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Modelling resource use competition in *Paraserianthes falcataria* based agroforestry systems in Indonesia

Master's Thesis

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List of Abbreviations

BCR	Benefit cost ratio
CEC	Cation exchange capacity
cm	Centimetre
cmol	Centimole
CD	Coefficient of determination
CRM	Coefficient of residual mass
DBH	Diameter at breast height
g	Gram
ha	Hectare
kg	Kilogram
LER	land equivalent ratio
LAI	Leaf area index
MAI	mean annual increment
m	Metre
EF	Modelling efficiency
NPV	Net present value
NGO	Non-governmental organizations
ppm	Parts per million
RMSE	Root mean square error
SOM	Soil organic matter

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Summary

Recently, international policy initiatives have contributed to the increase in recognition of agroforestry systems for sustainable rural development. This traditional land use, combining agricultural and forestry practices, has been promoted for its potential economic, environmental and social benefits. However, extending successful agroforestry practices has been proven challenging. Hence, modelling tools have been developed to assist the understanding of opportunities and limiting factors of mixed planting systems on long-term basis.

In this study, WaNuLCAS model was applied to explore agroforestry systems with *Paraserianthes falcataria* under different tree management options. The study was based on data from a project to rehabilitate degraded land in Central Kalimantan, Indonesia. Chili (*Capsicum annuum*) and ginger (*Zingiber officinale*) were selected to intercrop with *P. falcataria* due their suitability to local conditions, availability of planting material, and potential market. An extensive sequence of model calibration and validation for the different species was carried out for the monocultures, preceding the analysis of the agroforestry systems. In total, 122 scenarios were considered in order to: (1) simulate tree-crop interactions under different tree management practices, (2) identify most suitable and profitable scenarios for local conditions, (3) analyse resource competition, and (4) analyse environmental impacts regarding carbon content in soil organic matter, water evaporation rate from soil surface and potential CO2 sequestration.

According to the simulations, *Paraserianthes falcataria* based agroforestry systems presented productivity, financial, and environmental advantages when compared to sole tree plantations in a 7-year rotation scheme. In most cases, the results showed that tree growth was enhanced by intercropping with chili, mainly due to residual fertilizer, and light competition was the main limitation for crop growth through the rotation for both crops. When the priority was given to timber production, the profitability analysis demonstrated that initial tree densities of 400, 500 and 625 trees ha^{-1} and no thinning would be an interesting option for smallholders. To grow chili in these systems is economic viable until the third year of the rotation for 500 and 625 trees ha^{-1}, and until the fourth year of the rotation for 400 trees ha^{-1}, while ginger would be feasible throughout the rotation length. Analysing the environmental impact, mixed plantations presented around 20% higher potential to sequester CO_2 than tree monoculture, and soil evaporation rate was around 25% lower in agroforestry systems, particularly because of higher soil cover in the initial years of the rotation. Probably due to an underestimation of cumulative litterfall, carbon content in soil organic matter presented a tendency of continuous declining, independently if agroforestry systems or monoculture.

1 Introduction

Natural forests in Indonesia have been negatively impacted since the 1970s by introduction of logging and mining concessions as a government measure to promote economic development (Siregar, Rachmi, Massijaya, Ishibashi, & Ando, 2007; Tsujino, Yumoto, Kitamura, Djamaluddin, & Darnaedi, 2016) and, more recently, by forest conversion to oil palm plantations (Gibbs et al., 2010). Forest cover in Kalimantan, the Indonesian part of Borneo, declined around 30% between 1973 and 2010 according to a comparative study based on satellite data (Gaveau et al., 2014). In the first decade of the 2000s, the province of Central Kalimantan presented the fastest expansion of oil palm (*Elaeis guineensis*) in the country (Sumarga & Hein, 2016). Large-scale fires contribute to increase deforestation rates. In 1997, for example, it took months to extinguish the forest fires in Kalimantan and Sumatra attributed to the severe drought related to the El Niño Southern Oscillation event (Tsujino et al., 2016) and, in 2015, over 100000 fires were recorded in the country, raising the countries position as one of the greatest carbon emitters (Enrici & Hubacek, 2016). In a study of fire occurrences in Kalimantan, Santika et al. (2020) observed that the density of fires in primary forest was more prevalent in regions with industrial plantations than in villages outside the concessions areas.

The impact of deforestation and, consequently, the declining of ecosystems services related to secondary or primary forests is being understood in a broader socio-ecological context (Lamb, 2011). Land degradation, a term used to refer to "land with low agricultural productivity and capability because of soil infertility, erosion, weeds or recurrent fires" (Lamb, 2011, p. 11), is one of the most direct consequences of ecosystems degradation, undermining stability of land-dependent communities. This is particularly relevant in Indonesia, as 60% of poor people live in rural areas and rely on agriculture for their livelihood (BPS, 2020). Feintrenie, Schwarze, and Levang (2010) analysed the role of smallholder farmers as forests conservationists and showed that, driven by economic opportunities, they are changing their more diverse and traditional land use systems to monocultures plantations, contributing to the reduction of biodiversity. Moreover, on the long run, these land use transitions may expose the rural communities to higher economic risks due to price fluctuation of one product (Rist, Feintrenie, & Levang, 2010). Therefore, the importance of policy interventions considering broader socio-economic aspects in order to reconcile improving livelihoods and environment conservation, since local communities are most susceptible to the consequences of deforestation (Medrilzam, Smith, Aziz, Herbohn, & Dargusch, 2017; Piesse, 2016; Rist et al., 2010).

The Indonesian government recognized the problems associated with the decreasing area of natural forests and, in the 1980s, took measures to promote reforestation and land rehabilitation, restructuring the forestry sector in order to reduce the pressure on the natural forest and ensure the supply for timber industries in a sustainable way (Moeliono, Thuy, Waty Bong, Wong, & Brockhaus, 2017). *Paraserianthes Falcataria,* along with other fast growing species, were recommend for the forest plantation in this initiative (Siregar et al., 2007). However, after two decades, the results were not relevant and the involvement of local communities was lower than expected, leading to a series of decentralizing reforms that shaped new social forestry schemes (Djamhuri, 2008). Social forestry initiatives aim to alleviate poverty of rural communities and, at the same time, stimulating land rehabilitation since farmers participate in a long-term forest management and the state grants them property rights over the trees (Friedman, 2020).

In this context, encouraging agroforestry systems, a traditional land use applied by subsistence farmers in the tropics that combines trees and agriculture, presents a great potential for a more sustainable rural development (Belsky, 1993; FAO, 2013a). Global initiatives such as the Millennium Development Goals of the United Nations and its follow-up, the Sustainable Development Goals, have contributed to the increase in recognition of agroforestry and its benefits (van Noordwijk, 2019). The combination of agricultural and forestry practices lowers economic risks and increases the efficiency of the land use through diversification (Pratiwi & Suzuki, 2019; Zomer, Trabucco, Coe, Place, & Xu, 2014). Additionally, the mixed farming model supports a range of regulating ecosystems services when compared to monocultures, for instance, improving water quality, enhancing biodiversity and increasing carbon sequestration (DeClerk, Le Coq, Rapidel, & Beer, 2012). However, the ecological and social benefits of the synergy between trees and crops depend on a series of factors such as the initial selection of the plant species, adequate forest management, farmers' goals and market access (FAO & ICRAF, 2019). Additionally, for different environmental conditions and resource availability, tree-crop interactions vary between complementarity and competition, making it difficult to predict outcomes (García-Barrios & Ong, 2004). Hence, extending prosperous agroforestry practices in a systematic way has been proven challenging (van Noordwijk, 2019).

Since the 1990s, a series of models and simulation tools have been developed aiming to understand the interactions in agroforestry systems on long-term basis (García-Barrios & Ong, 2004; Luedeling et al., 2016), since analyses of tree-crop interactions in field experiments to quantify yields, exploring a range of different setups, are expensive and time consuming (Burgess et al., 2019; Hussain, 2015). Developed by World Agroforestry Centre, the Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model dynamically represents the interactions below and aboveground of intercropping systems that can be simulated in a wide range of simultaneous or sequential agroforestry schemes (van Noordwijk, Lusiana, Khasanah, & Mulia, 2011). This tool has been used to analyse tree-crop interactions in parkland systems in

Burkina Faso (Bayala et al., 2008), to determine water management options in rubber plantations (*Hevea brasiliensis*) (Boithias et al., 2012), to verify competition between maize (*Zea mays*) and hedgerows in soil conservation strategies (Hussain et al., 2016), trade-offs analysis for timber-based agroforestry (Khasanah et al., 2015; Martin & van Noordwijk, 2009), and for exploring mixed oil palm plantations patterns (Khasanah et al., 2020).

1.1 Research objectives

In this master thesis, WaNuLCAS model was applied to explore agroforestry systems with *P. falcataria* under different tree management options based on data from the program One Million Trees (1mTrees) in Central Kalimantan. Despite the increasing engagement of rural communities in tree planting after the implementation of the new social forestry schemes in Indonesia, the impact of commercial forestry in the farmers' household income remains small (Muktasam et al., 2019). The main restrictions for a higher profitability were identified as poor tree management practices and limited market access (Irawanti, Race, Stewart, Parlinah, & Suka, 2017). 1mTrees program assists local communities to set up tree planting and agroforestry systems providing technical and logistical support to market their products (IKI, 2017). Supported by the German Government, with partners in Germany and Indonesia, this project focuses on rehabilitation of degraded land, mostly areas of former slash-and-burn or cut-clear forests covered by *Imperata cylindrica,* in four districts of Gunung Mas Regency in Central Kalimatan: Manuhing, Manuhing Raya, Rungan and Rungan Hulu (IKI, 2017).

Specific objectives of the study are:

1) to simulate tree-crop interactions in *Paraserianthes falcataria* based agroforestry systems under different tree management practices (initial planting spacing, thinning, and pruning)

2) to compare different tree management and crop options and, from the productivity and economic perspective, in order to identify most suitable and profitable scenarios for local conditions

3) to analyse resource competition between *Paraserianthes falcataria* and selected crops

4) to analyse environmental impacts of the agroforestry systems regarding carbon content in soil organic matter, water evaporation rate from soil surface and potential CO_2 sequestration

2 Literature review and theoretical framework

2.1 Tree management

Generally, tree growth presents a sigmoidal curve with age, but its shape may change depending on sunlight and growing space availability (Evans, 1992). After a slow establishment phase, the tree grows rapid as foliage and roots development allows faster resource assimilation, until the growth rate reaches a peak and, eventually, the tree slows down its expansion (Oliver & Larson, 1996). After the crown closure in a stand, tree height growth continues in the fixed growing space, while the canopy size remains constant (Oliver & Larson, 1996). Progressively, more energy is use for respiration and less is available for diameter growth, hence this tree measurement is closely related to crown size and consequently tree planting space. Tree height is relatively independent of the canopy expansion, with exception of very narrow spacing (Oliver & Larson, 1996). Planting space also affects bole format, as trees with weak epinastic control benefit when growing at relative narrow spacing that provides side shade on shoots not centred, which start to suffer from light deficiency and lose vigour, giving a more apical dominance to the centre terminal in full sunlight (Oliver & Larson, 1996). Therefore, the number of trees planted per hectare (or initial tree density) in commercial forestry is one of the most important silvicultural decisions, as it influences stem form, diameter growth and total volume production (Evans, 1992).

Stand density management consists of a manipulation of the number of trees on a given site through initial spacing and (or) a series of thinning events, aiming to minimise the establishment, management costs and, at the same time, maximise the total revenue from the plantation, controlling resource competition (Evans, 1992; Newton, Lei, & Zhang, 2005). These silvicultural decisions depends on the tree species and the intended product output, for instance, timber or pulp production (Varis, 2011). Generally, narrow initial space is applied for pulpwood production since stem size is not important and the objective is to maximise the total volume at minimum rotation length, while for sawn wood production the aim is to produce logs with marketable diameter achieved by widely space stands (Evans, 1992). The potential losses in productivity might be compensated with a higher value of the produced timber and with the additional income from the wood recovered from thinning practices (Khasanah et al., 2015).

By thinning, some trees are removed, reducing competition for light, water and nutrients within the stand, and also increasing growing space (Evans, 1992). The crown expansion of the remaining trees, occupying the space left by felled trees, results in a greater photosynthetic area increasing their growth rate and, consequently, allocating more energy to diameter growth until canopy closure (Evans, 1992; Oliver & Larson, 1996). Hence, foresters apply thinning in order to adjust the production capacity of the site, promoting diameter growth and redistributing growth on fewer trees in order to maximise financial return and minimise rotation length (Evans, 1992). Besides the intensity, the timing of thinning regimes is important, as trees take longer to respond to extra growing space when there is a delay to manage competition and the growth lost can only be compensated by extending the rotation length (Varis, 2011).

In specific cases, depending on the tree species and final use, pruning is introduced to the silvicultural management of the stand in order to produce knot-free timber that has higher market value (Khasanah et al., 2015; Sabastian, 2012). In a more general application, Oliver and Larson (1996) discussed pruning of non-functional branches, lower and shaded ones, to remove sink of energy from stem growth. Conversely, besides increasing management costs, studies have shown that this practice impact tree growth negatively (Fontan et al., 2011; Muhamad & Paudyal, 1992).

2.2 Sengon (*Paraserianthes falcataria*)

Indigenous to Indonesia, Papua New Guinea, Solomon Islands and Australia, *Paraserianthes falcataria (L.) Nielsen* is a fast growing tree that belongs to the Fabaceae family and can reach up to 40 m in height and 100 centimetres in diameter or more (Soerianegara & Lemmens, 1993). This species is also identified with other scientific names (*Adenanthera falcatoria L., Albizia falcata (L.)* Backer*, Albizia falcatoria (L.)* Fosberg*, Falcataria moluccana*) and it has a series of common names depending on the country. In the area of this study the tree is commonly known as sengon (Krisnawati, Varis, Kallio, & Kanninen, 2011). As a pioneer species, it occurs in primary forest, but it is also found in a vast range of habitats, from seacoast and grassy plains to secondary lowland rainforest and montane forest (Soerianegara & Lemmens, 1993).

Sengon can form a large umbrella-shaped canopy when grown in the open, but if planted in high densities it establishes a narrow crown (Varis, 2011). Its bark surface is smooth or slightly rough with white, grey or greenish colour and the leaves are alternate, bipinnate having a light green colour on topside and being lighter on underside (Soerianegara & Lemmens, 1993). The species is well adapted to different climates and is resistant to dry season, although its development can be drastically reduced on dry sites (Krisnawati et al., 2011). An annual rainfall of 2000 to 3500 mm with a temperature range of 22-29°C, up to a maximum of 30-34°C and a minimum of 20-24°C, are considered optimal climate conditions for sengon development (Webb, Wood, Smith, & Henman, 1984).

Widely planted throughout the tropics, *P. falcataria* is capable of growing on relatively poor soils, especially on nitrogen deficiency, as the association with *Rhizobium spp*. enables N_2-fixation, when there is no important obstruction for root development (Garcia-Montiel & Binkley, 1998; Hughes, Johnson, & Uowolo, 2013). Like other leguminous species, sengon will perform better on slightly alkaline soil, but it tolerates wide variety of soil conditions, from salty to acidic soils (National Research Council, 1980). Although it does not require fertile soils, Krisnawati et al. (2011) recommend fertilizing impoverished soils in order to stimulate initial growth, but the cultivation plot needs to be well drained, since the trees will not thrive on flooded or waterlogged areas.

2.2.1 Wood characteristic and utilization

Paraserianthes falcataria produces a comparatively soft and lightweight wood, with density ranging between 230 and 500 kg/m^3 at 12–15% moisture content (Krisnawati et al., 2011). Generally, the wood is white coloured, but in older trees the heartwood colour varies from a whitish to reddish-brown, its texture is moderately course and wood grain is interlocked or straight (Prawirohatmodio, 1994; Soerianegara & Lemmens, 1993). It is recognized for its excellent pulping characteristics and used for paper production, having as an advantage the pale coloured colour that requires minimum bleaching to produce a high quality white paper (Soerianegara & Lemmens, 1993). Although poorly evaluated for its nailing properties, sengon wood is easy to work, being very suitable source for plywood, particleboard, hardboard, as well for general purposes as furniture and turnery (Prawirohatmodio, 1994). It is considered unsuitable for structural components in house building and it is not durable for outdoor uses without treatment (Soerianegara & Lemmens, 1993).

In Indonesia, *P. falcataria* is a common species for farm forestry, especially in Java, and the market for its timber has been expanding during recent years (Irawanti et al., 2017). As a fast growing and nitrogen-fixing species, *P. falcataria* is commonly used for reforestation and afforestation projects for soil improvement (Krisnawati et al., 2011; Siregar et al., 2007), since its abundant and nitrogen-rich litterfall enriches the soil upper layers (Agus, Putra, Faridah, Wulandari, & Napitupulu, 2016; Boithias et al., 2012; Garcia-Montiel & Binkley, 1998). These characteristics in combination with its feathery foliage, that cast light shade, sengon is suited for cultivation in agroforestry systems (Irawanti, Ginoga, Prawestisuka, & Race, 2014). Commonly, Indonesian smallholder farmers intercropped the species with short-cycle crops such as chili, maize, pineapple, ginger, cassava (Siregar et al., 2007; Steward et al., 2020), with fruit trees such as papaya, banana, snake fruit, and also as a shade tree in coffee and tea plantations (Rahman, Sunderland, Roshetko, Basuki, & Healey, 2016; Roshetko, 1998; Szulecka, Obidzinski, & Dermawan, 2016).

