and number of observations in open belowground environment

<table>
<thead>
<tr>
<th>Site (Mix species)</th>
<th>Species</th>
<th>Age (Years)</th>
<th>Total</th>
<th>Root growth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Teak</td>
<td>3½</td>
<td>1</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>3½</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>

Teak and flueggea had similar patterns of development in their root architecture. Initially, both species roots developed a herringbone pattern at age 2 years, where alternate lateral roots branches out from a parent or tap root. However, at age 4 years, both species developed a dichotomous pattern, where tap roots proliferated from more than one vertical root through forking in opposite directions. The tap roots divided into two at length of 20-30 cm at an angle of 170°-180° for both species and continued to doubly divide at the same rate as they grew vertically. Sinker roots were also observed to proliferate vertically from the lateral roots at an angle of 150°-170° and continued to divide at an angle of 170°-180° for both species. Sinker roots were more common and woody at 4 years than at 2 years. The primary lateral roots radiated out from the root collar horizontally for teak at 135°-150° and flueggea at 90°-100°. Both species mostly occupied different soil zones. At age 4 years, teak lateral roots branched out and divided into two or three secondary roots at depth of 15-50 cm while flueggea lateral roots mostly divided and branched out at the depth of 0-25 cm. Root structures observed in the field are presented in Figures 6.2-6.7.
Figure 6-2: Top view of 2 years old flueggea horizontal root topology and distribution

Figure 6-3: Top view of 2 years old teak root horizontal topology and distribution
Figure 6-4: Side view of 2 years old teak vertical root structure

Figure 6-5: Top view of 4 years old teak root horizontal topology and distribution
Figure 6-6: Side view (a) and top view (b) of 4 years old flueggea root structure, topology and distribution of the same tree.
Teak occupied a greater volume of soil than flueggea at both ages (Table 6.7) within the isolation plots as it had extensive horizontal and vertical roots. However, there were no significant differences in the volume of soil occupied by both species at either sampling time. The schematic diagram in Figures 6.8 and 6.9 present the volume of soil explored by both species at ages 2 and 4 years.
Table 6-7: The explored volume of soil of both teak and flueggea in the isolation plots

<table>
<thead>
<tr>
<th>Species</th>
<th>Age (Years)</th>
<th>Range</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teak</td>
<td>2</td>
<td>1.23 – 3.14</td>
<td>2.04±0.57</td>
</tr>
<tr>
<td>Flueggea</td>
<td>2</td>
<td>0.22 – 2.30</td>
<td>1.34±0.61</td>
</tr>
<tr>
<td>Teak</td>
<td>4</td>
<td>3.02 – 36.97</td>
<td>19.92±7.44</td>
</tr>
<tr>
<td>Flueggea</td>
<td>4</td>
<td>1.81 – 6.41</td>
<td>4.52±0.97</td>
</tr>
</tbody>
</table>

Values represent means ± standard errors. Different letters within column indicate significant differences at P<0.05.

Figure 6-8: Schematic diagram of soil volume explored by the root systems of both species at age 2 years represented by dotted area.
Teak accumulated significantly higher root biomass than flueggea at age 4 years (Table 6.8). Across age and within species, both teak and flueggea had significant increase in root biomass. Teak grew longer lateral roots and tap roots that had undergone secondary growth, resulting in larger surface area and rigid structure. Such structural roots had woody structure and therefore influenced the total biomass of the teak when weighed. These structural roots were the roots that had prolific vertical sinker roots for support against windthrow. Teak also had higher amount of fine roots compared to flueggea at age 4 years. Flueggea had secondary growth lateral roots but they were slightly shorter compared to teak. Flueggea had many non-woody
and smaller size lateral roots which may have shorter turnover and thus reduce the trees root biomass. At age 2 years, teak accumulated 66% of total tree root biomass per plot and flueggea had 34% while teak accumulated 66% and flueggea 34% at age 4 years. Both species have a mean root biomass of 20-22% over total tree biomass at both ages.

Table 6-8: Fresh root biomass in actual weight (kg) and as a percentage (%) of total tree biomass of teak and flueggea for each age group

<table>
<thead>
<tr>
<th>Species</th>
<th>Age (Years)</th>
<th>Range</th>
<th>Mean</th>
<th>Mean (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teak</td>
<td>2</td>
<td>7 – 14</td>
<td>9.50±2.26 c</td>
<td>20.93±1.40</td>
</tr>
<tr>
<td>Flueggea</td>
<td>2</td>
<td>2 – 8</td>
<td>5.00±1.73 c</td>
<td>22.18±4.13</td>
</tr>
<tr>
<td>Teak</td>
<td>4</td>
<td>57 – 93</td>
<td>74.00±9.85 a</td>
<td>20.57±0.46</td>
</tr>
<tr>
<td>Flueggea</td>
<td>4</td>
<td>31 – 48</td>
<td>38.75±3.59 b</td>
<td>22.08±0.93</td>
</tr>
</tbody>
</table>

Values represent means ± standard errors. Different letters within column indicate significant differences at P<0.05

6.5 Discussion

6.5.1 Tree growth

Teak and flueggea had similar aboveground growth rates across ages though these were species specific (Plates 1 and 2). Both species had initial rapid growth and therefore had accumulated aboveground biomass. The early rapid growth pattern of teak has been noted by Jha (2003) and Lugo (1988). In our study, teak and flueggea had similar aboveground total biomass accumulation rates; however, teak had twice the total fresh or dry mass of flueggea within age and across ages. The difference in aboveground growth while growing together in isolation plots, may be attributed to each species growth characteristics. Teak acts very much like a
pioneer species as it rushes for the sky trading height for spread or crown diameter development. Flueggea, on the other hand will happily develop its crown diameter unless crammed closely together. Flueggea trade height for spread early when grown in high density, especially stockings above 2,500 sph as was observed on the nearby Nelder fan established by ACIAR Project. Both species specific aboveground growth have influence over their belowground growth. Because teak grows rapidly and more like a pioneer species than flueggea aboveground, it grows much longer roots or pioneer roots which explores and sources nutrients from a wider perimeter. Consequently, teak invests in its root thickness to support the root network and provide stability to the growing crown. Flueggea root network was observed to be occupying lesser area than teak in depth and spread and may reflect a steady development in response to the rate of the aboveground growth.

Plate 6-1: Teak at age 2 years invested in height and stem more than in crown structure development (Right side). Flueggea invested in crown development and in horizontal direction (left row).
Plate 6-2: Teak (middle row) at age 4 years has well developed crown structure. Flueggea invested in crown development but was not affected by teak crown structure. Notice also that teak has larger and broader crown than flueggea.
6.5.2 Root system development

Growing teak with flueggea under the same environment and soil properties confirmed that, teak roots were more extensive horizontally and vertically than flueggea. Other studies have reported differences in rooting spread and depth between species grown under the same conditions. For example, a study in Nigeria by Akinnifesi et al (1998) showed that, under the same conditions *Enterolobium* and *Nauchlea* had larger woody lateral roots than other species, and *Enterolobium* and *Lonchocarpus* had the deepest and most vigorous tap root system.

Several factors that may have influence the development of teak and flueggea root systems include, genetic (Van Noordwijk and Purnomosidhi, 1995; Xu and Chen, 2006; Das and Chaturvedi, 2008), nutrient supply (Van Noordwijk et al., 1993) and anchorage requirements (Nicoll and Ray, 1996). In general, flueggea had a shallow root network while teak had a more extensive and exploratory network. Our study confirmed Thomson’s (2006) work, reporting shallow rooting behavior of flueggea. Root development of teak and flueggea at 2 years showed a herringbone pattern but by 4 years that had developed into a dichotomous pattern. The change from herringbone to dichotomous pattern suggests that both teak and flueggea have potential as tree species for agroforestry systems because their roots would forage within the soil volume and therefore minimize competition with food crops that utilize surface soil. Studies have shown that trees having a dichotomous pattern root system had a greater potential for intensive exploration of the soil volume while those having herringbone root system needed to explore larger or unrestricted volumes of soil (Spek and Van Noordwijk, 1994; Van Noordwijk et al., 1994; Richardson and Dohna, 2003).

Networks of fine roots proliferating from the lateral roots in search of water and nutrients simultaneously increase the root surface area and the rhizosphere of both species. We observed
that, at age 4 years, because teak had a more aggressive root system, its lateral roots already overlapped (Figure 6.9) into the growing area of flueggea. However, the overlap was mostly below 10-15 cm. There is a strong potential for competition for available resources between the two species should this overlap of rooting systems increase over time. A previous study (Srivastava et al., 1986) found that teak at age 19 years growing in plantation at a dry tropical region in India had the bulk of its root mass distributed at depth of 10-30 cm. That result is similar to our study, except that trees in that study were 15 years older than ours. However, the Indian study was from a drier environment than in Solomon Islands where teak is anticipated to have the bulk of its root below 15 cm, thus minimizing competition over time.

Both species response to wind movement through their adaptive growth confirmed that wind had influence over root development and distribution. There was a greater allocation of resources towards the leeward side, as was observed by the density of lateral roots, secondary growth and girth thickening (Figures 6.2 and 6.3) as has been reported by Ritson and Sochacki (2003) and other studies (Watson and Tombleson, 2002; Coder, 2010). In the first stages of development, teak invested in its height and stem more than in crown structure development (Plate 3). Teak also has very large, broad leaves (Plate 4) resulting in a tall, thin tree with quite high wind resistance. To support this configuration the root structure did not have a radial distribution when compared to flueggea at age 2 years (Figures 6.2 and 6.3). Teak lateral roots were unevenly distributed and developed towards the leeward side, which may suggest an adaptive growth response to help anchor the tree to the ground. Flueggea had well developed and radially distributed lateral roots at 2 years, however, its surface roots with investment in height growth and canopy development may be the reason for its susceptibility to windthrow at well drained sites. This was observed at Ringgi and Poitete trial sites during the study period. Therefore, flueggea silvicultural management requires green crown pruning as an important
intervention operation to prevent it from windthrow during its earliest stages, especially from age 1 to 3 years before canopy closes. It was also observed that, flueggea trees are susceptible to some form of root rot on poorly drained clay loam soil. As flueggea have a shorter but heavier crown, it is easily susceptible to windthrow when its root experienced some form of root rot, as was observed at Ringgi trial site. It is therefore important to note that when planting flueggea, they are best allocated to the well-drained clay loam sites. In comparison to 4 years (Figure 6.5), teak at age 2 years (Figure 6.2) did not have evenly distributed and developed root structure and therefore leeward side growth may indicate higher influence by adaptive growth in response to greater mechanical stress from wind sway (Ritson and Sochacki, 2003) than nutrient exploration. One sided elongation in Figures 6.6 (b) and 6.7 were mainly due to the isolation barrier. Both species root systems lateral branches increased in size, elongated and divided into two or three secondary branches as has been observed in other species such as *Pinus pinaster* (Ritson and Sochacki, 2003).

