GIS based Land use Simulation of Sustainable Forest Management and Wood Utilization

in Thai Nguyen Province, Vietnam

Dissertation

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Declaration

I hereby declare, under oath, that I have written the present dissertation on my own and have not used any resources and aids other than those acknowledged.

Hamburg, July 2018

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Dang Cuong Nguyen

English review testimonial

I certify that the English in the thesis:

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Research summary

The concept of Sustainable Forest Management (SFM) is well established. Its principles of sustainable forest development and land use planning often require a compromise between socio-economic development and environmental interests. Biophysical factors have a significant effect on the productivity of forest plantations, while socio-economical and economic factors impact profitability and management systems. To enhance profits from forest plantations, the tree species grown need to match the specific site conditions. At the same time, the efficiency of forest plantations depends not only on forest site productivity, but also on market driven factors such as timber price, timber demand and transportation cost..

This study uses a combination of a land suitability assessments based on FAO framework for land suitability classification, multi-criteria, linear programming (LP) and a Geographic Information System (GIS) framework to identify suitable locations and achieve the highest profit for forest plantation management. A suitability analysis and an optimization analysis were used. The suitability analysis with classes highly suitable, moderately suitable, marginally suitable, and unsuitable was conducted through a combination of land suitability assessments and multi-criteria decision analysis (Analytic Hierarchy Process, AHP). Three main criteria were used in the suitability analysis comprising soil properties, climate and topography. Maps presenting suitability classes were established in ArcGIS environment by Weighted Linear Combination (WLC). To reflect growth of the studied species, volume growth was modeled using three models including Chapman Richard, Gompert and Koft models. All three models reflected growth well based on coefficient of determination (r^2) and root mean square error (RMSE). However, the Koft model performed best and was selected in the optimization analysis to assign productivity on each suitability class.

The results of the suitability analysis were used in the optimization analysis. The optimization model was built by combining programming (visual basic application environment) and GIS (ArcGIS environment). The optimization model indicates

that the optimal harvest age of a *Acacia mangium* plantation in the study area is 6 years, at which time the highest profits can be reached. The model used shows the tradeoff between timber demand and timber supply. When timber demand increases, profit obtained from forest plantations has a decreasing trend because of the assignment of areas having lower profit due to lower productivity and higher costs. The optimization model also illustrates that even considerably small variations in timber price and costs have significant effects on the profit obtained and land area allocated to respective mills.

The optimization model suggests the possibility of combining the needs of environmental conservation with socio-economic demands of stakeholders by establishing nature conservation areas. Shadow pricing can be used as a mean to derive compensation payment to assign and maintain forest areas for protective use. Additionally, the optimization model provides a tool to study the establishment of co-operated mills. Three new mills could replace 215 existing mills and 3 new mills could be added with higher capacities.

The findings of this study provide evidence for the need of a concurrent forest land utilization and mill development planning in order to maintain and enhance economic and ecological objectives and to improve local livelihoods. This holds especially true under extensive afforestation and reforestation activities, as recently promoted by the Bonn Challenge and the New York Declaration.

Content

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List of abbreviations

5MHRP	The Five Million Hectare Reforestation Program
AHP	Analytic hierarchy process
AIJ	Aggregation of individual judgments
AIP	Aggregation of individual priorities
CAI	Current Annual Increment
CFS-AFM	Canadian Forest Service – Afforestation Feasibility Model
CI	Consistency index
CR	Consistency ratio
DBH	Diameter at Breast Height
Dg	Quadratic mean diameter
DEM	Digital elevation model
FAO	Food and Agriculture Organization of the United Nations
FO	Current forest approach
FIPI	Forest Inventory and Planning Institute
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Position System
GSO	General Statistics Office
Ha	Hectare
IDW	Inverse Distance Weighted
LA	Landscape approach
LEV	Land expectation value
LP	Linear programming
MAI	Mean Annual Increment

MARD	Development of the Ministry of Agriculture and Rural Development
MCDA	Multiple Criteria Decision Analysis
NYDF	New York Declaration on Forest
NPV	Net Present Value
PA	Pallet
PCT	People’s committee Thai Nguyen
R^2	Coefficient of determination
RI	Random index
RMSE	Root mean square error
SUF	Special Use Forest
SRTM	Shuttle Radar Topographic Mission
SWOT	Strength, Weaknesses, Opportunities, Threats
UNESCO	United Nations Educational, Scientific and Cultural Organization
USD	United States Dollar
VAAS	Vietnam Academy of Agricultural Sciences
VE	Veneer
VN2000	Vietnam coordinate projection
WC	Woodchip
WLC	Weighted Linear Combination

1 Introduction

1.1 The demand and supply wood from planted forest

A forest plantation is defined as “forest stands established through planting or seeding of one or more indigenous or introduced tree species by afforestation or reforestation programs, which demands a series of criteria: one or two species at planting, even age class, and regular spacing” (FAO 2006). The main aim of forest plantations is to provide wood supply as timber, fiber, fuel wood or bioenergy, non-wood forest products (FAO 2015b). Planted forests provided about 35% of the global wood supply in 2000 (Brockerhoff et al. 2008), and 46.3% of industrial roundwood in 2012 (Payn et al. 2015).

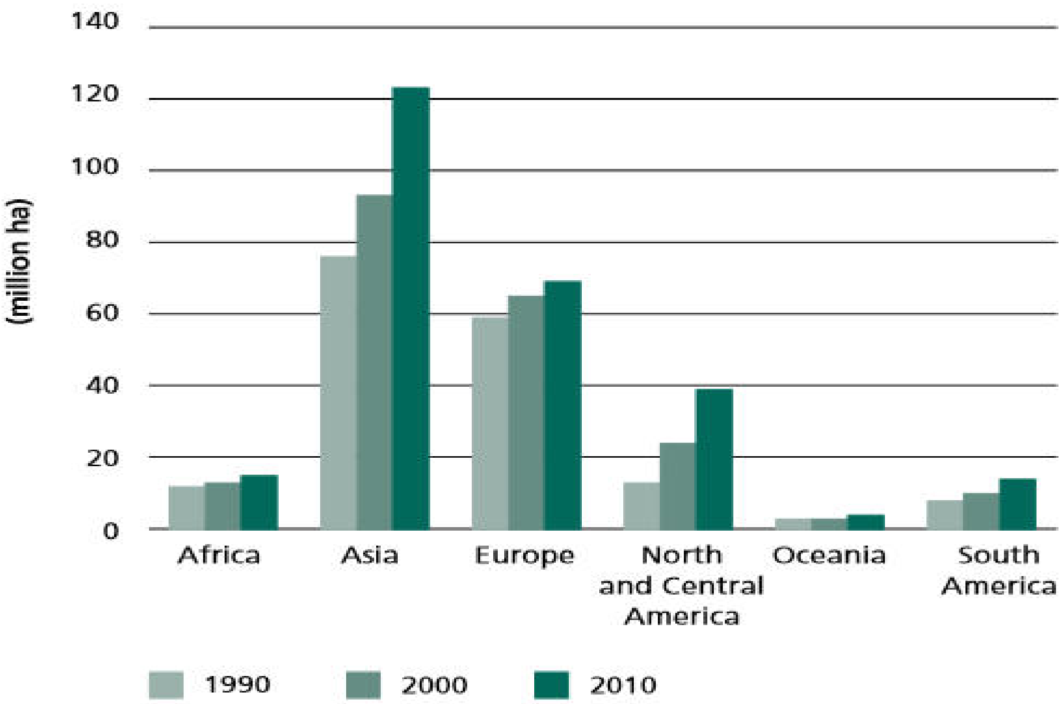


Figure 1.1 Trend in area of planted forest between 1990 and 2010 (source: FAO 2010a)

Due to the rapid growth in forest plantations, they have been able to meet the increasing global demand for timber, fuel and fiber. The total planted forest area increased by around 5 million hectares per year from 2000 to 2010, amounting to 264 million hectares in 2010 and estimated to reach 300 million hectares in the near future (FAO 2010b). The average annual amount of planted area increased more slowly between 2010 and 2015, by around 3.1 million hectares, than in the period between 2000 to 2010 (FAO 2015b). Most of the planted forests were established through afforestation programs (FAO 2010a).

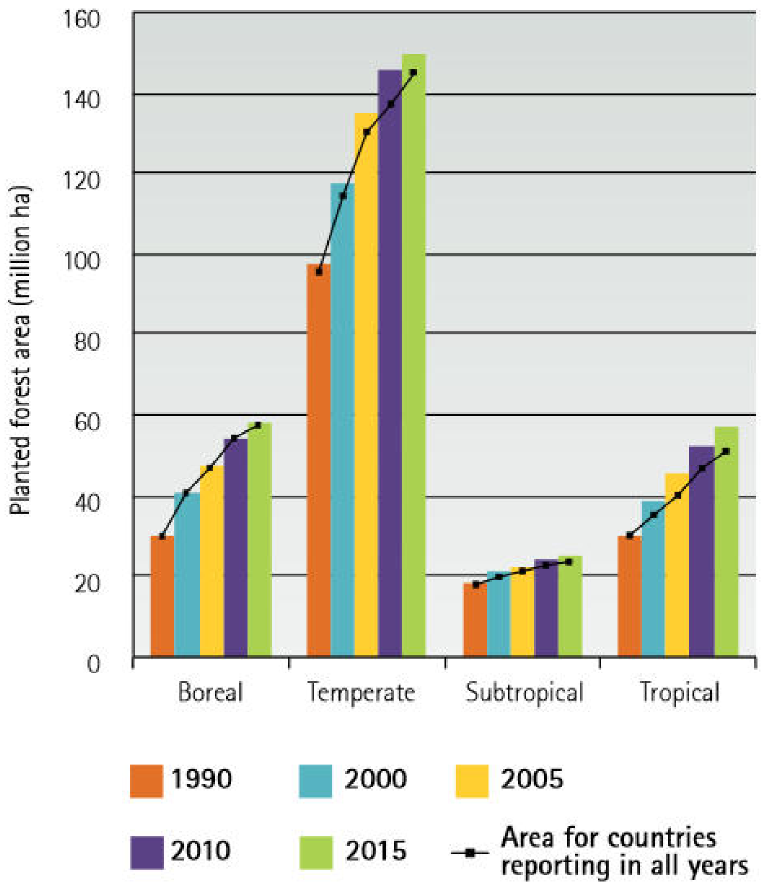


Figure 1.2 Planted forest area by climate domain (Source: FAO 2015b)

Figure 1.2 shows that the planted area continuously increased from 1990 to 2015, increasing its share in the global forest area from 4.1% to 7% (FAO 2015b). The largest area belongs to the temperate zone, followed by the Boreal and tropical zone, and the smallest area to the subtropical zone. Estimation of the future supply and demand for wood and wood products are an important aid to planning and decision making in the forestry sector at a national, regional and global level (FAO 1999). The global production of all major wood products including roundwood, sawnwood, wood-based panels, pulp and paper increased in 2013 compared with 2009. For instance, the paper and paperboard production increased from 371 million tons in 2009 to 398 million tons in 2013 (FAO 2013). The rise in the global human population, sustained economic growth, regional shifts, regulations and energy policies are the main reasons for the change in the long term global demand for wood products; along with a decline in harvesting from natural forests. This places a significant pressure on the global forest to use planted forests to meet the demand for wood products (FAO 2009a, 2012).

As demand for forest products grows, and natural forests are increasingly degraded and decreased in size, the total area of forest land has remained unchanged (FAO 2010a, 2015b). Natural forests have declined by 6.6 million hectares per year from 2010 to 2015 and the trend is predicted to continue in the future. This has increased the demand on planted forests to supply forest products. Consequently, commercial forest plantations are increasingly replacing natural forests as a timber source (Heilmayr 2014), accounting for 26% (816 million m^3) of the global timber harvest (Buongiorno and Zhu 2014).

The amount of planted forest area worldwide significantly increased in the period 1990 to 2010, as shown below in Table 1.1.

Table 1.1 Area of planted forest by region from 1990 to 2010

Region	**Area of planted forest (1000 ha)**				**Annual increment (%)**		
	1990	2000	2005	2010	1990-2000	2000-2005	2005-2010
Africa	11580	12873	14032	15326	1.1	1.7	1.8
Asia	70873	92871	109670	122777	2.7	3.4	2.3
Europe	58166	65309	68500	69318	1.2	1.0	0.2
North-Central America	20056	30186	35786	38659	4.2	3.5	1.6
Oceania	2542	3322	3849	4100	2.7	3.0	1.3
South America	8115	10058	11123	13821	2.2	2.0	4.4

Source: Borges et al. (2014)

The largest area of planted forest was found in the Asia, but the highest annual rate of change in area belonged to South America in the period 2005 to 2010.

