Commercial Eucalyptus Plantations with Taungya system in Lao PDR: Analysis of Tree Root Biomass

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Master Thesis no. 241

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A 6-year old Eucalyptus plantation in Ban Sang. Photo: Emma Sandell Festin 2013

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Abstract

The increasing demand for wood, fibre and pulp coupled with efforts to mitigate greenhouse gas emission has put immense importance on the development of forest plantations. The rapidly growing human population will also face shortage of food, particularly in developing world where agricultural productivity is generally low. The taungya system – an age-old agroforestry practice involving intercropping of crops with trees on the same unit of land – is opined as a win-win strategy to meet the needs of wood products and food at the same time. In recent years, the taungya system has gained increasing attention by big forest companies as a tool and an opportunity to contribute to the social well-being of the local community. Stora Enso Lao Co, Ltd is one of these forest companies that adopted the taungya system in its commercial Eucalyptus plantations in Laos. The tree spacing commonly used is 9 × 1 m, and 5 × 2 m on a trial basis. *Eucalyptus camaldulensis* was intercropped with rice and cassava, and stands were established in 2007 (7-yr old) and in 2012 (2-yr old). The main objective of this thesis was to examine whether the intercropping has an effect on the root system of trees; thereby generating knowledge that supports evidence-based plantation management decisions involving taungya system. The key research questions were: (a) Does intercropping of rice/cassava with Eucalyptus influence the horizontal and vertical distributions of root biomass of trees compared with monoculture plantation of different spacing? (b) Does spacing (5 × 2 m versus 9 × 1 m) influence the horizontal and vertical distributions of root biomass of trees intercropped with rice? (c) Does root biomass differ between young (2-yr old) and mature (7-yr old) intercropped stands with 9 × 1 m spacing compared with monoculture plantation? If so, does the effect vary in relation to distance from the tree and soil depth? To characterize the root system architecture, trenches were made on six young trees in both pure monoculture and intercropped stands. To quantitatively estimate root biomass, a total of 324 soil cores (6 stands × 6 trees × 3 distances × 3 soil depths) was collected, roots sorted and dried to constant mass in an oven at 60°C for 48 hours. The root dry mass data were subjected to analysis of variance to examine significant effects of intercropping, spacing and stand age. The results show that (1) the root system of *E. camaldulensis* is mainly confined to shallow depth but well elongated horizontally in both pure and intercropped stands with 4-6 thick lateral roots; (2) Intercropping of rice/cassava with Eucalyptus has no effect on total root dry mass of the tree component ($p > 0.05$) irrespective of the plantation models (5 × 2 m or 9 × 1 m); however root biomass decreases with increasing horizontal distance from the tree base and in deeper soil layer; particularly for trees in young stands; (3) The effects of spacing design, narrow (5 × 2 m) versus wide (9 × 1 m), on root dry mass are dependent on horizontal and vertical distribution of the root system; and root biomass appears to be higher at 40 cm soil depth for the stand with narrow spacing between trees and crops than stands with wider spacing; (4) Root biomass was larger for older than younger trees in both monoculture and intercropped stands; suggesting lack of carry-over effect of intercropping on root biomass. As root biomass varies with horizontal distribution, further research is recommended to test buffer zones between trees and crops other than 1 m (which is currently used).

Keywords: *Eucalyptus*, agroforestry, root development, root system, Southeast Asia

Preface

This is a master thesis on advanced level, it consists of 30 hp and is the finish of my education for the Jägmästare (Master of science in Forestry) given at SLU. The work has been done for the Department of the Southern Swedish forest research Centre in Alnarp. The study was done in collaboration with Stora Enso Lao Co, Ltd (SEL) and Burapha agroforestry Co, Ltd (BAFCO) and the fieldwork was carried out in Laos.

Acknowledgements

I would like to thank Mrs Emma Sandell Festin, Former R&D assistant at Stora Enso Laos, for her support in providing background information and material about the on-going spacing projects in Savannakhet and Saravanh Provinces, Lao PDR and putting me in contact with Stora Enso Laos. And for assisting me in the writing process.

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1. Introduction

The increasing demand for wood, fibre and pulp coupled with efforts to mitigate greenhouse gas emission has put immense importance on the development of forest plantations. As a result, a considerable surge in areas of new forest plantations has been observed over the past decades (FAO, 2010). Particularly, planting short-rotation trees (e.g. Eucalyptus, Acacia), long recognized as sources of raw material for bioenergy (Shepherd et al., 2011), pulp and paper industries, as we all as potentially sequester carbon, is actively pursued in the tropical world. The global extent of forest plantations has been increasing by an average of 2% annually, and today there are about 140 million ha of forest plantations, of which nearly 110 million ha have been established primarily for wood production. The proportion of the world's industrial wood sourced from forest plantations is expected to continue to increase, to nearly 50% by 2040 so as to meet the demand for wood products by the growing human population. This demand can be met with intensive management of planted forests. Intensively-managed planted forests are highly productive, and hence the owner invests sustainably over the life of the forest so as to optimise wood production. The scale of intensively-managed planted forests can vary from the tens to hundreds of thousands of hectares to smallholders as little as 0.1 ha. The nature of ownership also varies from big forest corporations or governments to the estates of larger-scale private landowners. Nowadays, big forest companies are moving to the south (tropics) to establish commercial short-rotation forest plantations to supply wood and fibre industries with the desired quality and quantity of raw materials in the shortest possible time. One of this forest companies is Stora Enso Co. Ltd., which has been engaged in the establishment of intensively-managed short-rotation plantations in Asia, including China and Laos.

The rapidly growing human population will not only face shortage of wood products but also shortage of food. Food security is indeed key issues today, particularly in developing countries, where there is scarcity of arable land, in the one hand, and high population pressure and low means of production, on the other. Therefore, an approach that balances these wood and food demands must be sought after. Over the past several decades, agroforestry system has been proven to be a win-win solution for producing both wood and food at smallholder farm size. Agroforestry is a land management technique that provides both food and timber production as the agriculture and forest management is combined on the same unit of land (Alexander et al. 1980). There are several different agroforestry systems globally; one of the most commonly used is the Taungya system – where agricultural crops are intercropped between rows of trees on the same unit of land (Jordan et al 1992). Although the taungya system is an age-old practice, it has gained increasing attention in recent years as a tool and as an opportunity by external private forest owners to contribute towards the wellbeing of local communities – a moral obligation to fulfil corporate social responsibility. Many scientists have stated that the usage of the Taungya system influences the afforestation cost in a positive way at the same time as short-term goals like food production is fulfilled (Victor & Bakare 2004).Intercropping trees with crops secures the food and energy resources, reduces the reforestation cost, creates more job opportunities, and increases the participation of local people in the reforestation procedure

(Kalame et al. (2011). Agroforestry can also play an important role in poverty alleviation and as a tool for the 3rd world countries to fulfil the millennium development goals (Garrity, 2004). It can be seen as a financial security for local communities/families to have a wood resource in case of failed agricultural results. (Victor & Bakare 2004). As part of its corporate social responsibility, Stora Enso Lao Co. Ltd. has adopted the taungya system in the commercial Eucalyptus plantations. However, there is a lack of knowledge on how the tree and crop components interact; particularly for below-ground resources. An understanding of the root interaction is paramount to support evidence-based plantation management decisions. In the subsequent sections, an overview of taungya system, general information about Laos and the current taungya practice by Stora Enso Lao will be presented. This will be followed by key research questions, methodology and finally the results, discussion and conclusions.

1.1 The Taungya system – historical overview

Originally, the term Taungya was the name used by mountain Karen tribe in Burma to refer to the shifting cultivation system (Evans et al 2006). It is unclear exactly when the first Taungya system was practiced, but the large-scale usage began in 1868, when the forest service promised farmers bonuses for the successful sowing of teak. After the crops were harvested and the farmers have moved on to another spot, the young teak plantation was handed over to the forest service. This involvement of farmers in the practice meant that they were enlisted for forestry purposes (Jordan et al. 1992). This can be seen as the real starting point and it rapidly spread throughout British India. A couple of years later it was also introduced to several African countries (Kenya, Nigeria, the Ivory Coast, Ghana and Sierra Leone) and also to some extent in Latin America (Evans & Turnbull 2006). However, undocumented stories exist where the usage of the Taungya system occurred much earlier than the 1800th century in Burma (Jordan et al 1992). Dietrich Brandis is seen as one of the founders to the reorganized teak management in Burma in the mid-1800th (Evans & Turnbull 2006).

Over time, the original taungya system has been modified in a variety of ways in countries and regions in which it has been introduced. Since the introduction of the taungya system, the areas under this practice have been constantly growing. Although relevant statistics are lacking, it can roughly be estimated that in the region of southern Asia, around 1-2 million ha of natural forest have been managed under the taungya system. Whereas the area coverage of taungya system in other parts of the tropics, like Africa and South America, is roughly half of the area coverage in southern Asia (Jordan et al 1992). Although this information may not be very reliable, it still shows that Taungya systems have small presence in comparison with the total area of tropical forests. The major advantages of the system presented in the next section makes this fact not comprehensible. The lacking of a breakthrough on a bigger scale is hard to find any answers to. It can only be explained by the existing disadvantages such as the demand of intense labour, which also questions the financial viability (due to increasing labour salaries). It could also be answered by the fact that the practice is tied to certain conditions, such as reachable location, access to water for the crops and trees and enough nutrients in the soil for Taungya, which might not be met everywhere (Jordan et al 1992).