Plate 6-3: Teak (middle row) invested in its height and stem more than in crown structure development.
Plate 6-4: Notice teak has larger and broader leaves than flueggea (middle row).

Teak’s root growth demonstrated its simultaneous investment in lengthening and thickening of its root network resulting in a higher biomass. The average root biomass of flueggea was almost half that of teak at ages 2 and 4 years. Although root biomass was lower in flueggea than teak (Table 6.8), the rate of increase of 87 % from age 2 to 4 years was similar for both species. The higher root biomass (fresh) as a result of wider root distribution of teak compared to flueggea could have been in response to the aboveground growth resource demand and to support the growing biomass. Both species have around 20 % of total biomass at both ages, however, teak has greater root biomass than flueggea at both ages. The similar belowground biomass growth rate between age 2 and 4 years for both species may suggest competition was still at a minimum and belowground growth strategies were species specific. Our study data shows that the root biomass compared to the overall tree biomass was 20-22 %, which is close to or within values of 20-30 % reported for other species (Perry, 1982a; Nair, 1993; IPCC, 2006). A previous study by Jha (2003) reported a lower root biomass of 12.08% for teak stands in northern India at a
plantation growing in moist deciduous forests. The difference may be due to stocking density as higher density would induce shading and competition causing a shift of biomass from the root to the shoot (Van Hees and Clerkx, 2003).

**6.6 Conclusion**

Teak and flueggea have species specific development of above- and below-ground productivity and biomass. Teak had twice the amount of flueggea’s aboveground biomass accumulation at age 2 and 4 years although they have similar growth rates. Both species aboveground growth may relate to belowground root architecture development. Teak and flueggea have different root topology and distribution; however, they have similar root development patterns which suggest they are suitable for both mixed species plantations and for agroforestry systems. Both species lateral and tap roots development are species specific and bulk of their roots occupied different soil zones and did not have significant differences in growth within age and within species across ages. Studies showed that double the root biomass can be accumulated at ages 2 and 4 years for teak trees when compared with flueggea trees of the same ages. Both teak and flueggea root biomass had 87 % increment between 2 and 4 years and had 20-22 % of root biomass over total tree biomass at both ages. Root overlap at age 4 years, indicated early competition is possible. However, this can be controlled by better practices involving initial spacing and thinning intervention to maintain growing space for cropping needs beyond 4th year. Similar studies could be carried out in the future to determine the systems mid and end rotation belowground interactions.

**6.7 References**


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6.8 Pictures of Teak and Flueggea Root Architecture

Plate 6-5: Two years old teak root structure of Plot 6
Plate 6-6: Two years old flueggea root structure of Plot 6

Plate 6-7: Two years old teak root structure of Plot 7
Plate 6-8: Two years old teak root structure of Plot 8

(6.9a)
Plate 6-9: (a) and (b) Two years old flueggea root structure of Plot 8.

Plate 6-10: Four years old flueggea root structure of Plot 1.
Plate 6-11: Four years old teak root structure of Plot 1.

Plate 6-12: Four years old flueggea root structure of Plot 2.
Plate 6-13: Four years old teak root structure of Plot 2.

Plate 6-14: Four years old flueggea root structure of Plot 3.
Plate 6-15: Four years old teak root structure of Plot 3.

Plate 6-16: Four years old flueggea root structure of Plot 4.
Plate 6-17: Four years old teak root structure of Plot 4.

Chapter 7  Growth and yield of five years old teak and flueggea in single- and mixed species forestry systems in the Solomon Islands

7.1 Abstract

Effects of stocking rate and the intercropping of flueggea on early teak growth in a mixed species system were evaluated on Kolombangara Island in a humid tropical region of Western Province, Solomon Islands. The experimental design included Treatment 1 where teak was planted at 833 stems per hectare (sph) representing the normal stocking rate; Treatments 2, 3 and 4 had teak planted in rows alternating with 2 rows of flueggea at 833 stems per hectare; 625 stems per hectare; and 416 stems per hectare respectively. Treatment 5 had teak planted in alternating rows with a single row of flueggea at 833 stems per hectare. Intercropping with flueggea promoted diameter, height and form of teak. Teak diameter growth significantly increased with wider planting spacing though height was statistically similar to teak in single-species stands.
Intercropping with flueggea resulted in teak developing smaller branches which facilitated a self-pruning habit that promoted clear wood production. Sixty months after planting, total mean height of teak for all treatments followed the order: Treatments 1>3>2>5>4 while flueggea followed the order: Treatments 5>3>2>4 at Ringgi. At Poitete, teak followed the order: Treatments 5>3>2>1>4 while flueggea followed the order: Treatments 3>2>4>5. Diameter at breast height of teak of all treatments followed the order: Treatments 4>3>5>2>1 while flueggea followed the order: Treatments 4>3>5>2 at Ringgi. At Poitete, teak followed the order: Treatments 4>3>2>5>1 while flueggea followed the order: Treatments 4>3>2>5. Diameter at breast height of flueggea in Treatment 4 was significantly greater than diameter of flueggea of Treatment 5 (p<0.05). Between species and treatments, teak had significantly greater total height and diameter at breast height than flueggea at both sites (p<0.05). At age 5 years, both teak and flueggea did not have any significant difference in total height mean annual increment while diameter at breast height mean annual increment for flueggea was only significant for flueggea between Treatment 4 and Treatment 5 at both sites beginning at 5 years. Teak form was best at the pure and mixed species stands due to self-pruning while larger crown and big branches occurred at lower stocking rates. While this can be corrected with timely silviculture, a 4x3 m spacing would seem to optimise the benefits of higher stocking and lower maintenance. As the present investigation was confined to the first 5 years which is considered as establishment phase for teak, more studies are needed on older trees to fully understand the systems development to maturity.

**Keywords:**

Total height, DBH, basal area, volume, single-species system, mixed species systems, *Tectona grandis, Flueggea flexuosa*
7.2 Introduction

Plantation grown teak (*Tectona grandis* L.f.) forms an important alternative means of wood production in the tropics and subtropics (FAO, 2001; Langenberger and Liu, 2013). The high yield, uniformity, rapid growth and high value have been the main incentives for developing and rapidly expanding teak plantations in many countries in the tropics (Bermejo *et al.*, 2004; Langenberger and Liu, 2013) including the Solomon Islands. However, the productivity at many sites is below the potential due to low availability of nutrients, especially nitrogen (N) (Zech and Dreschel, 1991; Kumar *et al.*, 1998), and opportunities exist for increasing short rotation wood production by establishing teak in mixed species and agroforestry systems (Kumar *et al.*, 1998; Mutanal *et al.*, 2001; Sharma *et al.*, 2011).

Mixed species plantation establishment has increased over the decades due to demands for diversified products, maintenance of soil quality (ecological services), improved nutrient cycling and greater biomass and tree growth (Binkley *et al.*, 1992; Parrotta, 1999; Montagnini, 2000; Plath *et al.*, 2011). Previous work has shown greater productivity in mixed than in single species stands (Mutanal *et al.*, 2001; Forrester *et al.*, 2004). However, more information is needed to determine growth and yield dynamics of the various possible species mixtures over time and space to ensure the best possible choices are made to suit climate and edaphic conditions (Vanclay, 2006; Subasinghe, 2008).

Establishment of teak in agroforestry and mixed species systems has been conducted in Indonesia and India (Van Noordwijk *et al.*, 1996; Kumar *et al.*, 1998). They reported that interplanting treatments had exerted a profound influence on teak growth and yield and soil
quality. Teak does little to improve soil quality (Kumar et al., 1998), and an admixture of teak with flueggea (*Flueggea flexuosa* Muell. Arg), a shallow rooted and a non-nitrogen fixing tree, with potential to circulate N might improve teak growth and maintain soil quality in Solomon Islands. More importantly, flueggea is a locally useful native tree and it was hoped that mixed species planting would overcome the reluctance of growers to thin pure teak stands. The gradual removal of the flueggea for domestic use would effectively thin the entire stand promoting the growth and form desirable for the final crop of teak. However, as a novel species mix there were uncertainties about the effects of planting teak and flueggea in mixed species system. Data on the growth and yield of both species grown under such a system is not available.

Work on teak growth and yield has been reported for Southern Asia (Laurie and Ram, 1939; Islam, 1988; Phillips, 1995; Langenberger and Liu, 2013; Jha, 2014), Central America (Miller, 1969; Bermejo et al., 2004; Ivan et al., 2004) and Africa (Abayomi, 1984; Nunifu and Murchison, 1998). However, annual growth records of teak are scarce (Perez and Kanninen, 2005) but if reported they are mostly developed from single species plantations and growing at different environmental and soil conditions. Therefore such external growth and yield cannot be used to sustainably manage teak plantations in either single species or mixed species systems in the Solomon Islands.

In this chapter, we examine the growth and yield of teak and flueggea in single and mixed species systems as a result of their interactions over 5 years period. The total height (TH) and the diameter over bark at 1.3 m above ground level were measured biannually during the study period and the basal area (BA) and volume were determined.
The objective of this study was to determine the growth and yield of teak and flueggea growing in different stockings and species ratios over the first 5 years, which are critical to initial growth of the components in the system.

7.3 Materials and Method

7.3.1 Site description

The study was conducted from April 2009 to April 2014 on the mixed species trials established at Ringgi (8° 05´ 16.33´´ S and 157° 08´ 46.62´´ E) and Poitete (7° 52´ 34.39´´ S and 157° 07´ 46.78´´ E) on Kolombangara island, western Solomon Islands. Both mixed species trials were planted on April 2009 on land formerly covered with regenerated secondary forests and located on Oxisol soil (Hansell and Wall, 1975). Ringgi and Poitete mixed species trials are situated at the coastal region at an altitude of 84 m and 27 m a.s.l, where the slope is flat for Ringgi and slightly undulating for Poitete.
The climate is humid tropical and temperature is consistent all year with a yearly mean of 28°C. Ringgi has a monthly rainfall range of 209-376 mm and Poitete 241-425 mm (Figure 7.1). Although the rainfall is fairly evenly distributed throughout the year, there is often a drier period around August and September and wetter period between December and March for both sites. Soil physical and chemical properties are presented in Table 7.1. Very light thinning to remove suppressed and poorly growth trees was applied after assessment at age 4 years to Replicates 2 and 3 at Ringgi and 1 and 3 at Poitete respectively.