In a report on the state of the world's forest to the year 2030, one scenario mentioned is an annual productivity increase in wood supply from planted forests. An estimation of the amount of wood supplied from planted forests in 2030 compared with 2005 shows that the global volume produced in planted areas will increase from 1.4 billion m^3 in 2005 to 1.7 billion m^3 in 2030, as shown in Table 1.2.

Table 1.2 Predicted change in wood volume produced in planted forests between 2005 and 2030 (million m^3 $year^{-1}$)

Region	Fuel/bioenergy		Pulp/fiber		Wood products	
	2005	**2030**	**2005**	**2030**	**2005**	**2030**
Africa	11	10	9	15	55	56
Asia	79	88	141	146	264	321
Europe	17	18	123	129	166	185
Southern Europe	3	6	26	55	26	56
America	7	8	98	117	24	31
South America	19	23	133	173	91	115
Oceania	1	1	11	13	31	36
Total	**136**	**155**	**540**	**647**	**659**	**800**

Source: Borges et al. (2014)

Figure 1.3 shows an increasing trend in planted forest area for the top 20 countries, except for Germany and Japan. Around 87% of the global industrial round wood production was provided by these top 20 countries.

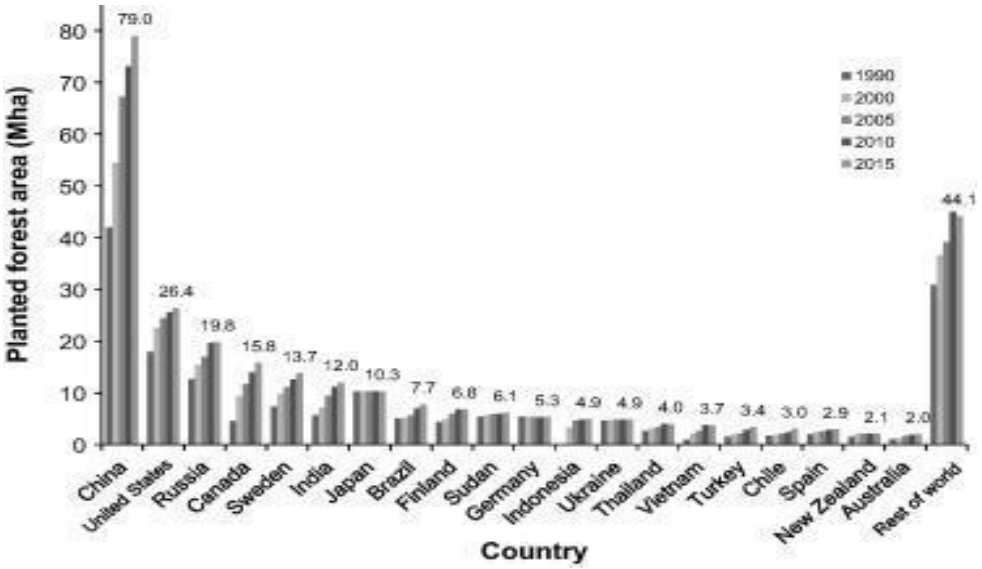


Figure 1.3 The trend in planted forest area from 1990 to 2015 in 20 countries (Source: Payn et al. 2015)

Improved forest productivity can result from the planting of fast-growing, short rotation species specifically matched to the site (FAO 2009a, 2009b). Aligning timber production to forest site suitability makes it possible to meet timber demands without having to increase the planted forest area. For example, in the USA and Brazil, forest plantations were able to meet the increased demand for pulpwood production by increasing productivity through species and site suitability and the application of silvicultural activities instead of by increasing plantation size (Borges et al. 2014). Meanwhile, afforestation and reforestation also contribute to an increase in forest cover and rise in forest carbon stock worldwide (FAO 2010a). Furthermore, many countries, including Vietnam, are responding to the New York Declaration on forest (forestdeclaration.org). By cutting natural forest loss in half by 2020 and attempting to end natural forest loss by 2030 (Climate Focus 2015). The extension of forest areas through afforestation and reforestation along with improved forest productivity in forest plantations are solutions for contributing to the successful restoration of globally degraded and deforested land as well as the mitigation of global greenhouse gas emissions as called for by the New York Declaration and Bon Challenge (www.bonnchallenge.org).

1.2 The role of forestry in the Vietnam economy

In Vietnam, the forestry sector's contribution to the national economy was 3.8% of the total GDP, which in 2011 was USD 5,123 million (FAO 2014). The trend in growth is positive with forest production values, for example, climbing from USD 955 million in 2012 (5.5%) to USD 1.09 billion (7.09%) in 2014 (To and Tran 2014). Growth in the value of forest production (including forest product processing and environment services) is estimated at between 3.5% and 4% per year, and the forestry sector is targeted to contribute about 2-3% of the country's GDP in 2020 (FAO 2009b).

In 2008, Vietnam exported approximately USD 2.8 billion in wood products to 120 countries around the world including Europe, North America, and the Asia Pacific region (Le, 2008). Wood production export turnover continuously rose from 2004 (USD 1,154 million) to 2011 (USD 3,945) as shown in Figure 1.4.

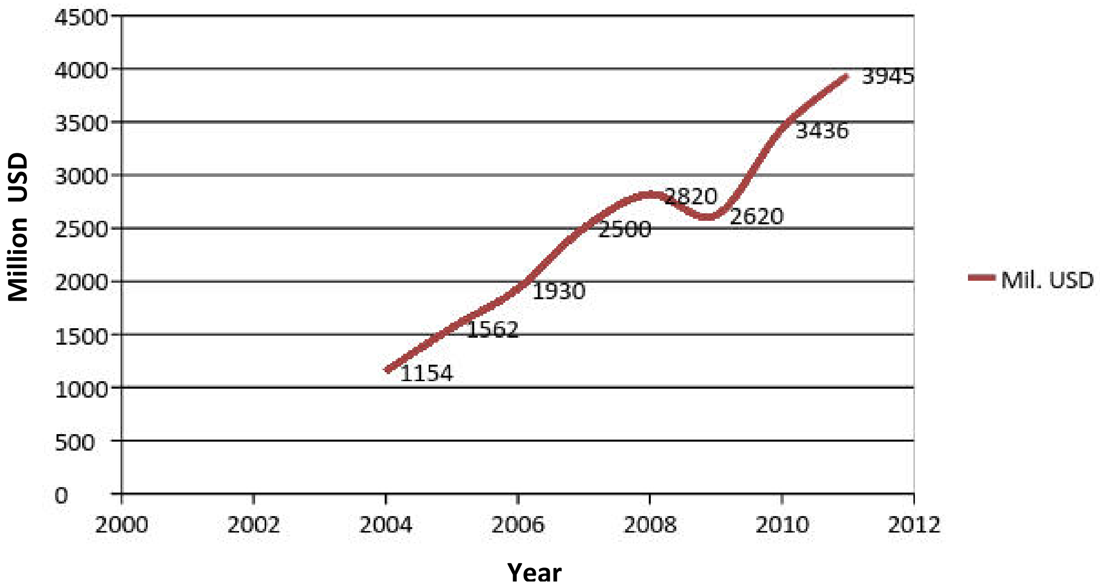


Figure 1.4 Wood production export turnover varied in the period 2004 - 2011 (MARD 2014b)

The timber export turnover reached USD 6,210 million in 2014, in the first six months of 2014, and wood production reached 2616000 m^3, a rise of 8.5% compared with that of 2013 (GSO, 2014). The main international markets are China, the USA, European countries and Japan.

The amount of timber harvested from forest plantations is around 63% and mainly consists of woodchips used for paper production and exported to China, Korea, and Japan. The remaining 37% of total timber harvested is used domestically for pulp, paper, particle boards, furniture, construction or fuel-wood (Zwebe et al. 2014). The amount of timber harvested is predicted to increase to 10 million m^3 by 2020, meaning 80% of the raw wood needed for the Vietnamese economy will be supplied domestically (EU FLEGT Facility, 2011).

Currently, however, the domestic wood supply is not sufficient to meet the timber demand, and Vietnam has to import raw material from 26 countries, among others from Laos, China, the USA, Thailand, and Cambodia. The main reason for the shortage in supply is the slow development of forest plantations and the reduction, due to environmental concerns, of wood harvested from the nation's natural forests (EU FLEGT Facility, 2011). The amount of wood imported has continuously increased by an average of 12. 1% per year (MARD 2014b). Wood production import turnover climbed from USD 755 million in 2006 to USD 1,500 million in 2012, as shown in Figure 1.5.

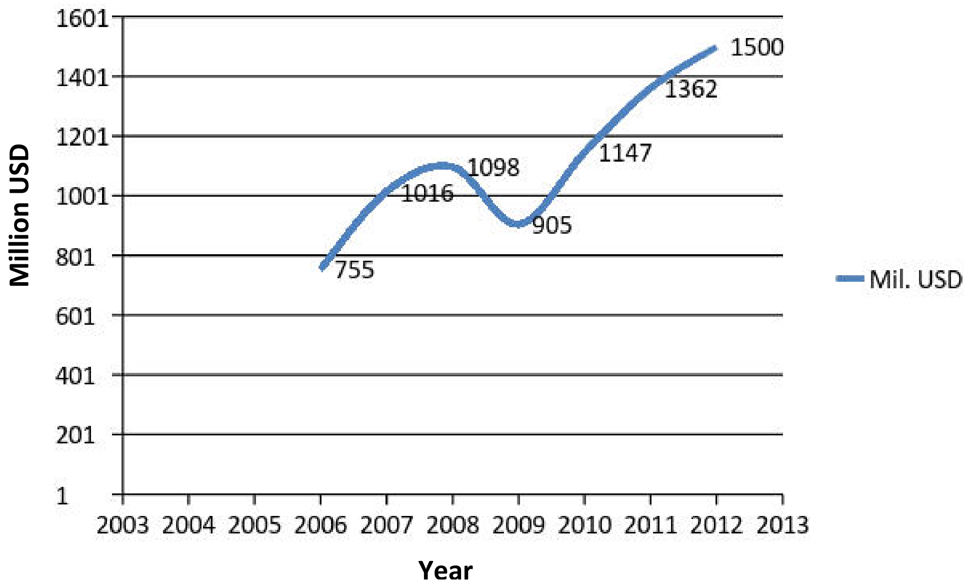


Figure 1.5 Wood production import turnover varied in the period 2006 - 2012 (MARD 2014b)

Yet, based on Vietnam's development strategy for the period 2006-2020, the aim by 2020 is to have a stable supply of raw material that can support the timber processing industry. The goal is to reduce dependence on imported timber from 80% to 20%. The country's recent policy measures have focused on efforts to increase the amount of domestic raw material supplied to the timber processing sector.

To reach this objective, it is necessary to provide an adequate supply to meet the high demand of the wood processing industry and increase efficiency of the forest plantations through appropriate silvicultural strategies, centralized plantation areas, selection of suitable tree species and sustainable forest management.

1.3 Forest cover and plantations in Vietnam

The forest cover of Vietnam has continuously increased from the year 1990 to today, reaching to 41.5% in 2014 (MARD 2014a), Table 1.3 shows the specific data.

Forest land is divided into two categories, natural forests and plantation forests. By the end of 2012, Vietnam had around 13.8 million hectares of forest, of which 10.4 million hectares were natural and 3.4 million hectares planted. Forest functions are classified into three groups, consisting of special use (2 million ha), protection forest (4.68 million ha) and production forest (6.96 ha) (To Xuan Phuc and Tran Huu Nghi 2014).

Table 1.3 The change in forest cover for the period 1995 -2014

Year	1990	1995	2000	2005	2010	2011	2012	2013	2014
Forest cover (%)	27.2	28.2	34.3	37.0	39.5	39.7	40.7	41.1	41.5

Source: (MARD 2014a)

The planted forest area has increased significantly from 1990 to 2011. Table 1.4 presents a comparison of the planted forest area over the years. The planted forest area has mainly expanded as forest plantations for the production of paper and pulpwood.

Table 1.4 The planted forest area

Year	1990	1995	2000	2005	2007	2010	2011
Area (1000ha)	745	1050	1638	2334	2553	3000	3229

Source: (FAO 2010a; MARD 2014b)

The total planted forest area of Vietnam reached 3.4 million hectares by the end of 2012, of which forest plantations accounted for 2.5 million hectares, or 73.5 percent (MARD 2014a). Planted forest areas provide numerous environmental as well as socio-economic benefits, such as reducing soil erosion, increasing carbon sequestration, improve soil quality and biodiversity, job creation and enhanced household livelihoods (To Xuan Phuc and Tran Huu Nghi 2014). The forest plantations have concentrated on planting fast growing species such as *Acacia mangium, Acacia auriculifomis, Eucalyptus camaldulensis, and Acia hybrid*.