1.2 Taungya system – descriptions and advantages

The taungya system is a form of agroforestry, where agriculture crops are intercropped with trees for a certain time (Jordan et al. 1992). The original goal with the taungya system was to reduce deforestation by the former shifting cultivation method and at the same time make it possible for the local people to produce their food (Alexander et al. 1980). The general idea behind the taungya system is to simultaneously plant agricultural crops and trees at the same area and let it grow until the tree canopy closes. It usually occurs 2-3 years after planting, but it is highly dependent on the types of crop that are being cultivated (Schlonvoigt & Beer 2001). After the closure of crop cultivation, grass is often planted underneath the trees to create an opportunity for the local communities to have grazing for their cattle up until the end of the rotation. After the clear cut there are different ways to proceed depending on planting material, community wishes, and company directives if a company is managing the land. The first alternative is to leave the grass cover and continue to have the grazing opportunity for the local communities and establish the new plantation through coppice. The second alternative is to do soil preparation again and do intercropping with cash crops or rice and plant new improved Eucalyptus clones, and the third alternative is to leave the grass and only do soil preparation in the tree lines and plant improved Eucalyptus clones and let it grow into dimensions suitable for the local markets. It is important to note that the farmers and their crop production are seen as the short-term goal of the agroforestry system, while the main aim and long term goal is to have productive tree plantations in the end (Chamshama et al. 1992). In this regard, taungya fits well into the concept of multiple land use and is still practiced throughout the tropics. The system can effectively avoid the most serious consequences of shifting cultivation, is generally accepted by farmers where possibilities of earning a living are few, is the cheapest conversion system for forest administration today, and it eventually leads to the establishment of even-aged, homogenous monocultures. However, some studies have observed tendencies that the taungya system may lead to soil erosion in forest plantations that might lead to soil degradation and/or cause run-offs into important water resources if it is implemented on steep slopes that are not suitable for this purpose. This has the potential to cause high environmental and social negative impacts (Alexander et al. 1980).

Nonetheless, the taungya system has long been seen as a sustainable practice when managed correctly and as an important approach to meet the need of the local population. Food is the key problem for many rural communities in developing countries. Taungya is one way to contribute to food security for these communities. The agriculture practice is often inefficient with the lack of modern equipment, facilities and generally insufficient land cultivation. As a result, the famers seldom have the possibility to grow enough food to feed their family and to do profitable business (Victor & Bakare 2004). Thus, a combination of experiences from farmers, qualified foresters and good organization are all important factors for the success of the Taungya system as an approach to boost food production (Alexander, Sobhana et al. 1980).

Since the system was founded, it has been modified and improved along the way, especially the conditions for the farmers. In general, farmers, land owners, Non-governmental organizations (NGOs) and local communities are involved in the decision making role nowadays (Agyeman, Marfo et al. 2003). The trees that most often are included in the Modified Taungya system are both indigenous and exotic tree species like for example Teak (*Tectona grandis*), Cedrela (*Cedrela odorata*), Eucalyptus species, Cassia (*Cassia siamea*), Wawa (*Triplochiton scleroxylon*), and East African Mahogany (*Khaya anthotheca*). Common crops used by the farmers are okra, pepper, plantain, cocoyam, maize, yams, tomatoes, cassava, cabbage and groundnut. The majority of the farmers stated that their most important benefit gained from the system was the access to farm land and not a significant interest regarding income generation (Kalame et al. 2011). Ros-Tonen et al. (2013) have summarized some major social and sustainable goals that the taungya system fulfil and contributes to. The contributions include:

- providing legal security to farmers in the form of legitimate access to land for agroforestry and rights to timber resources
- creating an incentive to adapt to a changing situation and establishing a legal source of timber for small and medium enterprises (soft law enforcement)
- Setting an example of a societal agreement for more equitable sharing of forest benefits
- contributing to capacity building and the development of skills in tree planting, seedling production and social organisation, and to the building of social and economic capital
- Finally, the system helps to expand the forest resource base through reforestation. Timber from taungya farms is legally produced and therefore meets the Timber Legality Standards.

Basically it secures local people's needs, is well adapted to the market, is working towards equity in the rural areas and contributes to the development of forestry knowledge, skills and forest resources that are meeting sustainable standards and regulations. All variants of the taungya systems are likely to continue having an important role in forest plantation development in the tropics. In comparison to other agroforestry practices, the taungya system will probably remain an inexpensive system, which often does not require radical change in life-style by the local people.

1.3 Laos – General information

Laos is a landlocked nation in Southeast Asia and is surrounded by Burma, Thailand, Vietnam, China and Cambodia. The size of Laos is 236 800 km^2 which is approximately half the size of Sweden and has a population of 6.4 million inhabitants (Ketphanh 2012). Laos is also a mountainous country, especially in the northern parts, where they also have a more dense forest cover compared to the other parts of the country (Utrikespolitiska institutet 2014). Laos is one of the poorest countries in Asia. One reason is that it is landlocked with poor infrastructure that does not allow for much processing of their resources. Laos also has poor communication possibilities and lack of both capital and skilled labour, which makes the country's natural wealth largely untapped, something that is now changing (Utrikespolitiska institutet 2014). Just over a quarter of Lao people live in extreme poverty, despite the fact that the poverty rate has declined in relation to economic growth in the 2000s. The social difference between the metropolitan area of Vientiane (the capital) and the mountainous regions, where minority people lives, is huge. Laos was at number 139 out of 187 countries on the UN Development Index for 2014 http://hdr.undp.org/en/content/table-1-human-development-index-and-its-components. The level of education in Laos is low and illiteracy is relatively widespread. This is partly due to the lingering problems after the Civil War, 1954-1973, which hit the education sector hard. In addition, poor infrastructure in mountainous areas makes it difficult for many children to go to school, and some children are needed at home as labour to help their family.

Laos is considered one of the most bombed countries in the world throughout the history. Around one third of all the bombs dropped did not explode and is still today a major problem for the local communities with their agricultural practices. Having bombs in the ground makes it very difficult to have and maintain a safe and efficient agriculture and the people are everyday risking their lives practicing their common agricultural system, shifting cultivation. The situation is also considered bad due to the low utilization of the agricultural land and its inability to provide the increasing population with enough food (SLU 2008). Agriculture is the main livelihood for most Laotians. About three-quarters of the population are employed in agriculture, which accounts for almost a third of gross domestic product (GDP). Most farmers however have small compounds and can only cultivate for their own household consumption (Utrikespolitiska institutet 2014).

Laos is rich in timber, hydropower and minerals such as iron ore, copper, coal and gold. According to the land use and forest cover of Laos, the total land area of 23,680 million hectares, 41.5 percent of these are covered by the current forests in 2005 (http://theredddesk.org/sites/default/files/fs_2020.pdf). Until the beginning of 2000th century the extraction of most natural resources was limited, but since then, the Lao government has entered into several agreements with foreign companies for exploitation. As a result, the mining industry has grown substantially as well as the forestry and hydropower sectors. The most important exports are wood products (legal wood), coffee, electricity, tin, copper, gold, clothes and other textiles. Most of the exports are going to China, Vietnam and Thailand (Landguiden 2015). The natural forest cover is around 40 % or approximately 9,5 million hectares from which 360 000 hectares are forest plantations. As Figure 1 illustrates, rubber plantations are dominating (234 000 ha) followed by Eucalyptus and Acacia (42 000 ha), *Tectona grandis* (33 000 ha), *Aquilaria sp.* (12 000 ha) and others (39 000 ha). The majority of the species are for economic purposes while the category “others” are planted mostly for restoration operations.

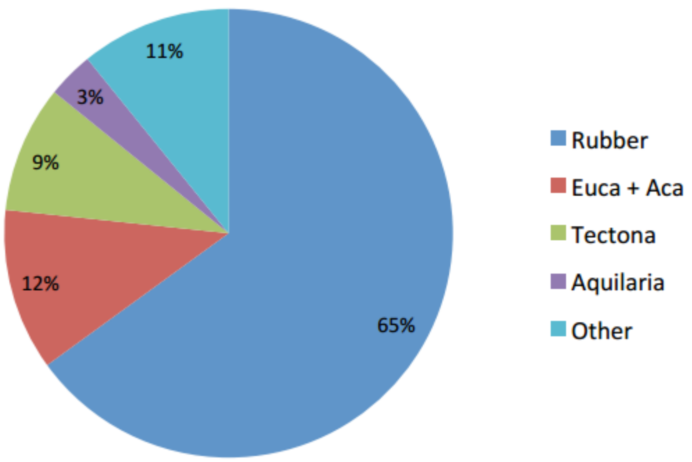


Figure 1: Distribution of species in forest plantations in Laos 2012

Laos has a general forest cover target for 2020, which is to increase the forest cover to 70 % of the total land area. This goal may have an impact on availability of potential agricultural land and a combination of agriculture and forestry is therefore needed to balance timber production, improving ecosystem services and goods as well as food security (Ketphanh 2012).