Table 7-1: Soil physical and chemical properties of Ringgi and Poitete trials

<table>
<thead>
<tr>
<th>Soil physical and chemical properties</th>
<th>Trial 1 (Ringgi)</th>
<th>Trial 2 (Poitete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density (g cm$^{-3}$)</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>pH</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Cation Exchange Capacity (cmol (+) kg$^{-1}$)</td>
<td>12.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Figure 7-1: Rainfall and temperature of Ringgi (a) and Poitete (b) trial sites
<table>
<thead>
<tr>
<th></th>
<th>6.23</th>
<th>4.30</th>
<th>6.75</th>
<th>5.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Carbon (TC) (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Nitrogen (TN) (%)</td>
<td>0.73</td>
<td>0.48</td>
<td>0.76</td>
<td>0.58</td>
</tr>
<tr>
<td>δ¹⁵N (‰)</td>
<td>7.37</td>
<td>8.30</td>
<td>6.96</td>
<td>7.52</td>
</tr>
</tbody>
</table>

**Table 7-2: Detail of each treatment replicated in 4 blocks at the Ringgi and Poitete trials.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Species ratio</th>
<th>Stems per Hectare (sph)</th>
<th>Planting space</th>
<th>Treatment plot area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teak</td>
<td>1 : 0</td>
<td>833</td>
<td>4 m × 3m</td>
<td>0.058</td>
</tr>
<tr>
<td>2</td>
<td>Teak and flueggea</td>
<td>1 : 2</td>
<td>833</td>
<td>4 m × 3m</td>
<td>0.058</td>
</tr>
</tbody>
</table>

**7.4 Experimental design**

Each trial was established on a 2 ha area and consisted of a similar randomized complete block design with five treatments and four blocks, allowing for spatial variation across both trial sites. The trials were established to examine and determine optimal spacing for teak and flueggea in a mixed species system. The 5 treatments were characterised by species ratio and stocking rates at a given stems per hectare (sph) or planting spacing (Table 7.2). In each treatment, there were 6 lines planted with 8 trees. Each treatment is buffered by the 1st and the 6th lines and the 1st and the 8th trees of each line. Each treatment had a total of 24 measured trees of which T1 had 100 % teak and mixed species stands (T2, T3, T4 and T5) have 33.33 % teak and 66.67 % flueggea. Undergrowth was rich with shrub layer and herbaceous community. During the study period, two pruning operations were conducted at the Ringgi trial and only one was conducted at the Poitete trial. Both trials were treated with manual clear weeding annually.
### 7.4.1 Total height and stem diameter measurements

Total height (TH) of each teak and flueggea were measured biannually. The TH was measured using measuring pole and Suunto Clinometer from ground level to the tip of the leading shoot of the crown. Diameter at breast height (DBH) over bark at 1.3 m above ground of teak and flueggea were measured as of 12 months growth using diameter tape. The volume index of each tree was calculated as the volume of a cone with form factor of 0.5.

### 7.4.2 Data analysis

Average TH, DBH, basal area (BA) and volume were calculated for each plot, and at the tree level for each species. Mean annual increments (MAI) of these variables were calculated over the 5 years growth by dividing the current values by the plantation age.

Individual trees’ basal area is determined by the generic formula (Abed and Stephens, 2003) (Newbould, 1976).

\[
\text{Basal area (m}^2\text{)} = \pi \left(\frac{\text{DBHOB}}{200}\right)^2
\]

(1)

The volume of individual tree was estimated using the volume generic formula (Abed and Stephens, 2003). As Solomon teak has cylindrical and straight bole, the form factor used in the
volume formula was 0.5. This is the same as used by the commercial company, Kolombangara Forest Products Limited (KFPL), to estimate individual tree and stand volume using similar genetic teak material. This form factor is only used for the improved teak genetic material. South American teak has similar form factor of 0.5 (Vriend, 1998) while Indonesian coppiced teak used form factor of 0.7 for volume calculation (Bailey and Harjanto, 2005). Flueggea had similar stem form and therefore form factor of 0.5 was used to determine its volume. This also allows for comparison between species growth.

\[
\text{Volume (m}^3\text{)} = \text{mean basal area} \times \text{mean top height} \times 0.5
\] (2)

7.4.3 Statistical analysis

The SPSS Statistics 22 software was used for statistical analyses. Normality of variables was tested using Shapiro-Wilk test and homogeneity of variance was tested with Levene’s test. The data was further analysed using multiple univariate ANOVA and Tukey post hoc test where necessary to investigate pairwise significant differences in TH, DBH, BA, volume and MAI within species and across species, and across treatments. Origin pro 8.5 was used to plot graphs. If not stated otherwise, all reported values are given as arithmetic mean ± standard error.

7.5 Results

7.5.1 Height growth

There was no significant difference in TH of teak or of flueggea between treatments at age 5 years at Ringgi (Table 7.3). Similarly, there was no significant difference in TH of teak or
flueggea across treatments at Poitete. However, when TH was compared between teak and flueggea, teak had significantly greater TH than flueggea at both sites (p<0.05).

THt growth of teak and flueggea at both sites over 5 years study period is presented on Figure 7.2. While THt for both species is increasing, TH MAI (Figure 7.3) showed that teak growth of all treatments only peaked at 12 months for Ringgi while for Poitete only T4 and T5 peaked at 12 months and T1, T2 and T3 peaked at 24 months and progressively descends thereafter. TH MAI for teak varied at 12 months for teak at Poitete however the variations were not significant and marginalised over time. TH MAI for flueggea at Ringgi increased almost at a constant rate between 12 and 36 months and descended thereafter while for Poitete TH increment peaked at 36 months and descended thereafter.

At age 5 years, either teak or flueggea had no significant difference in TH MAI between treatments at Ringgi, however, across species, teak of T1, T2 and T3 had significantly greater TH MAI than flueggea of T2 and T4 (p<0.05). At Poitete, there was no significant difference in TH MAI of either teak or flueggea across treatments, however, across species and treatments, teak had significantly greater TH MAI than flueggea (p<0.05).

Table 7-3: THt (mean±SE) of teak and flueggea at age 5 years in single and mixed species treatments at Ringgi and Poitete trials

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Ringgi</th>
<th>MAI</th>
<th>Poitete</th>
<th>MAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Teak</td>
<td>20.95±0.29</td>
<td>4.19±0.06</td>
<td>17.46±0.93</td>
<td>3.49±0.19</td>
</tr>
<tr>
<td>T2</td>
<td>Teak</td>
<td>19.60±1.09</td>
<td>3.92±0.22</td>
<td>17.75±0.29</td>
<td>3.55±0.06</td>
</tr>
<tr>
<td>T3</td>
<td>Teak</td>
<td>19.75±0.70</td>
<td>3.95±0.14</td>
<td>17.95±0.71</td>
<td>3.59±0.14</td>
</tr>
<tr>
<td>T4</td>
<td>Teak</td>
<td>18.93±0.29</td>
<td>3.79±0.06</td>
<td>17.41±0.48</td>
<td>3.48±0.10</td>
</tr>
<tr>
<td>T5</td>
<td>Teak</td>
<td>19.11±0.64</td>
<td>3.82±0.13</td>
<td>18.09±0.98</td>
<td>3.64±0.16</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>15.10±0.76&lt;sup&gt;Ac&lt;/sup&gt;</td>
<td>3.02±0.15&lt;sup&gt;Ad&lt;/sup&gt;</td>
<td>12.90±1.36&lt;sup&gt;Ab&lt;/sup&gt;</td>
<td>2.58±0.27&lt;sup&gt;Abc&lt;/sup&gt;</td>
</tr>
<tr>
<td>---</td>
<td>------------</td>
<td>------------------------</td>
<td>----------------------</td>
<td>------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td></td>
<td>15.84±0.62&lt;sup&gt;Abc&lt;/sup&gt;</td>
<td>3.17±0.12&lt;sup&gt;Acd&lt;/sup&gt;</td>
<td>12.97±0.91&lt;sup&gt;Ab&lt;/sup&gt;</td>
<td>2.59±0.18&lt;sup&gt;Abc&lt;/sup&gt;</td>
</tr>
<tr>
<td>T4</td>
<td></td>
<td>14.94±0.68&lt;sup&gt;Ac&lt;/sup&gt;</td>
<td>2.99±0.14&lt;sup&gt;Ad&lt;/sup&gt;</td>
<td>12.36±0.61&lt;sup&gt;Ab&lt;/sup&gt;</td>
<td>2.47±0.12&lt;sup&gt;Ac&lt;/sup&gt;</td>
</tr>
<tr>
<td>T5</td>
<td></td>
<td>16.07±0.63&lt;sup&gt;Abc&lt;/sup&gt;</td>
<td>3.21±0.13&lt;sup&gt;Abcd&lt;/sup&gt;</td>
<td>12.05±1.67&lt;sup&gt;Ab&lt;/sup&gt;</td>
<td>2.41±0.33&lt;sup&gt;Ac&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within columns and by species are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns and regardless of species are not significantly different at p<0.05 (Tukey post hoc test)
Figure 7-2: Mean TH (m) of teak and flueggea over the 5 years period at Ringgi (a) and Poitete (b) trials.

Figure 7-3: TH MAI of teak and flueggea at (a) Ringgi and (b) Poitete trials over the 5 years period.
7.5.2 Diameter growth

Teak of T4 had significantly greater DBH than teak of T1 (p<0.005) while flueggea of T4 had significantly greater DBH than flueggea of T2 and T5 (p<0.05) at age 5 years at Ringgi (Table 7.4). There was no significant difference in DBH of teak between treatments at Poitete while flueggea of T4 had significantly greater DBH than flueggea of T5 (p<0.05). Between species and treatments, teak had significantly greater DBH than flueggea at both sites (p<0.05).