Vietnam has one of the largest annual increases in forest cover in the world. The forest cover increased about 129 thousands hectare per year in the period between 2010 and 2015, and 216.4 (1.8%) hectare per year in the period between 1990 and 2015 (FAO 2015a, 2015b). The natural forest area, however, has decreased while the planted forest area increased between 1990 and 2015. The annual rate of change in planted forest area in the period from 1990 to 2015 was 107.8 thousand hectare per year, or 5.5%. Meanwhile, the woodland and primary forest area had a downward trend. For example, the annual rate of change for primary forests amounted to a loss of-12 thousands hectare per year, or -5.9% in the period between 1990 and 2015 (FAO 2015b).

The distribution of planted forest areas by region is shown in Figure 1.6.

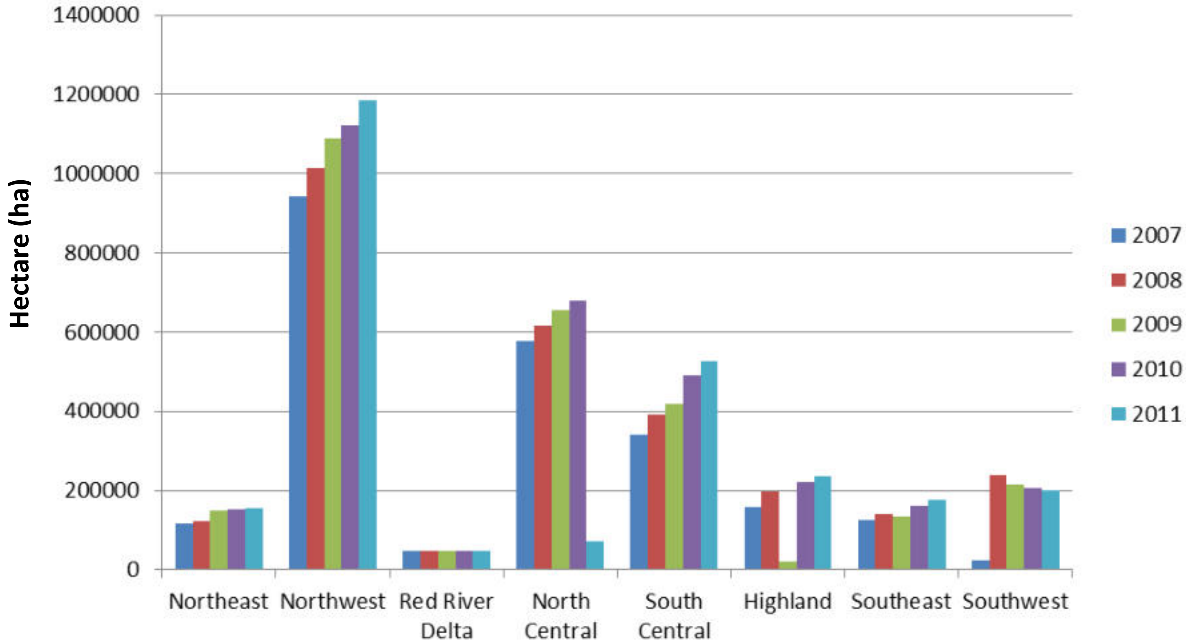


Figure 1.6 The distribution of planted forest areas by region in Vietnam

Generally, the amount of planted forest area varies according to regions and has an upward trend for the period between 2007 and 2011. In all years, the Northwest region accounted for the highest amount of area at around 1 million hectares, followed by the North Central and South Central regions at 400,000 to 700,000 hectares. The Red River Delta region had the lowest number of hectares at around 5,000 hectares (Zwebe et al. 2014).

Timber harvest from plantation forests for pulp, woodchips for export, particle board and forest products for export and domestic use is about 2-3 million m^3/year (FAO 2009b). Wood production output from plantation forest increased from 3.1 to 14 million cubic meters in the period 2006 – 2015, and the timber removed from natural forests fluctuated from 160,000 to 359,600 m^3/year (Zwebe et al. 2014). The industrial roundwood production from plantations in Vietnam in 2012 was 3700,000 m^3 (Jürgensen et al. 2014).

Many major national programs have been initiated for afforestation and reforestation purposes such as programs 327661147 and decision 829/QD-TTg by the Prime Minister dated 23 April 2014 which approved a national action program for the "reforestation to change forest use into other use". Their aim is to encourage organizations, households and individuals to plant forest plantations on bare land and open treeless hills. Program no.327 was carried out from 1992 to

1998 and the results show that this program successfully provided the silvicultural knowledge required to plant tree species such as eucalyptus and acacia, but insufficient farmer interest in tree growing and the low quality plantation sites were shortcomings (Lamb and Nhan 2006). The national afforestation program no.661 also called the Five Million Hectare Reforestation Program (5MHRP), implemented between 1998 and 2010, overcame the problems in program no.327 and focused on reforesting degraded land (Hung et al. 2011). Nevertheless, 5MHRP had little success and was unable to foster economic development or alleviate poverty in the northern uplands (Clement and Amezaga 2009).

One of the main incentives for increased forest plantation expansion are the government policies on forest land allocation (Clement and Amezaga 2009). Decree 02, dated 15 January, 1994 and decree 01/CP and decision 304, dated 23 November 2005 promoted organizations, households, and individuals to plant forest plantations in order to protect soil on bare land. Forest land was mainly allocated to households and individuals, commune committees, economic entities, state-owned organizations, other types of organizations, joint-venture companies, foreign companies and communities. Local people had very limited rights to these forests through their participation in forest protection and thus had little incentive to protect the forest (To and Tran 2014) and the effect on afforestation was minimal (Clement and Amezaga 2009). Nevertheless, the laws and decrees along with the development programs have created a certain legal framework for forest and forest land use rights. And as a result, forest resources have improved and poverty has been reduced. Among others, forest land allocation also brings access to favorable loans while the opportunity to invest in forest production provides a means for increasing household income and livelihoods (To and Tran 2014). In addition, financial incentives funded by foreign countries such as Finland, the Netherlands, Switzerland, Germany, or the USA have been providing funding to support the implementation of emission reduction efforts defined in the development strategy to reduce deforestation and forest degradation in Vietnam. As one of the governments endorsed in The New York Declaration on Forest (NYDF), Vietnam has a good chance of receiving financial incentives that reward tropical forest countries as mentioned in NYDF (Climate Focus 2015).

1.4 The problem statement

The long-term investment for planted forests requires a sufficient awareness of planning and policy practices (FAO 2010b). Based on the principle of sustainable development, land use planning often comes up with a compromise between economic development and environmental conservation while favoring social sustainability (Zhang et al. 2012; FAO 2010b). FAO recommends that to be sustainable, planted forests need to be aligned with ecological site conditions, market conditions and specific management objectives (FAO 2010b).

Site conditions have a significant effect on the productivity of plantation forests (FAO 2002). To increase profitability, the tree species planted in a forest plantation need to match the specific site conditions, i.e. the more suitable the species are to the site, the higher the forest productivity (Seifert 2014). Forest growth rates increase by selecting the best land and management practices to fit a site's different soil types (FAO, 1984). One of the main causes of failure for planted forests is adherence to traditional planting practices, which often entailed selection of suitable site conditions without matching ecological requirements of tree species (FAO 2010b). Planting forests in areas that do not match with ecological requirements may cause low yields and make them less effective.

In addition to site suitability, increased forest yields can also result from intensive management. Both approaches can enable a smaller area to produce the same amount of output as would be achieved in a larger area (Ewers et al. 2009). Many studies have shown that management practices can improve growth rates in forest plantations. Intensive management practices focus on enhancing potential yield and economic value through extensive field cultivation and application of fertilizer, herbicide, insecticide and genetic improvements (Hibbs et al 2007; Vance et al 2010; Sadanandan Nambiar 1999; Stanturf 2001; Pottinger 2014). Through intensive management practices, tree species selection and site suitability, optimal forest plantation growth and productivity can be reached (Netzer et al 2002; Seifert 2014).

In terms of sustainable development, sustainability is by definition a compromise aiming at concurrent realization of multiple objectives. In traditional forestry practices, land suitability assessments are only based on geo-morphological and ecological factors, and do not take into account socio-economic aspects. This can lead to misuse and social conflicts in selecting tree species in land use planning. While the goal of a productive plantation is to supply wood products, traditional plantation management often does not reflect the socio-economic aspects of planted forests. In a land suitability assessment it is necessary to consider the different socio-economic conditions influencing a site.

Several studies focused on potential or suitable sites for habitat based on ecological requirements or site productivity (Nyeko 2012; Nguyen Van Loi 2008; Do and Nguyen 2000; Yue et al. 2014; Rivano et al. 2015) and considered optimization management strategies for productive planted forests, these studies only considered optimal rotation age and the net present value (NPV) for planted forest at stand level (Mathey et al. 2009; Backéus et al. 2005; Thi Hong Nhung Nghiem 2011). They have, however, not demonstrated the optimal suitability for land use allocation.

In forestry, land use competition is driven by many socio-economic factors. Increasing demand for wood and bioenergy is a significant example (Azar 2005; FAO 2012; Heilmayr 2014). An adequate supply of forest products is needed to meet the demands of the wood processing industry and requires a highly productive plantation managed by an efficient forest planning strategy. While large areas of land that meet the definition of forest for inventory purposes are not available for timber production due to the small size of the ownership or reduced access due to isolation from road networks by other ownerships (Tyrrel et al 2004) and road network has an effect on the size of the procurement biomass area for energy facilities (Ranta and Korpinen 2011).

Previous studies have shown that the income generated from forest plantations not only depends on forest site productivity, but also on market conditions such as timber price, demand for goods and transportation cost. For example, transportation cost has a significant effect on the revenue of forest plantations (Ying 2014). Other studies have confirmed that the transportation cost has significant effect on biomass cost (Perpiñá et al. 2009). An increase or decrease of transportation costs could also provide economic incentives for the establishment of forest plantations devoted to woody crops grown specifically for energy production (Yemshanov and McKenney 2008).

Recently, in order to generate more profit from land use processes, studies on optimization of power plants or bioenergy facilities locations have gained significant attention. For example, studies on optimum geographic distribution of energy storage facilities with minimum collection cost conducted by Yu et al (2012) based on a mathematical model to locate power plant and GIS model showing the optimum number of satellite storages and the optimum geographic distribution of the satellite storages or by combining remote sensing and geographical information systems (GIS) to evaluate the feasibility of building new biomass power plants and optimizing the locations of plants (Shi et al. 2008).

The FAO framework is used widely as the guideline for the land-use suitability assessment. This approach produces principles and procedures for the qualitative evaluation of the suitability of land for alternative uses based on biophysical, economic and social criteria. With respect to ecological evaluation, the purpose of a land suitability evaluation is to understand how specific land use (FAO 2007) and tree species are matched with site conditions based on ecological requirements. The land expectation value (LEV) is also used as an indicator to assess the potential economic efficiency of a planted forest. LEV represents the value of land being considered for potential timber production and also determines the optimal time to harvest (Borges et al. 2014). However, the FAO framework does not specify which factor is more important than others in land suitability evaluations. Each factor used in the assessment process makes its own contribution; the significances usually are expressed as different weights, the weight depends on the importance of each factor. Determination of the weight of factor influencing land suitability assessment plays a significant role in making decisions.

Multi-criteria decision analysis (MCDA) is used to set the weights for the evaluation criteria, which allows the decision maker to define the importance of each factor and explain how the overall goal will be achieved. The analytic hierarchy process (AHP) is one of the most common methods used to gain criteria weights in MCDA (Saaty 1980b; Saaty 2008; Ying et al. 2007; Kangas et al. 2015). AHP allows decision makers to create a preference matrix where all criteria in relation with land suitability can be compared with each other. With the development of geographical information systems (GIS), integration of MCDA and GIS became more widespread (Malczewski 2006). By using a weighted linear combination, the process of integrating multi-criteria evaluation for land suitability evaluation is easily implemented; spatial pattern visualization can be performed. A combination of GIS and MCDA is spatial and flexible (Chen et al. 2010).

Land-use planning is perceived as a land-use optimization process. Land-use optimization models involve the optimization of the area size as well as the spatial pattern when regarding economic and social needs. The model used for land suitability must explore possible changes of land use according to driving forces. In term of sustainable development, models are adjusted for optimizing land-use patterns in line with different objectives. In economic evaluations of land suitability for growing forest plantation, the optimization of land use allocation cannot consider only ecological factors but also needs to take into account the driving forces which affect changes of land use for both size and pattern such as timber price, demand for wood, etc. By building the model showing changes, it allows policy makers, managers, local authorities to make adjustments to improve the problem.