1.4 Adoption of Taungya by Stora Enso in Laos

Stora Enso Lao Co.,Ltd. (SEL) is one of the forest companies involved in the establishment of commercial tree plantations in Laos. SEL has worked toward a forestry practice that can play a greater role in the work of mitigating the conditions and the situation of poverty in Laos. Through good forest management and communication with the people in those areas both SEL and Burapha Agroforestry Co., Ltd. (BAFCO) see good opportunities in both having an efficient agricultural practice, but also be able to grow trees in the same area. A combination of forestry and agriculture will generate employment, create income, and increase the possibilities for the poor people in the rural areas of Laos (SLU, 2008). SEL has therefore come up with an agroforestry project in the remote parts of the Savannakhet and

Saravanh provinces to enhance the agricultural situation and meanwhile maintain short rotation forestry. The model is based on wide spacing between trees, 9 x 1 meter (1111 seedlings per hectare), and instead of doing the traditional shifting cultivation system the project gives possibilities to plant rice and cassava between the tree rows (SLU 2008). The intercropping model (modified Taungya system) is improving the welfare for local communities by increasing both the yield of rice and cassava, but also allowing for commercial wood production. This system has created jobs for the local communities (bush clearance, soil preparations, plantation, maintenance, and harvesting of trees) and has thereby enhanced their economic situation (SLU 2011).

SEL does not own any land in Laos, instead the company rent the land from the villages on a 50 years contract. The payment for the lease does not go to the village leaders; instead they have created a system with village development funds to help improve the living conditions for the villages, such as providing electricity, running water, infrastructure, and so on. Through discussions and agreements with the local people who lease out their land, plantation areas that do not exceed 500 hectares were made available and aimed to create a scattered mosaic of land uses and native forest. The plantations were established with a wide spacing (9 × 1 m) to open up and create enough space for villagers to do their agricultural practices. Local people (villagers and farmers) involved in this project receive cash income from the land lease and from the work opportunities and are therefore enhancing their living standards. In addition, SEL is committed to have a hundred per cent bomb clearance in the areas they plant. The main purposes for clearing bombs is to keep the workers safe and to have a safe place for the villages to plant their rice (SLU 2011).

The planted areas consist of mainly *Eucalyptus spp*. (*Eucalyptus camaldulensis* hybrids) and in some cases *Acacia spp*. Between the tree rows, agriculture crops, such as rice and cassava, are planted and managed until the tree canopy closes, usually two to three years after planting. The trees shall have a one-meter buffer zone free from crops on both sides of the trunk (Figure 2), meaning that the roots have two meter of undisturbed soil. The villagers can therefore plant seven meters between the tree rows (SLU 2008).

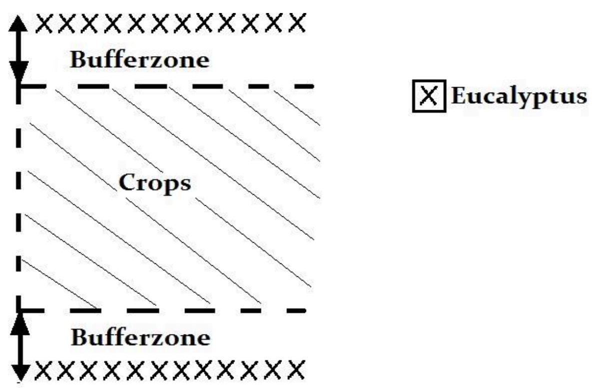


Figure 2: Illustration of current plantation design

When establishing a new plantation, the land is cleared of other vegetation, to be noted is that SEL only plant on degraded land that the local people no longer use for agriculture, mainly former shifting cultivation areas. The taungya system is only implemented on areas where the local people are interested in intercropping. When plantations are far from villages or areas where the agriculture is inefficient, the agroforestry model with wide spacing is not used. Instead 3 × 3 m spacing of pure eucalyptus stands are established. The local people are involved in managing the plantations and therefore more work opportunities are created (SLU 2011).

The soil preparation is done either with harrowing or ripping depending on soil depth and soil conditions. Before planting, approximately 330 kg Dolomite fertilization per hectare is added, followed by 220 kg one year after the establishment. During one rotation, SEL totally adds around 0.55 ton/ha fertilizer in all plantations (SEL fertilization scheme). Weeding is done at least once a year, firstly by hand around the seedlings and then by machine as the trees grow.

SEL is interested to see if the agroforestry practice is beneficial for the trees as the soils are disturbed few times each year and the left over from the crops is ploughed down in the soil or if the practice has no influence on the root development at all. As the root systems and its development have not yet been studied in Laos, SEL recognises the need from knowledge to make evidence-based decision regarding future establishment of Eucalyptus plantations. This includes short- and long term effects, negative and positive, from current establishment methods on the root systems of planted Eucalyptus trees.

1.5 Objectives and research questions

The study aims at examining how the integration of agriculture practices into short rotation tree plantations affect the development of tree roots; thereby generate knowledge for improved implementation of the taungya system implementation in the forest plantations in Laos. The fact that SEL is using wide spacing and have their main focus on rice and cassava as agricultural crops in the plantations with Eucalyptus, factors such as spacing and crop type are expected to influence the development of root systems of trees. In this research, the age factor was also considered to investigate the carry-over effects of intercropping on root development after the crops have been ceased. The key research questions and their corresponding hypotheses were:

a) Does intercropping of rice/cassava with Eucalyptus influence the horizontal and vertical distribution of root biomass of trees compared with monoculture plantation of different spacing?

   Hypothesis: Root biomass would be less in intercropped than pure eucalyptus stand.

b) Does spacing (5 × 2 m versus 9 × 1 m) influence the horizontal and vertical distribution of root biomass of trees intercropped with rice?

   Hypothesis: root biomass will be more in the stand with wider than narrow spacing.

c) Does root biomass differ between young (2 yr old) and mature (7 yr old) intercropped stands with 9 × 1 m spacing compared with monoculture plantation? If so, does the effect vary in relation to distance from the tree and soil depth?

   Hypothesis: root biomass will be lower in young than mature intercropped stand as the farthest away the root system is from the tree and at deeper soil depth.

2. Material and methods

2.1 Study site

The study was carried out at four different sites/villages (Kean Luang, Ban Takor, Ban Sang and Sabong kokhai) in Saravan and Savannakhet provinces in southern Laos close to the border to Vietnam (Figure 3) in September 2014 to coincide with the rainy period, because the soil was easier to work with at that time of the year (end of wet season). The plantations were all established with 9 × 1 m and 5 × 2 m spacing with or without intercropping with rice or cassava under similar silvicultural prescription and in agreement with the local people living in the areas. The tropical climate in Laos with its Southeast Asia monsoons produces distinct seasons. The rainy season generally starts in May and continues to the end of September, but the rain can continue well into October, especially in the mountain range. December to January have the lowest temperatures with big diurnal variation, sometimes the temperature can be as low as 5°C. Frost can occur in some areas. February to April is the hottest season with temperatures up to 40°C (http://theredddesk.org/sites/default/files/fs_2020.pdf). The mean annual precipitation is between 1800-2500 mm and approximately 90% falls during the wet season (May-September). The temperature in the area can vary between 14- 35°C and the average temperature of the Savannakhet region is 26°C (SLU 2008).

Figure 3: Map of Laos and location of the study area
(Source: http://www.worldatlas.com/webimage/countrys/asia/laos/lalatlog.htm)

2.2 Design of the study

For this study, three intercropped and three pure Eucalyptus monoculture stands were selected. The stands were established with 5 × 2 m spacing in 2007 and 9 × 1 m in 2007 and 2012. The 5 × 2 m stand was intercropped with rice for the first two years; the 9 × 1 m stand established in 2007 was intercropped with rice while the 9 × 1 m stand established in 2012 was intercropped with cassava. The stands established in 2007 were 7 years old and considered hereafter as mature stand as the rotation period is between 5-7 years while stands established in 2012 were 2 years old and considered hereafter as young stands. All trees were planted on ripped lines with homogenous soil properties in the plantation spots chosen.

The study was conducted by using two different methods; namely trenching and core sampling. Trenching was done to gain insights into the root architecture and to guide subsequent soil coring (where and how to do it) for quantitatively determining root production. For trenching, a total of 6 healthy and dominant trees, excluding edge trees, were subjectively selected since trenching is destructive and time-consuming. In addition, dominant trees normally have a more developed root system than suppressed trees and fully utilize their growth potential. Once the tree was selected, a rectangular area of 2.5 x 1.0 m to a depth of 0.5 m was dug out (Figure 4), and the root systems were observed and photographed. Due to the limited number of samples, trenching was only conducted in two different stands that were both established in 2012 with 9 x 1 m spacing. The differences between the stands were that one stand had a history of intercropping with rice and the other stand had no history of intercropping at all. Trenching was done close to the tree, about 0-75 cm away from the stem base, and on two sides of the selected trees (Figure 5).