2.2.2 Establishment and management

In managed sengon plantations, one of the first stages of establishment process is the seedlings classification and selection from the nursery (Varis, 2011). It is recommended that sengon seedlings have a height of 20-25 cm with a woody stem and a viable root system to be transplanted (Soerianegara & Lemmens, 1993). This stage can be achieved in 2 to 2.5 months after the seeding, but, usually, the seedlings remain in the nursery until they reach an age of 4 to 5 months, and, at this point, they are ready to be planted on the field (Soerianegara & Lemmens, 1993). Planting seedlings at the beginning of the rainy season and weeding within 40-50 cm around them in the first two years will improve sengon growth and survival rate (Roshetko, 1998).

In published literature, the initial planting space for sengon varies from 2x2 m to 6x6 m (Krisnawati et al., 2011) and depends on the management objectives (Varis, 2011). According to Roshetko (1998), for pulpwood production, a common spacing is 3x3 m on a 6 to 8-year rotation, while for saw log production the trees are spaced at 6×6 m on fertile sites and thinning is applied for a same rotation age. In Indonesia, (Kurinobu, Prehatin, Mohanmad, & Matsune, 2007) reported that, in state managed sengon plantations, trees were usually planted with an initial spacing of 3x2 m (1667 trees ha^{-1}), while Varis (2011) found that smallholders in West Java practice even narrower planting space with initial tree density of 2300 trees ha^{-1} on average. At higher initial stand density, *P. falcataria* trees produce taller and straighter trunk, a favourable characteristic for timber production (Roshetko, 1998), however, too dense stocking leads to a decrease in the trees diameter and the necessity of density management by thinning (Varis, 2011).

Studies present different suggestions of intensity and timing for thinning in *P. falcataria* plantations. For timber production, Soerianegara and Lemmens (1993) recommended that the first thinning should take place when the stand is 4-5 years old to a density of 250 stems/ha, and then after 10 years to 150 stems/ha. For the same rotation length, Prajadinata. and Masano (1998), cited by (Varis, 2011), suggested a more regular thinning regime starting at year 2 of the rotation and, then, every year until the harvesting. In a rotation of 8 years, on sengon plantations managed by the Indonesian government, thinning starts when the trees are 3 years old and are applied annually until a final density of 300 trees per hectare is achieved (Kurinobu, Prehatin, Mohanmad, & Matsune, 2007). In addition, Krisnawati et al. (2011) recommend selecting for thinning trees that are pest-infested, deformed or poorly shaped.

At an early stage of the stand development, it is recommended formative pruning in order to produce high-quality timber, since sengon trees have propensity to fork (Soerianegara & Lemmens, 1993). Usually, pruning is applied for the first time at the age of 6 months and then semi-annually until 2 years after the plantation (Krisnawati et al., 2011). Another aspect regarding the timber quality is the influence of the rotation age on the wood colour. When the goal is to achieve a light-coloured wood, harvesting should happen before the heartwood formation, which takes place at the age of 8 to 12 years, depending on the quality of the site (Prawirohatmodio, 1994).

2.2.3 Growth and productivity

P. falcataria is recognized for its outstanding rapid growth (Soerianegara & Lemmens, 1993). Measurements from plantations in multiple countries showed that, on good sites with adequate rainfall, after a little more than a year sengon trees can reach a height of 7 metre, in 3 years 13 to 18 meters, in 5 years 21 to 25 meters and, in 10 years, 30 to 33 meters (Prawirohatmodio, 1994; Roshetko, 1998). As result of this vigorous development, yield is often high. Soerianegara and Lemmens (1993) reported that, in a 8 to 12-year rotation scheme, a mean annual increment (MAI) in volume of 25 to 40 m^3 ha^{-1} y^{-1} can be achieved and, under favourable conditions, even higher volume MAI may be attained, up to 50 to 55 m^3 ha^{-1} y^{-1}. Over a rotation length of 10 years, Roshetko (1998) and Prawirohatmodio (1994) described a volume MAI between 39 to 50 m^3 ha^{-1} y^{-1}.

For Indonesia, almost all publications report sengon development data from plantations established in the island of Java and the growth performance varies according to different sites, soil conditions and tree management options. In West Java, Krisnawati (2011) recorded high variation in the sengon diameter and height on 106 smallholder plantations, for instance, trees in 5-year stands presented height ranging between 9.9 to 27.9 m, corresponding to diameters between 8.7 to 40.1 cm. In state-owned 5-year plantations in East Java with same initial tree density but different thinning, regime and, consequently, different intermediate density stand, *P. falcataria* height varied between 17.9 to 23.5 m and diameter between 16.6 to 24.8 cm for a density of 880 and 380 trees ha^{-1}, respectively (Kurinobu, Prehatin, Mohanmad, & Matsune, 2007). For the same stand age and higher tree density (930 trees ha^{-1}) in Central Java, Steward et al. (2020) reported lower tree dimensions with diameter of 14.6 cm and height of 14.9 m.

2.3 Resource competition in agroforestry systems

In agroforestry systems, resource sharing between trees and crops encompasses competitive and complementary aspects, in which the positive or negative effects of the interaction depend on environmental conditions, management options, and chosen plant species (Buck, 1986; Newaj, Bhargava, Shanker, & Ajit, 2005; Rao, Nair, & Ong, 1997). A key concept in agroforestry is that mixing plants with different features and forms increases the resources use efficiency and promotes complementarity effects at some level, since trees and crops can occupy to some extend differently soil layers and aboveground space (Cannell, van Noordwijk, & Ong, 1996; Schroth, 1998).

Unlike sunlight, belowground growing resources may be accumulated in the systems depending on the soil type, the hydrogeological profile of the area and the climatic conditions, as evaporation and percolation below root zone can cause water losses and nutrients, through volatilization and leaching (Buck, 1986; Newaj et al., 2005). Van Noordwijk, Lawson, Soumaré, Groot, and Hairiah (1996) discussed the hypothesis of trees acting as 'safety nets' in agroforestry systems, in which they develop a root system under the crop root zone absorbing part of leached nutrients that can return to topsoil through litterfall or pruning. In a recent review of empirical studies of various agroforestry systems in diverse locations, with emphasis on environmental impact in agriculture, Pavlidis and Tsihrintzis (2018) reported reductions of nitrogen leaching to groundwater ranging from 24% to 97.7% attributed to tree roots. However, trade-offs between positive and negative effects of trees are found in most mixed plantation (García-Barrios & Ong, 2004).

Trees present a competitive advantage in agroforestry systems, having a longer lifecycle, eventually exploring larger areas, modifying microclimate environment and being better adapted to shortage of growing resources (Rao et al., 1997; van Noordwijk et al., 1996). Tree-crop interactions change continuously with the maturity of the system (Hussain, 2015) and trees may suppress crops or reduce yields below economic acceptable levels (García-Barrios & Ong, 2004). Through proper design and management practices, the competition for growth resources can be minimised. However, under field conditions, developing and replicating successful agroforestry systems to achieve a balance between the production of the different components has been proven a challenge (García-Barrios & Ong, 2004). Hence, the importance of considering above and belowground interactions in establishment of mixed plantations.

Although it is possible to analyse visually the aboveground tree-crop interactions, in practice, it is not a simple task to plan planting space and management practices taking into account changes in canopy structures and light capture through time and space. Even more complex to interpret and handle are the invisible belowground interactions and yet limited knowledge is available about its spatial pattern and effects on crop yields (Hussain, 2015). Simulation tools can assist to understand part of these interactions in agroforestry systems and likely outcomes exploring management options (García-Barrios & Ong, 2004).

2.4 WaNuLCAS model

WaNuLCAS model was developed to explore the dynamics processes of tree-soil-crop interactions in a wide range of agroforestry systems and management options in space and time (van Noordwijk et al., 2011). It runs on the STELLA modelling environment software (version 7.0, isee systems Inc.) linked to Microsoft Excel spreadsheets for data and model parameters input, allowing the modification by the users. The configuration requires information about daily rainfall, soil temperature and evapotranspiration and soil parameters, such as nitrogen and phosphorous content, soil texture, soil organic matter, bulk density. It should be noted that part of these inputs are used as bases to generate soil hydraulic properties (van Noordwijk et al., 2011). Moreover, the model has crop and tree libraries with growth parameters that includes length of vegetative and generative stage, root distribution, maximum leaf area index, and crop and tree management options such as planting dates, amounts and timing for fertilizer application, intensity, and timing for pruning and thinning practices. The WaNuLCAS considers four soil layers and four planting zones where trees and crops can be placed, and it simulates tree and crop growth on a daily basis determined by light, water, nitrogen, and phosphorus availability. For trees, allometric equations are used to allocate growth, providing the relationship between relative increases in its dimensions (Gayon, 2000), .

According to van Noordwijk and Lusiana (1999), a main characteristic of the model is that water and nutrients uptake are driven by plant demand factors, but limited based on root length densities, the effective diffusion constants, and soil water content, i.e. potential uptake. The model uptake equations follow principles described by Willigen and van Noordwijk (1987, 1989, 1991, 1994) van Noordwijk and van de Geijn (1996). Nutrient demand is estimated by empirical relationships of maximum uptake and dry matter production under non-limiting conditions, while for water, the demand is estimated by plant transpiration rate and potential dry matter production, which considers current shading and water use efficiency. Besides, in the calculation steps to estimate nutrient uptake, the plant development will not be affected if N content is 80% of the required value, however it will be stop when decreases to 40% of the N content demand, between these two limits a linear function is applied to define the reduction (van Noordwijk et al., 2011). Belowground competition for water and nutrients is based on sharing the potential uptake that is allocated to the plants, as a function of their share in total root length in the respective cultivation zone and soil layer (van Noordwijk & Lusiana, 1999).

At the aboveground level, the model considers the leaf area index (LAI) and relative heights of crops and trees to predict light capture for each zone. For trees, light capture is separated by branches and leaves, which allows to represent shading even when trees are leafless. WaNuLCAS distinguishes three different layers: an upper canopy, a mixed strata and a lower one. The model considers LAI in each canopy layer and a plant-specific light extinction coefficient to calculate light capture, in which the pattern of light absorption is described as a logarithmic function consistent with Beer's Law (van Noordwijk et al., 2011).

WaNuLCAS provides as an output the Crop_PosGro which indicates the magnitude of limiting factors for plant growth related to water and nutrients (N, P) stress per planting zone, varying between ‘zero’, which denotes ‘no growth’, and ‘one’ that means ‘no stress’. Additionally, the model has an index to point the growth constrain associated with light capture (Light_C_RelCap), ranging from ‘zero’, which indicates ‘no light capture’, to ‘one’ that corresponds to the maximum of light capture (van Noordwijk et al., 2011).

The water balance of the system in WaNuLCAS considers a number of combined processes with different dynamics, including rainfall or irrigation and its surface run-off, infiltration, drainage, and the exchange between zones, with the water uptake by crops and trees, soil water retention, evaporation of canopy intercepted water, and water evaporation from surface soil. Soil evaporation daily rate depends on ground cover, which is estimated based on LAI of trees and crops, and water content of the topsoil (van Noordwijk et al., 2011).

Based on Century model terminology, WaNuLCAS considers that soil organic matter (SOM) consists of active, slow, and passive pools (C and N) which present different decomposition rates. Input of organic matter from crop residues, tree litterfall, pruning and other external organic source supply, are divided into structural (resistant to decomposition) and metabolic (readily decomposable) plant material, as a function of the initial lignin and nitrogen ratio (van Noordwijk et al., 2011). The dynamics and transformations on SOM-C and SOM-N are function of soil texture, soil temperature, and soil water content. As an output of the carbon balance, WaNuLCAS provides an estimation of the CO_2 sequestration potential of the system over the duration of the simulated time horizon (van Noordwijk et al., 2011).

3 Methodology

3.1 Study area

The exploration of agroforestry with sengon using WaNuLCAS model is based on the climate and soil characteristics of sengon plantations of 1m Trees project area in Gunung Mas District, Central Kalimantan, Indonesia (1°15'10" S, 113°28'30"E). Based on data from the Beringin meteorological station between 2015 and 2019 (BMKG, 2020), the region has minimum and maximum annual air temperatures of 24 and 33◦C, respectively (Figure 1), and benefited from cumulative rainfall of 3000 mm (Figure 2), distributed with a peak from November to April and a dry season from May to October.

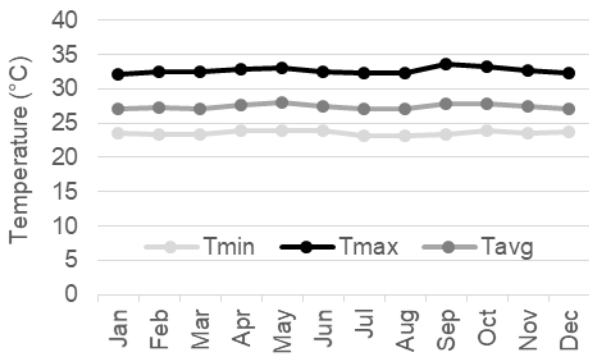

Figure 1. Arithmetic mean of monthly minimum, mean and maximum temperature between 2015 and 2019. Source: BMKG - Badan Meteorologi, Klimatologi, dan Geofisika.

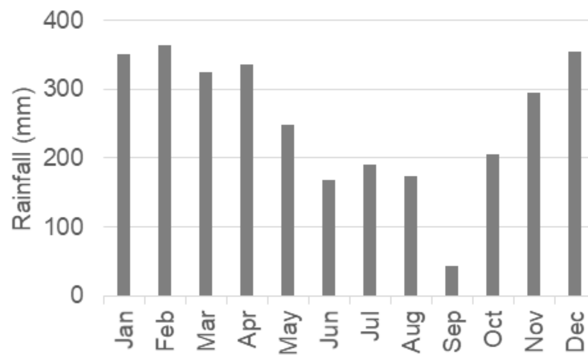

Figure 2. Arithmetic mean of monthly rainfall between 2015 and 2019. Source: BMKG - Badan Meteorologi, Klimatologi, dan Geofisika.

Table 1. Soil physical and chemical properties in the project site used for model parameterisation.

Soil layer (cm)	Clay	Silt	Sand	C/N (-)	P_2O_5 (ppm)	Bulk density (g cm^{-3})	C_{org}	N	CEC (cmol kg^{-1})	pH H_2O	pH KCl
		(%)					(%)				
0 - 10	27.1	8.3	64.6	16.8	3.81	1.14	1.33	0.09	3.99	5.9	4.1
10 - 30	27.1	8.3	64.6	16.8	3.81	1.14	1.33	0.09	3.99	5.9	4.1
30 - 60	28.9	8.4	62.7	14.8	2.85	1.21	0.74	0.05	2.88	5.6	4.1
60 - 100	28.9	8.4	62.7	14.8	2.85	1.21	0.74	0.05	2.88	5.6	4.1

C/N carbon to nitrogen ratio, P_2O_5 concentration of available phosphorus, C_{org} total organic carbon, N total organic nitrogen + total ammonia, CEC cation exchange capacity

The soil in the project area is classified as Cambisol with sandy clay loam texture. Soil physical and chemical properties, as presented in Table 1, are the results of laboratory analysis used to parameterise the model for four different soil layer depths. The laboratory analysis data was compiled by PT Harfield Indonesia in a report done in March 2019 and it comprised results for depth of soil layer of 0 – 30 cm and 30 – 60 cm, hence some of the values were repeated for the model configuration.

3.2 Crops selection

In order to decide which cash crops should be analysed in combination with sengon in an agroforestry system, a pre-selection was done including 10 species suitable for the Indonesian climate conditions, reported as successfully cultivated in country. A matrix ordering these species according to fertility requirements, shade tolerance, weed suppression, low soil pH tolerance and drought tolerance is presented in Table 2. Each species received a classification number based on the sum of each characteristic, scored as shown in Table 3, with an additional point for crops traditional to Dayak people, indigenous peoples of the island of Borneo, based on a study done by Mulyoutami, Rismawan, and Joshi (2009). Subsequently, the crops were classified from the highest to the lowest agronomic suitability score and, to better identify which characteristics are an advantage (green) or a disadvantage (orange), a colour scheme was applied to Table 2. The classification was based according to different literature sources such as extension service and technical booklets, species datasheets and research papers, as cited in the table. Besides the cash crops, strategies involving leguminous species were compiled during the desk research, since they can improve soil fertility and help with weed suppression. Taking this into consideration, velvet bean (*Mucuna pruriens)* and Butterfly pea (*Centrosema pubescens*) were included in the list (Table 2).

Table 2. Matrix of ten pre-selected cash crops and two leguminous species to combine with sengon in agroforestry systems. The crops were classified according to different agronomic requirements and scored based on the system presented in Table 3.