Linear programming (LP) is a flexible tool and the most commonly used technique for optimization, which is applied in land use allocation analysis and can combine with GIS framework to show optimal land use allocation. A combination of LP with GIS can establish a model which enables decision makers to analyze the change in size and pattern of land use according to driving forces (Kangas et al. 2015). Therefore, a combination of the FAO, multi-criteria, LP and GIS frameworks of can increase the efficiency of land suitability evaluations under different scenarios.

To date, however, little attention has been paid to identifying suitable and economically efficient sites to establish dedicated forest plantation in afforestation programs based on production cost, timber demand, timber price and site productivity with aim at providing commercial timber sources to mills. Hence, this study will develop a spatially explicit model for the optimization of forest plantation management and indicate how the factors timber price, timber demand and production cost influence the amount and distribution of forest plantation, which will help decision makers enhance the effectiveness of forest plantation planning and determine which land is suitable for new forest plantations using a combination of FAO, multi-criteria, LP and GIS frameworks to maximize economic benefit and comprehensive analysis of land use management.

1.5 Research question and objectives

1.5.1 Research questions

1. How could a combination of FAO approach based land suitability evaluations, multi-criteria analysis, LP and GIS frameworks identify optimal forest plantation locations?

2. How sensitive is the optimization of management strategies to variations in timber demand, timber price, costs and harvesting age?

3. Could the optimization model be dedicated to the simultaneous study of land use planning (locations for the installment of plantations)?

Hypothesis:

1. A combination of FAO, multi-criteria, LP and GIS frameworks could provide an appropriate tool for identifying suitable forest plantation locations that meet future timber demands.

2. Optimized forest land use increases the profitability of forest plantations.

1.5.2 Research objectives

The specific objectives are:

1. To model the suitability and productivity of a *Acacia Mangium* plantation.

2. To maximize profitability and determine optimal assignment of area for growing a *Acacia Mangium* plantation.

3. To analyze scenarios for maximizing profitability in a regional context and determining optimal assignment of area for growing *Acacia Mangium* plantations with variations in timber demand, timber price and harvest age.

1.6 The structure of thesis

The thesis comprises six chapters. Chapter 1 shows the overview of the change in forest plantation area worldwide and its role in meeting the demand for timber. The changes in forest cover attributed to forest plantation extension and the contribution of forest plantations to the Vietnam economy. It also includes a problem statement, research objectives, research questions, and brief description of the study area. Chapter 2 describes the literature review of methodology that is used this study. This chapter also explains the reason why different methods should be combined to address the stated problem. Chapter 3 provides the method used for data collection and how data analysis and how the optimization model is built. A combination of the FAO, multi-criteria analysis, linear programming and GIS environment frameworks is implemented step by step. Chapter 4 presents the results of the study. Chapter 5 presents discussion of the result of the study. Chapter 6 concludes the findings of the study and possible application of the methodology used.

2 Literature review

2.1 Application of the FAO framework and multi-criteria decision analysis in land suitability assessment

2.1.1 FAO framework

Land-use suitability analysis aims to define the most suitable locations for land use components in the future and is considered a vital tool in land use planning.

'Land use planning is the systematic assessment of land and water potential, alternative patterns of land use and other physical, social and economic conditions, for the purpose of selecting and adopting land use options that are most beneficial to land users without degrading the resources or the environment, together with the selection of measures most likely to encourage such uses' (Pretzsch et al. 2014).

According to FAO (1984), suitability is defined as the fitness of a given type of land for a defined use. The identification of suitable forestry land use requires knowledge of desirability for sustained practice of given land use, which is linked to the purpose of forestry. For example, if the aim of land use is to provide for wood production, it is necessary to study growth requirements (temperature, nutrients, moisture, radiation, soil drainage) and management requirements (FAO 1984). Land evaluation has become a core component of land use planning (FAO 1993; Nguyen et al. 2015). The FAO framework is applied to assess land suitability that is based on both ecological and socioeconomic criteria.

The defined land use plays an important role in planning strategy. Land use suitability analysis aims at identifying the most appropriate spatial pattern for future land use to meet specific demands (FAO 2007, 1984, 1976; Pretzsch et al. 2014) while avoiding the inefficient exploitation of the land. To achieve successful land use planning in terms of ecological factors in afforestation and reforestation, the required ecological factors are soil properties, topography and climate regime, which are relevant for tree growth. Analysis of land use suitability not only takes into consideration a variety of criteria such as ecological factors, but also includes economic and social aspects (FAO 2007).

The suitability level which is the basis for procedures of land planning and management can be determined for each land use and spatial unit based on land suitability criteria for field crops by matching species with site conditions. The FAO framework for land evaluation suggests the following suitability classes shown in Table 2.1.

Table 2.1 Land suitability classes (FAO 1984)

Class	Designation	Definition
1	Highly suitable	Land having negligible or slight limitations affecting site productivity (productivity class 1), and with negligible of slight management limitations or degradation hazards
2	Moderately suitable	Land having moderate limitations affecting site productivity (productivity class 2) or land having higher productivity but with moderate management limitations or degradation hazards
3	Marginally suitable	Land having severe limitations affecting site productivity (productivity class 3), or land having higher productivity but with severe management limitations or degradation hazards
4	Unsuitable	Land having severe limitations affecting site productivity (productivity class 4), or land having higher productivity but with very severe management limitations or severe to very degradation hazards

In Vietnam, the evaluation of land suitability is a basic part of the land-use planning process. Potential forest land evaluations are also represented in the research conducted by Do and Nguyen (2000). In this study, potential productivity assessment of forest land is based on primary factors in close relationship with soil productivity such as land slope, soil depth, surface soil organic matter and soil texture. This research is carried out in 8 forestry economic zones in Vietnam with different forest land groups (land on feralit soils (ferralsols) on hilly and mountainous areas, land on coastal sandy soils (arenosols), land on mangrove saline soils (gleyi salic fluvisols), and land on acid sulphate soils (thionic fluvisols). According to Ngo and Do (2009), when regarding to commercial forest plantations in some main regions of Vietnam, four criteria are used to assess potential sites consisting of parent materials and soil types, slope gradient, soil depth, and vegetation. The study has provided the guidelines for selecting potential forest plantation locations in Vietnam.

Mohan and Phuong (2003) generalized a principle that is applied to assess forest land embracing a combination of criteria (soil type, slope, soil depth, vegetation status, elevation and rainfall). The assessment of suitability of species is indicated by comparing biological requirements of tree species with the actual site conditions. As a result, suitability classes are divided into four categories: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N). In other research conducted by Nguyen (2008) in Thua Thien Hue – Vietnam, the FAO (1984) approach was applied to define suitable areas for seven tree species: *Pinus merkussi, Pinus caribaea, Acacia auriculiformis, Acacia mangium, Acacia hybrid, Acacia crassicarpa,* C*asuarina equisetifolia*. Soil property factors (soil type, soil depth, soil texture, soil pH, soil fertility and organic matter), topographic factors (slope gradient and elevation) and climatic factors (mean annual rainfall and mean annual temperature) are considered as suitable factors to compare the ecological requirements of tree species.

According to Do et al. (2005), land suitability assessments are implemented using the following procedure:

- Identifying land use
- Identifying land units
- Identifying land conditions
- Identifying ecological requirements of tree species
- Matching ecological requirements with land conditions based on land units

The FAO framework is applied globally in land suitability evaluations, especially in the rural land-use planning process (Santé-Riveira et al. 2008). In the forest land use planning the land evaluations for forest plantations or site assessments are required before the establishment of trees (Ryan et al. 2002). Deng et al. (2014) conducted a study on land suitability evaluation for alfalfa cultivation in northern China. The FAO framework is applied to assess land suitability that is based on both ecological and socioeconomic criteria. Ecological suitability is evaluated by a combination of topographic factors, soil properties, and climate factors that have different effects on the growth of alfalfa. Another example is presented for Jordan, where land suitability classification is based on land suitability criteria for field crops consisting of soil, rockiness, erosion hazard and topography, which results in four suitability classes (Ziadat 2007).

In summary, to match species with site conditions, land classification procedures take into consideration generic components such as climate, topography, geology, and soil. The results of land classifications serve as the basis for land evaluations to assess land suitability for selected tree species. Application of the FAO framework can enable the comparison between the requirement of a land use and the land to ensure that the appropriate land use matches the selected tree species. Land suitability classification in forestry needs to be based on the function of the forests and forest management in line with other land use.

2.1.2 Multiple criteria decision making

The FAO framework can enable the requirements of selected tree species to be matched with the land qualities and characteristics of a given location. Meanwhile multi-criteria decision making can aggregate factors into land suitability maps. Integration of a geographical information system (GIS) and multi-criteria evaluations is becoming more and more prevalently in land suitability analysis (Pereira and Duckstein 1993; Malczewski 2004, 2006; Chen et al. 2010; Deng et al. 2014). Thanks to multi criteria decision making, several criteria can be evaluated and formed into a more appropriate index of assessment process. The analytic hierarchy process (AHP) approach is commonly utilized in multi-criteria decision making, especially in land use suitability analysis in line with GIS (Chen et al. 2010; Zhang et al. 2012).

The AHP is included in the family of multi-criteria decision making techniques (Nekhay et al. 2009). This method introduced by Saaty (1980b) is widely used in determining which factor is more important than other. AHP has been applied in studies related to decision making. In general, AHP is based on three principles: decomposition, comparative judgment, and synthesis of priorities. This technique is implemented based on expert knowledge and makes it possible to take into account various qualitative and quantitative criteria in the decision making process on a hierarchical basis (Samari et al. 2012; Nekhay et al. 2009). AHP is utilized to assign weights for standardization of criteria maps with validation from expert knowledge (Feizizadeh et al. 2014; Murayama 2012; Mishra et al. 2015).

The AHP which is a multi-criteria decision method delineates the decision process of identifying various and important roles of each criterion by using pairwise comparison (Rad and Haghyghy. 2014). The AHP provides a systematic approach for weighting of multiple criteria simultaneously. The proposed scale ranges from 1 to 9, with 1 implying ‘least valued than’ and 9 implying ‘absolutely more important than’ in the pairwise comparison matrix (Vaidya and Kumar 2006) is illustrated in the Table 2.2.

Table 2.2 Scale for pairwise comparison (The Saaty fundamental 9-point scale)

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two factors contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one over the other.
5	Strong importance	Experience and judgment strongly favor one over the other.
7	Very strong importance	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Extreme importance	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values between adjacent scale values	Sometimes one needs to interpolate compromised judgment numerical

Source: (Saaty 2008)

Vaidya and Kumar (2006) pointed out seven main steps defined as:

1. Identifying problem

2. Taking account of objective of problem and the result of process
3. Identifying the parameter or criteria that impact the objective
4. Taking consideration of a hierarchy of different criteria and sub-criteria
5. Using pairwise matrix to assess and assign the importance of each factor with scale ranges from 1 to 9
6. Determining eigen value, consistency ratio (CR) based on consistency index (CI) and random index (RI) and the normalized value for each criteria/alternative
7. Checking the satisfactory of eigen value, consistency ratio (CR) is to decision maker obtain the final normalized values for criteria.

AHP has been applied for solving a wide variety of problems with divergent aspects. For example, AHP is practical and easy to use for setting up a model to assess forest quality at the stand level in China. The results showed that forest structure was the most important factor, followed by regeneration status, and that economic profit was the least important (Wang and Bao 2011). Other research also indicates that AHP is an appropriate method for assessing stakeholders' perceptions of forest biomass-based bioenergy development in the southern USA. It enables the stakeholders to assign a relative priority to each factor by using pairwise comparison (Dwivedi and Alavalapati 2009). Nefeslioglu et al. (2013) carried out a study on natural hazard evaluation in Turkey. Identification of optimum construction of new educational land use is defined through a combination AHP and GIS in Tehran (Javadian et al. 2011).

Expert knowledge can be obtained through single - discussion or group - discussion to solve the decision-making problem. Until now, no studies have stipulated how many experts are needed in the process, but the more expert knowledge included the more reliable the information (Feizizadeh et al. 2014). Several studies have been conducted that applied single – discussions to obtain the expert knowledge (Nekhay et al. 2009; Samari et al. 2012; Xu 2000) For example, Nekhay et al. (2009) applied AHP single discussion to assess the influence of landscape objects (water surface, vegetation area, national park area, urban area, and agriculture land and high electricity lines) on the ecological diversity and habitat restoration. Six experts were interviewed separately for their evaluations, then the geometric mean from these assessments was calculated. Another study illustrated that AHP is an effective tool for determining the weight of criteria for decision making by the forestry extension service in

Zagros area with a total of 50 individuals in three provinces being chosen (Samari et al. 2012). A group decision making process was also applied in this situation.