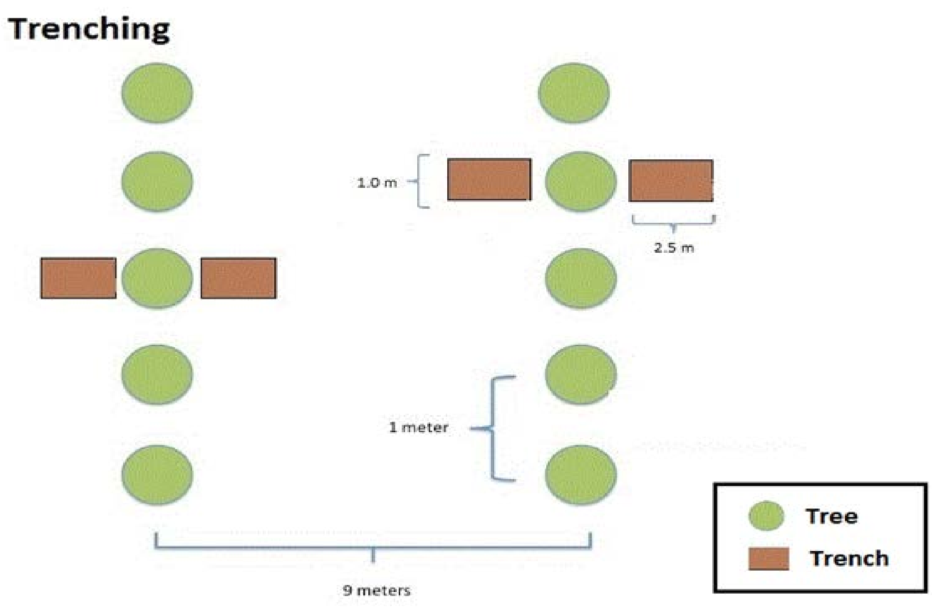


Figure 4: Illustration of the trenching procedure in 9 x 1 plantations.

Figure 5: An outline of trenching made to characterize the root system of Eucalyptus (Photo: Simon Edberg).

For core sampling, 36 sample trees were subjectively selected from stands established in 2007 and 2012 with 9 x 1 m and 5 x 2 m that were intercropped with rice/cassava and monoculture. For each sample tree, 9 core samples were taken at different soil depths (0-20 cm, 20-40 cm and 40-60 cm) and distances from the sample trees (Figure 6). The core samples were taken with a soil core cylinder with a cylinder volume of 1570 cm^3. As the volume of the cylinder is the same on all samples the volume of the soil core device was not considered. sThe first distance was 100 cm from the tree base, and the subsequent distances were determined using the formula, [((Spacing/2)-1)/2]. Thus, for 5 x 2 m stand, the two subsequent distances were set at 75 cm interval (i.e. 175 cm and 250 cm from the tree base) while for the 9 x 1 m stand the two subsequent distances were set at 175 cm interval (i.e. 275 cm and 450 cm from the base of the sample tree.

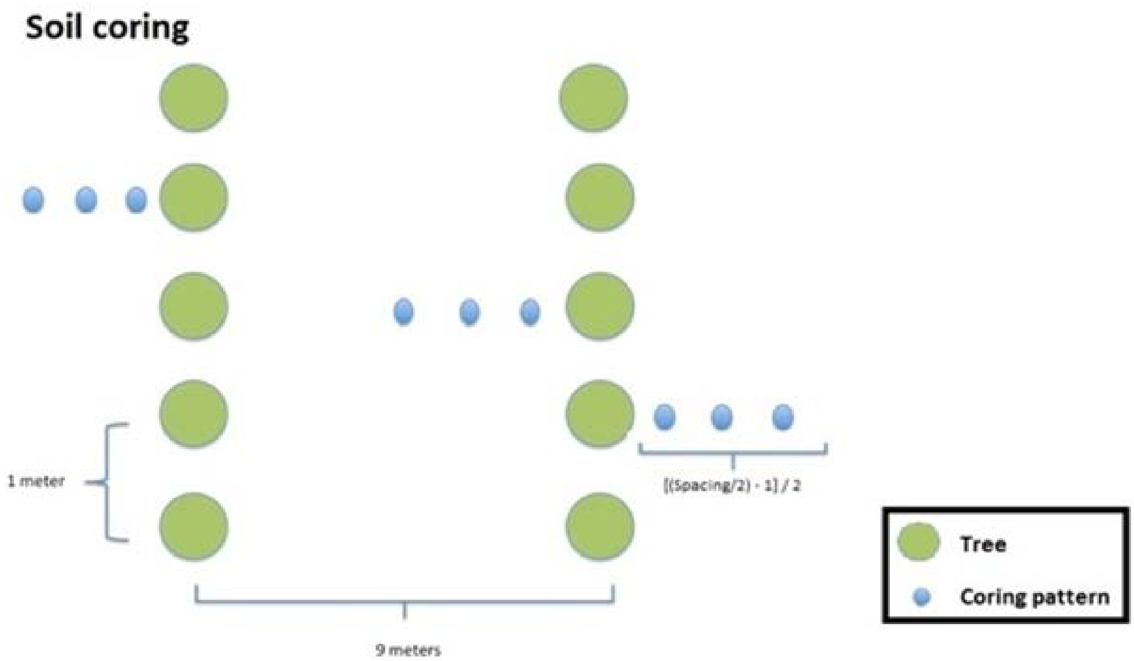


Figure 6: Illustration of soil coring procedure.

2.3 Collection of root samples

For each individual sample tree, root samples were collected using a stainless steel soil corer (100 mm internal tube diameter). During the sampling, 1 tree within the row was selected; excluding the edge trees (end of the row), as those trees will benefit from the edge effect on 3 sides instead of 2 sides like most of the trees. The tree chosen was always one of the dominant trees. Cores were sampled stepwise for each soil depth at 20 cm interval down to 60 cm. A total of 324 cores (6 stands × 6 trees × 3 distances × 3 soil depths) was collected and packed separately in plastic bags. To be able to distinguish Eucalyptus roots in the field, visual root characteristics, morphology, colour and the architecture were used as identification kit. Before drying, all roots were carefully washed under a gentle flow of tap water to remove adhering soil. Thereafter, the roots were dried in an oven at 60°C for 48 hours until the root dry mass remained constant.

2.4 Statistical analysis

For each sample tree, total root dry mass was computed by summing up root dry mass from different soil depths; and two-way ANOVA was computed to determine the effects of intercropping and distance from the tree for each stand separately. To examine the variation in root dry mass across soil depth in relation to intercropping and distance from the tree, three-way ANOVA was performed. To examine the effects of spacing (5 × 2 m versus 9 × 1 m), distance from the tree and soil depth on root dry mass, three-way ANOVA was performed for stands intercropped with rice and established in 2007. Three-way ANOVA was also performed to examine the effects of stand age (young versus mature stands with 9 × 1 m), distance from the tree and soil depth on root dry mass. As the 9 × 1 m stands were intercropped with rice (mature stand) and cassava (young stand), three-way ANOVA was performed for the intercropped and monoculture stands separately to disentangle the confounding effects of crop type. Results of the statistical analyses were considered significant if $p < 0.05$ and show tendencies if $0.05 < p < 0.10$. Means that exhibited significant differences were compared using Tukey's test.

3. Results

3.1 Overview of root system architecture

The typical root system of two-year old *E. camaldulensis* tree in the 9 x 1 m spacing plantations is shown in Figure 7. The root system is located in the upper parts of the soil (shallow depth) but well elongated horizontally in both pure and intercropped stands. The number of main lateral roots ranged from 4-5 in intercropped stand and 5-6 in pure Eucalyptus stand (Table 1). The corresponding number of secondary lateral roots was 12-22 in intercropped stand (B) and 12-13 in pure Eucalyptus stand (A).