Although DBH growth of teak and flueggea were increasing (Figure 7.4), the DBH MAI (Figure 7.5) showed that the incremental growth is decreasing for both species over the study period. Only the difference of DBH growth between teak of T4 and teak of T1 was significant as of 42 months (p<0.05). Significant difference in DBH of flueggea of T4 over flueggea of T2 and T5 (p<0.05) began as of age 54 months. Similarly, at Poitete, DBH growth difference of teak of T4 and T1 was significant as of 36 months (p<0.05) until was corrected by thinning at age 60 months. Significant difference in diameter over the study period between flueggea of all treatments was only observed at age 5 years between flueggea of T4 and T5 (P<0.05).

Although differences in DBH MAI exist between teak across treatments, only the difference between T4 and T1 was significant at age 5 years at Ringgi (p<0.05). Only the difference in DBH MAI between flueggea of T4 and flueggea of T2 and T5 were significant at age 5 years (p<0.05). Between species and across treatments, teak had significantly greater DBH MAI than flueggea of all treatments (p<0.05). There was no significant difference in MAI DBH of teak across treatments at age 5 years at Poitete. Flueggea of T4 had significantly greater MAI DBH
than flueggea of T5 (p<0.05). Across species and treatments teak had significantly greater DBH MAI than flueggea (p<0.05).

Table 7-4: DBH (cm) (mean±SE) of teak and flueggea at age 5 years in single and mixed species treatments at Ringgi and Poitete trials

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Ringgi</th>
<th>MAI</th>
<th>Poitete</th>
<th>MAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Teak</td>
<td>22.82±0.68&lt;sup&gt;Bb&lt;/sup&gt;</td>
<td>4.56±0.14&lt;sup&gt;Bb&lt;/sup&gt;</td>
<td>21.85±1.53&lt;sup&gt;Aabc&lt;/sup&gt;</td>
<td>4.37±0.31&lt;sup&gt;Aabc&lt;/sup&gt;</td>
</tr>
<tr>
<td>T2</td>
<td>Teak</td>
<td>24.98±0.94&lt;sup&gt;ABb&lt;/sup&gt;</td>
<td>4.99±0.19&lt;sup&gt;ABab&lt;/sup&gt;</td>
<td>25.42±1.39&lt;sup&gt;Aa&lt;/sup&gt;</td>
<td>5.08±0.28&lt;sup&gt;Aa&lt;/sup&gt;</td>
</tr>
<tr>
<td>T3</td>
<td>Teak</td>
<td>26.73±2.04&lt;sup&gt;ABab&lt;/sup&gt;</td>
<td>5.35±0.41&lt;sup&gt;ABab&lt;/sup&gt;</td>
<td>25.72±1.88&lt;sup&gt;Aa&lt;/sup&gt;</td>
<td>5.14±0.38&lt;sup&gt;Aa&lt;/sup&gt;</td>
</tr>
<tr>
<td>T4</td>
<td>Teak</td>
<td>29.71±0.69&lt;sup&gt;Aa&lt;/sup&gt;</td>
<td>5.94±0.14&lt;sup&gt;Aa&lt;/sup&gt;</td>
<td>27.68±1.17&lt;sup&gt;Aa&lt;/sup&gt;</td>
<td>5.54±0.23&lt;sup&gt;Aa&lt;/sup&gt;</td>
</tr>
<tr>
<td>T5</td>
<td>Teak</td>
<td>25.01±0.67&lt;sup&gt;ABb&lt;/sup&gt;</td>
<td>5.00±0.13&lt;sup&gt;ABab&lt;/sup&gt;</td>
<td>22.96±1.32&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>4.59±0.26&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

| T2        | Flueggea| 14.88±0.21<sup>Bc</sup> | 2.98±0.04<sup>Bc</sup> | 15.47±0.91<sup>ABd</sup> | 3.09±0.18<sup>ABcd</sup> |
| T3        | Flueggea| 15.97±0.30<sup>ABc</sup> | 3.19±0.06<sup>ABc</sup> | 15.60±1.22<sup>ABCd</sup> | 3.12±0.24<sup>ABCd</sup> |
| T4        | Flueggea| 16.50±0.32<sup>Ac</sup> | 3.30±0.06<sup>Ac</sup> | 16.62±0.15<sup>Abcd</sup> | 3.32±0.03<sup>Abcd</sup> |
| T5        | Flueggea| 14.60±0.65<sup>Bc</sup> | 2.92±0.13<sup>Bc</sup> | 12.45±0.45<sup>Bd</sup> | 2.49±0.09<sup>Bd</sup> |

Values followed by the same capital letter within columns and by species are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns and regardless of species are not significantly different at p<0.05 (Tukey post hoc test)
Figure 7-4: Mean DBH (cm) of teak and flueggea over the 5 years period at Ringgi (a) and Poitete (b) trials
Figure 7-5: DBH MAI (cm) of teak and flueggea at Ringgi (a) and Poitete (b) trials over 5 years period

7.5.3 Stem basal area

When BA of teak was compared between treatments, teak of T4 had significantly greater BA than teak of T1 (p<0.005) while flueggea at T4 had significantly greater BA than flueggea of
T2 and T5 at age 5 years at Ringgi (p<0.05) (Table 7.5). Between teak and flueggea and across treatments, teak had significantly greater BA than flueggea of all treatments (p<0.05). There was no significant difference in BA of either teak or flueggea across treatments at Poitete though across species and across treatments, only teak at T2, T3 and T4 had significantly greater BA than flueggea of T5 (p<0.05).

While BA of teak and of flueggea were increasing (Figure 7.6), BA MAI of both species were also increasing (Figure 7.6). Teak of T4 had significantly greater BA than teak of T1 (p<0.05) beginning at 3½ years while for flueggea, BA of T4 was significantly greater than of T2 and T5 at 4½ years (p<0.05). At Poitete, only BA growth of teak in T4 was significantly greater than of teak of T1 (p<0.05) beginning after age 3 years until thinning corrected the difference at 5 years assessment at Poitete (Figure 7.6). There was no significant difference in BA between flueggea of all treatments over the study period.

Teak of T4 had significantly greater BA MAI than teak of T1 (p<0.05) while flueggea of T4 had significantly greater BA MAI than flueggea of T2 and T5 at age 5 years at Ringgi (p<0.05). Between species and across treatments, only teak of T2, T3, T4 and T5 had significantly greater BA MAI than flueggea of T2, T3 and T5 (p<0.05). At Poitete, there was no significant difference in BA MAI in either teak or flueggea across treatments at age 5 years due to removal of suppressed and badly formed trees by thinning at age 4 years. Generally, teak had significantly greater BA MAI than flueggea.
Table 7-5: Stem BA (m²) (mean±SE) of teak and flueggea at age 5 years in single and mixed species treatments at Ringgi and Poitete trials

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Ringgi</th>
<th>MAI</th>
<th>Poitete</th>
<th>MAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Teak</td>
<td>0.0410±0.002Bb</td>
<td>0.00820±0.001Bbc</td>
<td>0.0381±0.01Aab</td>
<td>0.00762±0.001Aab</td>
</tr>
<tr>
<td>T2</td>
<td>Teak</td>
<td>0.0492±0.004Abb</td>
<td>0.00984±0.001Abb</td>
<td>0.0512±0.01Aa</td>
<td>0.01024±0.001Aa</td>
</tr>
<tr>
<td>T3</td>
<td>Teak</td>
<td>0.0571±0.01ABab</td>
<td>0.01142±0.002ABab</td>
<td>0.0528±0.01Aa</td>
<td>0.01056±0.001Aa</td>
</tr>
<tr>
<td>T4</td>
<td>Teak</td>
<td>0.0694±0.003Aa</td>
<td>0.01388±0.001Aa</td>
<td>0.0605±0.01Aa</td>
<td>0.01210±0.001Aa</td>
</tr>
<tr>
<td>T5</td>
<td>Teak</td>
<td>0.0492±0.003ABB</td>
<td>0.00984±0.001ABB</td>
<td>0.0418±0.004Aab</td>
<td>0.00836±0.001Aab</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Ringgi</th>
<th>MAI</th>
<th>Poitete</th>
<th>MAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2</td>
<td>Flueggea</td>
<td>0.0174±0.001Bc</td>
<td>0.00348±0.0001Bd</td>
<td>0.0190±0.002Abc</td>
<td>0.00380±0.0004Abc</td>
</tr>
<tr>
<td>T3</td>
<td>Flueggea</td>
<td>0.0200±0.001ABc</td>
<td>0.00400±0.001ABd</td>
<td>0.0195±0.003Abc</td>
<td>0.00390±0.001Abc</td>
</tr>
<tr>
<td>T4</td>
<td>Flueggea</td>
<td>0.0214±0.001Ac</td>
<td>0.00428±0.0001Ac</td>
<td>0.0217±0.0004Abc</td>
<td>0.00434±0.0001Abc</td>
</tr>
<tr>
<td>T5</td>
<td>Flueggea</td>
<td>0.0168±0.002Bc</td>
<td>0.00335±0.0003Bd</td>
<td>0.0122±0.001Ac</td>
<td>0.00244±0.0002Ac</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within columns and by species are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns and regardless of species are not significantly different at p<0.05 (Tukey post hoc test)
Figure 7-6: Mean BA (m²) of teak and flueggea over the 5 years period at Ringgi (a) and Poitete (b) trials
Figure 7-7: DBH MAI (cm) of teak and flueggea at Ringgi (a) and Poitete (b) trials over 5 years period
There was no significant difference in volume of teak between treatments at age 5 years at Ringgi after thinning of suppressed trees was applied at age 4 years (Table 7.6). Similarly, there was no significant difference in volume of flueggea between treatments. When teak and flueggea were compared within and across treatments, teak of all treatments had significantly greater volume than flueggea of all treatments (p<0.05). Similar pattern was observed at Poitete, where there was no significant difference in volume between teak and flueggea of all treatments. Across species and treatments, teak had significantly greater volume than flueggea of all treatments at Poitete (p<0.05).

There was no significant difference in volume MAI of either teak or flueggea of all treatments at age 5 years at Ringgi (Table 7.5). Generally, teak had significantly greater volume MAI than flueggea of all treatments when compared at age 5 years. Similarly, there was no significant difference in volume MAI in either teak or flueggea between treatments at Poitete. Across species and treatments, teak had significantly greater volume MAI than flueggea of all treatments.