Crop	Fertility requirement	Shade tolerance	Drought tolerance	Low soil pH tolerance	Weed suppression	Traditional crop	References
Ginger (*Zingiber officinale)*	Medium	High	Medium	High	Medium	X	Bindu and Podikunju (2019) Dinesh, Srinivasan, and Srambikkal (2012) Nair (2013a)
Turmeric (*Curcuma xanthorrhiza)*	Medium	High	Medium	High	Medium	X	Hossain (2005) Nair (2013b) Purnomo, Budiastuti, Sakya, and Cholid (2018) Sachdeva, Kumar, and Rana (2015)
Cassava (*Manihot esculenta)*	Low	Medium	High	High	Low	X	FAO (2013b) Ghosh, Kumar, Kabeerathumma, and Nair (1989)

Crop	Fertility requirement	Shade tolerance	Drought tolerance	Low soil pH tolerance	Weed suppression	Traditional crop	References
							Miccolis et al. (2016)
Pineapple (*Ananas comosus)*	Low	Medium	High	High	Low	X	Miccolis et al. (2016) Robin, Pilgrim, Jones, and Etienne (2011) UNCTAD (2016)
Lemongrass (*Cymboppogon flexuosus)*	Medium	Medium	Medium	Medium	High		Boer (2005) Dhurve, Nema, Upadhyaya, and Khan (2016) Murch (2008) Yadava (2001)
Patchouli (*Pogostemon cablin)*	Medium	High	Low	Medium	High		Mahanta, Chutia, and Sarma (2007) Ramya, Palanimuthu, and Rachna (2013) Swamy and Sinniah (2016)
Sweet sorghum (*Sorghum bicolor)*	Medium	Low	High	Medium	Medium		Espinoza and Kelley (2002) Khawaja et al. (2014)
Chili Pepper (*Capsicum annuum)*	High	Medium	Low	Medium	Low	X	Amador-Ramírez (2002) Berke et al. (2005) Mariyono (2009) Sultana, Rahman, Naher, Masum et al. (2018)
Eggplant (*Solanum melongena L.)*	High	Low	Medium	Medium	Low		Chen, Kalb, Talekar, Wang, and Ma (2010) Marques, Bianco, Cecílio Filho, Bianco, and Lopes (2017) Salunkhe and Kadam (1998)
Papaya (*Carica papaya)*	High	Low	Medium	Low	Low		Miccolis et al. (2016) Orwa, Mutua, Kindt, Jamnadass, and Simons (2009)
Velvet Bean (*Mucuna pruriens*)	3 - 6 month previous tree plantion - leguminous cover crop to increase organic matter, nitrogen and weed control						Friday, Drilling, and Garrity (1999)
Butterfly pea (*Centrosema pubescens*)	Intercropping with trees to suppress weeds and N fixation						

Table 3. Classification system for species suitability for project area

Score	Fertility requirement	Shade tolerance	Drought tolerance	Low soil pH tolerance	Weed suppression
High	1	3	3	3	3
Medium	2	2	2	2	2
Low	3	1	1	1	1

Based on the availability of planting material and potential market, it was decided to focus on intercropping sengon with chili and galangal (*Alpinia galanga*). Belonging to Zingiberaceae family, galangal is a ginger-like spice and it is commonly used for gastronomic and medicinal purposes in Southeast Asia (Zhou et al., 2018). A dedicated parameterisation campaign to gather in-situ data for the specific crops selected was not possible due to travel and field work restrictions imposed by the ongoing COVID-19 pandemic. For the model parameterisation, phenological and agronomic data for ginger was used, considering its similarity to galangal and its greater data availability. Regarding the leguminous cover crop strategy, jack bean (*Canavalia ensiformis*) was chosen and, for modelling proposes, datasets for cowpea (*Vigna unguiculata*) were used due to the availability in the standard crop library on WaNuLCAS.

3.3 Model calibration and validation

An extensive sequence of model calibration and validation for the different species was carried out for the monocultures, preceding the use of WaNuLCAS to analyse agroforestry systems with sengon. As a starting point, standard input parameters to model tree and crop growth were used from the model library. Subsequently for chili, parameterisation and calibration for crop growth and production were based on field measurements by Vos and Frinking (1997) in West Java and by Wisnubroto et al. (2017) in East Java, Indonesia. Just as for ginger, results of field experiments by Bindu and Podikunju (2019) and by Shadap et al. (2018) were used to adjust the model input parameters. Additionally, a comparison of the simulation results and the average chili and ginger production between 2014 and 2018 in Indonesia as presented by the FAO statistics (FAO, 2020) provided the basis for a fine-tuning in the model calibration.

Daily rainfall and temperature data, as registered by Beringin meteorological station in 2019 (BMKG, 2020), and soil data, as presented in Table 1, were used for model parameterization for all crops and repeated for all years considered in the simulation. Regarding fertilizer application, nitrogen (N) and phosphorous (P) were implemented to the systems with dosage recommended by Berke et al. (2005) and by Wahocho et al. (2016) for chili (N: 150 kg ha^{-1} P: 20 kg ha^{-1}) and by Parthasarathy and Sudhakaran (2008) and by Singh et al. (2015) for ginger (N: 75 kg ha^{-1}

P: 50 kg ha^{-1}). For the trees, the quantities were applied according to the NGO partner of 1mTrees project for fertilization practices, which is 90g of NPK 15:15:15 per tree divided in two applications.

For the tree model calibration and validation, the data set used was based on a combination of 15 sengon plots from smallholder farmers associated with the project. In these sengon plantations, tree management practices are minimal, and it is usual to encounter irregular tree spacing on the smallholder farms. Hence, based on the field measurements, an average tree density of 390 trees per hectare was used for model calibration. The assessment of the model fitting compares measured and simulated data of tree height and diameter according to statistical criteria proposed by Loague and Green (1991) and cited by Khasanah et al. (2015) (Table 4), including the coefficient regression as done by Bayala et al. (2008). During tree model calibration other growth parameters, such as width and height of crown, were used to check if the simulation results captured field measurements.

Table 4. Statistical criteria for evaluation of model results

Criteria (symbol)	Formula	Optimum value
Modelling efficiency (EF)	$\frac{(\sum_{i=1}^{n}(O_i - O_{mean})^2 - \sum_{i=1}^{n}(P_i - O_i)^2)}{\sum_{i=1}^{n}(O_i - O_{mean})^2}$	1
Coefficient of determination (CD)	$\frac{\sum_{i=1}^{n}(O_i - O_{mean})^2}{\sum_{i=1}^{n}(P_i - O_{mean})^2}$	1
Coefficient of residual mass (CRM)	$\frac{(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i)}{\sum_{i=1}^{n} O_i}$	0
Root mean square error (RMSE)	$\left(\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right)^2 \times \frac{100}{O_{mean}}$	0

n number of samples, P_i predicted values, O_i observed values, O_{mean} the mean of the observed data

Table 13 in appendix presents details of sengon parameterisation.

3.4 Scenarios analyses

3.4.1 Simulated scenarios

Sengon plantation in monoculture and in agroforestry systems with chili, ginger and cowpea were simulated under different tree management options, in which pruning practices were simulated only for the scenario with 825 trees ha^{-1}:

- Initial tree density – 278, 400, 500, 625 and 825 trees per hectare

- Thinning intensity (1st | 2nd thinning) – T0: no thinning, T1: 25%| 25%, T2: 50%| 25%, T3: 50%| 35% to 70%
- Pruning intensity – P0: no pruning, P40: 40% of the crown, P60: 60% of the crown

Regarding the planting systems, the following species combination were simulated:

- Sengon monoculture (T mono)
- Chili monoculture (C mono)
- Ginger monoculture (G mono)
- Sengon + chili (T + C)
- Sengon + ginger (T + G)
- Sengon + chili + cowpea (T + C + CP)
- Sengon + ginger + cowpea (T + G + CP).

Table 5 presents more details about these tree management scenarios and Table 7 shows a matrix indicating by the colour green which scenarios were simulated for which species combination. Including the monoculture systems, 122 simulations were run for a time period equivalent to 7 years, which represents a normal tree rotation for fast-growing species (Krisnawati et al., 2011).

For the cash crops, it was considered one season per year and harvest time was determined internally in WaNuLCAS based on the specifications of vegetative and generative phases for each crop. When included in the system, cowpea was cultivated on the same date of the cash crops. For sengon, all the management options were scheduled in the 'Tree management' spreadsheet on WaNuLCAS.xls file. The wood was harvested at year 7. The first thinning took place at year 2 and 18 months later the second one, the time for thinning was adapted from recommendations by Krisnawati et al. (2011). When pruning practices were implemented, they happened once a year before the establishment of the cash crop cultivation. The planting space available for cash crop varies depending on tree spacing (Table 6). The distance left between the trees and cash crops was 0.75 metre, whereas for cowpea, the space between trees and crop was 0.50 metre and the row width for the pulse was 0.50 metre.

Table 5. Detailing tree management options applied to the simulated scenarios: initial tree density (spacing), thinning intensity at each period (percentage of trees removed), pruning (percentage of crown removed) and final tree density after thinning practices.

Initial tree density (trees ha^{-1})	Initial tree spacing (m)	Thinning (%)			Pruning		Final tree density (trees ha^{-1})
		Intensity	1st (24 months)	2nd (36 months)	Intensity	% crown pruned	
278	6 x 6	T0	-	-			278
		T1	25	25			156
		T2*	50	-			130
400	5 x 5	T0	-	-			400
		T1	25	25			225
		T2	50	25			150
		T3	50	35			130
500	5 x 4	T0	-	-			500
		T1	25	25			281
		T2	50	25			188
		T3	50	50			130
625	4 x 4	T0	-	-			625
		T1	25	25			352
		T2	50	25			235
		T3	50	60			130
825	4 x 3	T0	-	-	P0	-	825
					P40	40	
					P60	60	
		T1	25	25	P0	-	464
					P40	40	
					P60	60	
		T2	50	25	P0	-	310
					P40	40	
					P60	60	
		T3	50	70	P0	-	130
					P40	40	
					P60	60	

* Only the 1st thinning is applied in order to get the minimal final tree density of 130 trees per hectare

Table 6. Tree spacing and planting space available for cash crops

Alley spacing (m)	Initial tree density (trees ha^{-1})	Width of planting space for cash crop within the alley (m)	
		No cowpea	With cowpea
6	278	4.5	4
5	400 | 500	3.5	3
4	625 | 800	2.5	2

Table 7. Simulated scenarios – green colour indicates when a determined tree management option (initial tree density, intensity of thinning and pruning) was applied to a system: T mono (sengon monoculture), C mono (chili monoculture), G (ginger monoculture), T + C (sengon + chili), T + G (sengon + ginger), T + C + CP (sengon + chili + cowpea), T + G + CP (sengon + ginger + cowpea)

			Systems						
Initial tree density (trees ha^{-1})	Thinning Intensity	Pruning Intensity	T mono	C mono	G mono	T + C	T + G	T + C + CP	T + G + CP
278	T0	-							
	T1	-							
	T2*	-							
400	T0	-							
	T1	-							
	T2	-							
	T3	-							
500	T0	-							
	T1	-							
	T2	-							
	T3	-							
625	T0	-							
	T1	-							
	T2	-							
	T3	-							
825	T0	P0							
		P40							
		P60							
	T1	P0							
		P40							
		P60							
	T2	P0							
		P40							
		P60							
	T3	P0							
		P40							
		P60							

* Only the 1st thinning is applied in order to get the minimal final tree density of 130 trees per hectare

3.4.2 Productivity analysis

For the productivity trade-off analysis, the simulated results for wood volume and cumulative crop yield, considering the different intercropping practices, were divided by the simulated results achieved in monoculture systems. The relative productivity for sengon wood volume and cash crop yield were then plotted against each other, as done previously by Martin and Noordwijk

(2009) and Khasanah et al. (2015). In this analysis, the system has a positive result when the combination of tree and crop production is found above the 1:1 line. On the other hand, when points are below this line there is no advantage in intercropping (Figure 3).

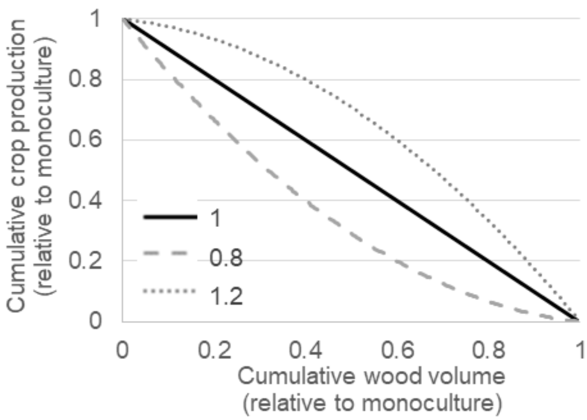

Figure 3. Trade off analysis comparing relative productivity wood volume versus crop production in simultaneous agroforestry systems, with net negative (X < 1) or net positive (X > 1) interactions. Adapted from Khasanah et al. (2015).

Additionally, the resulting relative productivities of wood and crop yields were summed for each scenario resulting in the land equivalent ratio (LER), which indicates the equivalent area under monoculture required to achieve the same yield response as with an intercropped system (Khasanah et al., 2020). For instance, LER value of 1.1 means that the area of the monocropping system would need to be 10% greater than the area planted as an intercrop in order to produce the same combined yields. Therefore, LER above one suggests that there is an advantage for the intercropping system. The calculation is presented in Equation (1), where PI and PM are the productivity in intercrop and monoculture systems, respectively, subscript ‘t’ indicates wood productivity (m^3 ha^{-1}), and ‘c’ subscript represent crop productivity (t ha^{-1}).

$$LER = \frac{PI_t}{PM_t} + \frac{PI_c}{PM_c} \quad (1)$$

3.4.3 Financial analysis

For the financial analysis, net present value (NPV) and benefit cost ratio (BCR) were used as indicator to determine whether the mixed system is profitable. NPV is calculated according to Equation (2), where R_t is revenue at year t, C_t is cost at year t, and r is discount rate. It represents the current value of net benefits generated from a project, considering time value of money. The system is cost-effective when NPV is higher than zero. BCR is the relation of the present value of benefit (revenue minus costs) and the present value of cost Equation (3). BCR higher than one indicates a profitable system.

$$NPV = \sum_{t=0}^{t=n} \frac{R_t - C_t}{(1+r)^t} \quad (2)$$

$$BCR = \frac{\sum_{t=0}^{t=n} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{t=n} \frac{C_t}{(1+r)^t}} \quad (3)$$

The financial analysis requires a set of data on farming activities, market prices of each input and its simulated yield results. Data consisting of labour hours for different farm duties (land preparation, planting, weeding, harvesting), price for fertilizer, planting material and other inputs were provided by German partner of the project, according to traders at the local area. Wood selling prices are classified according to tree diameters and follows sales price matrix. For the financial analysis, it was assumed that sengon logs have a length of 1.3 m and it was considered an interested rate of 7%.

Table 14 and Table 15 in appendix present more details about the values assumed for the financial analysis for sengon, chili and ginger.

3.4.4 Resource competition and environmental impacts

For resource competition analysis related to water and nutrients (N and P), the results from WaNuLCAS given by Crop_PosGro, which varies between ‘zero’ (no growth) and ‘one’ (no stress), were used. WaNuLCAS output Light_C_RelCap was used as indication of light competition. It also ranges from ‘zero’ (no light capture) and ‘one’ (maximum of light capture). For the analysis, this indicator was compared for the crop cultivated in monoculture and in mixed systems.

Besides, some outputs provided by the WaNuLCAS model related to ecosystem-regulating functions systems were compared between tree monoculture and agroforestry. In order to have a general overview of environmental impact, a limited number of scenarios combining chili and sengon were analysed regarding carbon content in soil organic matter, water evaporation rate from soil surface and potential CO_2 sequestration.

4 Results

4.1 Model validation

The evaluation of the model for tree diameter and height for sengon is presented in Table 8, while comparisons between the simulated and measured data for these parameters are shown in Figure 4. The results indicate a good ability of the model to predict tree dimensions, with satisfactory values for the assessed statistical criteria with model efficiency (EF) values of 0.95 for tree diameter and 0.96 for tree height. The relationship of observed and simulated data for tree height presented a better fitting with coefficient of determination (CD) of 1.12 (optimum value 1) and coefficient of regression (a) of 0.85 (optimum value 1), while for tree diameter the respective values were 1.49 and 0.81.

Table 8. Tree model results evaluation through statistical criteria comparing simulated and measured data for sengon on project area.

Criteria (optimum value)	Tree diameter (cm)	Tree height (m)
EF (1)	0.95	0.96
CD (1)	1.49	1.12
CRM (0)	-0.05	0.16
RMSE (0)	10.45	15.05
a (1)	0.81	0.85

EF model efficiency, CD coefficient of determination, CRM coefficient of residual mass, RMSE root mean square error, a coefficient regression

When comparing simulated and real results for sengon growth, it is possible to observe that the model overestimated tree diameter in the beginning of the simulation, while it underestimates tree height and diameter over time. However, the real datasets present a high variability within the same farm and consequently same tree age. In the graphs presented in Figure 4 b, the different markers represent the farms where the measurements were taken, for instance on the farm represented by the plus marker (+) trees diameter varies from 8.8 to 20.2 cm.

Table 9. Expected production level of chili and ginger for Indonesia, according to FAO (2020), and simulated results of chili and ginger in a monoculture system

Crop	Production ($t\ ha^{-1}\ y^{-1}$) fresh product	
	Expected	Simulated
Chili	7.6	7.7
Ginger	19.3	18.5

Regarding the crops, the simulated average annual production for chili and ginger monoculture systems are shown in Table 9. These values are close to the average production level per area for Indonesia between 2014 and 2018, according to data provided by Food and

Agriculture Organization of the United Nations (FAO, 2020), labelled as expected production in the table.