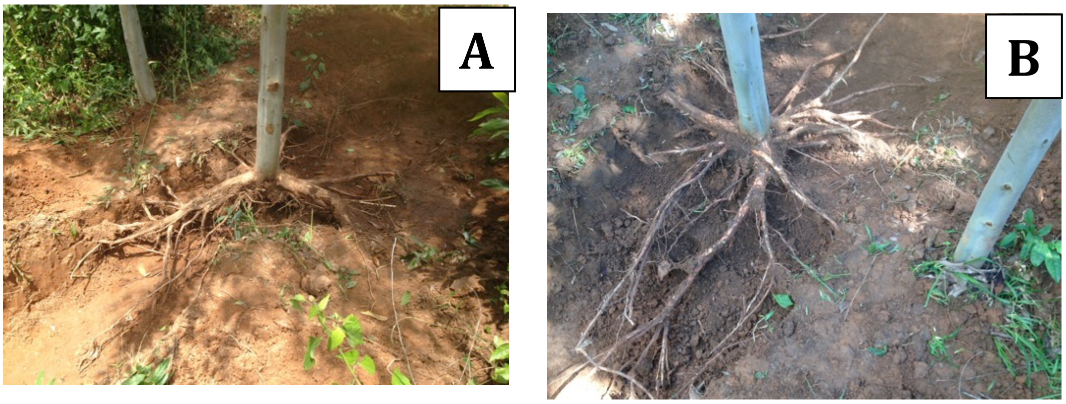


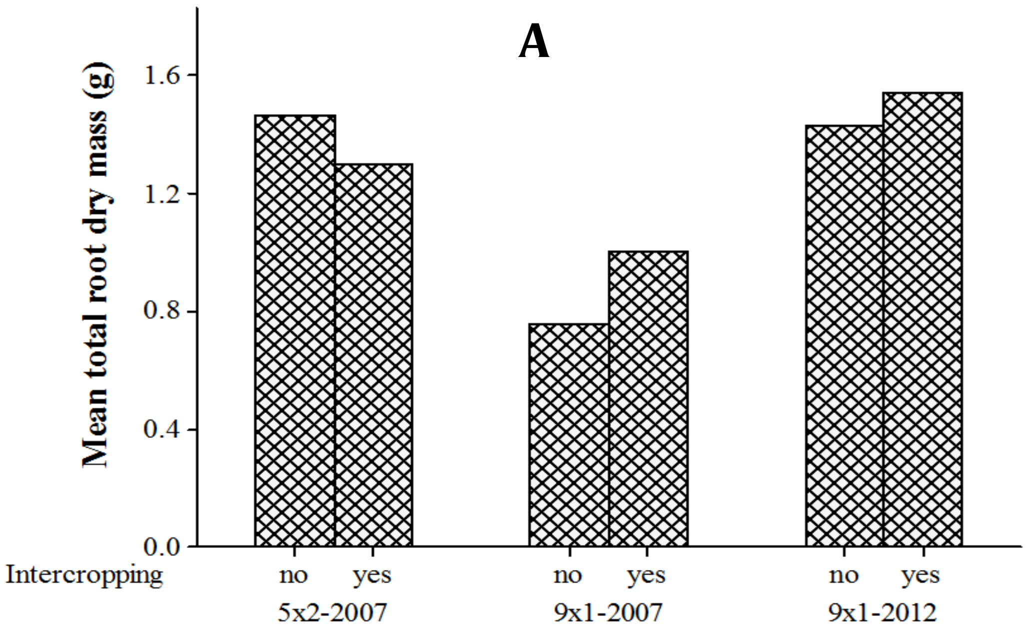
Figure 7: Typical root system of two-year old *Eucalyptus camaldulensis* tree in monoculture (A) and intercropping (B) (Photo: Simon Edberg).

Table 1. Descriptive statistics of no. of main and lateral roots of two-year old E. camaldulensis grown in pure and intercropped stand (n = 6).

		Stand type	
Variable	Statistics	Intercropped	Pure
No. main roots	Minimum	4	5
	Maximum	5	6
	Mean	4.7	5.3
	Standard deviation	0.6	0.6
No. lateral roots	Minimum	12	12
	Maximum	22	13
	Mean	16.7	12.7
	Standard deviation	5	0.6

3.2 Effects of intercropping and distance from the tree on root dry mass

For 7-year old *E. camaldulensis* stand established in 2007 with 5 × 2 m spacing, two-way ANOVA revealed lack of significant differences in total root dry mass between stands intercropping with rice and tree monoculture (p = 0.711); however, total root dry mass tended (p = 0.097) to decrease with increasing distance from the tree base. There was also no significant interaction effect (p = 0.155) of intercropping and distance from the tree base on total root dry mass. The mean total root dry mass (g) of E. camaldulensis trees in stands that were intercropped with rice and tree monoculture (A) and at different distances from the tree base (B) is shown in Figure 8.



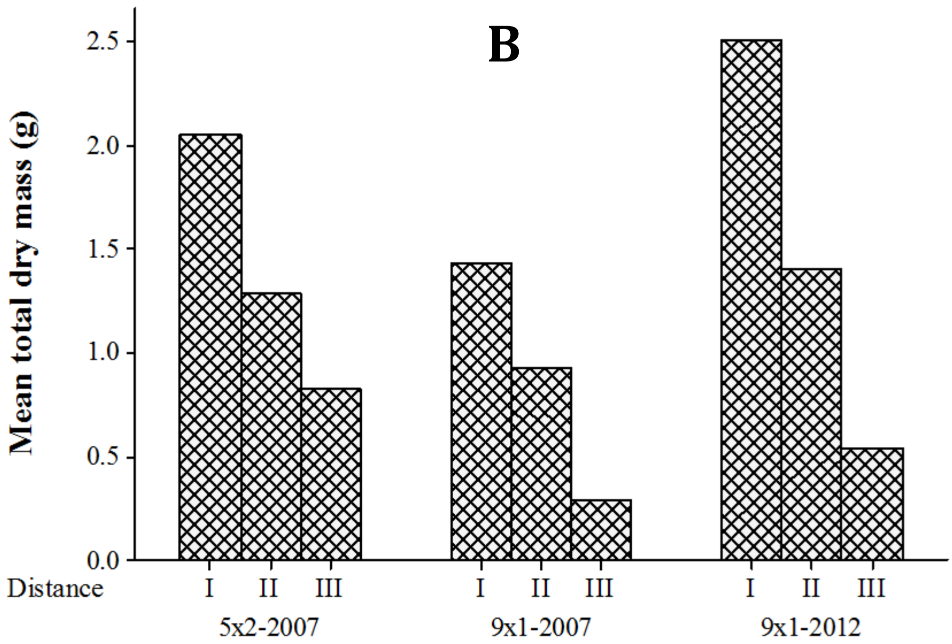


Figure 8. Main effects of intercropping (with and without) and distance from the tree on total root dry mass of *E. camaldulensis* trees in stands established with 5 × 2 m spacing in 2007 and 9 × 1 m spacing in 2007 and 2012.

For mature stand established with 9 × 1 m spacing in 2007, intercropping had no significant effect on total root dry mass compared with monoculture ($p = 0.502$) but total root dry mass showed a decreasing tendency with increasing distance from the tree base (Figure 7); the interaction effect was also insignificant ($p = 0.187$). However, for the young stand established 9 × 1 m spacing in 2012 total root dry mass varied significantly ($p = 0.001$) with distance from the tree base (Figure 7); although total root dry mass didn't differ significantly between intercropped and pure stands ($p = 0.956$) and for the interaction between intercropping and distance from the tree base ($p = 0.194$).

Three-way ANOVA performed to examine variation in root dry mass at different soil depths in relation to intercropping and distance from the tree base (Table 2) revealed that the main effect of intercropping on root dry mass was insignificant while distance from the tree base had a significant effect irrespective of the spacing used to establish the stands. The main effect of soil depth was significant in the stand with 5 × 2 m spacing and showed tendency in young stand with 9 × 1 m spacing but not in mature 9 × 1 m stand. Significant three way interaction effect of intercropping, distance from the tree base and soil depth on root dry mass was also detected for the stand with 5 × 2 m spacing and mature stand with 9 × 1 m spacing while the young 9 × 1 m stand show highly significant two way interaction effect of intercropping by soil depth.

The mean root dry mass at different soil depths for each stand is shown in Figure 9. For 7-year old 5 × 2 m stand, the mean root dry mass at 40 cm soil depth and at a distance of 175 cm away from the tree base was higher than the pure Eucalyptus stand, whereas, the root dry mass at 20 cm soil depth was higher in the pure eucalyptus stand than intercropped stand at the same 100 cm distance from the tree base.

For 7-year old 9 × 1 m stand, the mean root dry mass at 20 cm and 60 cm soil depths was higher for intercropped stand than pure Eucalyptus stand at 275 cm distance from the tree base while root dry mass at 60 cm tended to be higher for pure Eucalyptus stand than intercropped at 275 cm distance from the tree base. For the young pure 9 × 1 m stand, root dry mass at 20 cm soil depth was the highest at the second farthest distance from the tree base (275 cm) compared to the farthest distance (450 cm) across all soil depths and at 60 cm soil depth in the first 100 cm from the tree base. For the young intercropped stand, root dry mass at nearly all soil depths was higher than in the first 100 cm distance from the tree than the farthest distance from the root base.

Table 2. ANOVA results for variations in root dry mass of *E. camaldulensis* at different soil depth as affected by intercropping and distance from the tree for stands with 5 × 2 and 9 × 1 m spacing.

A) 7-year old stand with 5 × 2 m spacing

Sources of variation	DF	MS	F	P
Intercropping	1	0.3174	2.55	0.114
Distance	2	0.6051	4.87	0.010*
Depth	2	0.9921	7.98	0.001*
Intercropping × Distance	2	0.1275	1.03	0.363
Intercropping × Depth	2	0.0826	0.66	0.517
Distance × Depth	4	0.4987	4.01	0.005*
Intercropping × Distance × Depth	4	0.3297	2.65	0.038*
Error	90	0.1244		
Total	107			