Table 7-6: Volume (m$^3$) (mean±SE) of teak and flueggea at age 5 years in single and mixed species treatments at Ringgi and Poitete trials

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Ringgi</th>
<th>MAI</th>
<th>Poitete</th>
<th>MAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Teak</td>
<td>0.429±0.02$^{Aa}$</td>
<td>0.0859±0.005$^{Aa}$</td>
<td>0.339±0.06$^{Aab}$</td>
<td>0.0678±0.012$^{Aabc}$</td>
</tr>
<tr>
<td>T2</td>
<td>Teak</td>
<td>0.486±0.05$^{Aa}$</td>
<td>0.0972±0.011$^{Aa}$</td>
<td>0.457±0.06$^{Aa}$</td>
<td>0.0913±0.011$^{Aa}$</td>
</tr>
<tr>
<td>T3</td>
<td>Teak</td>
<td>0.572±0.10$^{Aa}$</td>
<td>0.1144±0.020$^{Aa}$</td>
<td>0.474±0.07$^{Aa}$</td>
<td>0.0948±0.011$^{Aa}$</td>
</tr>
<tr>
<td>T4</td>
<td>Teak</td>
<td>0.658±0.04$^{Aa}$</td>
<td>0.1316±0.008$^{Aa}$</td>
<td>0.527±0.05$^{Aa}$</td>
<td>0.1054±0.010$^{Aa}$</td>
</tr>
<tr>
<td>T5</td>
<td>Teak</td>
<td>0.472±0.04$^{Aa}$</td>
<td>0.0944±0.008$^{Aa}$</td>
<td>0.386±0.05$^{Aa}$</td>
<td>0.0773±0.011$^{Aab}$</td>
</tr>
<tr>
<td></td>
<td>Flueggea</td>
<td>Yield comparison</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>-----------</td>
<td>------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>0.131±0.004</td>
<td>0.0262±0.001</td>
<td>0.126±0.03</td>
<td>0.0252±0.005</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>0.159±0.01</td>
<td>0.0319±0.002</td>
<td>0.127±0.02</td>
<td>0.0254±0.004</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>0.160±0.01</td>
<td>0.0319±0.002</td>
<td>0.134±0.01</td>
<td>0.0268±0.002</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>0.135±0.02</td>
<td>0.0271±0.003</td>
<td>0.0741±0.01</td>
<td>0.0148±0.003</td>
<td></td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within columns and by species are not significantly different at p<0.05 (Tukey post hoc test).

Values followed by the same letter (lower case) within columns and regardless of species are not significantly different at p<0.05 (Tukey post hoc test).

7.5.5 Yield comparison

Volume per hectare (Ha) of both species showed that teak of T1 had significantly greater volume than the teak of T5, T2, T3 and T4 (p<0.05) while teak of T5 had significantly greater volume than teak of T4 (p<0.05) (Table 7.7). Flueggea of T2 and T3 had significantly greater volume per hectare than flueggea of T4 (p<0.05). When teak and flueggea volumes were compared within and across treatments, the results showed that teak had significantly greater volume per hectare than the flueggea of all mixed species treatments (p<0.05).

For Poitete trial, teak of T1 had significantly greater volume than teak of T5, T2, T3 and T4 (p>0.05) while there was no significant difference in volume of flueggea across treatments. When teak and flueggea were compared, overall, teak had significantly greater volume than flueggea (p<0.05).
Table 7-7: Effect of various treatments on standing volume per tree and standing volume of teak and flueggea per hectare at Ringgi (a) and Poitete (b)

(a) Ringgi

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Volume (m$^3$/tree)</th>
<th>Density (stems/ha)</th>
<th>Volume (m$^3$/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Teak</td>
<td>0.429±0.02$^{Aa}$</td>
<td>833</td>
<td>357.36±20.74$^{Aa}$</td>
</tr>
<tr>
<td>T2</td>
<td>Teak</td>
<td>0.486±0.05$^{Aa}$</td>
<td>300</td>
<td>148.17±16.75$^{BChc}$</td>
</tr>
<tr>
<td>T3</td>
<td>Teak</td>
<td>0.572±0.10$^{Aa}$</td>
<td>225</td>
<td>128.61±22.75$^{BCcd}$</td>
</tr>
<tr>
<td>T4</td>
<td>Teak</td>
<td>0.658±0.04$^{Aa}$</td>
<td>150</td>
<td>94.81±5.75$^{Cced}$</td>
</tr>
<tr>
<td>T5</td>
<td>Teak</td>
<td>0.472±0.04$^{Aa}$</td>
<td>433</td>
<td>202.56±16.56$^{Bb}$</td>
</tr>
<tr>
<td>T2</td>
<td>Flueggea</td>
<td>0.131±0.004$^{Ab}$</td>
<td>533</td>
<td>69.12±2.11$^{Ade}$</td>
</tr>
<tr>
<td>T3</td>
<td>Flueggea</td>
<td>0.159±0.01$^{Ab}$</td>
<td>400</td>
<td>63.75±4.72$^{Ade}$</td>
</tr>
<tr>
<td>T4</td>
<td>Flueggea</td>
<td>0.160±0.01$^{Ab}$</td>
<td>266</td>
<td>43.45±2.22$^{Be}$</td>
</tr>
<tr>
<td>T5</td>
<td>Flueggea</td>
<td>0.135±0.02$^{Ab}$</td>
<td>400</td>
<td>54.65±6.97$^{Ade}$</td>
</tr>
</tbody>
</table>

(b) Poitete

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Species</th>
<th>Volume (m$^3$/tree)</th>
<th>Density (stems/ha)</th>
<th>Volume (m$^3$/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Teak</td>
<td>0.339±0.06$^{Aab}$</td>
<td>833</td>
<td>282.58±49.09$^{Aa}$</td>
</tr>
<tr>
<td>T2</td>
<td>Teak</td>
<td>0.457±0.06$^{Aa}$</td>
<td>300</td>
<td>139.28±17.56$^{Bbc}$</td>
</tr>
<tr>
<td>T3</td>
<td>Teak</td>
<td>0.474±0.07$^{Aa}$</td>
<td>225</td>
<td>106.58±14.98$^{Bbcd}$</td>
</tr>
<tr>
<td>T4</td>
<td>Teak</td>
<td>0.527±0.05$^{Aa}$</td>
<td>150</td>
<td>75.83±6.90$^{Bbcd}$</td>
</tr>
<tr>
<td>T5</td>
<td>Teak</td>
<td>0.386±0.05$^{Aa}$</td>
<td>433</td>
<td>165.79±23.41$^{Bb}$</td>
</tr>
<tr>
<td>T2</td>
<td>Flueggea</td>
<td>0.126±0.03$^{Abc}$</td>
<td>533</td>
<td>66.72±14.58$^{Abcd}$</td>
</tr>
<tr>
<td>T3</td>
<td>Flueggea</td>
<td>0.127±0.02$^{Abc}$</td>
<td>400</td>
<td>50.75±8.51$^{Acd}$</td>
</tr>
<tr>
<td>T4</td>
<td>Flueggea</td>
<td>0.134±0.01$^{Abc}$</td>
<td>266</td>
<td>36.58±2.24$^{Acd}$</td>
</tr>
<tr>
<td>T5</td>
<td>Flueggea</td>
<td>0.074±0.01$^{Ac}$</td>
<td>400</td>
<td>29.93±6.23$^{Ad}$</td>
</tr>
</tbody>
</table>

Values followed by the same capital letter within columns and by species are not significantly different at p<0.05 (Tukey post hoc test)

Values followed by the same letter (lower case) within columns and regardless of species are not significantly different at p<0.05 (Tukey post hoc test)
7.1 Discussion

7.5.6 Tree growth

TH of teak and flueggea in either trial at Ringgi or Poitete showed no significant differences within species up to age 5 years and indicates that planting spacing or stocking and species ratio did not have negative impact on both species vertical growth. When TH of teak and flueggea were compared, teak at higher stocking, especially at T1, T2 and T5 had significantly greater TH and TH MAI than flueggea trees at both sites and this indicates that teak has rapid relative growth rate than flueggea. The significant difference between species emerged after 3 years when Solomon teak often began concentrating on developing its crown. As flueggea was purposely intercropped to influence teak’s form over time, species difference in vertical growth could hinder its purpose early in higher stocking stands. To continue promote flueggea’s role in the system, there is a need for human intervention by applying silvicultural operations such as pruning or thinning or both after age 3 years to promote flueggea’s vertical growth to continue its role as a nurse tree when suppressed by teak’s canopy.

Our study showed that TH increased with closer spacing in both mixed and single species treatments and indicates that intraspecific competition and closer spacing promoted height growth in single and mixed species stands. Closer spacing also promotes suppression of weeds and therefore reduces the cost of maintenance. Our study’s result showed that, teak TH in single species and mixed species stands were greater than the TH of teak that grew in single species stands of age 4 years reported by Nunifu (1998) at Ghana, at age 5 years reported by Medhi and Ahmed (2009) at India, at age 7 to 9 years reported by Langenberger and Liu (2013) at South China, and at age 5.2 years reported by Viquez and Perez (2005) at Costa Rica. The
Solomon teak TH growth suggests that the Solomon Islands, especially the Western Province has one of the best environment and soil condition to establish teak plantation.

Teak and flueggea diameter growth at wider planting spacing were significant over teak and flueggea trees growing in closer planting spacing at both trial sites. The significant difference of DBH growth emerged after age 3 years in single species stand indicates that intraspecific interactions have early negative impact on girth development of teak. This indicates that early thinning is required at higher stocking of single species stand around 3-4 years to maintain the rapid girth increment during the early years of the rotation. In stands of mixed species and at lesser stocking, significant difference in DBH growth was determined later around age 5 years and indicates that both species can grow together up to age 5 years before thinning is required. This allows for both species to develop their girth further compared to single species and higher stocking and can be used locally during progressive thinning. While lesser stocking promotes rapid girth development, bigger branches and larger crowns with weeding problem are usually associated with it. Pruning and clear weeding applications at the right time promotes clear wood growth aligned with rapid girth development. Pruning should promote vertical growth, faster rate of occlusion and reduces the intraspecific and interspecific competitions within the planting lines and across planting lines.