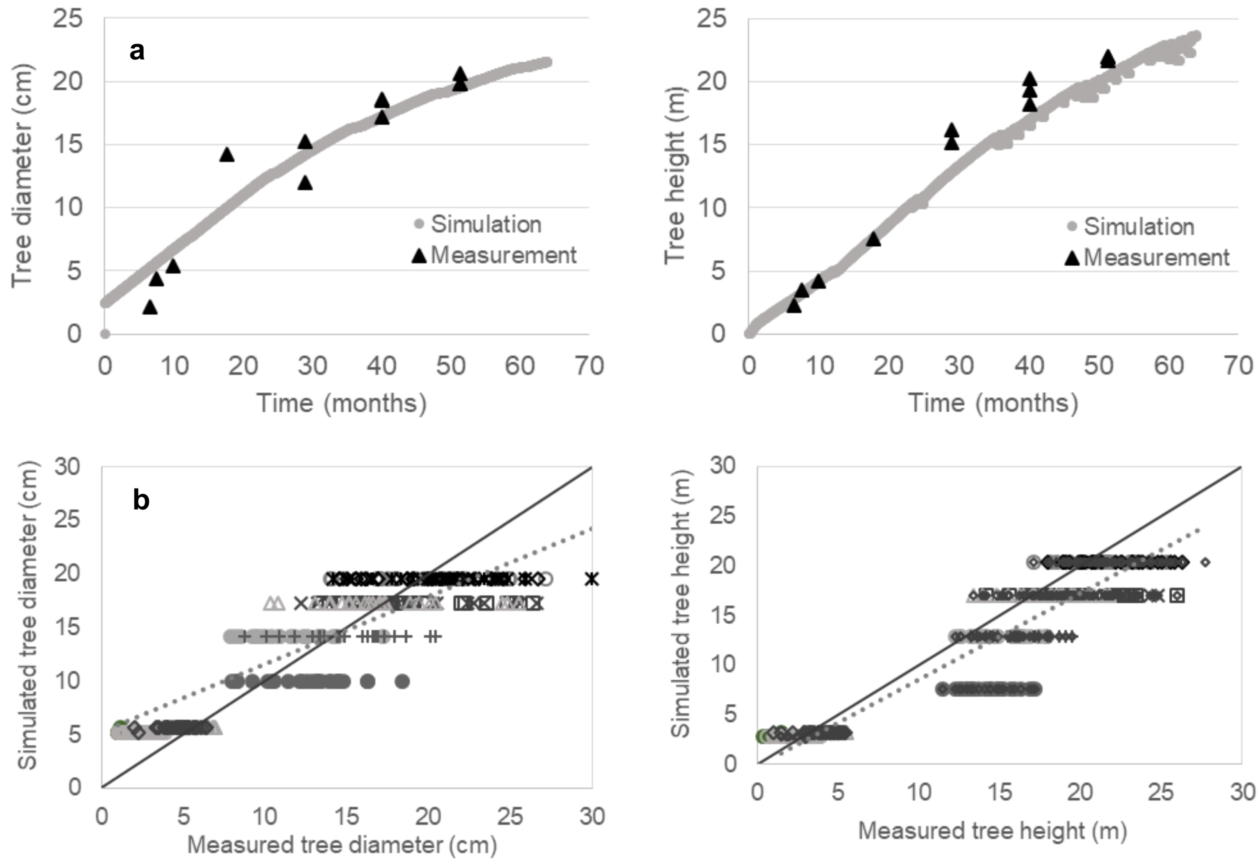

Figure 4. (a) Comparison of simulated and measured (average per farm) tree diameter and height. (b) Scatter graphs of simulated against measured tree diameter and height across the farms represented by the different markers. The solid line represents the 1:1 line and the dashed line is the regression.

4.2 Tree monoculture scenarios

Figure 5 shows the simulated harvested wood volume and respective stem diameter (DBH – diameter at breast height) at end of the rotation for the sengon monoculture system under different thinning systems and initial tree densities.

The highest sengon wood volume is achieved by the system with the highest initial tree density (825 trees ha^{-1}) and no thinning (T0), while the lowest wood volume is provided by the planting density of 278 trees ha^{-1} and thinning intensity T1. However, the greater stem diameter per tree is provided by the lowest tree density (130 trees ha^{-1}). Regarding thinning strategies, all the different intensities reduce the volume of the harvested wood when comparing to no thinning scenario. In contrast, thinning practices affect positively the stem diameter, the higher the intensity the greater the effect. Additionally, a more intense first thinning as in the case of scenarios with intensity T2 and T3, in which 50% of the trees are removed, show even a higher influence on the tree diameter growth.

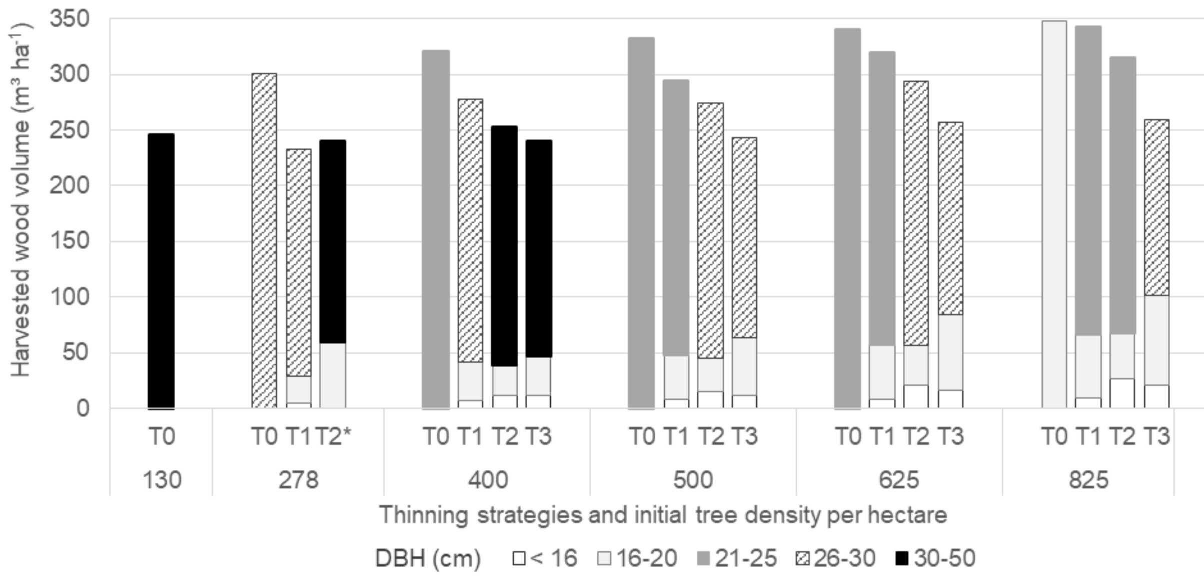

Figure 5. Harvested wood volume for tree monoculture scenarios at last year of the rotation. Wood volume is distributed by respective tree diameter (DBH – diameter at breast height), represented by different colours, comparing different thinning intensities (T0: no thinning, T1, T2, T3: most intense) and initial tree density per hectare (130 – 825 trees ha-1).

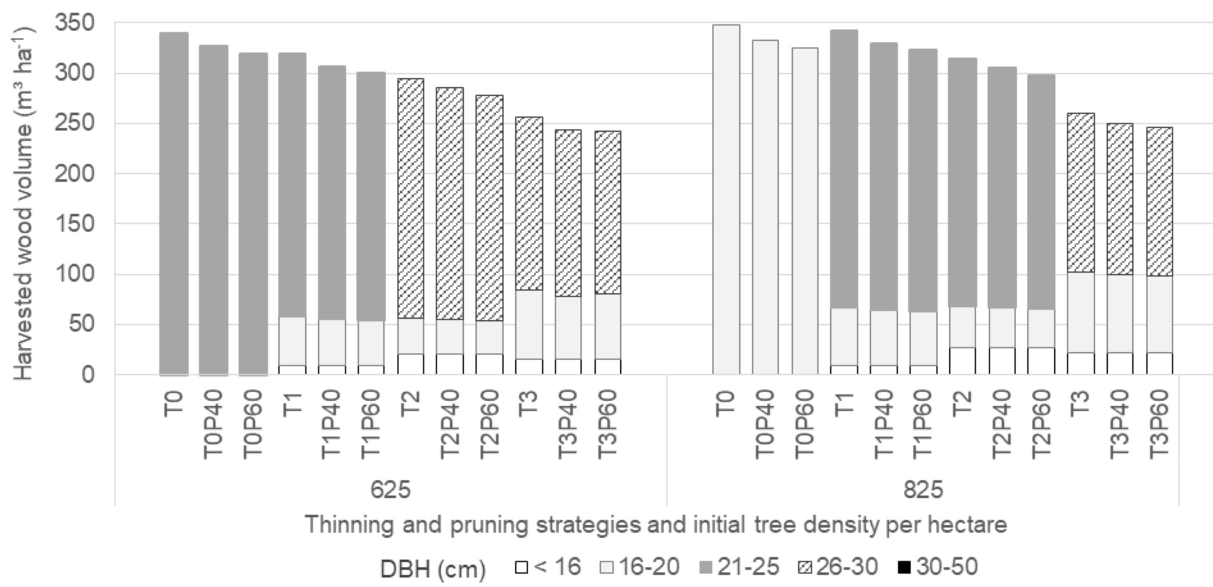

Figure 6. Harvested wood volume for tree monoculture scenarios at last year of the rotation. Wood volume is distributed by respective tree diameter (DBH) comparing different thinning intensities (T0: no thinning, T1, T2, T3: most intense), initial tree density per hectare (130 – 825 trees ha^{-1}) and pruning intensities (P40: 40% of the crown, P60: 60% of the crown).

Simulated results indicate that pruning practices have an adverse impact on tree growth when compared to unpruned trees (Figure 6). The comparison of systems with different pruning intensities shows that the greater the intensity of the pruning regime (P40: 40% of the crown and P60: 60% of the crown), the greater the impact on the systems, independently of the initial tree density. However, it is important to mention that the model does not explicit predict possible effects of pruning on wood quality such as knots in the wood.

4.3 Agroforestry scenarios: sengon and chili

Table 10 presents a comparison between the production ratios of each species in the mixed planting system relative to its correspondent total yield in a monoculture system after 7 years of rotation. It includes the land equivalent ratio (LER) and the relative production for the various tree management strategies in two intercropping systems, sengon with chili, and the same mixed plantation including cowpea. In total, the table presents the results of 46 simulations.

Table 10. Relative production of sengon and chili in agroforestry systems compared to respective monoculture after 7 years of rotation for different tree management scenarios. Scenarios vary by initial tree density, pruning intensity (P0: no pruning, P40: 40% of the crown, P60: 60% of the crown), thinning intensity (T0: no thinning, T1: 25% | 25%, T2: 50% | 25%, T3: 50% | 30 to 70 %) and crop combination.

Thinning intensity	Initial tree density (trees ha^{-1})	Pruning intensity	Initial tree spacing (m)	Relative production to monoculture						
				Sengon + Chili			Sengon + Cowpea + Chili			
				Chili	Tree	LER	Chili	Tree	Cowpea	LER
T0	278	P0	6 x 6	0.36	1.12	1.48	0.39	0.85	0.03	1.28
	400	P0	5 x 5	0.29	1.17	1.46	0.31	1.01	0.04	1.36
	500	P0	5 x 4	0.27	1.18	1.45	0.28	1.07	0.04	1.39
	625	P0	4 x 4	0.23	1.15	1.38	0.20	1.01	0.06	1.27
	825	P0	4 x 3	0.21	1.14	1.35	0.17	1.04	0.06	1.27
	825	P40	4 x 3	0.23	1.05	1.28				
	825	P60	4 x 3	0.25	1.02	1.27				
T1	278	P0	6 x 6	0.46	1.08	1.54	0.42	1.05	0.03	1.50
	400	P0	5 x 5	0.40	1.07	1.47	0.33	1.16	0.04	1.53
	500	P0	5 x 4	0.37	1.07	1.44	0.29	1.26	0.04	1.59
	625	P0	4 x 4	0.29	1.10	1.39	0.21	1.17	0.06	1.43
	825	P0	4 x 3	0.26	1.10	1.36	0.17	1.16	0.06	1.40
	825	P40	4 x 3	0.28	1.05	1.33				
	825	P60	4 x 3	0.30	1.02	1.32				
T2	278	P0	6 x 6	0.46	1.07	1.53	0.42	1.03	0.03	1.48
	400	P0	5 x 5	0.45	1.09	1.54	0.41	1.11	0.04	1.56
	500	P0	5 x 4	0.44	1.09	1.53	0.38	1.13	0.04	1.55
	625	P0	4 x 4	0.36	1.10	1.46	0.25	1.12	0.06	1.43
	825	P0	4 x 3	0.33	1.10	1.43	0.22	1.16	0.06	1.44
	825	P40	4 x 3	0.35	1.03	1.38				
	825	P60	4 x 3	0.37	1.01	1.38				

Thinning intensity	Initial tree density (trees ha^{-1})	Pruning intensity	Initial tree spacing (m)	Relative production to monoculture						
				Sengon + Chili			Sengon + Cowpea + Chili			
				Chili	Tree	LER	Chili	Tree	Cowpea	LER
T3	278	P0	6 x 6							
	400	P0	5 x 5	0.47	1.07	1.54	0.43	0.96	0.04	1.43
	500	P0	5 x 4	0.42	1.07	1.49	0.43	1.02	0.04	1.50
	625	P0	4 x 4	0.42	1.08	1.50	0.33	0.97	0.07	1.37
	825	P0	4 x 3	0.39	1.08	1.47	0.32	0.97	0.07	1.36
	825	P40	4 x 3	0.42	1.02	1.44				
	825	P60	4 x 3	0.44	1.00	1.44				

The results indicate that for all the simulated scenarios there is an advantage in combining trees and crops, when compared to the correspondent monoculture systems with land equivalent ratio above 1. The positive results of the combination of sengon and chili is suggested by the trade-off analysis (Figure 7), in which all the points representing the different scenarios are above the 1:1 line. When analysing the relative production for chili, the lowest cumulative yield is found for the system with the highest initial tree density, narrow spacing (4 m x 3 m), no thinning system (T0) and no pruning (P0). In the system combining trees + chili, this value is around 42% lower than the result for largest spacing (6 m x 6 m) and lowest initial tree density and around 56% lower in the intercropping including cowpea. This tendency of lower relative production for narrower spacing is seen for all scenarios, however, it can be noticed that the higher the thinning intensity, the higher chili relative cumulative production.

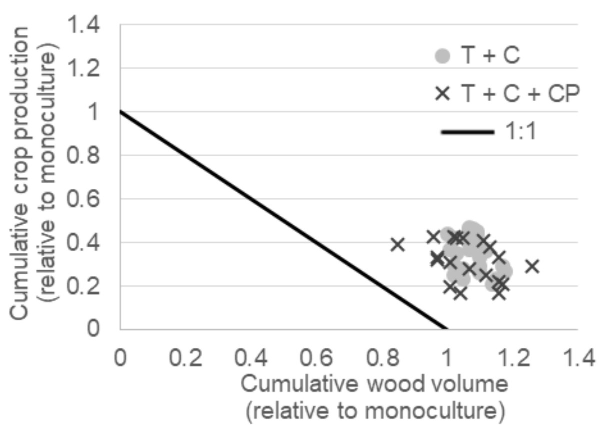

Figure 7. Trade off analysis comparing relative sengon wood volume versus chili production in simultaneous agroforestry systems combining sengon + chili (T + C) and sengon + chili + cowpea (T + C + CP). All the scenarios presented net positive interactions, points above line 1:1.

According to the simulation, the highest cumulative production, reported as around the half of the cumulative yield of chili monoculture, is provided by the system combining just trees and chili, thinning intensity T3 and initial tree density of 400 tree per hectare. Nevertheless, the value is quite similar for 278 trees per hectare and a thinning intensity T1 and T2 for the same combination of species. Considering the scenarios in which cowpea is included, the highest relative yield is also achieved in the scenario with T3 and initial tree density of 400 tree per hectare, however the value is 8% lower than just for trees + chili. It is possible to observe this tendency for almost all the scenarios, excluding no thinning with lowest tree densities. Another interesting point is the comparison of the results for pruning intensities in the tree densest system (825 trees per hectare), in which LER decreases with the intensification of the pruning, indicating that the reduction on the harvested wood is not compensated by the increase in chili yield.

Concerning the relative harvested wood volume, the results suggest that trees benefit from the intercropping systems for almost all management options and species combinations. In general, the same production level, or higher wood volumes, are reached when compared to the equivalent monoculture system (Table 10). Figure 8 illustrates this pattern with a comparison of the harvested wood volumes and stem diameter distribution for the different combinations of species and thinning strategies in the case of an initial tree density of 825 trees per hectare and no pruning practices. The increase in the wood production for the agroforestry systems varies from 1% to 26%, but exceptions are found for some scenarios when cowpea is added as an intercrop (Table 10). Including cowpea as an intercrop did not present a clear pattern regarding sengon growth. In general, wood volume results were higher for the scenarios with intermediate thinning intensities, T1 and T2, when the leguminous species was added to the system.