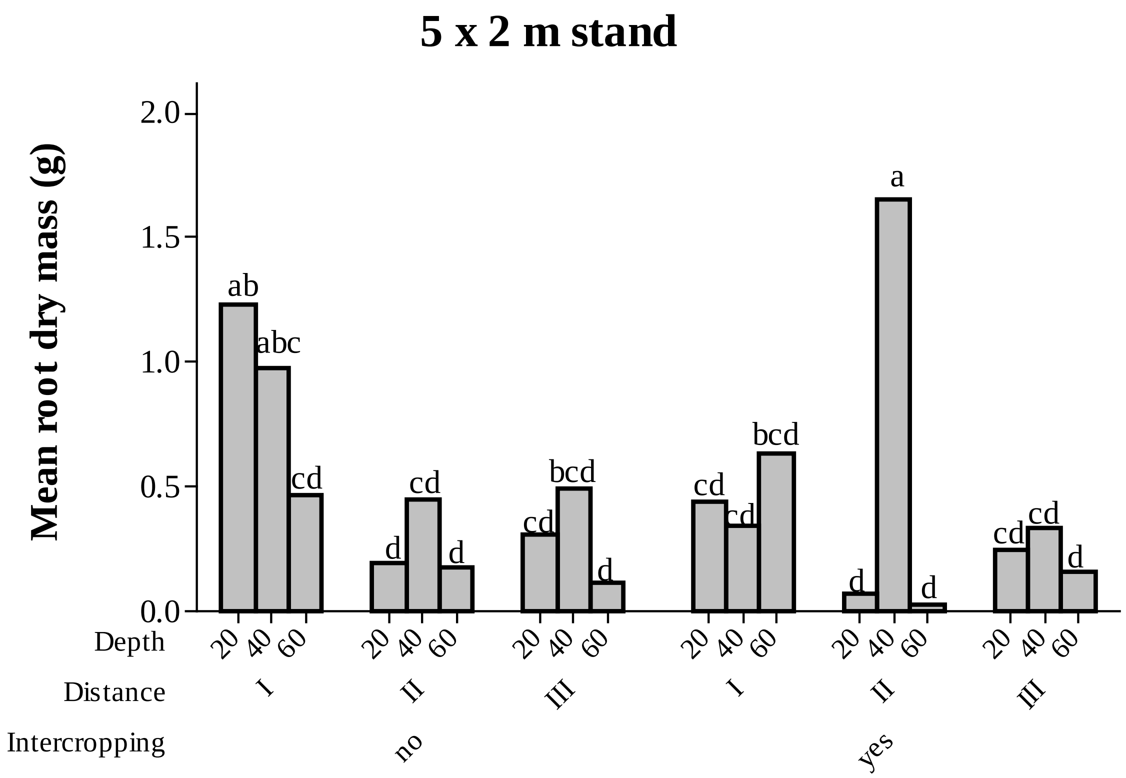
B) 7-year old stand with 9 × 1 m spacing

Sources of variation	DF	MS	F	P
Intercropping	1	0.3449	2.38	0.127
Distance	2	0.5021	3.46	0.036*
Depth	2	0.1629	1.12	0.330
Intercropping × Distance	2	0.2031	1.40	0.252
Intercropping × Depth	2	1.2118	8.36	0.000*
Distance × Depth	4	0.0694	0.48	0.751
Intercropping × Distance × Depth	4	0.4664	3.22	0.016*
Error	90	0.1450		
Total	107			

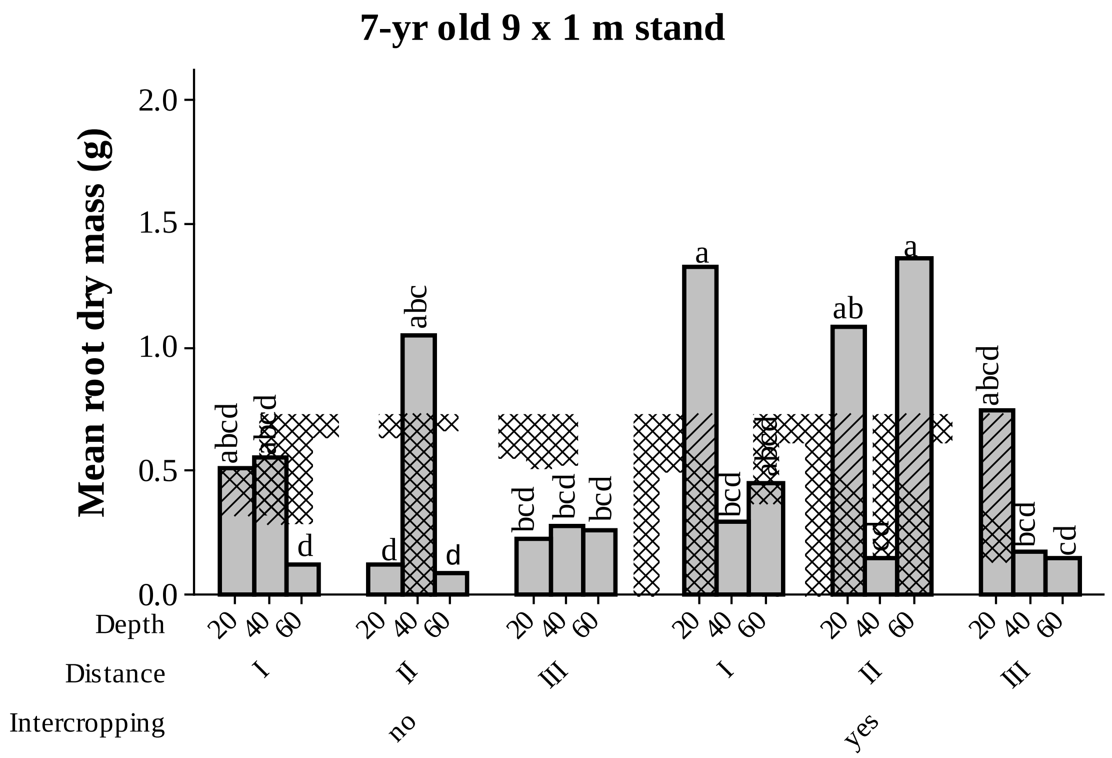
C) 2-year old stand with 9 × 1 m spacing

Sources of variation	DF	MS	F	P
Intercropping	1	0.3487	2.22	0.140
Distance	2	0.7863	5.00	0.009*
Depth	2	0.4164	2.65	0.076**
Intercropping*Distance	2	0.5108	3.25	0.044*
Intercropping*Depth	2	0.7908	5.02	0.009*
Distance*Depth	4	0.1107	0.70	0.592
Intercropping*Distance*Depth	4	0.1701	1.08	0.371
Error	90	0.1574		
Total	107			

DF = degrees of freedom; MS = adjusted mean square; * significant at $p < 0.05$; ** show tendency at $p < 0.01$



5 x 2 m stand
Mean root dry mass (g)
2.0
1.5
1.0
0.5
0.0
ab
abc
cd
d
cd
d
cd
bcd
d
cd
cd
bcd
d
a
d
cd
cd
d
Depth
20 40 60
Distance
I
II
III
Intercropping
no
yes



7-yr old 9 x 1 m stand
Mean root dry mass (g)
2.0
1.5
1.0
0.5
0.0
abcd
abcd
d
d
abc
d
bcd
bcd
bcd
a
bcd
abcd
ab
cd
a
abcd
bcd
cd
Depth
20 40 60
Distance
I
II
III
Intercropping
no
yes

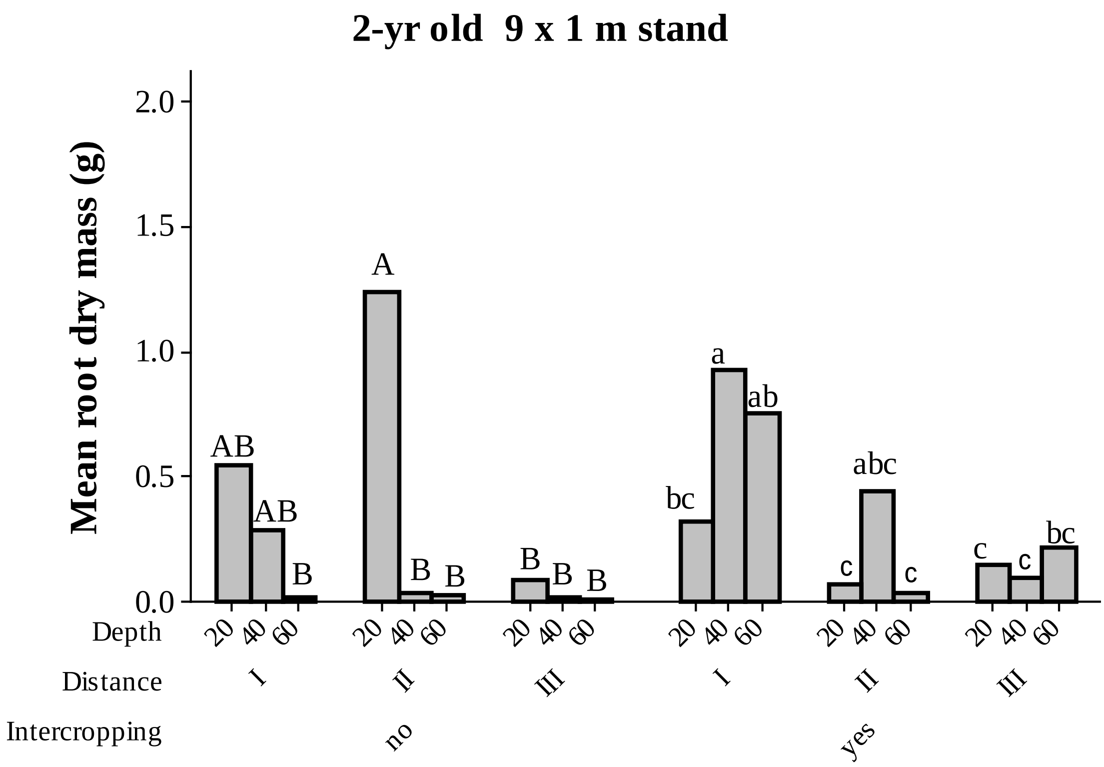


Figure 9. Mean root dry mass (g) of E. camaldulensis trees at different soil depth in 7-year old stands with or without intercropping, and at different distances from the tree base. Bars with the same letter (s) are not significantly different at 5% probability.