Group discussions were carried out in the study conducted by Kühmaier et al. (2014). A group of 15 Austrian experts attended the discussion and evaluated the criteria weights for selecting potential locations for forest plantations based on both an economic and an environmental point of view. In this process, AHP proved useful in addressing complex decision-making problems. The results of evaluation criteria were used to calculate a suitability index. In another study on land suitability, assessing cropland in protected areas in Vietnam, the criteria were weighted based on a group of twelve experts between the ages of 30 and 50 years old and including five agronomy experts, five soil experts, and two forestry experts. Experts have at least five years' experience of working at this area. This study pointed out that a combination of individual expert knowledge substantially improves the decision-making process in multi-criteria analysis (Murayama 2012).

Both single – discussion and group – discussions express different expert's preferences. Therefore, when synthesizing the judgments performed by experts it is necessary to ensure the judgments of decision makers are consistent. By applying a theorem called 'pareto principle' (unanimity condition), which states that if each member of a group of individuals prefers A to B, then the group must prefer A to B (Forman and Peniwati 1998). Two synthesizing functions generally applied are the geometric mean and the arithmetic mean, which are defined as:

The geometric mean: f $(x_1. x_2 \ldots\ldots x_n)$ = $\sqrt[n]{x_1. x_2 \ldots\ldots x_n}$

The arithmetic mean: f $(x_1. x_2 \ldots\ldots x_n)$ = $\frac{(x_1 + x_2 + \ldots + x_n)}{n}$

where:

$(x_1. x_2 \ldots\ldots x_n)$: are judgments of n individuals.

x_i: judgment of individual i

Two approaches, the aggregation of individual judgments (AIJ) and the aggregation of individual priorities (AIP), are widely used to aggregate individual perceptions. The selection of the AIJ or AIP method depends on whether individuals are willing to discuss together or separately (Adamcsek 2008; Forman and Peniwati 1998). AIJ is considered an approach to treat a group of experts as a new ‘individual’ when it meets the requirements of the reciprocity condition for the judgments, while AIP considers a group as individuals. The geometric mean becomes more consistently with both methods AIJ and AIP (Forman and Peniwati 1998).

A combination of AHP and SWOT (strengths, weaknesses, opportunities, and threats) also provides a useful tool to assess multi-criteria when covering different criteria. For instance, AHP can be combined with SWOT to assess the suitability of forest community-based management. AHP is applied to provide an effective way to assign the weight of factors that measure stakeholders’ view in selection of forest management planning (Masozera et al. 2006). The hybrid method by integration between AHP and SWOT to address the issue in sustainable management is used for determining a planning strategy. The AHP formulates decision-making problems based on pairwise comparisons of SWOT groups with indicating the priorities of the factors by the respective weights in strategic planning processes for forest certification application in Runni Organic Farming Expertise Centre, Finland (Kurttila et al. 2000).

To summarize, although the attribution of weights for describing the relative importance of different criteria by using AHP remained a more or less subjective matter. The attribution of weights is driven by the expert’s experience and preference to make decision (Chen et al. 2011; Nefeslioglu et al. 2013; Feizizadeh et al. 2014). However, this method is also broadly used in assignment of the weight of factors. In fact, the pairwise comparisons represent the current preferences of the decision maker. Therefore, the opinions of the stakeholders or experts are affected by the events of the day and by media coverage (Kühmaier et al. 2014).

In this study, the analysis process undergoes three phases consisting of pair-wise comparison, judgment and synthesis to assess the multi-criteria that related to forest growth by single discussion and then the calculated average value is adopted. The AIP is used for assessing different expert’s judgments with weighted geometric mean.

2.2 Application of linear programming in land use suitability analysis

In forest management, optimization techniques are a set of tools that facilitate optimal strategic planning by solving issues such as determining the optimum length for one full plantation cycle for a coppice forest (i.e., the number of crops or rotation intervals and the corresponding rotation ages before a forest stand is re-established by planting), identification of possible maximum revenue gain, scheduling regeneration harvest to best meet multiple management goals, or determining the thinning intensity in even – aged stands.

The most frequent tool used in optimization techniques is linear programming (LP) (Rustagi 1994). LP is defined as an objective function, which is expressed as maximized or minimized functions. The tasks of LP must define decision variables, and constraints and then find feasible solutions. LP is used for dealing with problems such as the allocation of the limited resources through optimal feasibility. In forest planning, decision variables might be area, production, income, and revenue that need to be maximized or minimized. Constraints are commonly illustrated as the barriers that need to be overcome (e.g., area available, the sequence of harvest) by finding feasible designs (Blockley and Shyy 2010; Kangas et al. 2015).

The function is usually defined as:

$$Max\ z = \sum_{i=1}^{n} c_i x_i$$

where:

z: value of the optimization equation

x_i : is a decision variable which needs to be calculated

c_i: is the coefficients

Up to date, land–use suitability analysis is an essential part in the land use planning process. The land–use suitability analysis not only concerns 'what to grow where', but also focuses on the optimization of spatial land use allocation and requires that the area meet the requirements of each land use to bring the highest efficiency (Santé-Riveira et al. 2008).

In the economic evaluation of land suitability, when the optimization problem is the expected revenue in the context of sustainable development, the economic evaluation needs to focus on cost, equilibrium of demand, and supply of natural goods; considered the market equilibrium for products. There are some studies stressing only forest site productivity (Laffan 2000; Watt et al. 2005; Ryan et al. 2002) to indicate the capacity of the land, but this point of view is insufficient for obtaining optimization without recognizing production costs, transportation costs and the trade-offs. A study was implemented by Restrepo and Orrego (2015) with regard to the financial aspects of growing plantations, and suggested landowners should establish forest plantation on lands with high productivity and low property costs.

It is widely accepted that cost has a significant effect on the economic aspects of growing a forest. For example, with regard to transportation cost, Spinelli et al. (2009) demonstrated that total delivered cost goes up by 0.1€ per km when the transportation distance increases from 15 km to 105 km. Transportation cost is considered the most important barrier in increased supply of timber for sawmills. A study on forest residue supply chain costs implemented by Ghaffariyan et al. (2013) also demonstrated that longer transportation distances lead to higher transportation costs per unit of delivered chips. Besides, previous studies have identified that timber prices significantly influences farmers' decisions on planting, keeping current land in forests (Abt et al. 2010), and suppose that timber prices are not only affected by transportation distance (Jagger and Luckert 2008) but also timber demand from the market (Rahman 2012).

Application of optimization techniques in land suitability assessment was considered in recent studies. The optimization of power plants or bioenergy facilities locations in particular has received considerable attention, and has the potential of creating more advantages for the use of forest products. Some recent studies on optimum geographic distribution of energy storage with minimum collection cost conducted by (Yu et al. 2012; Stasko et al. 2011) based on a mathematical model to locate power plant and GIS model showing the optimum amount of satellite storage and the optimum geographic distribution of the satellite storage, or by combining remote sensing and geographical information systems (GIS) to evaluate the feasibility of building new biomass power plants and optimizing the locations of plants (Shi et al. 2008).

In addition, optimization techniques based on cost – benefit using a spatial model were applied to determine the optimal location for land use types. For example, a cost - benefit model called Canadian Forest Service – Afforestation Feasibility Model (CFS-AFM) proved the efficiency of feasibility of bioenergy plantation selection, the result shows that minimum breakeven costs for poplar plantations on agriculture land is the basis information in selecting optimal bioenergy plantations. This cost benefit model is built based on GIS input maps (land use map, site suitability map, biomass demand, bioenergy plants' location) and transportation cost to identify feasibility of bioenergy plantation (Yemshanov and McKenney 2008). Höhn et al. (2014) illustrated that the identification of potential biomass and locations for biogas plants in Southern Finland based on a GIS model is essential to analyze the spatial distribution of biomass sources and facilities; this study uses the existing road grid which is a good example for providing accurate knowledge about transportation distance when considering suitable locations for biogas plants. In addition, logistics are also a major factor for considering optimum location of the biomass plant with regard to the minimization of transportation cost based on road network characteristics and accessibility to biomass source (Alfonso et al. 2009; Panichelli and Ganasounou 2008)

Optimization techniques were applied to address land suitability for land use management of lake areas or forest plantations. For instance, a goal programming method as one of potential optimization techniques was applied successfully by Bertomeu et al (2009) to gain sustainable forest management. They demonstrated the feasibility of using optimization techniques to solve timber harvest scheduling issues to demand full eucalyptus plantation cycle at the end of the planning horizon with respect to net present value achieved and to guarantee a constant harvest timber amount in relation with area control method. Liu et al. (2007) have developed a method for gaining maximum net economic benefit which is utilized for selecting land use allocation; this research covered different probabilities of total environmental capacity of water system, which provided a scientific basis for local authorities to deal with land use allocation problems.

Nevertheless, the most important aspect when analyzing the economic feasibility of growing forest plantations is the expectation that the value of forest productivity will be higher than costs for planting, maintaining, harvesting, and transporting, and will make it possible to determine an economically feasible location for growing plantations. Nepal et al. (2014) conducted a study in Northern Kentucky to indicate appropriate sites for planting woody energy crops based on expected biomass productivity, biomass price, and production cost. In this case it can be useful to determine the break - even biomass yield (amount of biomass required to attain a LEV = 0) for each land estate. Each land parcel with biomass yield higher than break – even biomass amounts is regarded as suitable for bioenergy crops. In the traditional way to calculate LEV (land expectation value), researchers used stumpage price to determine yield value, but Nepal et al. (2014) considered the transportation cost to avoid overestimating the yield value and economic return in forest evaluation. According to Borges et al. (2014), the LEV regarding to the receipts, payment, rotation and discount rate represents the comparison between cost and benefit and helps decision maker consider whether or not they should invest in growing plantation. The landowners can invest in the areas when seeking opportunities to benefit from forest plantations.

In the application of linear programming as an optimization technique to meet the requirements of different stakeholders in land suitability evaluation, Kalogirou (2002) conducted land suitability assessment using linear programing called 'CLIPS' to provide an economic evaluation of the land for different types of agriculture and select the crops with the income being maximum. Various multi-objective linear programming which was applied by Santé and Crecente (2007) to maximize gross margin obtained from land use allocation or by Shukla et al (2001) to maximize profit from new allocation of land use in Spain. However, these studies only regarded production costs and have not yet paid attention to other factors influencing the potential land suitability, such as transportation cost, the trade –off of demand and supply for products or an estimation of the demand of the land.

In conclusion, the model used in the economic evaluation of land suitability needs to consider not only ecological factors, but also other factors that can affect the suitability of land use. The linear programming models have provided valuable insight into the relation between decision variables and constraints in land use planning (Shukla et al. 2001). Optimization techniques are valuable and flexible approaches for modelling using the GIS framework. To date, few studies have considered the application of optimization techniques as linear programming on economic evaluation of land suitability in the selection of a suitable site for growing profitable plantations. LP is a promising tool to apply for evaluation and making decision in land suitability when addressing preferences to integrate different factors into the required optimization models.

In conclusion, a variety of methodologies for forest location decision making were studied, such as multi-criteria methodologies and optimization approaches. Multi-criteria methods were mainly used for finding individual criteria relations to multiple criteria, along with showing the trade - off between the criteria. Especially in land suitability assessments that are implemented according to the FAO framework, a combination between the FAO framework and multi-criteria provides a feasible and applicable solution. Optimization techniques are a set of tools that facilitate optimal strategic planning by solving issues such as optimal location-allocation, or optimal timber amount harvest. Linear programming is one type of general optimization technique. However, linear programming does not take into account any ecological considerations (Kangas et al. 2015). Hence, a combination of linear programming and multi-criteria decision analysis in relation with FAO framework is needed to support decisions in forest land use planning. Additionally, this combination can integrate bio-physical and socio-economic criteria to be integrated in the analysis and modelling of forest plantation planning.

3 Material and methodology

3.1 Materials

3.1.1 Study area

The study area is located in the northeast region of Vietnam and covers an area of slightly over 350,000 ha, with 87000 ha of planted forests and 94000 ha of natural forests. The area shares a boundary with Bac Kan province to the north, with Ha Noi to the south, with Tuyen Quang and Vinh Phuc provinces to the west and Lang Son and Bac Giang provinces to the east (PCT 2010).

Thai Nguyen province is divided into two cities (Thai Nguyen, Song Cong) and seven districts (Dinh Hoa, Phu Luong, Dai Tu, Vo Nhai, Dong Hy, Pho Yen, and Phu Binh). Thai Nguyen has eight ethnic groups such as Viet (Kinh, 75.47%), Tay (10.68%), Nung (5.2%) and others (8.65%). The average population density is about 327 people/ km^2. The highest population density is found in Thai Nguyen city (1366 people/km^2), and Vo Nhai district has the lowest population density (72 people/km^2). The income of the local people in Thai Nguyen origins from different sectors. More than 60 percent of the local people make their living in the agricultural sector. The agriculture, fishing and forestry sectors only contribute 8.7 percent of the national GDP.