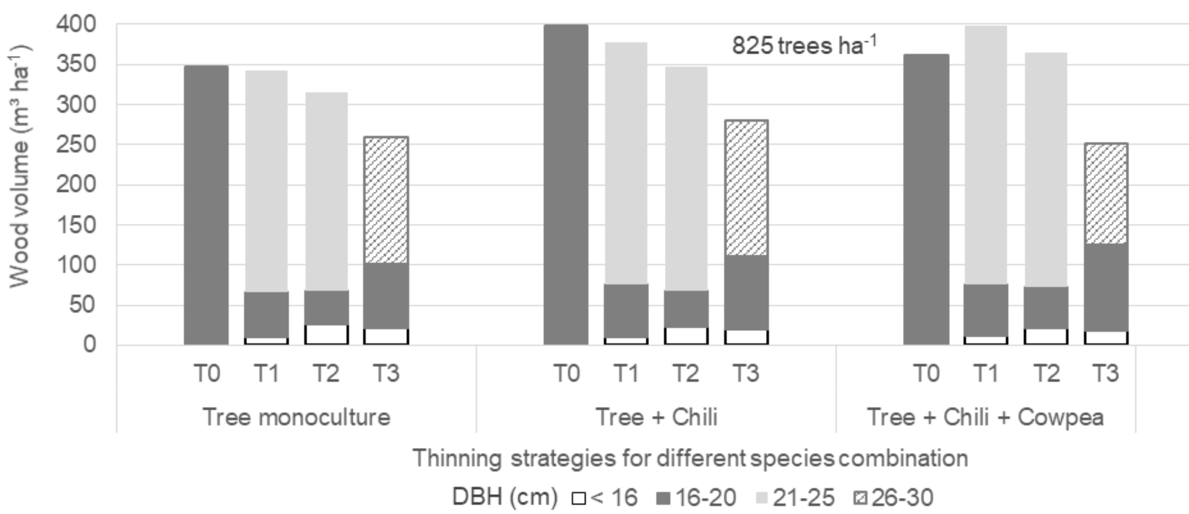

Figure 8. Harvested wood volume at last year of the rotation for an initial tree density of 825 considering different species combination and thinning options

Analysing chili performance at each cropping season, it is possible verify that the simulated production decreases over the years, as shown in Figure 9. The graphs present a comparison between annual chili yield for initial tree densities of 400 and 825 trees ha^{-1}, under different thinning intensities (T0 and T3). It is included the relative light capture, in which light capture by chili combined with sengon is compared to light capture by chili in monoculture, as an indication of light competition between crop and trees. At year 0, when the tree planting takes place, the light captured by the chili is quite similar as for the crop monoculture system and the production differences between the initial tree density systems are mainly due to the tree spacing conditions and, consequently, the area available for planting the chili seedlings.

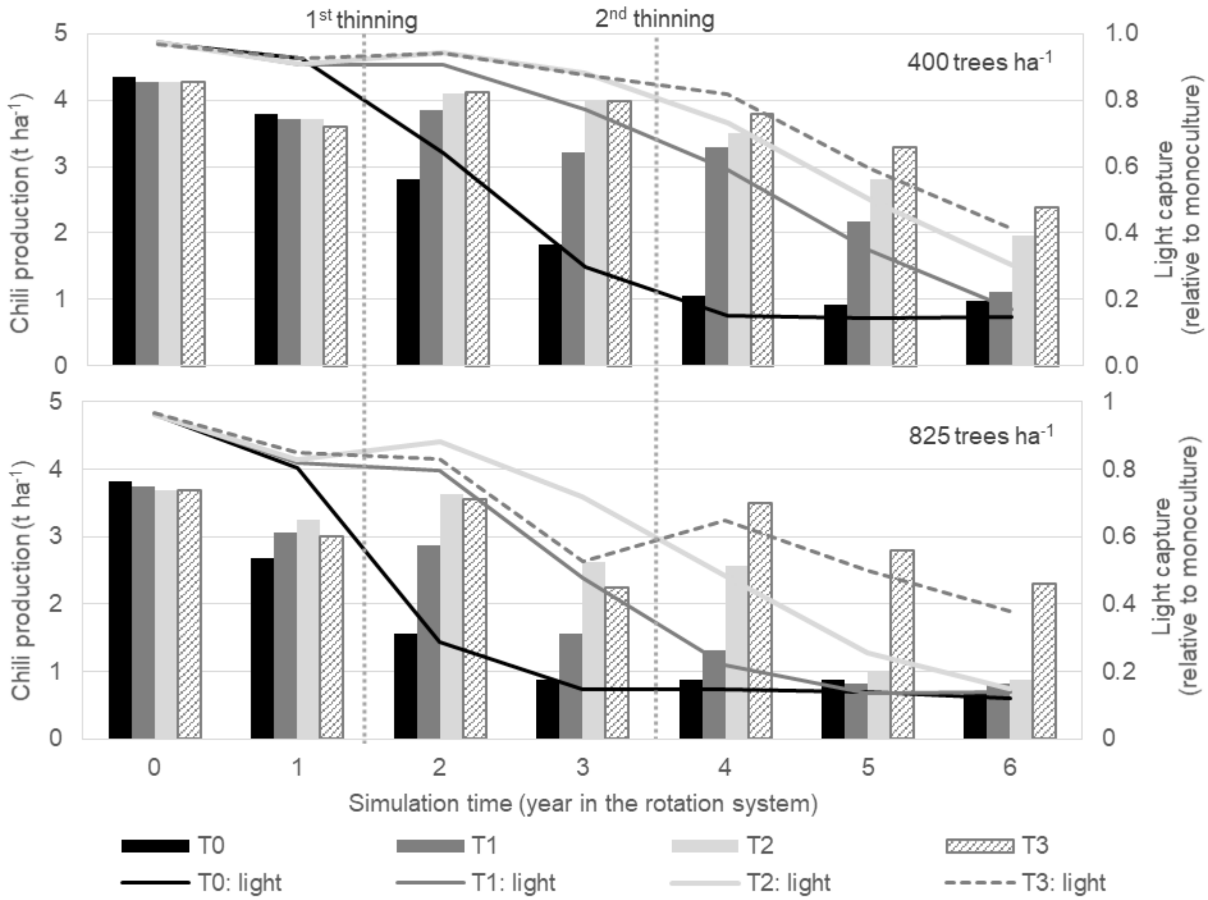

Figure 9. Annual chili yield (represented by bars) during the years of the rotation combining sengon + chili. The lines represent the light capture by chili intercropped with sengon relative to the crop when cultivated in monoculture. Production and light capture are compared for two different initial tree densities (400 and 825 trees ha^{-1}) and for different thinning intensities indicated by the colours (T0, T1, T2, T3).

Aboveground tree-crop interaction changes with the trees development and for no thinning (T0) scenarios, light capture decreases to 40% of the initial level at year 3 for density plantation of 400 trees ha^{-1}, resulting in a reduction in the chili yield of almost 60%. For the denser tree planting (825 trees ha^{-1}) this occurs earlier, at year 2, affecting productivity with similar magnitude. It is possible to observe that a faster decrease in the relative light capture happens for all the thinning intensities in the scenarios with 825 trees ha^{-1} when compared to the less dense tree plantation.

At the last year of the sengon rotation (represent by 6 in the graph), the scenario with tree density of 400 trees ha-1 and no thinning (T0), there is a reduction in the production level of 77% when compared to the first season, while this decrease is around 45% for the most intense thinning option (T3). The impact is great for the denser tree planting scenarios (825 trees ha-1), in which the reduction in the last season relative to the first one is 82% in the no thinning (T0) and 38% for T3. Another interesting observation is that, after thinning, the chili yield presents an increase in the next season, the increase being greater the more intense thinning regime, independently of the initial tree density.

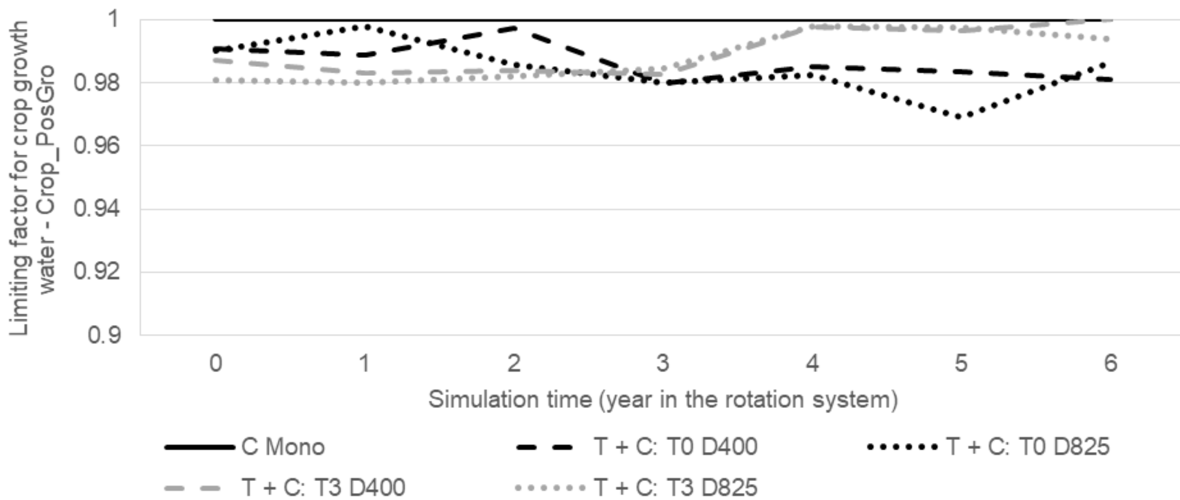

Figure 10. Water as limiting factor for chili growth per season as indicated by Crop_PosGro (1 - 'no stress' 0 - 'no growth'), comparing chili in monoculture (C mono) and in mixed plantation with sengon (T + C) for initial trees densities of 400 trees ha-1 (D400) and of 825 trees ha^{-1} (D825) under different thinning intensities (T0: no thinning, T3: most intense).

Besides light capture, constraining factors for the crop growth related to water, N and P were analysed based on WaNuLCAS indicator Crop_PosGro. A comparison of Crop_PosGro-water between chili in monoculture (C mono) and in combination with sengon (T + C) is shown in Figure 10. The systems are compared per planting season under different initial tree densities D400 and D825 (400 and 825 trees ha^{-1}) and two thinning regimes (T0 and T3). There is no indication of chili growth restriction due to water in the different scenarios, as the values are around one, but adding trees to systems increases slightly water competition that is reduced by removing part of the trees through thinning practices.

For analysis of N limitation, it is considered scenarios under the same tree management regime, 400 trees per hectare (D400) and no thinning (T0), and then compared chili monoculture

(C mono), chili intercropped with sengon (T + C) and chili combined with sengon and cowpea (T + C + CP) (Figure 11). For chili monoculture, Crop_PosGro-N decreases over time, indicating a tendency of reduction of N availability, while the mixed planting systems presented no substantial variation over the seasons and no difference due to addition of the cowpea. Despite the trend of N restriction for chili monoculture, there is no indication of growing limitation by this resource in the analysed systems as Crop_PosGro-N values vary between 0.88 and 0.93.

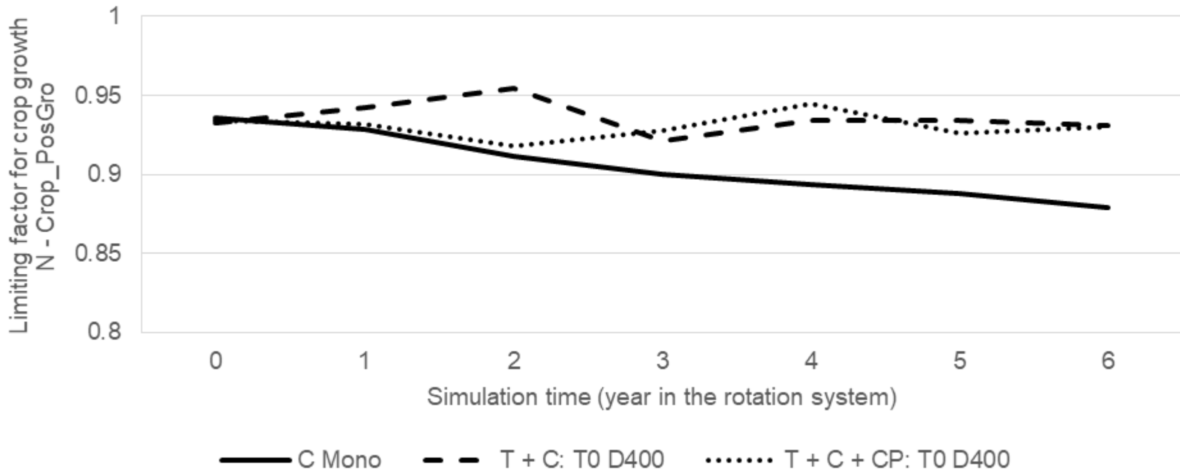

Figure 11. N as limiting factor for chili growth per season as indicated by Crop_PosGro (1 - 'no stress' 0 - 'no growth'), comparing chili in monoculture (C mono), in mixed plantation with sengon (T + C), and with sengon and cowpea (T + C + CP) for initial trees densities of 400 trees ha-1 (D400) and no thinning (T0)

Similar to the analysis of water competition, growing limitation due to P limitation was compared between chili in monoculture (C mono) and in combination with sengon (T + C) under different tree management options, initial tree density of 400 and 825 trees ha^{-1} and two thinning intensities (T0 and T3) (Figure 12). Crop_PosGro-N indicate that, over the crop seasons in the agroforestry systems, the higher thinning intensity (T3) scenarios get closer to the condition presented by chili monoculture. For the no thinning practices (T0), there is a tendency of increasing P availability and the dynamic differs depending on the initial tree density, for 825 trees per hectare it occurs after the second year of the rotation and one year later for 400 trees per hectare (D400). Based on the values of Crop_PosGro-N for the different systems, which varies between 0.85 and 0.98, there is no indication of growth limitation due P availability.

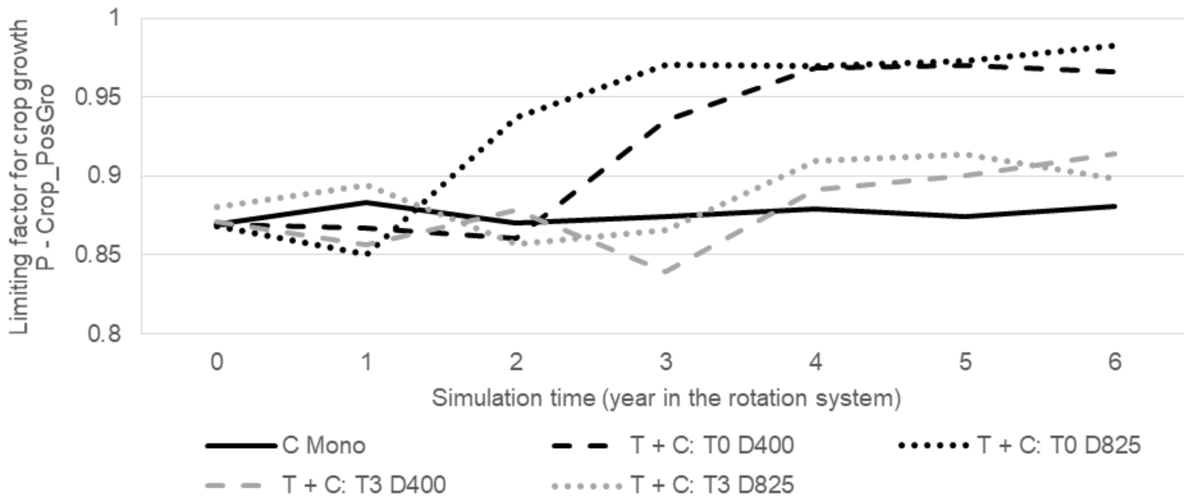

Figure 12. P as limiting factor for chili growth per season as indicated by Crop_PosGro (1 - 'no stress' 0 - 'no growth'), comparing chili in monoculture (C mono) and in mixed plantation with sengon (T + C) for initial trees densities of 400 trees ha-1 (D400) and of 825 trees ha^{-1} (D825) under different thinning intensities (T0: no thinning, T3: most intense).

4.4 Agroforestry scenarios: sengon and ginger

The previously presented analyses were replicated for the intercropping of sengon and ginger. Similarly to chili cultivation in combination with trees, the comparison between the cumulative yield for ginger in the agroforestry systems relative to its respective total yield in a monoculture system shows that the wider the tree spacing and higher the thinning intensity the greater the relative ginger production (Table 11). Moreover, the relative production levels are lower in scenarios including cowpea than in the ones combining just tree and ginger. However, ginger cultivation presents higher relative production than chili, with values varying from 0.51 to 0.64 for the cropping system trees + ginger, whereas, considering the same species combination, the maximum value for relative cumulative chili yield was 0.47 (Table 10).

The highest cumulative production for ginger is achieved by the system combining just trees and ginger, thinning intensity T3 and initial tree density of 500 trees per hectare. Nevertheless, as seen for scenarios with chili, the value is quite similar for 278 trees per hectare and a thinning intensity T1 and T2 for the same combination of species. Regarding the pruning options, for the most tree dense system, also for the agroforestry with ginger, the negative impact on tree growth is not compensated by the increase in the crop yield.

Table 11. Relative production of sengon and ginger in agroforestry systems compared to respective monoculture after 7 years of rotation for different tree management scenarios. Scenarios vary by initial tree density, pruning intensity (P0: no pruning, P40: 40% of the crown, P60: 60% of the crown), thinning intensity (T0: no thinning, T1: 25% | 25%, T2: 50% | 25%, T3: 50% | 30 to 70 %) and crop combination.