The slower growth of DBH at higher stocking may be caused by smaller canopy size and photosynthetic surface area (Dickens and Will, 2004) and may indicate that intraspecific competition may had begun at age 3 years. Our study’s significant difference of DBH growth in closer planting spacing especially T1 was similar to teak that grew at 952 sph (3.5m x 3 m) in single stand which showed DBH difference was significant at age 3.2 years (Viquez and Prez, 2005). Teak performs at higher growth rate during the first 5 years of the rotation (Perez...
and Kanninen, 2003; Bailey and Harjanto, 2005). Poor management and foregoing the early
growth of girth is losing the peak of wood increment which represent lost increment and cannot
be recovered over the rotation period.

Teak significant DBH growth in mixed species and at lesser stocking may indicate minimum
interspecific interactions effect between teak and flueggea, and therefore influenced teak to
concentrate early growth in girth development. A study conducted by Mutanal (2001) and
Sharma (2011) in India reported that teak that grew in the mixed system or agroforestry system
had significant DBH growth than those that grew in the single species stands. DBH MAI of
teach and flueggea at both trial sites and especially at lesser stocking were significant and
indicates that both species develop their girth earlier at wider planting spacing than at closer
planting spacing. Loss of girth increment at closer planting spacing can be prevented by timely
thinning to maintain the early girth development and ensure maintenance of this growth rate
over time.

7.5.7 Tree yield

Tree yield as measured by relative growth rate of BA was greatest for teak and flueggea at
lesser stocking rate and indicates that teak and flueggea diameter growth was in response to
the available space that enable foliage to gain carbon through photosynthesis that was available
for stem growth (Dickens and Will, 2004). BA can be used to measure competition within a
stand (Rivas et al., 2005) and the lack of significance between teak treatments indicates that
teach growing in various stocking and species ratio had similar girth development up to the 5th
year. Similar BA of flueggea also indicates girth development was not significantly influenced
by stocking or planting spacing and species ratio up to the 5th year. However, the significant
difference of BA between teak and flueggea indicates that teak girth development had higher relative growth rate than flueggea beginning at the 3rd year and suggests that teak begin to invest in its stem to support the developing crown. Teak as observed, began to develop its crown between 3 to 4 years. Flueggea girth development may still have no negative impact from teak growth and the stocking, and therefore was not negatively affected by the increase of teak BA relative growth rate.

According to a study conducted in India, Sharma (2011) reported that, teak BA developed at a faster rate during the first 5 years. Our study relative growth rate was similar to that of Jha (2003; 2014), although both trials have different soil and environmental conditions. Although teak of higher stocking rate had greater total BA per hectare, teak of lesser stocking rate had the greatest BA per tree which is important for individual tree sale into larger diameter teak market. It is anticipated that teak of lesser stocking rate will catch up with teak of higher stocking rate BA per hectare when thinning of 50% removal is implemented.

Tree yield as measured by relative growth rate of volume was not significantly different within each species across treatments and suggests that either teak or flueggea has similar growth rate across all treatments. The stocking rate or planting spacing and species ratio had minimum negative influence over tree growth up to 5 years. However, the significant difference between teak and flueggea in volume indicates species difference in relative growth rate, in which teak may grow at rapid rate than flueggea. Although teak of higher stocking rate had greater total volume than the other treatments, over time it is anticipated that the other treatments will marginalize the difference when schedule thinning is executed over the rotation. During which only flueggea will be removed from the mixed species stands while teak will be removed from the single species stand. Benefits offered by the mixed species system to tree growers include
flueggea wood for local use and nutrient cycling through mixed species litterfall which ensure better soil quality than under single teak stand.

7.5.8 Tree form

Establishing teak under 5 treatments present 5 different management options for teak growth in Solomon Islands. The best treatment would have positive influence over teak TH and BA growth. Teak growers are anticipating rapid growth rate with greater commercial volume and good form. According to field observations over time using scoring technique (result not included) and based on the 5th year growth and yield, lesser stocking especially T4 met the above requirements followed by T3, T2, T5 and T1. Comparing teak tree form, teak form were graded according to the following order T1, T5, T2, T3 and T4 while flueggea followed the order T5, T2, T3 and T4. Tree form was influenced by intraspecific competition where individual tree competes for radiation interception and photosynthetic surface area (Dickens and Will, 2004). Crown and branching development were best at T3, T2, T5, T1 and T4. T4 showed bigger branches and lower that could be controlled by intense silviculture to archive clear wood on the base of the tree, which is the prime log. This is worth doing if short rotation of 25-30 years wood is anticipated by the tree growers.

7.6 Conclusion

The successful establishment of the two scientific trials that accommodated the five treatments have showed various responses of teak and flueggea in different treatments although are very preliminary. When managed and continued to be monitored these trials will provide regimes on the ways teak plantings can be established and managed by smallholders in Solomon
Islands. Teak and flueggea that grew at the higher stocking representing the normal stocking (833 sph) presented the greatest total height while basal area is optimized at the 412-625 sph for both species. Significant differences in growth especially diameter occurred between ages 4 and 5 years and this indicate that progressive thinning regime should begin around the 4th-5th year to optimise basal area. There was clear effect of flueggea on teak form and crown development in mixed species stands that have direct effect on the basal area development over time and space. As the data represented the first 5 years which is usually referred to as establishment period, monitoring and assessment need to continue to maturity to fully determine the overall growth of teak and flueggea in single and mixed species stands. By then the overall outcome of both species growing in various density and ratio will be fully understood. Meanwhile, the tables and graphs could be provisionally adopted as a guide for managing teak in Solomon Islands and the region and could form a useful basis for future studies. In the interim, this study provides limited but extremely promising observations and results of teak growth and yield in single species and mixed species systems and their potential in the Solomon Islands.

7.2 Reference


Laurie, M., Ram, B., 1939. Yield and stand tables for teak (*Tectona grandis* L.f.) plantations in India and Burma. Indian Forest Record Silviculture 4-A (1). Forest Research Institute, Dehra Dun, India.


**7.7 Photos of Teak and Flueggea Tree Growth**

**Plate 7-1:** One (1) year old teak and flueggea in a 833 sph mixed species stand intercropped with potato. Notice teak concentrate on vertical growth with minimal crown development compared to flueggea on either sides.

**Plate 7-2:** Two (2) years old single teak stand at 833 sph.
Plate 7-3: Two (2) years old teak planted in alternating rows with a single row of flueggea at 833 sph. Notice the angle of the branches and the height of the first live branch compared to teak branches in Plate 7.1.

Plate 7-4: Two and half (2½) years old teak in single teak stand at 833 sph. Notice the height and form.
Plate 7-5: Two and half (2½) years old teak in mixed teak and flueggea stand at 833 sph. Notice the height of teak first live branch and the size of teak crown base, the branches are small as influenced by flueggea crown development. Flueggea crown influence on teaks’ crown enables self-pruning and straight form in teak over time.

Plate 7-6: Four (4) years old teak in mixed teak and flueggea stand at 833 sph. Notice that
teaks’ DBH (right side) is greater than flueggeas’ DBH (left side).

Plate 7-7: Four (4) years old teak in unthinned single teak stand at 833 sph. Notice that teaks’ DBH is smaller than that of teak in mixed teak and flueggea stand as showcased in plate 7.6
8.1 Summary

Solomon Islands have been subject to logging multiple times and it has been projected that the flow of timber from the natural forests will decrease significantly by 2020. Re-entry of logging companies into previously logged forest areas has opened up the country’s island forests, and landscapes have been degraded and deforested at an unsustainable rate, calculated at an average of 2.0 million m$^3$ of timber per year over the last 3 years (2012-2015). Approximately, 1.1 million m$^3$ of round logs had been exported by June 2015 and it was projected that the log export for 2015 would exceed the average round logs exported over the last 3 years. Many of these logged over forest areas are overtaken by weeds and creepers which slow or even halt natural regeneration. The logged areas are generally regarded as wasteland by local communities and have lost most if not all of the traditional values and uses that communities placed on them.

Agriculture in Solomon Islands follows the common tropical practice of shifting subsistence farming whereby forests are slashed and burnt during land preparation. Farming is an important economic activity for the 80% of Solomon Islanders who live in rural areas and sale of excess produce is one of the few income generating activities for a predominantly subsistence farming population. After crops are planted, they are maintained through routine clear weeding to prevent competition and allow crops to bear maximum production. All the unwanted weeds are heaped and burnt. After crops are harvested, the farm areas are commonly left to fallow in most areas of the Solomon Islands. However, in the highly populated areas such as Malaita Province, and other smaller Islands where arable land is scarce, the length of bush fallow may be considerably reduced when compared to lesser populated islands and Provinces. In Malaita and
other populated islands and areas, the plant residues are heaped and burnt following harvesting
in preparation for the next cropping. Such practices rapidly degrade the soil fertility through
loss of nutrients via residue burning and harvesting and with little time for the land to recover
through bush fallow. The research projects described within this thesis therefore took place
within this context of traditional practices of slash and burn, shifting subsistence agriculture.

Growing high value timber species is one of the few potential means for people to earn money
in rural areas in Solomon Islands, where land is still available for tree plantings. However, a
basic lack of understanding of silvicultural management of plantations and of the principles of
land use planning has left a legacy of problems for timber growing communities. Exotic species
such as teak and mahogany are only grown for sale, not for personal use and each tree is
regarded as having a high potential value. This has led to reluctance to thin (seen as lost
potential income) with no understanding of the timber for own use and with no market access
for even the commercial thinnings. As a result plantations are overstocked with suppressed
growth and poor log quality.

In areas of high population, land is at a premium and the conflicting needs of land for
agriculture and land for growing potentially high value timber has led to unrest within
communities and families and led to situations where people have to walk long distances to do
farming (still the major economic activity) because arable land has been taken over by trees. In
highly populated areas like Malaita and other inhabited smaller islands, people will argue over
user and occupational rights of the land and this has prevented people from having a broader
socio-economic base to support their livelihoods. In areas where the need for timber and food
competes with the need for income generation, interplanting of crops between trees is a viable
alternative means to satisfy competing demands and a way forward.
In response to the need for timber and to address the reluctance in applying thinning, and the need for farming for food and income generation, the Australian Centre for International Agricultural Research project FST/2007/020 developed a novel silvicultural system to address the problem. Several agroforestry trials were established to test the hypothesis that teak could be successfully grown together with a local tree *Flueggea flexuosa*. Flueggea is a widely used timber for local construction and fencing. It was interplanted between rows of teak with the progressive harvesting of the flueggea for local use effectively thinning the plantation and allowing teak to develop through to harvestable size. The trees could be further intercropped with food crops over time as an agroforestry system, allowing for continuous multiple land use and income generating opportunities whilst the trees grew through to maturity. With correct management, this integrated system should also promote maintenance of soil fertility and at the same time improve nutrient cycling to guarantee sustainable production for future generations using the same land.