3.3 Effects of spacing and distance from the tree on root dry mass

To examine the effects of spacing (5 × 2 m versus 9 × 1 m) and distance from the tree base on root dry mass at different soil depths, ANOVA was performed for rice intercropped stands that were established in 2007. The analysis shows that the main effects of spacing and soil depth were not significant, but distance from the tree had a significant effect on root dry mass (Table 3). There were also significant interaction effects of spacing × depth and spacing × distance × depth.

The mean root dry mass at 40 cm soil depth was significantly higher for 5 × 2 m stand than for 9 × 1 m stand at the second farthest distance from the tree base; whereas root dry mass at a depth of 20 cm and 60 cm was higher for the 9 × 1 m stand than the other spacing as a distance of 275 cm away from the tree base (Figure 10). In addition, root dry mass at a soil depth of 20 cm was significantly at 100 cm distance away from the tree base than other soil depths.

Table 3. ANOVA results for the effects of spacing, distance from the tree and soil depth on root dry mass of *E. camaldulensis* intercropped with rice at the age of 7 years.

Sources of variation	DF	MS	F	P
Spacing	1	0.4592	2.58	0.112
Distance	2	0.5702	3.20	0.045*
Depth	2	0.1314	0.74	0.481
Spacing × Distance	2	0.1945	1.09	0.340
Spacing × Depth	2	1.2931	7.26	0.001*
Distance × Depth	4	0.1756	0.99	0.420
Spacing × Distance × Depth	4	0.8501	4.77	0.002*
Error	90	0.1782		
Total	107			

DF = degrees of freedom; MS = adjusted mean square; * significant at $p < 0.05$

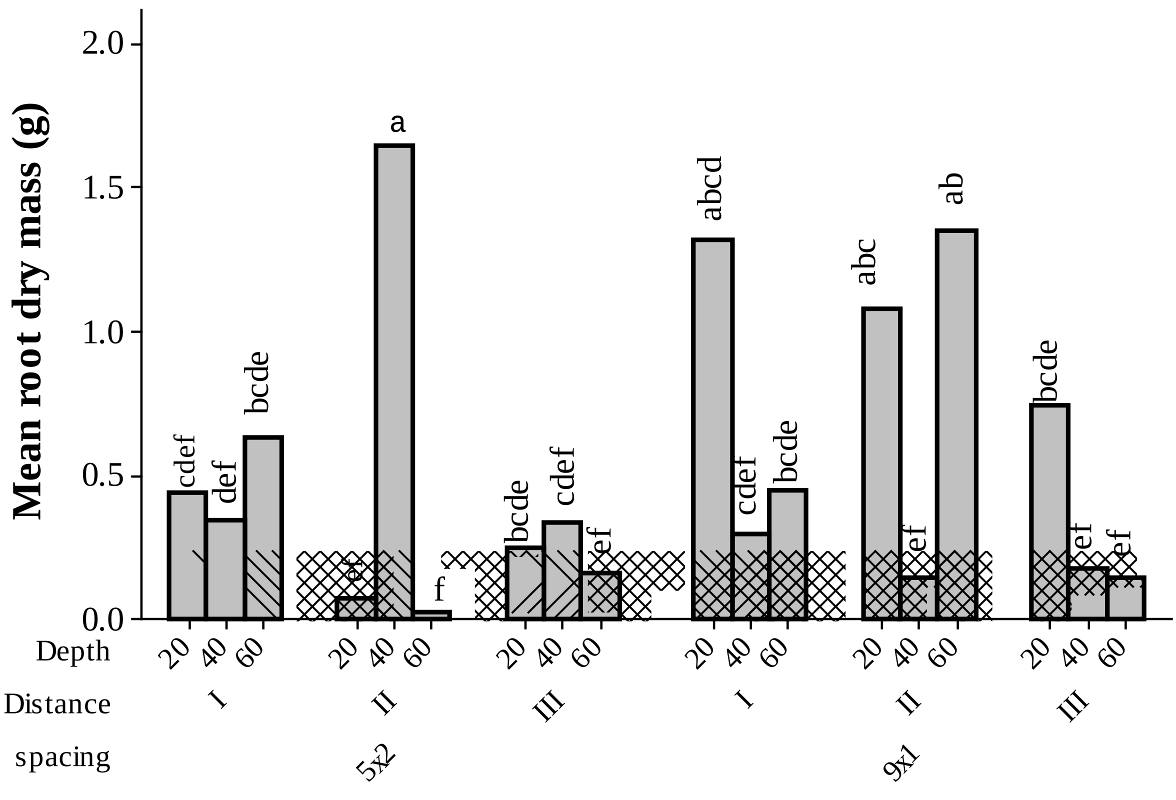


Figure 10. Mean root dry mass (g) of E. camaldulensis in relation to spacing (5 × 2 m versus 9 × 1 m) distance from the tree and sol depth for stands established in 2007 with rice intercropping. Bars with the same letter (s) are not significantly different at 5% probability.

3.3 Effects of stand age and distance from the tree on root dry mass

The effects of stand age and distance from the tree base on root dry mass at different soil depths were studied for pure and intercropped stands that were established using 9 × 1 m spacing separately. For intercropped stand, stand age, distance to the tree base and the interaction between stand age and depth had significant effects on root dry mass while the interaction effect of stand age and distance from the tree base was marginally significant (Table 4A). The overall mean root dry mass was lower in young (0.33 ± 0.08 g) than mature stand (0.64 ± 0.15 g). Trees in mature stand had higher root dry mass at 60 cm soil depths in at 275 cm distance away from the tree base than the young stand; whereas root dry mass in young stand was high in the first 100 cm distance away the tree compared to other distances (Figure 11). Similar analysis on pure stand revealed significant differences in root dry mass between stand ages, soil depths, and their interaction, as well as three way interaction between stand age, distance from the tree base and soil depth (Table 4B).

Table 4. ANOVA results for the effects of stand age, distance from the tree and soil depth on root dry mass of *E. camaldulensis* in monoculture and intercropped stands.

A) Intercropping

Sources of variation	DF	MS	F	P
Stand age	1	1.5585	7.92	0.006*
Distance	2	1.0646	5.41	0.006*
Depth	2	0.1391	0.71	0.496
Stand age × Distance	2	0.6079	3.09	0.050**
Stand age × Depth	2	0.7029	3.57	0.032*
Distance × Depth	4	0.0540	0.27	0.894
Stand age × Distance × Depth	4	0.3195	1.62	0.175
Error	90	0.1968		
Total	107			

B) Monoculture

Sources of variation	DF	MS	F	P
Stand age	1	1.5665	14.84	0.000*
Distance	2	0.2616	2.48	0.090**
Depth	2	0.8867	8.40	0.000*
Stand age × Distance	2	0.0682	0.65	0.527
Stand age × Depth	2	0.8534	8.08	0.001*
Distance × Depth	4	0.1532	1.45	0.224
Stand age × Distance × Depth	4	0.2900	2.75	0.033*
Error	90	0.1056		
Total	107			

DF = degrees of freedom; MS = adjusted mean square; * significant at $p < 0.05$; ** show tendency at $p < 0.01$

For the young stand, root dry mass at 20 cm soil depth and at 275 cm distance away from the tree base was high compared to 60 cm depth, while for mature stand root dry mass at 40 cm depth and at 275 m away from the tree base was higher than at 40 cm and 60 cm depths across all distances from the tree base of young stands (Figure 10).