Thinning intensity	Initial tree density (trees ha^{-1})	Pruning intensity	Initial tree spacing (m)	Relative production to monoculture						
				Sengon + Ginger			Sengon + Cowpea + Ginger			
				Ginger	Tree	LER	Ginger	Tree	Cowpea	LER
T0	278	P0	6 x 6	0.63	1.00	1.63	0.55	0.75	0.03	1.34
	400	P0	5 x 5	0.58	0.97	1.55	0.47	0.86	0.04	1.38
	500	P0	5 x 4	0.57	0.97	1.54	0.47	0.91	0.04	1.42
	625	P0	4 x 4	0.51	0.97	1.48	0.40	0.97	0.06	1.38
	825	P0	4 x 3	0.51	0.98	1.49	0.39	0.99	0.06	1.40
	825	P40	4 x 3	0.51	0.97	1.48				
	825	P60	4 x 3	0.52	0.95	1.47				
T1	278	P0	6 x 6	0.64	0.95	1.59	0.58	0.96	0.03	1.57
	400	P0	5 x 5	0.62	0.95	1.57	0.49	1.03	0.04	1.56
	500	P0	5 x 4	0.61	0.95	1.56	0.48	1.07	0.04	1.58
	625	P0	4 x 4	0.56	1.01	1.57	0.41	1.11	0.06	1.53
	825	P0	4 x 3	0.53	1.01	1.54	0.41	1.10	0.06	1.52
	825	P40	4 x 3	0.54	0.97	1.51				
	825	P60	4 x 3	0.55	0.95	1.50				
T2	278	P0	6 x 6	0.64	0.98	1.62	0.58	0.99	0.03	1.59
	400	P0	5 x 5	0.63	0.95	1.58	0.50	1.04	0.04	1.57
	500	P0	5 x 4	0.62	0.95	1.57	0.49	1.02	0.04	1.55
	625	P0	4 x 4	0.57	0.97	1.54	0.42	1.08	0.06	1.51
	825	P0	4 x 3	0.55	0.97	1.52	0.42	1.10	0.06	1.53
	825	P40	4 x 3	0.56	0.96	1.52				
	825	P60	4 x 3	0.57	0.95	1.52				
T3	278	P0	6 x 6							
	400	P0	5 x 5	0.64	0.99	1.63	0.51	0.90	0.04	1.45
	500	P0	5 x 4	0.65	0.96	1.61	0.51	0.97	0.04	1.52
	625	P0	4 x 4	0.58	0.99	1.57	0.44	0.97	0.07	1.43
	825	P0	4 x 3	0.57	1.06	1.63	0.44	0.95	0.07	1.40
	825	P40	4 x 3	0.58	0.98	1.56				
	825	P60	4 x 3	0.60	0.98	1.58				

As seen in section 4.3 for the agroforestry with chili, the trade-off analysis suggests that growing ginger associated with trees also brings benefits when compared to respective monocropping systems, as LER values for all the scenarios are above 1 and scenarios above the line 1:1 in the trade-off analysis (Figure 13). Nevertheless, differently from the chili scenarios, the values for relative wood volume are moderately lower in the agroforestry systems compared to sengon monoculture, with an average value of 0.98 for the combination of sengon + ginger and an average value of 0.99 when cowpea is added.

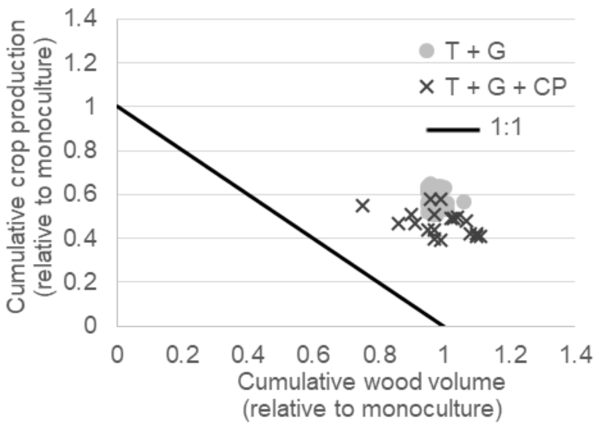

Figure 13. Trade off analysis comparing relative sengon wood volume versus ginger production in simultaneous agroforestry systems combining sengon + ginger (T + G) and sengon + ginger + cowpea (T + G + CP). All the scenarios presented net positive interactions, points above line 1:1.

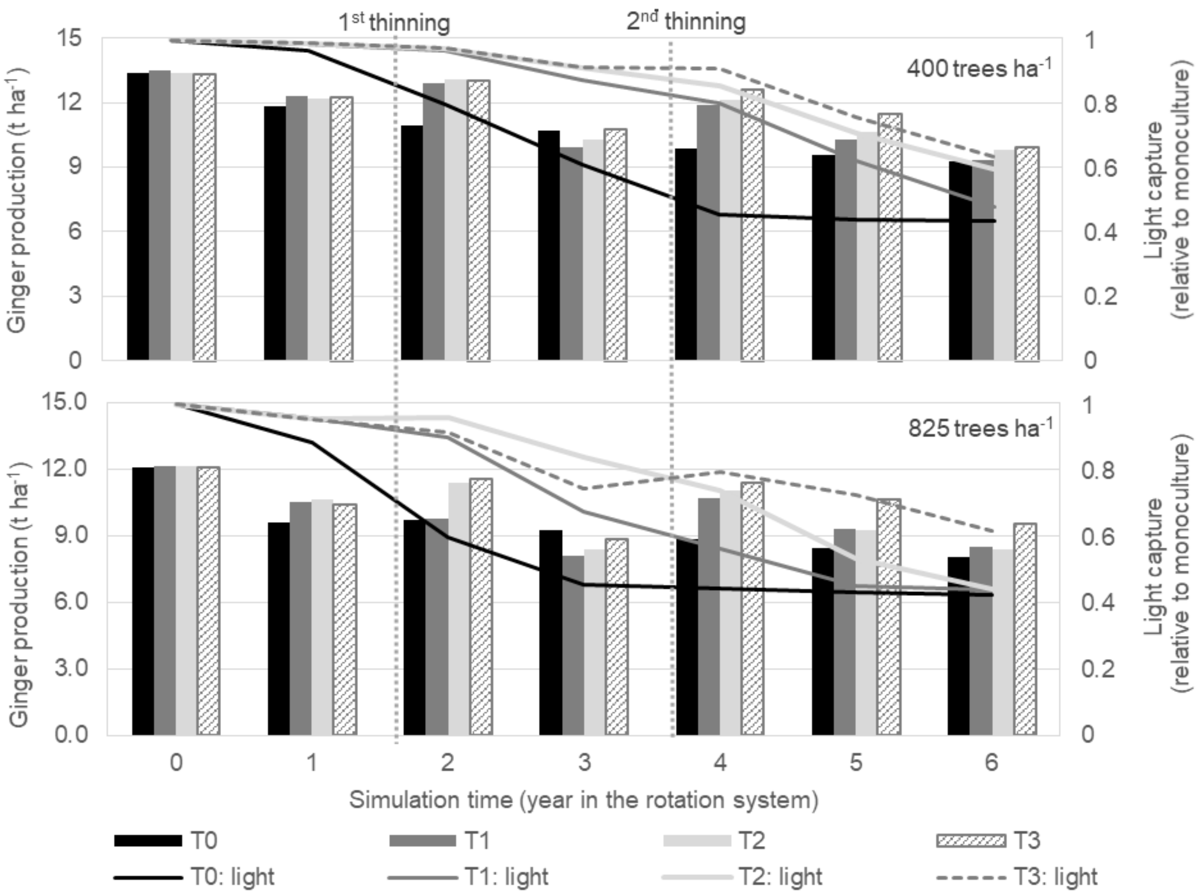

Figure 14. Annual chili yield (represented by bars) during the years of the rotation combining sengon + ginger. The lines represent the light capture by ginger intercropped with sengon relative to the crop in monoculture over time. Production and light capture are compared for two different initial tree densities (400 and 825 trees ha^{-1}) and for different thinning intensities (T0, T1, T2, T3).

When examining annual ginger yield and relative light capture during the rotation, it can be observed that the production levels are less sensitive than chili to the light decrease through the years of sengon rotation (Figure 14). Just as for the chili scenarios, there is a faster reduction in light capture in scenarios with initial tree density of 825 trees ha^{-1} than with lower planting density (400 trees ha^{-1}). However, in the case of ginger cultivation, the impact in yield caused by light competition between ginger and trees was less intense. Considering the last cropping season (year 6) for planting density of 400 trees ha^{-1}, there is a yield reduction of 30% in the no thinning (T0) scenario and 25% for most intense thinning option (T3), when compared to the production level achieved at first year. Nonetheless, the shading impact of T0 was different from T3 in last year of the rotation, in the former ginger was able to capture 40% of light that would be available in system without trees, while the removal of trees in most intense thinning regime (T3) resulted in light capture of 60% of a ginger monoculture condition.

On the same terms presented for the chili scenarios, Figure 15 and Figure 16 present a comparison of Crop_PosGro, as an indication of water and P limitations, for ginger growth in different scenarios. Crop_PosGro-N presented values equal to one for all the compared systems, with no indication of any tendency over the planting seasons. Hence, no graph is present for analysis of N competition.

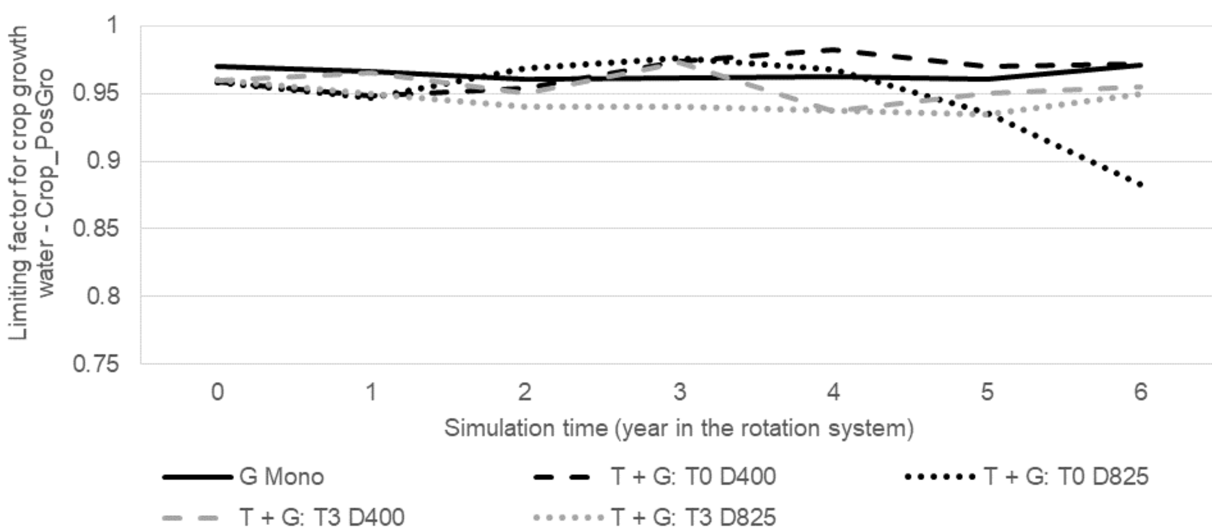

Figure 15. Water as limiting factor for ginger growth per season as indicated by Crop_PosGro (1 - 'no stress' 0 - 'no growth'), comparing ginger in monoculture (G mono) and in mixed plantation with sengon (T + G) for initial trees densities of 400 trees ha-1 (D400) and of 825 trees ha^{-1} (D825) under different thinning intensities (T0: no thinning, T3: most intense).

There is no indication of water competition as a restriction for ginger growth when comparing the crop growing as monoculture or in combination with sengon under different tree management options (Figure 15). For no thinning (T0) and 825 trees per hectare (D825) scenario, Crop_PosGro-water presents a tendency of increasing competition for this resource after year 4, but its value indicates no growing limitation until the end of the rotation, when reaches 0.85.

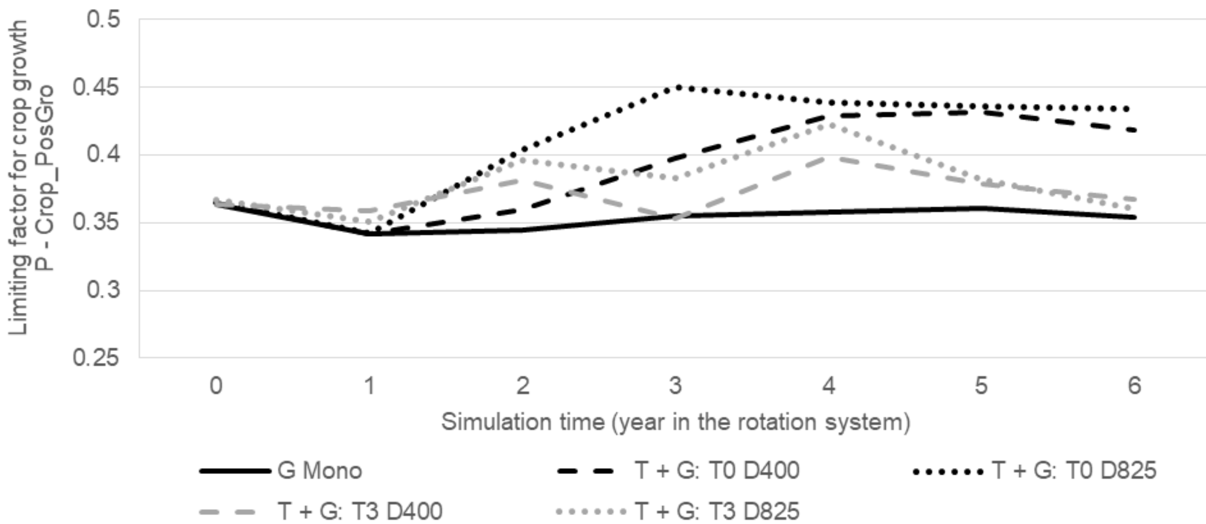

Figure 16. P as limiting factor for ginger growth per season as indicated by Crop_PosGro (1 - 'no stress' 0 - 'no growth'), comparing ginger in monoculture (G mono) and in mixed plantation with sengon (T + G) for initial trees densities of 400 trees ha-1 (D400) and of 825 trees ha^{-1} (D825) under different thinning intensities (T0: no thinning, T3: most intense).

Despite the adequate simulated yield, that was similar to national production levels, all the compared scenarios, including ginger in monoculture, presented Crop_PosGro-P around 0.4, indicating that the standard P fertilization was not adequate to supply the crop requirements. There is a similar pattern with chili scenarios when analysing tendency, in which the most intense the thinning regime (T3) shows P availability closer to the one presented by ginger monoculture, while no thinning practice (T0) presents a tendency of increasing P availability and the dynamic differs depending on the initial tree density. Due to similar Crop_PosGro-P values among the compared scenarios, the competition for this resource cannot be indicated as limiting growing factor when comparing the simulated ginger monoculture and agroforestry with sengon.

4.5 Financial analysis

Table 12 shows a profitability assessment represented by the net present value (NPV) and the benefit cost ratio (BCR) for the different simulated scenarios, not considering the cowpea as intercrop. According to the simulated yield results, almost all the management options provide favourable economic performance with NPV higher than zero and BCR higher than one, exception for three scenarios with chili. The financial analysis includes only seasons where the benefits were higher than the cultivation costs, the number of economically viable seasons are indicated in Table 12. Compared to tree monoculture over a 7-years rotation, the combination of tree and crops can provide until six times higher NPV, depending on the scenario. For both agroforestry systems, the highest NPV was obtained by intercropping chili or ginger with an initial tree density between 400 and 500 trees per hectare and thinning intensity T2.

When considering sengon monoculture, higher returns are provided by the less intense tree management regime in which no thinning option and initial tree densities between 400 and 625 trees per hectare, presented NPV varying between 6647 to 6805 euros per hectare, respectively. In this case, in which the financial return by sengon wood is the main target of the system, intercropping with chili and ginger continues to be advantageous, for instance, considering the scenario of 625 trees per hectares and no thinning the financial return including chili more than doubles, while when intercropping with ginger there is an increase by around fivefold.

Table 12. Economic performance indicators Net Present Value (NPV) and Benefit Cost Ratio (BCR) for each simulated scenario for a rotation cycle – no cowpea included in the intercropping

Initial tree density (trees ha^{-1})	Thinning intensity	NPV (€ ha^{-1})					BCR (-)		
		Sole tree	Tree + Chili (no. seasons)		Tree + Ginger (no. seasons)		Sole tree	Tree + Chili	Tree + Ginger
278	T0	6221	26433	(4)	36050	(7)	2.8	1.4	1.9
	T1	3858	32473	(6)	41724	(7)	1.7	1.2	2.2
	T2*	3898	32282	(6)	42049	(7)	1.7	1.2	2.2
400	T0	6395	22785	(4)	40444	(7)	2.8	1.2	2.2
	T1	4127	28939	(6)	41385	(7)	1.7	1.1	2.2
	T2	4899	32723	(6)	41925	(7)	2.1	1.2	2.2
	T3	4125	32474	(6)	42781	(7)	1.7	1.2	2.3
500	T0	6647	21468	(3)	39058	(7)	2.9	1.4	2.1
	T1	4974	27009	(5)	40897	(7)	2.1	1.2	2.2
	T2	4567	32473	(6)	41308	(7)	1.9	1.2	2.2
	T3	3650	32347	(6)	42278	(7)	1.5	1.2	2.2
625	T0	6805	17816	(3)	34301	(7)	2.9	1.1	1.8
	T1	5495	19181	(5)	37530	(7)	2.2	0.8	2.0
	T2	4846	24158	(5)	37195	(7)	2.0	1.0	2.0
	T3	3635	25399	(6)	36943	(7)	1.5	0.9	1.9
825	T0	3046	11530	(2)	34188	(7)	1.3	1.0	1.8
	T1	6031	17825	(3)	35149	(7)	2.4	1.1	1.8
	T2	4956	22789	(5)	35748	(7)	2.0	1.0	1.9
	T3	3463	20689	(5)	34013	(7)	1.4	0.8	1.6

4.6 Ecosystem-regulating functions analysis

Some management scenarios for sengon monoculture and agroforestry systems with chili were compared from an environmental perspective having outputs provide by WaNuLCAS related to ecosystem-regulating functions: potential CO_2 sequestration, water evaporation rate and carbon content in soil organic matter.