The gross output of the forestry sector slightly increased from 2000 to 2013. The gross output of forestry only accounted 3.32 % in 2000 and 3.46% in 2013 of the total gross output for agriculture, forestry and fishing at current prices (TNSO 2014).

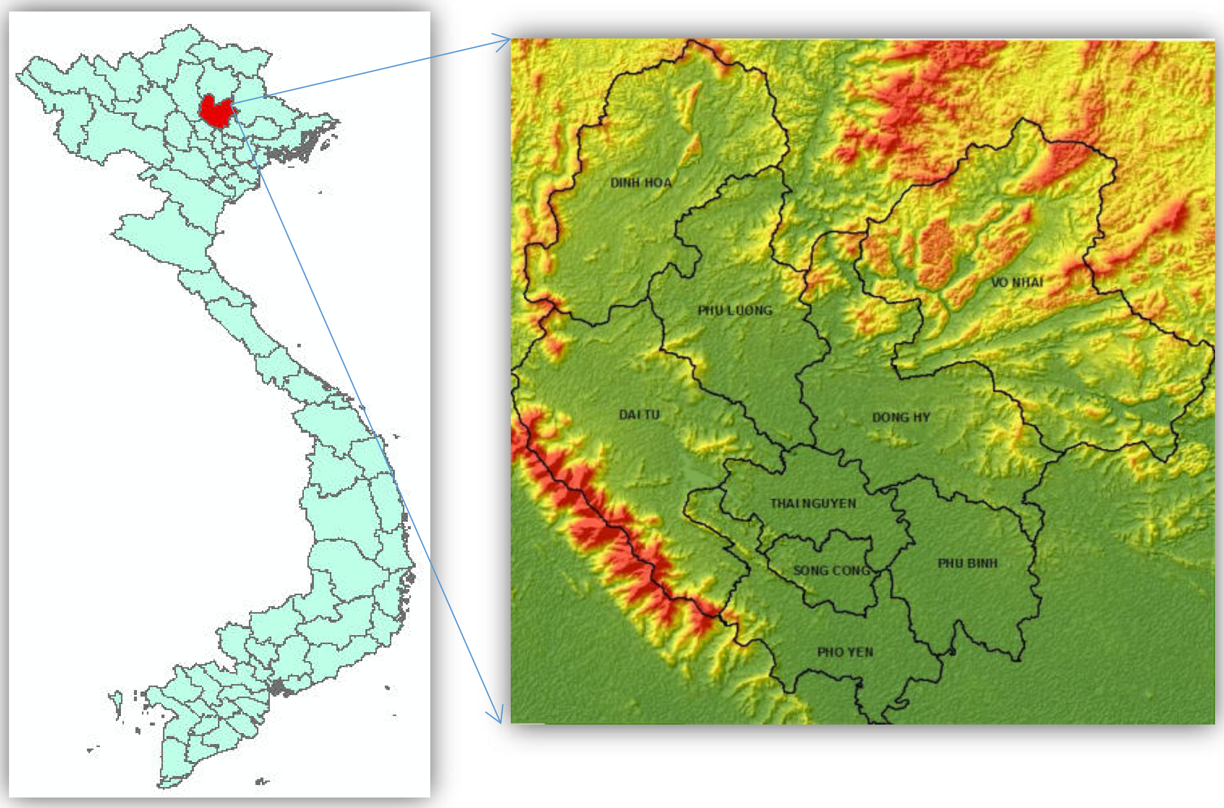


Figure 3.1 Location of study area

The elevation is from about 50m to more than 900m above the sea level. The slope varies between 0 and more than 35 degrees. The mean annual temperature is 23^{o}C, the lowest air temperature drops to 3^{o}C, while the highest air temperature can reach 42.6^{o}C. The rainy season lasts from May to October with rainfall levels of 1400 - 1700 mm. The difference between Thai Nguyen city and other districts in mean annual rainfall is significant due to topography characteristics (PCT 2010).

According to the results of studies on the forests and forest land planning in 2015, the total forest area is 197263 ha, of those 112309 ha was planned for production forest, 44567 ha for protection forest, and 40387 ha for special use forest (PCT 2014, FIPI 2015). 50% of the land area is covered by forest, Forest are classified as production, protection and special-use forests. The main objectives of the production forest is to provide timber, non- timber forest products and environmental protection. The protection forest was designated to protect ecosystem services, to mitigate environmental degradation (soil erosion), and to restrict the collection of non-timber forest products. The main aim of special use forests is nature conservation, protection of historical and cultural relics, tourism and environmental protection.

Table 3.1 shows that the amount of natural forest significantly decreased by roughly 28000 hectares between 2005 and 2015, while planted forest increased by about 44000 hectares in 10 years. The upward trend of the area of planted forests not only satisfies timber demands but also environmental protection requirements.

Table 3.1 Forested area according to forest types

Year	Total forested area (ha)	Planted forest (ha)	Natural forest (ha)
2005	156524	50936	105588
2007	157321	56813	100508
2008	160333	60411	99922
2009	171697	73064	98633
2010	176731	80428	96303
2011	177763	80806	96957
2012	178815	83738	95077
2013	181039	87174	93865
2015	172491	95040	77451

(Source: PCT 2014, FIPI 2015)

There are two well-known special use forests (SUF), the Than Sa – Phuong Hoang nature reserve and Dinh Hoa historical reserve in Thai Nguyen, both of which are tourist attractions. The forest in Thai Nguyen also plays an important role in protecting the environment: i.e. through soil protection and water retention; prevention of soil erosion and sand flow;

protection of ecological environment and landscape; protection of fauna and flora genetic sources, creating aquatic resources for domestic consumption and production; providing fresh air for human life as well as helping to mitigate natural disasters such as floods. Understanding the importance of forests for sustainable development, the People's Committee of Thai Nguyen Province and different sectors and localities have promulgated various guiding documents on forest protection and management, especially in Forest Land Allocation, along with providing strict guidance on the establishment of forests and monitoring forest land changes.

The main aim of this study is to focus on commercial forest plantations that supply timber for mills to process. There has been an increase in demand for timber from forest plantations. The total volume of timber removed from forests has increased each year (27079 m^3 in 2005, 28685 m^3 in 2006, 28990 m^3 in 2007, 28990 m^3 in 2008, 80938 m^3 in 2011, 149960 m^3 in 2012, and 154855 m^3 in 2013). The timber supply from forest plantations is probably not sufficient to keep pace with the increasing timber demand (PCT 2014).

Until now, the utilization of forest land has not been highly efficient, especially in growing forest plantations. Planning measures for the productive forest have not yet paid attention to market needs and the timber supply procurement has been planned without considering the production base. In addition forest planning has not considered improving forest productivity and yield. Therefore, some sites are generating extremely productive forests while others show insufficient production. In conclusion, the land use planning in the productive forest area has not considered the demand, production and transportation costs and site productivity, which are major drivers leading to the low efficiency of plantation forestry in the study area (PCT 2014, 2010).

3.1.2 Studied species

Acacia mangium Willd, also known by its local name ‘Keo tai tuong’, is one of the fastest growing tree species and belongs to the family Leguminosae and sub–family Mimosoideae. The species originates from the humid tropical forest of northeastern Australia, Papua New Guinea and the Molucca Islands of eastern Indonesia (Krisnawati et al. 2011). It can grow to a height of 35 m and has a medium size.

A. mangium can grow with a mean annual rainfall of 1450–1900 mm in southern New Guinea, and 2100 mm in northern Queensland, and even can live under rainfall of less than 50 mm. The tolerated mean minimum temperature is approximately 12–16 °C and the mean maximum temperature is approximately 31–34 °C in natural conditions (Krisnawati et al. 2011). Unsuitable areas show a minimum temperature less than 0°C and are frost – free. *A. mangium* does not grow well where the absolute minimum temperature fall below 0^{o}C (Hegde et al. 2013). The species can grow in the dry season (Man and Hao 1993).

According to Otsamo (2002), *A. mangium* can grow well on lateritic soils, but it is constrained under saline conditions and shade (Krisnawati et al. 2011). Nghia and Kha (1993) supposed that this species can be planted in acid sulphate soil with low pH (3.2–3.5) in Southern Vietnam (Awang and Taylor 1993). Research from Indonesia indicates that a mean annual increment of $15m^3$/ha/year (Awang and Taylor 1993). In Vietnam, *A. mangium* can grow successfully on a variety of soils from coastal sandy soil, Feralite soils developed on ancient alluvium to alluvial soil with pH ranging from 3.8 to 6.5. The slope is generally less than 25^{o}.

Optimal sites for growing *A. mangium* are characterized by soils with pH 4.5-6 and slopes of less than 15^{o}, with mean annual rainfall of 2000 mm/ year. The productivity can reach 20-25 m^3/ha/year. For elevations below 700 m, *A. mangium* is the best performing tree species with MAI ranging from 11-$23m^3$/ha/year at age 4-5 years. Studies conducted in study area before show that the rotation varies from 7 – 8 years with an average yield in volume of 184.66 m^3/ha at 8 years (Pham, 2008). Seedlings of *A. mangium* were planted in dibber tubes for 4 to 5 months before planting in the field at 2.5 m x 2.5m spacing.

Acacia plantations provide industrial wood for Vietnam's wood-processing, pulp and paper industries and woodchip exports, as well as household fuelwood supplies in rural areas (Sein and Mitlöhner 2011). Wood from *A. mangium* can be used for pulp, fuelwood and saw timber in Vietnam (Booth et al. 1999). In the 1960s, Acacia was introduced in northern Vietnam. It became more prevalently and accounted for 23,000 ha in the period between 1986 – 1992 (Turnbull et al. 1998). According to Harwood and Nambiar (2014), the total area of Acacia plantations in Vietnam was estimated at around 1.1 million hectares in 2013, in which 600,000 hectares is *A. mangium* that is largely planted in North Vietnam. Wood coming from Acacia is the main source (woodchip) for export and process wood in pulp mills. It also produces many sawmill products such as sawn boards from small acacia logs in the diameter range 12–25 cm. In the study area, almost all of the *A. mangium* wood is used to produce woodchips and pulpwood as raw material for domestic use and export.

Figure 3.2 *Acacia mangium* planted in 1 year old (a); 2 years old (b); 3 years old (c); 4 years old (d); 5 years old (e); 6 years old (f); 8 years old (g); 9 years old (h)

3.1.3 Data sources as basis for suitability mapping

3.1.3.1 Soil properties

The soil map was provided by Vietnam Academy of Agricultural Sciences (VAAS), the map established in 2005 includes soil type and soil depth information. These maps are represented in Figure 3.3.

According to the FAO-UNESCO-based soil classification system in 1998, the major soil groups are Acrisols /Ferralsols, and 5 subgroups consisting of Fluvisols, Haplic acrisols, Luvisols, Ferralsols and Dystric gleysols. In specific, according to the information derived from the soil map, soil types and groups are shown in Table 3.2. The ferralic acrisols are the most frequent soil type of forest land in the study area. Soil depth is classified into 3 levels: Thick (> 100 cm), Medium (70 – 100 cm) and Thin (50-70 cm).