Previous studies of tree growth, crop production and soil fertility outside of Solomon Islands under different environmental conditions provide valuable insights into the productivity of agroforestry systems components (Kumar et al., 1998; Sharma et al., 2011a; Sharma et al., 2011b). However, these studies do not investigate how these system components interact over time as the result of competition, canopy development; nutrient losses and the biogeochemical cycling of C and N influenced by each component’s growth and yield. Although studies have reported on intercropping teak trees with leucaena trees and food crops (Kumar et al., 1998; Sharma et al., 2011a; Sharma et al., 2011b), the novel mix of teak and flueggea trees, further intercropped with food crops has never been examined. While understanding the growth and yield of these integrated systems is important, similar attention is needed to understand the
interactions and cycling of C and N in plant-soil systems that are critical for sustainable production and maintenance of soil fertility.

Competition for nutrients between individuals in mixed species and agroforestry systems can negatively affect overall growth and yield; however, complementarity and facilitation in the capture and efficient use of the available growth resources in the mixed species system would produce positive outcomes. Uptake and storage of N in tree biomass is important to understand as the cycling and loss of nutrients in a system partly depends on the removal and turnover from different parts of the tree. The research reported in this thesis therefore aimed to examine the different components of a novel mixed species system to better understand how the components of the system interacted together in order to improve the management and development of this system to suit the prevailing conditions within Solomon Islands.

In Chapter 4, we used $^{15}$N-labelled tracer to examine: nutrient uptake and concentration in teak and flueggea tree components of ages 2 and 4 years; nutrient cycling through teak and flueggea litterfall between ages 2½ and 3½ years; and nutrient uptake in the biomass of harvestable food crops intercropped in the 2 years old stand. The study looked at the uptake of $^{15}$N tracer and how it was partitioned between teak and flueggea in a mixed species system. This was to help us understand relative nutrient demand between teak and flueggea in the mixed species system at the industry standard stocking rate of 833 sph. The results showed that uptake of $^{15}$N-labelled tracer at ages 2 and 4 years was not significantly different between species and indicates that at the normal stocking and up to 4 years after establishment, competition for N was minimal. Both teak and flueggea grow rapidly in the humid tropical environment of Solomon Islands and canopy closure may occur within 24-30 months following planting. It is normally understood that trees are in competition for nutrients around this time when canopy closure
starts to happen and that the first, pre-commercial thinning should commence around this time to avoid competition. In light of these findings, it is recommended that, pre-commercial thinning should be considered after age 4 year in these mixed species stands so that tree growth can be kept at peak growth in the early period of the rotation when trees grow rapidly.

We also looked at how nutrients, especially N was taken up by crops that had been inter-planted between the rows of teak and flueggea trees in an agroforestry system. It was determined that recovery of labelled-$^{15}$N in food crops was statistically similar to the concentration of labelled-$^{15}$N in the soil and not significantly different to teak and flueggea uptake. This study indicated that teak, flueggea and food crop uptake of labelled-$^{15}$N were similar and suggested that food crops will remove as much Nitrogen from the agroforestry systems as the trees. The similar uptake of the tracer by teak, flueggea and food crops was possible because the tracer was surface applied and therefore was equally available to crops as to the deep rooted trees. However, food crops are planted on a short rotation and an actively managed system may have up to 4 rotations per year of food crops. The removal of N through harvesting may have serious implications for the longer term health of the agroforestry systems, especially in light of the traditional practice of burning residues after harvest. In order to manage the removal of N through food crops harvesting, it is recommended that residue retention be practiced as part of the agroforestry system and that at least 1 crop in 3 be leguminous to return N to the system through biological nitrogen fixation.

We looked at how nutrients, especially N were stored in different parts of teak and flueggea trees and how they were cycled through litterfall in a mixed species stand. It was determined through this study that teak and flueggea allocate higher $^{15}$N to foliage and this emphasised the importance of N cycling through foliage and leaf litterfall. In order to maintain the N cycling
within the agroforestry system, it is recommended that, the litterfall are not burnt but equally
spread on the ground surface to control weeds and left to decompose to release nutrients back
into the soil and be available to the food crops.

In Solomon Islands, farming practices involves harvesting of crops, burning of crops residues
after harvest and burning of weeds and leaf litterfall. For instance, at the end of each cropping
season, weeds, potato and bean residues including leaves, are piled at a spot and burned during
site clearance in preparation for the next cropping season. According to this study, it was
determined that allocation of labelled-$^{15}$N was higher in the foliage. This suggested that,
progressive removal and burning of weeds and harvesting of crops can lead to reduction of N
available to the trees in agroforestry systems. Although this study showed that there is no
significant difference in the uptake of N by weeds, crops and trees components of the system,
the initial N analysis could only indicate the sufficient fertility of the soil for the first few years
to maintain multiple cropping systems. Over time, this practice would not support and sustain
nutrient availability to the tree component of the system. In Solomon Islands, and many other
Pacific Island countries, if site clearance and maintenance of farm land continue to involve
burning of plant residues, foliage and litterfall, the soil for farming would rapidly loose
nutrients for plant growth over a short period of time. Commercial farmers often purchase
inorganic fertilizers to improve soil fertility but it is prohibitively expensive for small scale-
farmers in Solomon Islands. Growing legume crops in the interrow can maintain or improve N
availability through biological nitrogen fixation and this is the cheapest means of injecting N
back into the system to sustain productivity over time.

In Chapter 5, we examined the cycling of C and N through leaf litterfall over an 18 months
period in mixed stands of teak and flueggea and in monoculture stands of teak between ages 2
and 3½ years. The study looked at the leaf litterfall production of teak and flueggea and how it varied between stocking rates in monoculture and mixed species systems. This was to help us understand monthly and annual single species and mixed species total litterfall production during canopy development.

Monthly leaf litterfall production ranged from 250.51 to 541.61 kg ha\(^{-1}\) depending on treatment and trial. Although Treatment 1 produced the highest total leaf litterfall, individual teak tree total litterfall production was lower than individual teak tree production in Treatment 4; demonstrating higher individual litterfall production at lower stocking rates. The result demonstrated that intraspecific interactions have a direct effect on crown development by influencing trees to develop smaller crowns and compete on gaining height. This resulted in smaller crowns and lower foliage production and therefore reduced individual tree litterfall production at higher stocking rates. On the other hand, teak trees that grow in lower stocking treatments developed larger crowns and have higher foliage production that guarantee higher photosynthetic capacity which would give greater carbon acquisition than teak in higher stocking treatments with smaller crowns and lower foliage production.

We also looked at nutrient cycling especially C and N through teak and flueggea leaf litterfall production in monoculture and mixed species stands. This was to help us understand the monthly and annual cycling of C and N by single species and mixed species total litterfall production during canopy development. Overall, TC and TN returned via leaf litterfall was highest in treatments with the higher stocking rates without significant difference between single and mixed species stands and lowest in stands with lower stocking rates. However, on individual tree basis, highest return of TC and TN was from the lower stocking. Both the amount of litterfall and the C and N returned through litterfall are directly involved with the
competitive interactions in silvicultural systems. On the one hand, the lowest stocking rates give highest individual tree litterfall and nutrient return resulting from greater individual levels of sunlight interception and photosynthetic capacity. Conversely, higher stocking rates reduce the sunlight available to individual trees but achieve an overall higher collective litterfall and nutrient return. Good silvicultural management of these systems is dependent upon achieving the right balance as at wider spacing, pruning and weeding will have to be conducted on time to promote good form and this has proven to be difficult to achieve in smallholder plantings in Solomon Islands. Higher stocking rates may give a more efficient sunlight interception, but the competition for this resource can result in poor growth of individual trees and lower commercial returns. This has been the case in Solomon Islands where reluctance to thin has resulted in poor growth. Interplanting flueggea in between teak rows and progressively pruning both trees and thinning flueggea as canopy closes would promote good form at this stage of plantation development.

This study presents an alternative means for planting teak in Solomon Islands and the Pacific Islands using flueggea or any other suitable local or introduced species. The treatments represent different options that can be applied to different situations such as where higher population density leads to higher resource pressure compared with areas with low population density and low resource pressure. It may be in the areas where there is high resource pressure on land, that the smallholder grower may choose a wider spacing to allow for greater agricultural activity, but this would require higher maintenance of the trees to manage form, control of early branching and green crown pruning. The time for crown development is when the desired form has been acquired and thinning is applied to make growth space available for crown development. Making such growth space available in the woodlots guarantees higher
foliage production and promotes greater photosynthetic capacity, which leads to steady girth development over time.

In Chapter 6, we examined the root structure and biomass development of teak and flueggea of ages 2 and 4 years old, important for uptake of nutrients, stabilisation of the trees and responsible for competition belowground. The study looked at the root structure and biomass development of teak and flueggea at ages 2 and 4 years in mixed species systems using destructive sampling methods. Teak and flueggea stumps and roots were excavated to help us understand the development of the root architecture of both species and the roots occupation of the soil volume over time.

Total excavation of 7 teak and 7 flueggea trees within isolation plots showed that teak has a more aggressive root structure and occupied a larger portion of the soil volume than flueggea. Part excavation of both species growing outside of isolation plots (control) further confirmed that teak root architecture occupied more soil volume horizontally and vertically than flueggea.

We determined both species roots biomass at ages 2 and 4 years. This was to help us understand the biomass development of both species over time. Each tree’s total root fresh biomass was assessed using a Golden Lark 200 Kg scale. Root biomass of both species increased by about 87% from age 2 to 4 years although the difference was significant with teak the greatest. At both ages, the root biomasses for both species were 20-22% over the total tree biomass and the increase between ages showed that root productivity over time is species or genetically based and the difference was not influenced by competition. These results demonstrated that competitive interactions between both species were at minimum up to 4th year and that teak had greater biomass C belowground (Chapter 5) than flueggea which represents an important
C sink in forest plantations and agroforestry systems. Further, as teak has deeper roots, it captures and recycles the leached nutrients especially N in this study, that are beyond flueggea’s reach back into the system.