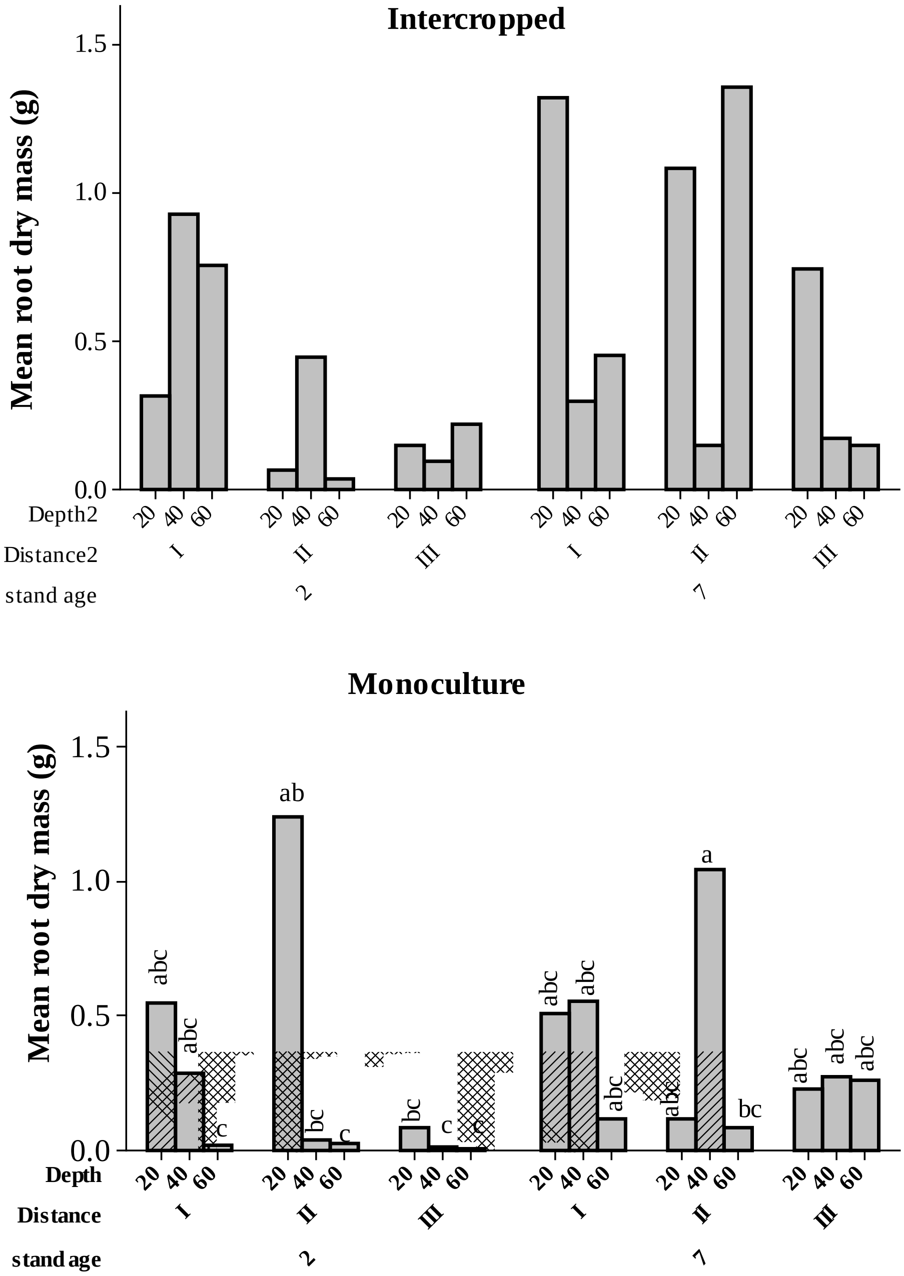


Figure 11. Mean root dry mass (g) of E. camaldulensis in relation to stand age (2 yr versus 7 yr old), distance from the tree and sol depth for stands established with 9 × 1 m spacing, which were either intercropped or pure monoculture. Bars with the same letter (s) are not significantly different at 5% probability.

4. Discussions

Increased root production (root biomass) is the front line adaptation reaction to below-ground resource limitation, so as to optimize resource acquisition (Hodge et al., 2009). In the present study, intercropping has no significant effect on root biomass, but distance from the tree base and soil depths appear to play a major role. During the sample collection in the field, few bigger roots were found in 60 cm soil depth, which also influence the total root dry weight results. The highest root dry mass was found at the depth of 40 cm in this study. There is a tendency of greater root biomass closer to the tree base and with the root mass decreasing with the distance from the tree, particularly at deeper soil layer. There are three possible reasons for this phenomenon. First, the root system may sense competition as they get closer to the crops, and hence investing the carbon in other parts of the root. It should be noted that the carbon cost for increased production of both large root biomass and longer roots simultaneously might be high for the plant. Consequently, the plant has to make a "decision" on resource allocation to either produce larger root biomass or longer roots to optimize nutrient capture (Hodge 2004). In addition, the disk harrow that is usually used in the gaps between tree-rows in pure stand creates ditches that can serve as water bodies, which might promote the growth of roots towards the water.

Second, root penetration in the soil might be constrained by compaction and poor site conditions (availability of rocks and big stones at deeper soil layer). During sample collection, big stones or rocks were observed at lower depth, which might have restricted root growth. Soil compaction is one of the most limiting factors for a good tree establishment by limiting root elongation rates (Kozlowski 1999). In the plantations included in this study, the soil is relatively compact, especially in the pure monoculture compared to the intercropped sites. Perhaps the crops might have loosened the soil a bit, and in so doing, enhances root elongation as evidenced from the interaction effect of intercropping and soil depth.

Third, the nature of root growth pattern of *E. camaldulensis* can be accounted for low root biomass production at deeper soil surface. As evidenced from analysis of root system architecture, the species produces several thicker but relatively shorter lateral roots that are confined at shallow depths. Azam et.al (2014) also found that root elongation correlates negatively with soil penetration resistance, especially for *E. camaldulensis*. Their study further concluded that both primary and lateral roots respond to soil compaction and that their diameter increased significantly with compaction. As a whole, the root biomass appears to be confined in the upper soil depths, which in turn could be related to nutrient availability at this depth as also observed in other studies (Montani et al. 1996; Savadago et al 2012). The findings from this study are consistent with previous studies from other plantations and species (Carbon et al., 1980; Nambiar, 1983, 1990; Livesley et al., 2000; Bouillet et al., 2002; Rau et al. 2009; Macinnis-Ng et al., 2010; Gwenzi et al., 2011; Levillain et al., 2011)

When comparing root dry mass between narrow (5× 2 m) and wide (9 × 1 m) spacing of trees and crops, the study revealed that more root biomass was recorded in the 5 x 2 meter stand, particularly at 40 cm soil depth than in 9 × 1 m stand. One possible reason would be competitions between trees, which are expected to be lower as the spacing between trees is wider (2 m vis-à-vis 1 m). Stand age has also an influence on root biomass; i.e. the older the trees are the larger the root biomass would be. This difference is more evident for intercropped than monoculture; suggesting that there is no carry-over effect of intercropping on root biomass. It should be noted that the 7-year old plantation in this study was intercropped the first two years only; whereas the 2-year old young plantation is being actively intercropped by the time the study was carried out. Thus, the observed difference in root biomass between young and old plantation would be ontogenic (development of roots over time). This is also evident from the significant variation in root biomass between young and mature monoculture stands. In addition, the incorporation of the crop harvest residues create nutrient “hot-spot” in older stands more than that in the young stands, thereby facilitating root proliferation. This is evident in the older stand, where root biomass was even high at 60 cm soil depth. Several studies have shown that plant roots respond to localized soil nutrient patches through root proliferation (Johnson et al. 2001; Nie et al. 2014). By doing so, roots acquire more soil nutrients in a heterogeneous than homogeneous environment by producing finer, more laterals roots, high root biomass, and specific root length in nutrient rich patch than elsewhere (Wijesing et al. 2001; He et al. 2003; Mou et al. 2013).

The Taungya models practiced today in commercial Eucalyptus plantations in Laos appear to have a minor influence on total root biomass of the tree component. Thus, the model will play a significant role in effectively rehabilitating forests on degraded lands to meet the growing demands for wood and food as well as in creating employment opportunity to landless people. But Taungya is far from ideal. Having wide spacing makes it easier for crop cultivation, but it also results in more weed growth after the termination of cropping. The grasses can be hard competitors to the trees and it also makes the plantations more susceptible to fires, which also can harm and damage the trees. However, in countries like Laos, where there is often an excess of labour, manual weeding will circumvent the potential risks associated with weeds.

From methodological point of view, the coring method for estimating root dry mass is a reasonable and good approach; although uprooting the whole tree and quantify the root biomass is more informative. But the latter is destructive and time-consuming. Throughout the sample collection we hit few objects (stone, big roots etc.) that limited the coring procedure. Soil cores give an objective estimation of the root biomass at different depth and distances from the trees. The influence is of minor importance due to the low amount of big objects being hit in comparison to the large sample collected.

5. Conclusions and recommendations

A study was conducted in commercial eucalyptus plantations integrating the taungya system in Laos to examine the effects of intercropping, spacing and stand age on horizontal and vertical distribution of root biomass in order to generate knowledge that supports evidence-based plantation management decisions. Trenching was used to characterize the root system architecture while soil coring was used to quantitatively determine root biomass.

Based on the findings the following conclusions can be drawn:

1) The root system of *E. camaldulensis* is mainly confined at shallow depth but well elongated horizontally in both pure and intercropped stands with 4-6 thick lateral roots.
2) Intercropping of rice/cassava with Eucalyptus has no effect on total root dry mass of the tree component irrespective of the plantation models (5 × 2 m or 9 × 1 m); however root biomass decreases with increasing horizontal distance from the tree base and in deeper soil layer; particularly for trees in young stands. This is partly because of the shallow root system of *E. camaldulensis*, poor soil quality at deeper soil layer and partly due to possible competition between tree and crop roots.
3) The effects of spacing design, narrow (5 × 2 m) versus wide (9 × 1 m), on root dry mass are dependent on horizontal and vertical distribution of the root system; and root biomass appears to be higher at 40 cm soil depth for the stand with narrow spacing between trees and crops than stands with wider spacing, which might be attributed to between-tree competition in the narrow spacing.
4) Root biomass differs between stand age; i.e., the older the trees are the larger the root biomass would be in both monoculture and intercropped stands; the difference being more evident in the latter than the former. The observed differences in root biomass could be attributed to ontogenic difference and preferential deployment of root towards the cropped spots due to temporary boost in nutrient release from decomposition of crop harvest residues incorporated after cessation of cropping in older than younger stands.

To get a complete picture of the pros and cons of the taungya system, survival and growth of the trees should be studied. From visual observation of the plantations, Eucalyptus with- or without intercropping seems to grow equally well. As root biomass varies with horizontal distribution, more research is recommended on spacing and tree/crop combinations to be able to benefit both farmers and the forestry sector optimally. Particularly, testing buffer zone between trees and crops other than 1 m (which is currently used) would be an important aspect to consider in future research. It is important to have in mind that optimal spacing and different combinations of crops and trees really depend on site conditions, such as soil properties, and hence site-specific tests need to be considered.

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