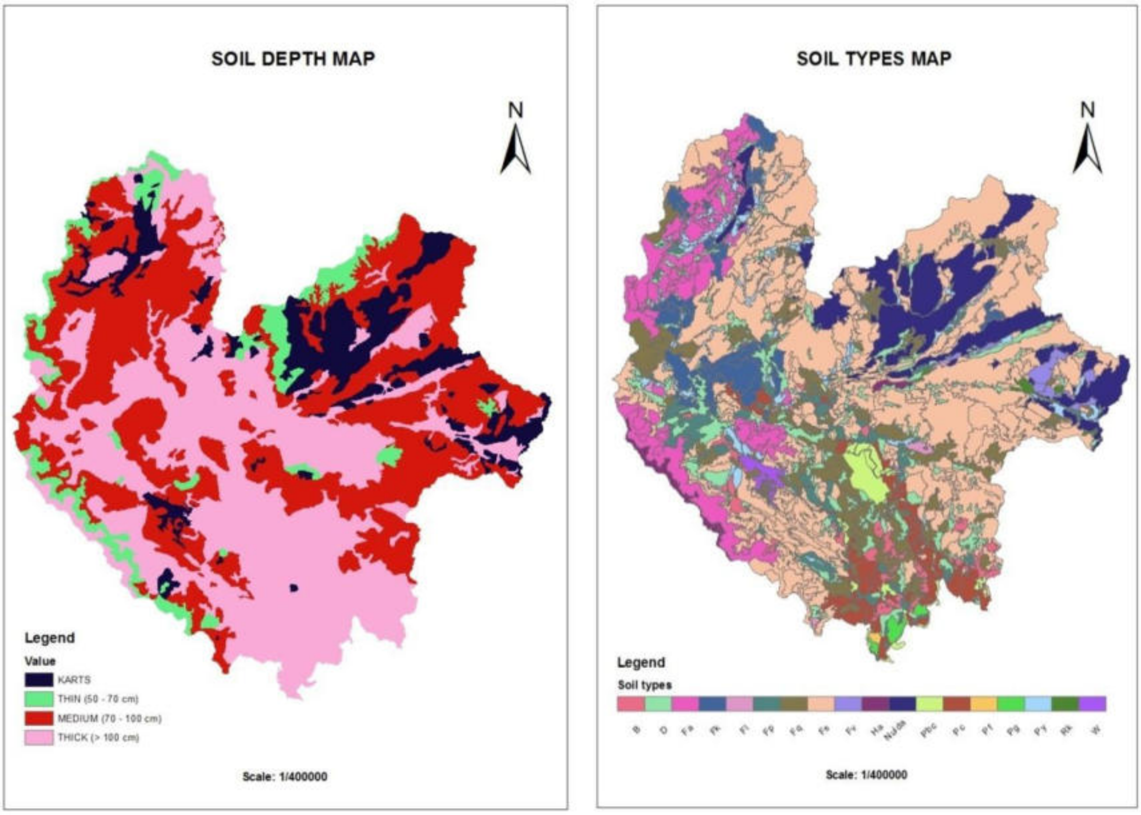


Figure 3.3 Maps of soil types and soil depth in study area

Table 3.2 The information of soil properties

No.	Soil type symbol	Description FAO-UNESCO	Group
1	Pbc	Distric fluvisols	Fluvisols
2	Pc	Eutric fluvisols	Fluvisols
3	Pg	Gleyic fluvisols	Fluvisols
4	Pf	Cambic Fluvisols	Fluvisols
5	Py	Umbric fluvisols	Fluvisols
6	B	Haplic Acrisols	Acrisols
7	Rk	Chrimic luvisols	Luvisols
8	Fk	Rhodic Ferrasols developed on bases and acid magma rock	Ferrasols
9	Fv	Rhodic Ferrasols developed on Limestone	Ferralsols
10	Fs	Yellowish red soil on metamorphic and sedimentary rock.	Ferralsols
11	Fa	Ferralic Arcrisols, is Yellowish red soil developed on acid magma, formed by the feralite process.	Ferralsols
12	Fq	Yellowish red soil developed on sandstone	Ferralsols
13	Fp	Ferralic Acrisols formed by the feralite process is ancient alluvial soil	Ferralsols/Acrisols
14	Fl	Plinthic Acrisols and yellowish red soil formed by cultivation	Ferralsols/Acrisols
15	Ha (Fh)	Humic ferralsols developed on acid magma rock	Ferralsols
16	D	Dystric gleysols	Gleysols
17	K2	Karst	Karst

3.1.3.2 Climate

Climatic constraints for production forests follow rainfall and temperature regimes, but the temperature does not differ significantly in the study area. Climatic information was collected from the Center for Marine Hydromet Research, Vietnam Institute of Meteorology, Hydrology and Climate Change. Climatic information within 15 years was collected from 3 weather stations where climatic data such as temperature, rainfall, evaporation, humidity and etc are recorded continuously. The locations of 3 weather stations are described in Table 3.3.

Table 3.3 The weather stations in study area

Name	Longitude	Latitude
Thai Nguyen city	105.5	21.36
Dinh Hoa	105.38	21.55
Tam Dao	105.39	21.28

Table 3.4 The locations of 11 stations in which rainfall regime is collected

Name	Longitude	Latitude
La Hiên	105.56	21.42
Chã	105.54	21.22
Đại Từ	105.38	21.38
Điềm mặc	105.32	21.50
Đình cả	106.06	21.45
Mỏ cẩm	105.41	21.41
Ký Phú	105.38	21.33
Phổ yên	105.52	21.27
Phú Bình	105.58	21.28
Phú lương	105.42	21.43
Vũ chấn(võ nhai)	106.04	21.50

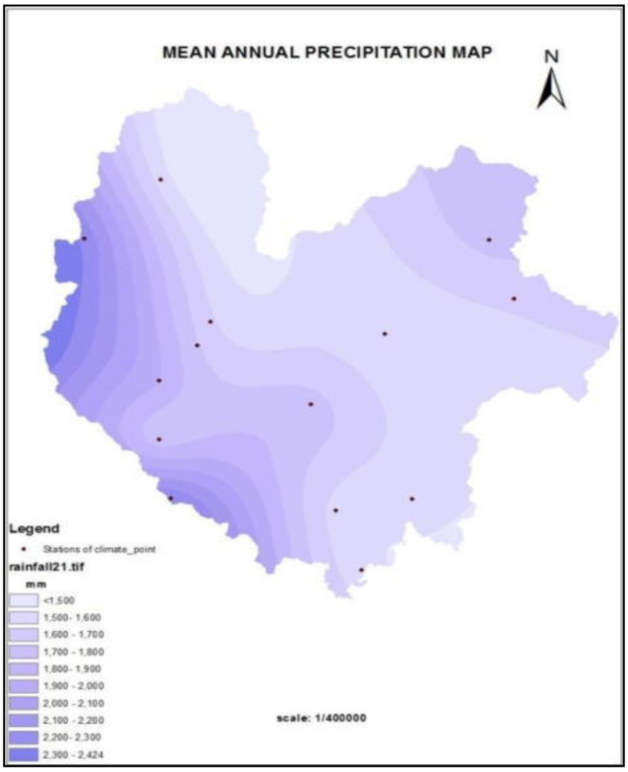


Figure 3.4 Mean annual precipitation map

The locations and information from 11 stations on the rainfall regime were captured in the period from 2000 to 2014 (15 years). The information on the locations is shown in Table 3.4.

The collected information indicates that mean annual rainfall ranges from 1528 mm to 2279 mm according to different stations. The mean annual rainfall map was built by using a spatial analysis tool (IDW technique) in ArcGIS 10.2.2 (Figure 3.4).

3.1.3.3 Topography

A digital elevation model (DEM) was derived from the shuttle radar topographic mission (SRTM) at a resolution of 30 m x 30m. This DEM was collected from http://srtm.csi.cgiar.org. Terrain parameter was slope that was extracted from DEM. The topographic factor including slope and altitude has an effect on the suitability of land for species cultivation and the distribution of moisture and temperature (Deng et al. 2014).

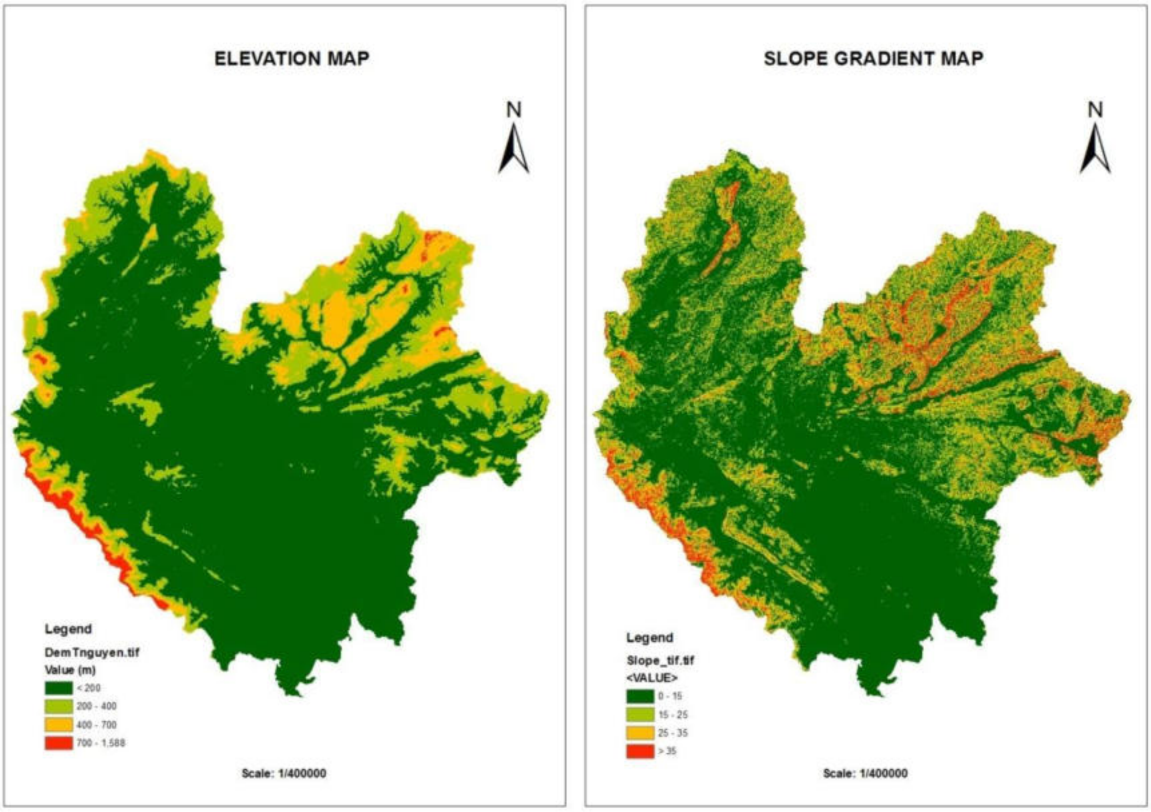


Figure 3.5 Elevation and slope gradient maps

3.2 Methods

3.2.1 Modelling suitability

Land suitability classification used in this study focused on commercial forest plantations. Forest land suitability assessments are an important step in the process of land use planning, as a proper land use planning increases forest yield. This study is conducted based on FAO (1984) and Mohan and Phuong (2003); Do and Nguyen (2000) provide guidelines for land evaluation.

The share of land that is planned to be used as forest land (FIPI, 2015) is categorized in suitability classes which describe the growth potential. The modeling approach for those suitability classes is described in this section. A diagram of the research method is shown in Figure 3.6.

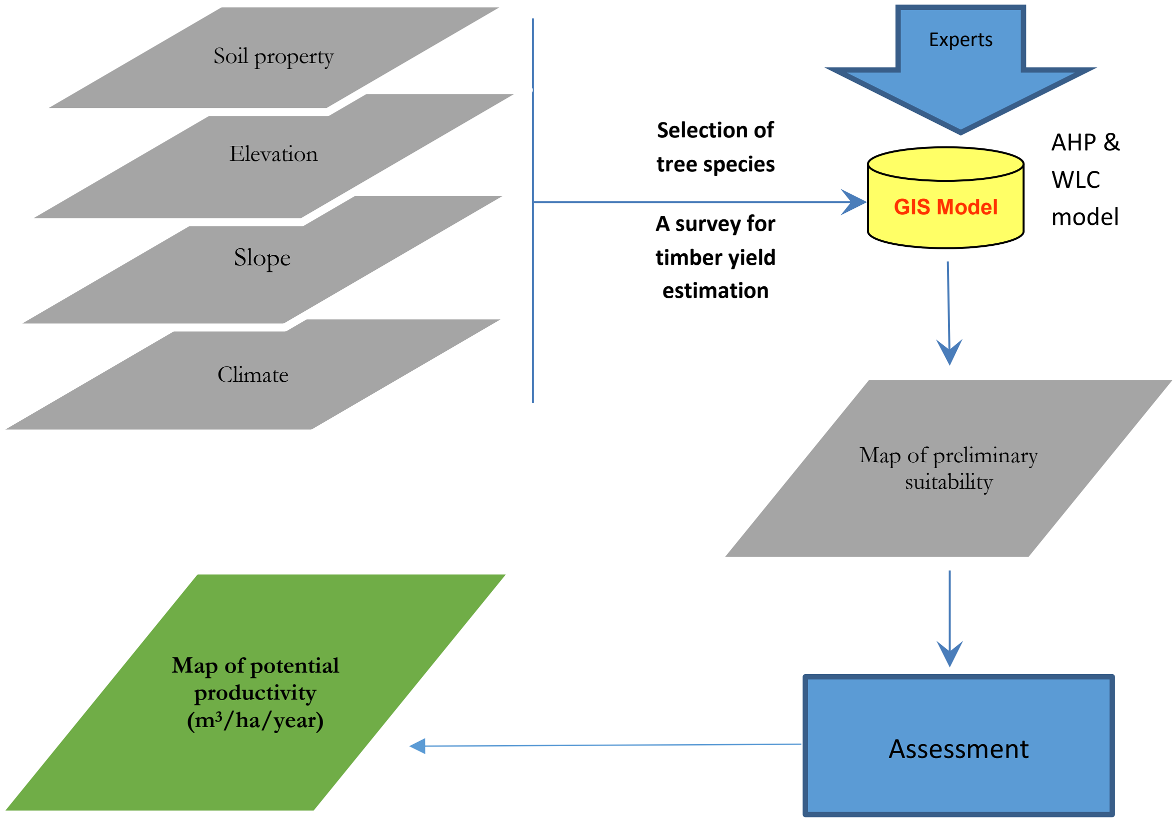


Figure 3.6 Research method for building a preliminary suitable site and potential productivity map for forest plantations (AHP: Analytical Hierarchy Process, WLC: weighted linear combination)

3.2.1.1 Determination of ecological factors and classes for each ecological factor

Identification of ecological factors was based on the ecological requirements of *A.mangium* with regard to environmental conditions. The selection of criteria for assessment should be readily available to forest managers (Battaglia and Sand 1998) and have a close relationship with forest productivity. Therefore, three main factors and five criteria of land characteristics have been chosen for the assessment of land suitability for establishing plantation::

- Soil properties (soil type, soil depth)
- Topography (elevation, slope)
- Climate regime (mean annual rainfall)

Suitability classes are determined based on ecological factors' assessment such as soil properties, topographic and climatic criteria that have effects on tree growth. The understanding of tree species behavior was the basis of classifying each class of each ecological parameter along with asking forestry experts who have been studying this tree species over ten years. The result of comparison between the ecological requirements of the tree species and site conditions is the basis of taking into account suitable locations for growing *A. mangium* plantations in study area to obtain a higher yield. Each suitability class of each ecological parameter was classified by a determined value for *A. mangium* species.