Figure 17 (a) potential CO_2 sequestration per hectare after 7 years of rotation, comparing sengon monoculture and agroforestry system with chili for different tree densities and no thinning. While Figure 17 (b) presents the comparison of the two systems for same regulation function having the same initial tree density (400 trees ha^{-1}) and various thinning intensity. The results indicate that the system mixing trees and chili presents around 20% higher potential to reduce the impact of greenhouse gases emissions than sole tree by sequestering CO_2, independently of the initial tree density and thinning intensity. Comparing the scenarios with no thinning (Figure 17 a), the highest predicted reduction of global warming impact is found for the greatest initial tree density for the mixed system, where about 200 tons of CO_2 equivalent per hectare would be remove at the last year of the rotation combining sengon and chili. Another interesting observation is that the higher the thinning intensity the lower reduction on the global warming effect, as seen in Figure 17 (b).

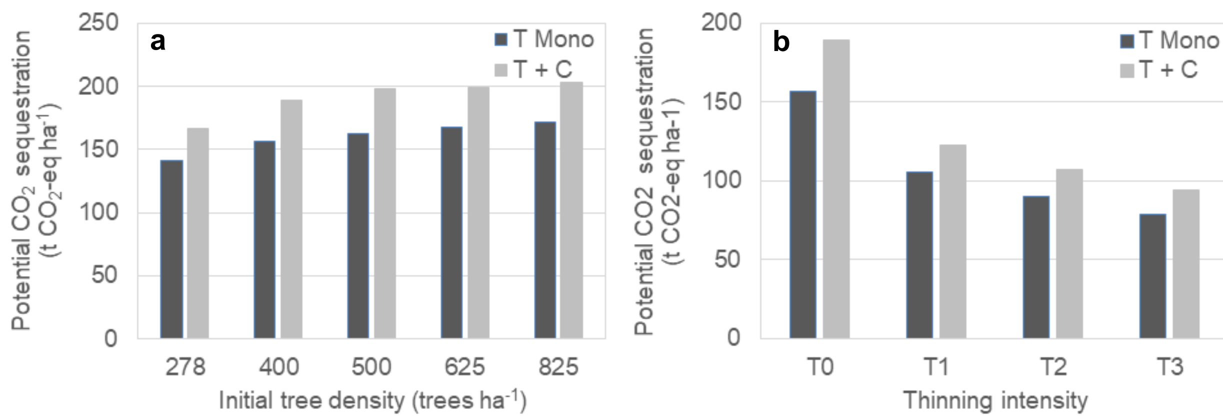

Figure 17. (a) Comparison of the expected CO_2 sequestration at year 7 of the rotation between sengon monoculture (T mono) and agroforestry system with sengon and chili (T + C) for different initial tree densities and no thinning. (b) Same comparison for initial tree density (400 trees per hectare), but different thinning intensities (T0, T1, T2, T3).

As a way to infer the capacity of the systems to retain water, the average daily water evaporation rate from the soil surface per year of rotation was compared between tree monoculture and a mixed system (trees + chili) at two different initial tree density (400 and 825 trees ha^{-1}) for no thinning practices (Figure 18 a and Figure 18 b). The effect of intercropping chili with trees can be seen already in the first year of the rotation, as the water evaporation rate decreases around 25% when compared to the sengon monoculture, from 2.5 to 1.9 mm day^{-1}. The trend of lower daily evaporation rate on agroforestry system can be observed throughout the rotation and for the different initial tree densities. As the trees develop, the water evaporation rate of sengon monoculture and agroforestry with chili become closer. This is observed for the two different initial tree densities, 400 and 825 trees per hectare, but for the denser scenario the water evaporate from soil surface slower as the system gradually increases canopy coverage.

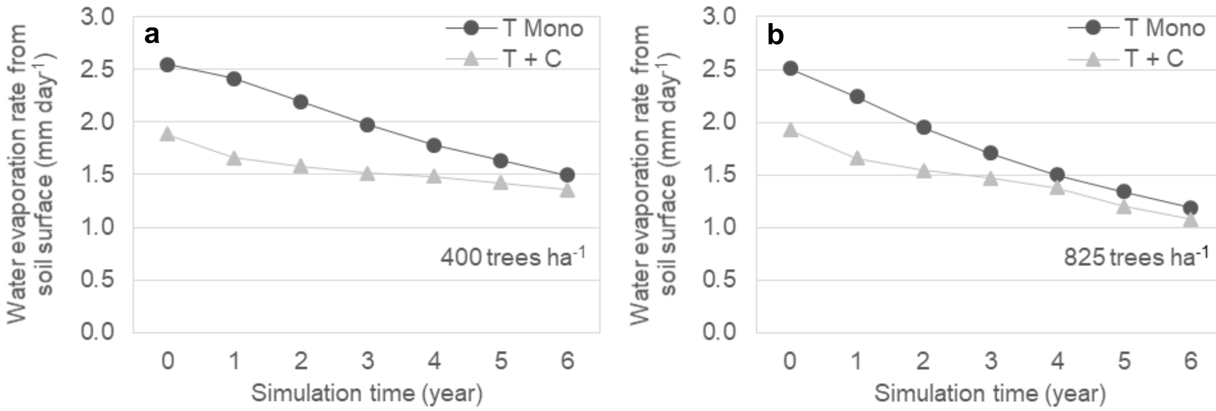

Figure 18. (a) Comparison of the average water evaporation rate between sengon monoculture (T mono) and mixed system of sengon and chili (T + C) for system initial tree densities of 400 trees per hectare and no thinning and (b) for system initial tree densities of 825 trees per hectare and no thinning.

As an indicator for soil health, content of carbon in soil organic matter (SOM) during the rotation was compared for sengon monoculture at different initial tree density and no thinning at the end of each year (Figure 19). Another analysis was done for sengon mixed with chili, having an initial tree density of 400 trees per hectare and two thinning options, no thinning and most intense thinning regime (T3), in the case in a daily basis (Figure 20).

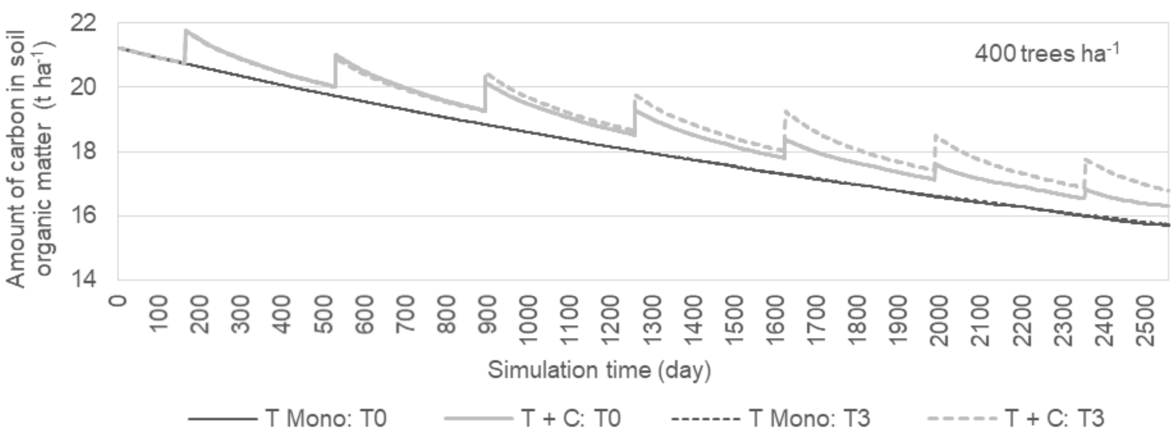

Figure 19. Comparison of content of carbon in soil organic matter (SOM: solid lines) and cumulative litterfall (LT: dashed lines) at the end of each rotation year for sengon monoculture with initial tree density of 400 (D400) and 825 (D825) trees per hectare and no thinning (T0).

In these comparisons, for all the scenarios carbon in SOM decreases over the years, with the reduction slightly lower for higher tree density (835 trees ha^{-1}) with a higher cumulative litterfall (Figure 19) and for sengon intercropped with chili, especially for the most intense thinning scenario (Figure 20). In the scenario with thinning T3, a higher light availability for crop growth understory allowed a greater crop development, which increases the residues left on field after chili was harvested, and, consequently, increases SOM in the system, represented by peaks in

Figure 20. In the same graph, it can be seen that the residues of the thinning practically did not change the SOM when comparing tree monoculture scenario with no thinning (T0) and most intense regime (T3).

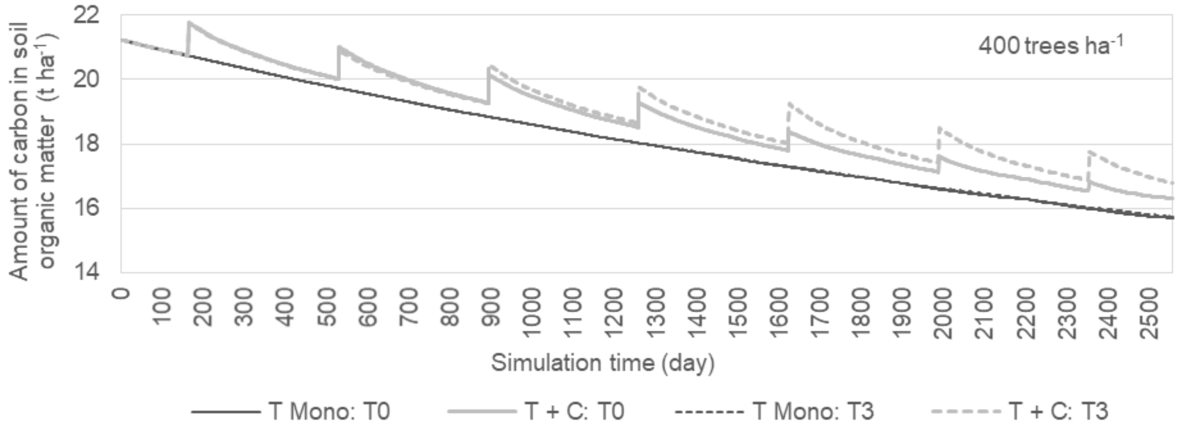

Figure 20. Estimated carbon content in soil organic matter comparing sengon monoculture (T mono), and sengon based agroforestry systems with chili (T + C) at a daily basis through years of the rotation for initial tree density of 400 trees per hectare for two thinning intensities (T0: no thinning- solid line and T3: most intense – dashed line). The peaks indicate input of organic residues after chili harvest for the mixed planting (T + C).

5 Discussion

5.1 Productivity in sengon-based agroforestry systems

According to the model results, it is clear that including chili and ginger into sengon plantations presents advantages when compared to tree monoculture for different tree management scenarios. Nissen and Midmore (2002) reported similar results in a field study in the Philippine, in which growth parameters of *Paraserianthes falcataria* were measured having intercropped and non-intercropped food crop. When intercropped with maize and vegetables, the diameter and height of sengon trees were 33 and 21% greater than sole trees, respectively. Another field experiment in Java Central, Indonesia, showed greater annual diameter increment for sengon when combined with groundnuts (*Arachis hypogaea L.*), compared to monoculture cultivation, with 5.25 and 3.20 cm per year, respectively (Swestiani & Purwaningsih, 2013). However, as found in a field experiment carried out in Cameroon, tree development was not affected by intercropping practices under no fertilization conditions in a agroforestry system when combining sengon and groundnuts (Duguma, Tonye, Kanmegne, Manga, & Enoch, 1994). Under unfertilized conditions, intercrops may even limit the tree growth of young seedlings due to increase competition for soil resources (Nissen, Midmore, & Keeler, 2001). In the simulation, cowpea rows were not fertilized and its impact on sengon growth did not present a clear trend in the results.

An advantage of simultaneous intercropping is that trees directly benefit from the nutrient management applied to the crops, as described by Martin and van Noordwijk (2009) and Khasanah et al. (2015) in simulations conducted with WaNuLCAS model to assess the trade-offs between timber trees and maize. In both studies, all intercrop scenarios under fertilization conditions considerably increased their tree performance. Besides fertilization application, Nissen et al. (2001) linked the poorer sengon performance observed in sole-tree plots to the higher weed pressure when compared to intercropped systems, despite weeds being removed around the tree base once every three months. Therefore, the combination of more intense land management practices in agroforestry systems when compared to tree monoculture, provides favourable growing conditions for tree growth, resulting in greater development in height and diameter (Cannell et al., 1996; Ikhfan & Wijayanto, 2019).

Regarding sengon productivity, predictions are aligned with the existing studies on growth of *Paraserianthes falcataria* that reported wood volume mean annual increment between 30 – 50 m^3 ha^{-1} yr^{-1} for similar rotation length and final density of 150 trees per hectare in monocultures, in which the variation depends on the site quality (Krisnawati et al., 2011). In general, thinning in the simulated scenarios, which range between low and intermediate tree initial tree densities, decreases the total wood volume, despite the increment on tree diameter. At relatively higher density, thinning is used as an strategy to optimise land use, as it accelerates tree growth for decreasing competition, and, at the same time, promotes higher total timber volume (Krisnawati, Kallio, & Kanninen, 2019). Since thinning practices were not applied on the project area, where the data was collected for the model calibration with WaNuLCAS, the extent of the impact of this treatment on tree diameter and height, and consequently timber volume, could not be evaluated.

5.2 Resources competition

Differences on residual fertilizer in the simulated agroforestry scenarios could explain the higher impact on sengon development when it is combined with chili, rather than with ginger, as result of the crops ability to tolerate low light levels, since ginger achieves better rhizome yield when cultivated in partial shade whereas chili performs best under full sunlight conditions. Over the years, the poorer performance of chili under the growing canopies increase the availability of nutrients to the trees when compared to ginger intercropping. In a field experiment conducted in Bangladesh, Sultana, Rahman, Naher, Md. Masum et al. (2018) reported that for a light intensity reduction of 40%, the yield of chili growing in a mahogany (*Swietenia mahagoni*) based agroforestry system achieved 70% of production level achieved under full sunlight. This result is similar to chili yield reduction presented by the simulation to a correspondent decrease in light intensity, but studies demonstrate that the impact of restricted light conditions on yield depends also on soil and climate conditions and chili variety (Manurung, Susila, Roshetko, & Palada, 2008; Pouliot, Bayala, & Ræbild, 2012).

In contrast, partial shade conditions affects ginger yield positively, however more extreme low light level regimes results in a decrease in the production when compared to full sunlight cultivation as shown by previous studies (Jaswal, Mishra, & Verma, 1993; Kumar, Sreenivasulu, Prashanth, Jayaprakashnarayan, & Hegde, 2010; Newman, Bennett, & Wu, 1997). Considering different agroforestry systems and light levels in a field trial in Bangladesh, Bhuiyan, Roy, Sharma, Rashid, and Bala (2012) found that a reduction of 35% in light intensity resulted in the optimum ginger yield, with a production increase of 30% compared to an open field. In the same study, higher yields under tree canopies than full sunlight were reached, until a decrease of 70% on the light intensity, after this level the production presented a reduction of around 25%. Nonetheless, as for chili, the impact of shade levels on ginger yields differs depending on local conditions and the ginger variety (Nair, 2013a). The simulated results for ginger did not describe this tendency of increasing yield with the decrease of light intensity reaching an optimum peak, but it captures the degree of reduction in ginger production at the end of the tree rotation, at maximum shade level, and the crop higher tolerance to shade conditions in comparison with chili.

Conceptually, benefits of growing mixed species are achieved when trees are able to capture resources not utilized by the crops (Cannell et al., 1996). However, in most agroforestry systems, belowground competition can occur even when there is abundant rainfall, and adequate fertilized soils since superficial tree roots are common, especially for fast-growing species (Nissen, Midmore, & Cabrera, 1999; van Noordwijk et al., 1996). Besides, as the temporal dimensions of the system changes, light becomes a primary limitation as tree canopy develops increasing understory shading (Rao et al., 1997; Sultana, Rahman, Naher, Md. Masum et al., 2018). The simulation on WaNuLCAS presented a correlation between the yield decline for chili and ginger and the decrease of light capture by the crops, whereas nutrients and water limitation indicated by Crop_PosGro did not present the same tendency. Light being the main limitation in sengon based agroforestry systems is in accordance with the results described by Nissen and Midmore (2002). Nonetheless, tree-crop interactions change depending on climate and soil conditions. In arid and semi-arid tropics competition is primarily for water (Odhiambo et al., 2001; Rao, Ong, Pathak, & Sharma, 1991; Singh, Saharan, & Ong, 1989), while in acid soil nutrients limitation is a major fact impacting crop yields in agroforestry systems (Rao et al., 1997; Sanchez, 1995).

In order to limit the light competition, Ong, Black, and Wilson (2015) highlight that tree species selection should focus on canopy shape and structure. In a study with other popular farm-forestry species, sengon was the least competitive tree per unit growth due its shade pattern (Nissen et al., 2001). Its irregularly shaped crown and feathery foliage provide a relative low light interception that favours the species application in agroforestry systems (Iskandar & Ellen, 2000; Varis, 2011). Besides adequate tree selection, choosing crops more appropriated for limiting light conditions also leads to an overall increase of productivity and more efficient resources utilization (Okorio, Byenkya, Wajja, & Peden, 1994). For example, studies have shown that tree shade impacts C4 plants, such as maize, more negatively than intercropped plants with C3, such as chili and ginger (Bertomeu, 2012; Jose, Gillespie, & Pallardy, 2004; Thevathasan & Gordon, 2004). In the case of the present study, the differences between chili and ginger yield under shading condition could be used as a strategy to keep a higher production level throughout the rotation. For instance, chili could be cultivated in the first years of the rotation, while the light level is still relatively high, while ginger would be intercrop until the trees are harvested.