This study provided information on root architecture and biomass growth of teak and flueggea which are not available during normal plantation management operations. The fact that, both species roots showed a slightly different root structure development over time and occupation of different soil zones confirms that teak and flueggea can be grown together and that the hybrid mixed species model is a viable option for outgrowers and farmers because it involves minimal below ground competition during the first 4 years of the model. Solomon Islands has both deep volcanic soils and shallow coralline soils. The rooting habit of the teak would suggest that, that species would flourish best on deeper soils and it is a generally accepted wisdom that mahogany (Swietenia spp.) should be grown in areas of coral soils rather than teak.

In Chapter 7, we examined teak and flueggea growth in monoculture and mixed species stands. We measured the total height and diameter at breast height over bark over a five (5) year period. This was to help us understand the growth and form development of both teak and flueggea over the initial 5 years of the mixed species stands and to determine if flueggea have positive impacts on teak growth over time in the system.

This study demonstrated that teak growth and form were enhanced with flueggea intercropping. Teak diameter increased with wider planting spacing while height was not significantly different across treatments. Intercropping flueggea between teak rows developed a positive interaction between species which was reflected in promotion of excellent teak form and rapid growth. The two species are morphologically very different (Fig 8.1), especially in the first 2 years with teak generally a single stem with broad leaves growing straight from the stem and
powering the upward growth. Flueggea branches early and tends toward crown development unless planted densely.

Plate 8-1: Teak and flueggea intercropped with sweet potato. Teak at the right of the picture, shows typical form at that age without branches at age 18 months. To the left are flueggea trees with well-developed crowns.

When grown together, the teak crown was pushed up by flueggea crown below resulting in teak producing smaller branches and facilitated a self-pruning habit. Smaller branches and self-pruning promote clear wood development and this is the preferred, and therefore higher priced, timber in world timber markets. Although wider planting spacing promoted significant increase in diameter increment, teak trees tend to develop wider crowns with lower and bigger branches which would require correction with timely and frequent pruning. This study determined that, while wider planting spacing is good for promoting diameter growth and allow longer period of intercropping of food crops, it encourages larger crowns with bigger branches that reduces the amount of clear wood. To promote clear wood and girth growth, timely pruning (at least 3 lifts) and weeding must be executed in the first 5 years while in closer planting spacing 2
prunings are required before self-pruning sets in and weeds are suppressed. It is determined by this study that the best treatments for establishment and promotion of good form of mixed teak and flueggea and that will allow for longer period of intercropping food crops and prevent thinning of teak are Treatment 2 and Treatment 3.

In Solomon Islands, most of the smallholder growers were reluctant to apply silvicultural operations such as pruning and thinning to their woodlots, as a result, woodlots were deprived of maintenance that would promote steady tree growth and wood quality. Lack of silvicultural awareness programs by the agencies involved in promoting smallholder plantings lead to the poor management of the private woodlots that resulted in underperformance of teak stands with slim stems and smaller crowns.

Smallholders need to be informed of the importance of the application of silvicultural operations. The message that pruning controls competition for sunlight and promotes clear wood and the thinning increases the amount of growth resources available to each tree and promotes girth growth and canopy development over time must be made known to the smallholder growers through awareness programmes. Because the benefit reaped from timely applications of the silvicultural operations is reflected through the quality of the logs with clear wood that has higher chances to command higher prices in the world timber market or to access niche timber markets.

The growth of teak and flueggea during the initial 5 years in the mixed species systems has shown the positive effect of intercropping flueggea on teak’s growth and form. Teak’s basal area was significantly greater in the mixed species stands with lowest stocking rate and promoted a steady height growth which should promote better timber quality over time,
compared to teak growing in monoculture stands that were competing on height with less concentration on their girth development under intraspecific interactions influence. This study has confirmed that teak can be grown with flueggea and highlighted an alternative means to grow teak in Solomon Islands that is equally applicable to other Pacific Island States.

8.2 Conclusions

At this stage in the development of this hybrid system which combines plantation silviculture, mixed species planting and food crops, it is still early to decide whether the hybrid model will finally overcome the problems faced by smallholder growers in Solomon Islands and the Pacific Island States. However, early indications are positive with excellent growth and form being shown by both teak and flueggea in the mixed species and agroforestry trials. The amount of food crop harvested over the first year of the rotation was encouraging, but to better understand the yield over time will require a longitudinal study that takes into account changes in light availability and grower attitudes to this novel method of food cultivation in Solomon Islands.

Mass spectrometer analysis of labelled $^{15}$N on teak, flueggea and food crops isolated in a close system indicated that, the agroforestry components can grow together with no significant competition in the first five years of the hybrid model. This allows for agroforestry diverse products and ecosystem services benefits to smallholder growers in the Island countries where arable land is scarce.

Thinnings in the trial plots were readily utilised by local communities though it is interesting to note that while the flueggea thinnings were all taken for community use, the teak thinnings
were not. This suggests that more effort must be put into education of local communities on
the excellent properties and durability of teak. Community members must be made aware that
tea thinnings can also be used in all applications where flueggea thinnings are being used
around the village and we suggest that teak thinnings can be trialed in taking the place of
flueggea in traditional houses rafters and panels, fencing and carvings.

Although teak trees can withstand cyclones or strong winds at early stage (Nancy et al., 2017),
the recent cyclone Raquel that hit the Solomon Islands in early July 2015 showed that non-
thinned teak stands are susceptible to wind-throw due to poor root growth and development.
On another mixed species trial, Saika at a neighbouring Kohingo Island, where flueggea was
planted at a higher density between teak rows (1 teak row: 5 flueggea rows at 2m between
planting rows) to promote height growth in flueggea, the root development of flueggea was
poor. Lateral roots were shorter and closer to the surface and susceptible to wind-throw. Teak
roots were well developed and vertical roots grew deeper because it was well spaced by the 5
rows of flueggea. The cyclone Raquel experience recommended the need for thinning
application when canopy closes to promote better root development for better above ground
growth and anchorage. There is a need to look on other species in mixed species models to suit
the Solomon Islands climate and therefore future research needs.

The study purposely addresses the issue of reluctance to implement thinning on close canopy
tea plantations in the Solomons. The outcome of this study showed that establishment of teak
plantations with flueggea is a way forward because intercropping flueggea enhances teak
growth in height and girth development at the growing phase important for the better
development of clear wood. Uniform crown development of all teak trees with smaller
branches above the flueggea canopy enabled self-pruning and promotes cylindrical stem
development. Tapering was minimal or controlled and buttresses were absent, highlighting high quality teak logs for niche market or higher recovery when milled. Thinning of flueggea trees as the canopy closes continues to make available space for interrow cropping of root crops and legumes that ensures supply of food, surface ground cover and nutrient cycling. It is obvious in Solomon Islands that teak plantations that were not thinned grew tall with slower girth growth and with smaller crowns that had less leaves for photosynthesis that ensures tree growth. Crown development is important for growing trees because good crown development ensures leaf production where photosynthesis takes place and leaf litter ensures nutrient cycling. Finally, the study confirmed that flueggea can grow with teak in a mix species system and timely thinning of flueggea gives way for intercropping of food crops to continue and supply of wood for local use by communities and land owners. In a country like Solomon Islands, where people are living in islands and there is an increase of dynamic populations and land for farming will become scarce in the coming years, agroforestry is the way forward because it ensures multiple products and ecosystem services that can be reaped on the same land. One can harvest food, timber and the soil would be replenished with nutrients over time for the continuous support of livelihood into the future.

The establishment of the two mix species trials at Ringgi and Poitete was expensive in terms of both money and time consumed. The four (4) years of work in the assessment of the two scientific mix trials had given data and info that suggests some adjustments to the local practice of farming to enhance productivity and management of nutrient cycling to achieve fast growing trees and food crops that are important and necessary to support local livelihoods. The recommendations and the outcome of the research will be made known to the public and the government ministries including the Ministry of Agriculture and Livestock, Ministry of Forestry and Research, Ministry of Environment, Conservation, Disaster and Meteorology and
Ministry of Rural Development and will be part of the Solomon Islands National University Agroforestry teaching manual to train students and resource owners. These Ministries and institution should drive the recommendations to support the livelihood of the people so that no further degradation and deforestation would occur in the country’s natural forests. International and locally established NGOs that work closely with the communities to improve their livelihood will be informed and given the recommendations of the research to adopt and drive the recommendations.

8.3 Future studies

This study provided a greater understanding of the growth of teak and flueggea above- and below-ground and uptake, storage and biogeochemical cycling of C and N important for tree and food crops growth and production in mixed species and agroforestry systems. However, as this study was undertaken in the first five years period of the mixed species and first 2 years of the hybrid agroforestry systems, the conclusions highlighted above were strictly for the establishment or early years. It cannot be used to predict the interactions going on between teak and flueggea as they approach their mid and late rotation years. How the intra- and inter-specific interactions will affect the cycling of C and N and their impact on soil quality and to tree growth and yield later in the rotation cannot be concluded with the gathered early growth productivity and biomass. Further, their allocations and storage on C and N in their biomass as they age, is still in question. Because of those restrictions and unknowns in the later stage of the mixed species and hybrid agroforestry systems, the shortcomings of this study needs to be further investigated to fully understand the overall systems interactions to maturity. By then, the mixed species and the hybrid agroforestry systems could be understood and be properly
and practically utilized to sustainably produce diverse products and maintains ecosystem services.

Thus the uncertainties later on in the systems further warrant future studies that could be conducted on the following areas:

(1) Study of C and N dynamics in mixed species systems over multiple rotations.

(2) Study of C and N dynamics of litterfall in mixed species systems over multiple rotations.

(3) Study of N loss through denitrification in mixed species systems over multiple rotations.

(4) Study of resource competition especially nutrients and water in mixed species systems over multiple rotations.

(5) Study of N re-translocation in teak and flueggea leaf litterfall in mixed species systems over multiple rotations.

(6) This is the first study in the tropical Pacific and especially the Solomon Islands to examine the root topology and distribution of teak and flueggea base on destructive and semi-circle exposer of standing tree root structure. Lack of assessment of control trees growing in free environment warrants further root architecture assessments at 2 and 4 years and further in the mid (10-13 years) and mature age (25-30 years) of each species. The root development examination can assist in the decision of when to execute the commercial thinning to control competition belowground.

8.4 Reference