The level of interaction between trees and crops grows with the increase of tree density, consequently, narrowing row space for crops and intensifying competition for resources (García-Barrios & Ong, 2004), which can be managed until some extend by silvicultural practices, such as pruning and thinning (Hussain et al., 2019; Rao et al., 1997). In the simulation, scenarios run at different initial tree density showed that the wider alley width, the longer crops kept acceptable production levels, resulting in higher cumulative crop yield especially for chili. Supporting these results, on-farm experiments conducted in the Philippines by Bertomeu (2012) showed that intercropping maize with timber trees on 10 meters wide alleys allowed crop cultivation for two more years than on 2.5 meters alleys. In a 4-year field trial in India, Prasad et al. (2010) reported that the decline of cowpea yield in a Eucalyptus-based agroforestry was twofold faster in 3 x 2 m tree spacing than with 6 x 1 m as a planting pattern. Martin and van Noordwijk (2009) and Khasanah et al. (2015) found similar impacts on crop yields due to tree spacing in analyses based on WaNuLCAS model. These studies also observed that tree density and spacing impact not only crops performance, but tree development itself.

Besides productivity trade-offs analysis for timber-based agroforestry, WaNuLCAS model was also applied by Hussain (2015) to evaluate resource competition in a field trial combining hedge-rows and maize in Thailand and also to explore mitigation options. The simulation results were validated with the experiment results that showed that nitrogen and phosphorus were the main limiting factor to crop growth. However, a study conducted by Bayala et al. (2008) in agroforestry parklands in Burkina Faso reported that the model, despite presenting a useful trend for resource competition, did not represent adequately all limitations and interaction occurring in the field between crops and trees under different pruning regimes.

5.3 Tree management scenarios

For sengon growth, the simulation suggests that higher stand densities result in higher wood volume, but lower tree diameter growth when compared to wider planting spacing. Additionally, increasing thinning intensity influences positively the tree diameter. Although the WaNuLCAS model shows average tree properties, not representing variation in the landscape affecting tree growth and uneven thinning practices (Khasanah et al., 2015), these findings are consistent with results of Kurinobu, Prehatin, Mohanmad, Matsune, and Chigira (2007) and Varis (2011) for sengon. Moreover, similar trends were observed with other tree species in various studies of the impact of stand density management on tree growth (Bertomeu, 2012; Krisnawati et al., 2019; Pettersson, 1993; Prasad et al., 2010; Sato & Dalmacio, 1991; Thi Ha, 2018). Varis (2011) demonstrated that the best thinning option and tree density depends on establishment conditions, when comparing tree management options for good, medium and poor quality sites in 106 sengon farms in Indonesia. Supporting the simulated results, the study indicates that for an initial tree density of 625 trees per hectare and good quality sites, which present similar trend for tree growth as presented in Figure 4, one or no thinning is required, depending on the rotation length. Nevertheless, a more intense tree management is necessary for more dense stands, for instance 1666 trees per hectare.

Regarding pruning treatment, the present study indicates that the greater the pruning intensity, the greater the negative effect on sengon growth. Field experiments conducted by Muhamad and Paudyal (1992) with acacia (*Acacia mangium*) and by Fontan et al. (2011) with a hybrid of *Eucalyptus camaldulensis* and *Eucalyptus grandis* corroborate with this result. In teak (*Tectona grandis*) plantations in Costa Rica, Víquez and Pérez (2005) reported that more intensive pruning practices result in higher timber quality, with less knots in wood. Regarding sengon, there is a recommendation for formative pruning until the second year for better stem formation, as the tree has a tendency to fork (Krisnawati et al., 2011). The effects of pruning practices on subsequent wood quality and stem formation is not include in the WaNuLCAS model (Khasanah et al., 2015). In a mixed system, if the priority is given to the crop, pruning can be used as a strategy to reduce shading in order to prolong the period of intercropping (Bertomeu, Roshetko, & Rahayu, 2011; Newaj et al., 2005; Saptono & Ernawati, 2011). However, the gains in yield of annual crops may not compensate for the increasing labour costs for tree management and the unfavourable effect on tree growth (Bertomeu, 2012).

In practice, smallholder farmers growing sengon in Indonesia undertake few silvicultural activities such as pruning and thinning due to limited labour, capital and access to information about tree management (Hani & Swestiani, 2020; Irawanti et al., 2014; Irawanti et al., 2017; Muktasam et al., 2019). In this context, a more effective management option would be using lower tree density (Khasanah et al., 2015), as for the simulated scenarios with 400 to 625 trees per hectare, since at relative higher stands thinning must be conducted in order to produce commercial timber (Varis, 2011). Despite a lower total wood volume when compared to high dense stands, low tree densities result in larger tree diameters with lower interventions, which are rewarded with price premiums, besides being more advantageous for intercropping (Martin & van Noordwijk, 2009). However, Bertomeu (2012) highlights that is uncertain if smallholder farmers growing trees at lower densities is suitable for producing quality timber as, for instance, a closer intra-row space promotes good stem form. Additionally, Krisnawati et al. (2019) point out that on poor sites the initial planting density should be sufficient to assure adequate stocking considering portion of tree mortality during the early stage of the rotation.

Despite the overall favourable simulated results, there is a bias of prediction for diameter and height size of trees that were closest to the rotation age (Figure 4). A similar underestimation of diameter and height was observed in the previous study to obtain a growth model for *P. falcataria* carried out by Kurinobu, Prehatin, Mohanmad, Matsune, and Chigira (2007). The authors associated this bias with a lack of data for trees at older ages, which could be the case in the present study since the data used for model adjustment includes tree age between 7 months and 55 months old (4.5 years) while the rotation length is 7 years. Hence, when available, including data for sengon development at older ages, in the area project, will improve the accuracy of model growth at rotation age.

5.4 Financial analysis

The financial analysis indicated no negative values for the simulated tree management scenarios, with higher profitability for mixed systems. Previous economic analyses in Southeast Asia have shown that combining timber trees and agricultural crops has the potential to increase the profitability of smallholder plantation forestry (Khasanah et al., 2015; Magcale-Macandog & Abucay, 2007; Midgley, Blyth, Mounlamai, Midgley, & Brown, 2007; Nissen et al., 2001; Siregar et al., 2007). In agroforestry systems, management costs are associated and therefore lower than tree monocultures, as trees benefit with the inputs and land preparation for the crop cultivation, thriving in the improved site conditions (Nissen et al., 2001). Moreover, the costs of tree plantation establishment can be compensated by agricultural production since mixing them with annual crops allows cash inflow already in the first year of the rotation (Roshetko et al., 2013).

In the case of sengon monoculture, the simulated results presented higher benefit-cost ratios in scenarios with no thinning in accordance with studies done by Nissen et al. (2001) and Steward et al. (2020) for sengon cultivation in Indonesia. Considering the combination of sengon and chili, the predicted profitability for a mixed system was higher than tree monoculture. This result is consistent, for comparable tree density and management practices, with the findings presented by Siregar et al. (2007) in an economic analysis of different sengon mixed plantations on farmers in East Java, Indonesia. For mixed systems with ginger, the profitability was higher than for chili due to a higher productivity and more continuous harvest level throughout the rotation. However, the economic benefits for the mixed systems may be overestimated since the crop yields were adjusted on WaNuLCAS based on average production levels in Indonesia, not for specific site conditions.

5.5 Environmental impact

Carbon sequestration involves the uptake of CO_2 from atmosphere during photosynthesis and its storage into pools aboveground (vegetation) and belowground (detritus, soil, roots) (Nair, 2012). When compared with arable crops and grasslands, agroforestry systems present a higher potential to sequester CO_2 due to the inclusion of trees in the land use, providing greater net C storage (Fialho & Zinn, 2014; Kirby & Potvin, 2007). In practical terms, as observed by Albrecht and Kandji (2003), net gain in carbon fixation in agroforestry systems is feasible for perennial systems, meaning continuous presence of trees. The author indicated that it is also possible to achieve a favourable balance in case harvested wood is used for last-longing products (construction, furniture) as C storage can continues, but it is limited in the case of pulp production due to the higher decomposition rate of the final product.

The potential carbon sequestration of an agroforestry systems is highly variable and depend on trees species and age, plantation density, site management, local climate and soil conditions (Nair, 2012). For instance, higher tree density and fertilization applications provides higher capture potential, in the latter case due to enhanced tree growing capacity (Nair, Nair, Kumar, & Haile, 2009). These two tendencies are represented in the simulated results. Additionally, the predicted amount of carbon sequestered for sengon monoculture scenarios is similar to results reported by Agus et al. (2016) in an analysis done in restoration areas with sengon in East Kalimantan in Indonesia. The study reported that 7-year sengon plantation have the capacity to capture 180 t CO_2 per hectare for a stand density of 433 trees per hectare. As a general trend, studies have found the higher the level of complexity of the land use the great the potential to capture carbon, in which primary forests represent the most complex systems (Leuschner et al., 2013; Nair et al., 2009; Stefano & Jacobson, 2017). For instance, it is estimated that oil palm monocultures sequester around 130 t CO_2 ha^{-1} in a 25-year economic life span (Germer & Sauerborn, 2008), whereas primary dryland forests in central Kalimantan capture 814 t CO_2 per hectare (Krisnawati, Adinugroho, Imanuddin, & Hutabarat, 2014). This value is around fourfold higher than the one achieved by the scenario combining chili and sengon with the densest planting system (825 trees ha^{-1}).

In terms of water use, agroforestry systems present advantages when compared to annual crops with the increase in water infiltration and reduction in runoff (Kizito et al., 2007; Phiri, Verplancke, Kwesiga, & Mafongoya, 2003) and, consequently, improving the groundwater recharge in the rainy season (Ong et al., 2015). Water that trees can then take in and redistribute through a process known as hydraulic lift, which involves the transfer of water from deeper soil layers to drier surface (Horton & Hart, 1998). Percolation is facilitated by the improvement of soil structure bellow the trees (Neris, Jiménez, Fuentes, Morillas, & Tejedor, 2012) and by the modification of rainfall pattern at ground level (Bargués Tobella et al., 2014). Generally, tree canopy reduces the impact of the raindrop on the soil surface that, in combination with improved soil stability, reduces the formation of soil crusts, a limiting factor for water infiltration (Ong et al., 2015).

Additionally, researchers have shown that the shade canopy can serve as an effective control on evaporation losses from the topsoil layers in the semiarid tropics (Jackson & Wallace, 1999; Siriri et al., 2013), since it influences the radiant energy of the system decreasing evaporation rates (Ong et al., 2000). The influence of shading on soil evaporation will depend on rainfall frequency and amount, soil type and the canopy shape (Ong et al., 2015). In coffee-based agroforestry plantations in México, Lin (2010) reported a decrease of 41% on daily soil evaporation rates in high shade cover when compared to the low shade site. The simulated results for the different scenarios with sengon presented a lower soil evaporation rate for higher tree densities and intercropped systems, similar to the findings reported by Droppelmann, Lehmann, Ephrath, and Berliner (2000) in experiments with *Acacia saligna*. In contrast, Jackson and Wallace (1999) found higher daily evaporation rate for mixed systems of 4-year *Grevillea robusta* and maize than for tree sole, however in the experiment trees in the intercrop scheme were regularly pruned while the tree monoculture were not, modifying the influence of the shade canopy in the understory.

Soil organic matter (SOM) plays a critical role in nutrient cycling and nutrient availability (Jackson et al., 2017). The simulated results are contrary to previous findings comparing different agricultural land-use systems, in which SOM in agroforestry sites was stable or had the tendency to increase in time (Bayala et al., 2007; Chander, Goyal, Nandal, & Kapoor, 1998; Dechert, Veldkamp, & Anas, 2004; Gupta, Kukal, Bawa, & Dhaliwal, 2009). In these studies, this pattern was attributed to higher inputs of organic residues aboveground (litterfall) and belowground (roots turnover). Comparing the results from the present study for cumulative litterfall (Figure 19) with the ones reported by Agus et al. (2016) in sengon monoculture plantations with similar tree density and stand age, the WaNuLCAS model underestimated the leaf litter biomass by fourfold. This could be one of the reasons for the discrepancy between the previous studies and the model output related to SOM content in the systems, as the parameters for litterfall were used from the model library for sengon. Moreover, when comparing sengon monoculture with different thinning intensities (Figure 20), no thinning (T0) and most intense (T3), it was not observed any relevant effect of the latter in simulated SOM after each thinning procedure nor any difference in the long run between the two systems, as it is expected for the additional input root biomass from the removed trees. Therefore, it is likely that the contribution of this input is not considered in the balance to estimate the carbon amount in soil organic matter.

6 Conclusions

According to the simulated results in this study, *Paraserianthes falcataria* based agroforestry systems presented productivity, financial, and environmental advantages when compared to sole tree plantations. Generally, sengon growth was enhanced by intercropping with chili, mainly due to residual fertilizer. As shown by WaNuLCAS indicators, light competition was the main limitation for crop growth through the rotation, especially for chili. For this crop, the yield dropped by half at the third year, while for ginger there was a decrease of 30% in production level in last year (in the scenario with 400 trees ha^{-1} and no thinning). Therefore, chili could be cultivated in the first years of the rotation, while the light level are still relatively high, this depending on the initial tree density. Ginger would be intercropped after chili until the trees are harvested, due to its higher shade tolerance.

Regarding tree management options, wider tree spacing or lower initial tree density, and more intense thinning regime, allow crops to keep higher production levels for a longer period. Pruning practices have a similar impact since it reduces light competition, although it has a negative effect on sengon growth. All the thinning options in the simulated scenarios decreases the total wood volume, despite the increment on tree diameter. That indicates this silvicultural practice is more advantageous for higher stand densities in order to optimise timber productivity, since the tree density of this study range between low and intermediate levels. Besides, independently of the initial tree density, following recommendation by Krisnawati et al. (2011) and having the first thinning at the second year of the rotation, it produces logs with diameter lower than 16 centimetres, which is not a marketable standard.

The profitability analysis showed no negative values across scenarios. Overall financial return to crops is higher than for trees, resulting in higher profitability to agroforestry systems, especially with ginger, due to its production levels. However, the financial benefits of the simulated agroforestry scenarios may be overestimated since the crop yield were adjusted on WaNuLCAS based on average production levels in Indonesia, not for specific site conditions. When the priority is given to the timber production, the present study demonstrates that initial tree densities of 400, 500 and 625 trees per hectare and no thinning would be an interesting option for smallholder, as implies less labour applied to tree management, consequently increasing the income coming from trees of the agroforestry system. According to the simulation, it would be economic viable to grow chili in these systems with no thinning until the third year of the rotation for 500 and 625 trees per hectare, and until the fourth year of the rotation for 400 trees per hectare, while ginger would be feasible throughout the rotation length. However, experimental studies should be carried out in order to analyse sengon stem development at low to intermediate initial planting density.

Analysing environmental impact, mixed plantations presented around 20% higher potential to sequester CO_2 than tree monoculture, mainly due to enhanced tree growing capacity result of more favourable conditions. Comparing sengon-based agroforestry systems and sole trees, the soil evaporation rate was lower for the former, around 25% of reduction at the first year, particularly because of higher soil cover in the initial years of the rotation, improving the exploitation of water by reducing ineffective mechanisms of its balance. Probably due to an underestimation of cumulative litterfall, carbon content in soil organic matter presented a tendency of continuous declining, independently if sengon was cultivated in agroforestry systems or monoculture. In this case, it would be interesting to apply WaNuLCAS to explore soil management strategies, validating the prediction for SOM and finding options to improve its levels in these systems, for instance, adding different sources of organic material (manure) and other options of crops rotation.

WaNuLCAS model presented adequate predictions for productivity, and interesting outcomes to analyse tree-crop interactions of *Paraserianthes falcataria*-based agroforestry systems under different tree management practices and crop options. Nevertheless, it is still necessary to validate the model results for chili and ginger yield levels with real data from the local conditions. The same is valid for the results regarding thinning practices in sengon plantations, in which the accuracy of the simulated results needs to be checked with data from field experiments. WaNuLCAS has been updated over the years to improve its flexibility and it requires an extensive parameterization, and, consequently, a certain level of expertise for its application. Discussing the challenges in modelling of tree-crop interactions, Luedeling et al. (2016) stated that an agroforestry model that covers a wide range of systems and combinations would likely required an also vast configuration of parameters.

The balance between the improvement of livelihoods from rural communities and the preservation of ecosystem services offers a complex challenge. To find alternative land use solutions requires a broader social, ecological, and economic perspective on local issues and agroforestry concepts, and praxis can contribute to a more holistic approach to social forestry schemes. At a policy level, an important step toward agroforestry development in Southeast Asia was taken in 2018, with the adoption of a set of guiding principles for policy design by the ten member states of the Association of Southeast Asian Nations (ASEAN) (van Noordwijk, 2019). Endorsed by ASEAN ministers of forestry and agriculture, and aligned with the association's vision and strategic plan for 2016–2025, the guidelines intent to facilitate the dialogue in agroforestry policy formulations, but also in the planning of state and private sector projects and investments, including education programs (ASEAN, 2018). The use of agricultural models representing tree-crop interactions, such as WaNuLCAS, could support policy makers and researchers in making operational and strategic decisions, identifying and prioritizing knowledge gaps. Expanding the research and development of modelling tree-crop interactions would increase reliable predictions and promote the use of these tools for exploring and understanding factors for prosperity or failure of agroforestry systems.

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