3.2.1.2 Determination score assignment to suitability classes and weight for ecological factor

The ranking score illustrates the suitability of each class of each criterion for each suitability class. The score of suitability class ranges from 1 to 4.

- Unsuitable class scored equally 1
- Marginally suitable class scored equally 2
- Moderately suitable class scored equally 3
- Highly suitable class scored equally 4.

Based on a comparison between tree species requirements and site conditions, classes of suitability were determined, but each criterion has a different effect on tree growth and forest productivity. In order to decide which criterion is more important when a decision is made, according to Saaty (1980b), the Analytical Hierarchy Process (AHP) method supports the opportunity to regard the decision and to determine the weight of each factor under both qualitative and quantitative assessments. The relative importance value allocated to each criterion, known as weight, is used for criteria prioritization (Geneletti 2005; Uribe et al. 2014). The consideration of weight for variables was performed after several consultations with forestry experts. Application of AHP based on AIP approach is to calculate the weight of each criterion by regarding soil properties, topography and climate regime.

There were three steps to obtaining the weight of factors and criteria. Firstly, the criteria were put into a hierarchical structure (Figure 3.7). The hierarchical structure was based on input provided by the first expert who had a good knowledge of the forest site evaluation in Vietnam. Furtheron, this hierarchical structure was received agreements by the remaining experts.

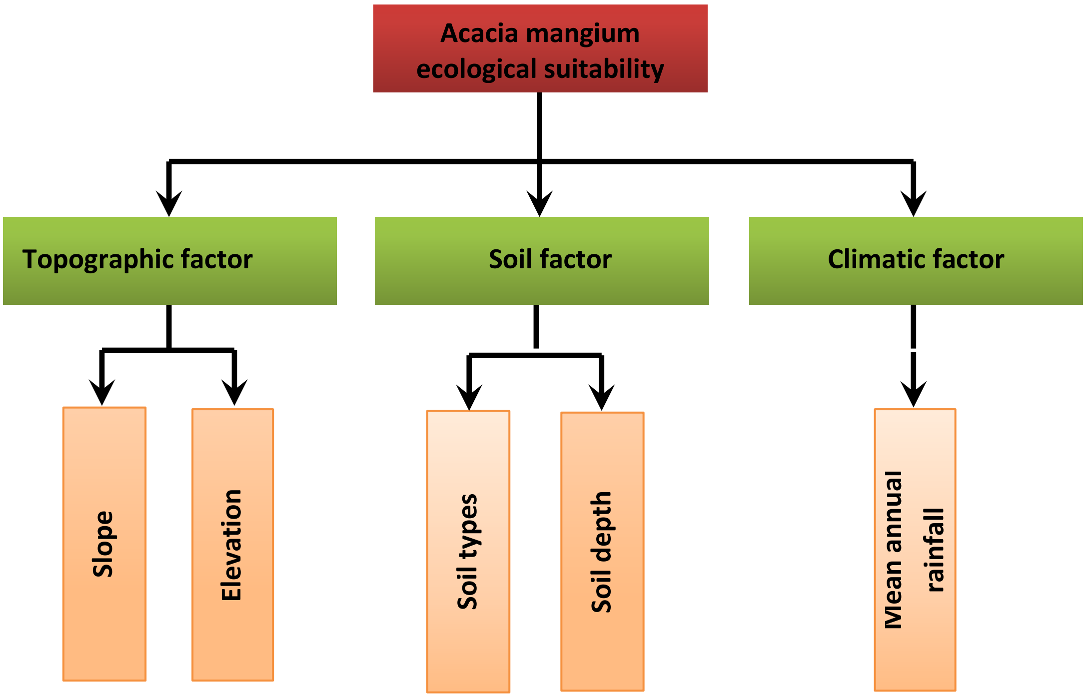


Figure 3.7 Hierarchical structure in the analytical hierarchy process

Secondly, all pairwise comparison matrixes were evaluated by experts, each of the criteria was allocated a weight ranging from 1 to 9. The experts were selected in this study not only based on their knowledge of the study area, but also of *A. mangium*. Four experts in the field of ecology, forest inventory and forest soil were consulted. Information on the experts' judgment was obtained by interviews. There are several methods of synthesizing experts' judgments (Forman and Peniwati 1998; Nekhay et al. 2009; Altuzarra et al. 2007; Escobar et al. 2004). We used the aggregation individual priorities (AIP) with geometric mean approach.

The geometric mean was defined: f $(x_1 . x_2 \ldots\ldots x_n)$ = $\sqrt[n]{x_1 . x_2 \ldots\ldots x_n}$ (Equation 3.1)

Where:

$(x_1 . x_2 \ldots\ldots x_n)$: are judgments of n individuals, where not all x_n are equal

Each input raster layer was weighted according to its proportion influence under the condition that the sum of the percentage influence weights for all the raster map (factors) equals 1 (100%).

To ensure consistent judgments of four decision makers, the consistency ratio (CR) was applied (Saaty 1980b; Saaty 2008) and was defined as:

$$CR = \frac{CI}{RI} \quad \text{(Equation 3.2)}$$

Consistency index (CI) was defined as: $CI = (\lambda_{max} - n)/(n-1)$ (Equation 3.3)

Where:

λ_{max} : is the maximum Eigen value of the normalized comparison matrix

RI: Random Index for number of criteria compared in a matrix, appropriate consistency index, corresponds to index of consistency for random judgments (Saaty 1980a).

n: number of criteria (factors)

If CR is less than or equal to 0.1 (10%) it is assumed that the assessment of the decision-maker is relatively consistent, on the contrary we have to re-examine for each factor.

Table 3.5 Random Index (Saaty 1980a)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.90	1.12	1.24	1.32	1.41	1.45	1.49

In the final step, all applied criteria were standardized using the AHP method. Weights were obtained from standardization of all factors and criteria were defined as:

$$X_n = (W_{n1} + W_{n2} + \ldots + W_{nn})/n$$

W_{nn}: weight of criterion n

3.2.1.3 Land suitability integration by weighted linear combination

After weighting the factors, as regards the relative importance of each criterion, all the criterion maps were overlaid by weighted linear combination method (WLC) in GIS environment. The advantage of a GIS-based approach is not only the reduction of time and cost of site selection, but also the provision of a digital database for long-term monitoring of the site (Moeinaddini et al. 2010; Nekhay et al. 2009). WLC technique enables each criteria map to be multiplied by their weight and summed, on a pixel – by pixel basis. WLC is the most common procedure for multi-criteria evaluation by a combination of respective factor weights (Nyeko 2012; Anane et al. 2012; Ying et al. 2007; Bunruamkaew and Murayam 2011; Liaghat et al. 2013; Abushnaf et al. 2013; Radiarta et al. 2008; Eastma et al. 1995). WLC in integration with AHP is the most direct and frequently utilized for assessment (Malczewski 2004). Based on the principle of WLC raster calculator tool in ArcGIS environment was utilized to combine raster inputs with different weights, the WLC analysis was applied using the following equation:

Figure 3.8 Discussion with a forestry expert (Do Dinh Sam) for AHP

$$\mathbf{S} = \Sigma \boldsymbol{W_i} * \boldsymbol{X_i} \quad \text{(Equation 3.4)}$$

Where,

S: suitability

W_i: weight of factor i

X_i: score of factor i

The suitability values were used to allocate four classes: highly suitable (Score ≥ 3.5), moderately suitable (Score ≥ 2.5 - < 3.5), marginally suitable (Score ≥ 1.5 - < 2.5) and unsuitable (Score < 1.5).

3.2.2 Modelling productivity

Productivity is an ultimate indicator of tree's reaction to the environmental condition. The most popular direct measure of productivity is 'volume', which is considered as sustainable production capacity. The rate of growth up to a point in time such as MAI (mean annual increment) was calculated to build a map of potential productivity. Based on the results the harvest time to obtain mean annual increment information for each suitability class was calculated. Finally, a map of potential productivity was built.

The mapping of potential productivity was established from a preliminary land suitability map. Firstly, productivity (m^3/ha) in each suitability class was assessed based on a forest inventory in the study area. Then, forest growth was modeled to show the potential productivity by age and suitability classes. Finally, potential productivity was allocated to each parcel of land according to the suitability classes on the map.

3.2.2.1 Technical equipment for execution of inventory on growth

- Garmin 78csx GPS
- Compass DQL-1
- 50 m measuring tape Laser RD 1000: measuring tree height
- Digital camera
- Caliper: measuring tree diameter
- Tree sampling inventory tables: canopy cover percentage, slope, aspect, tree height, diameter at breast height (DBH), species, and location.
- Forest land use maps were collected from the Forest Inventory and Planning Institute. These maps were built in 6/2015 with information being checked in the field in 2014. Maps of *Acacia mangium* plantation locations were supplied from Thai Nguyen forestry department in the period from 2009 to 2015.

3.2.2.2 Selection of stands for forest measurement

A forest survey was conducted to provide data for constructing growth functions of studied species and establishing a potential productivity map. Using forest inventories, information on the quality and quantity of forest resources such as forest growth, area, or species identification can be recorded (Köhl et al. 2006).

Based on a map of *A. mangium*, the distribution according to age classes (class 1: planted in 2015, 2014 and 2013; class 2: planted in 2012 and 2011; class 3: planted in 2010 and 2009) and map of suitability classes (S1: Highly Suitable, S2: Moderately suitable, and S3: Marginally suitable) was assigned. Both maps were overlapped by Union tool in ArcGIS 10.2.2 to prepare the forest inventory map.

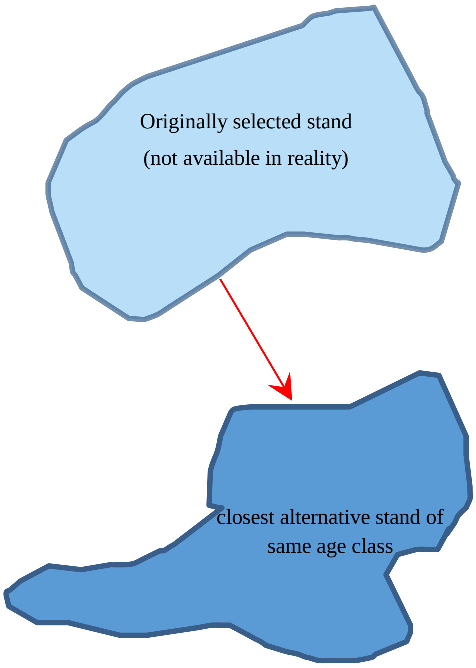


Figure 3.9 Sketch of selecting alternative stand from selected stand

The number of sample plots was determined in line with the percentage of stands that each suitability class occupied. 40%, 30%, and 30% of total stands for each suitability classes S1, S2, and S3 respectively were selected, which results in 123 samples of individual stands. Then, based on the list of stands for each suitability class, 123 samples were chosen through *"systematic sampling"*, and 116 samples were selected in forests planted from 2014 to 2009. 7 samples in forest planted 2015 were not used in the calculation of growth function because the diameter at breast height was too small to measure.

In addition, 36 older individual stands (planted between 2008 and 2006) were surveyed to increase estimation the accuracy for volume growth. Local households were asked for the positions of those stands.

When a selected individual stand was no longer available for measurement, the closest alternative stands to the originally selected stand with same age and suitability class was chosen by identification of distance and direction from original to closest point of the alternative stand (Figure 3.9).

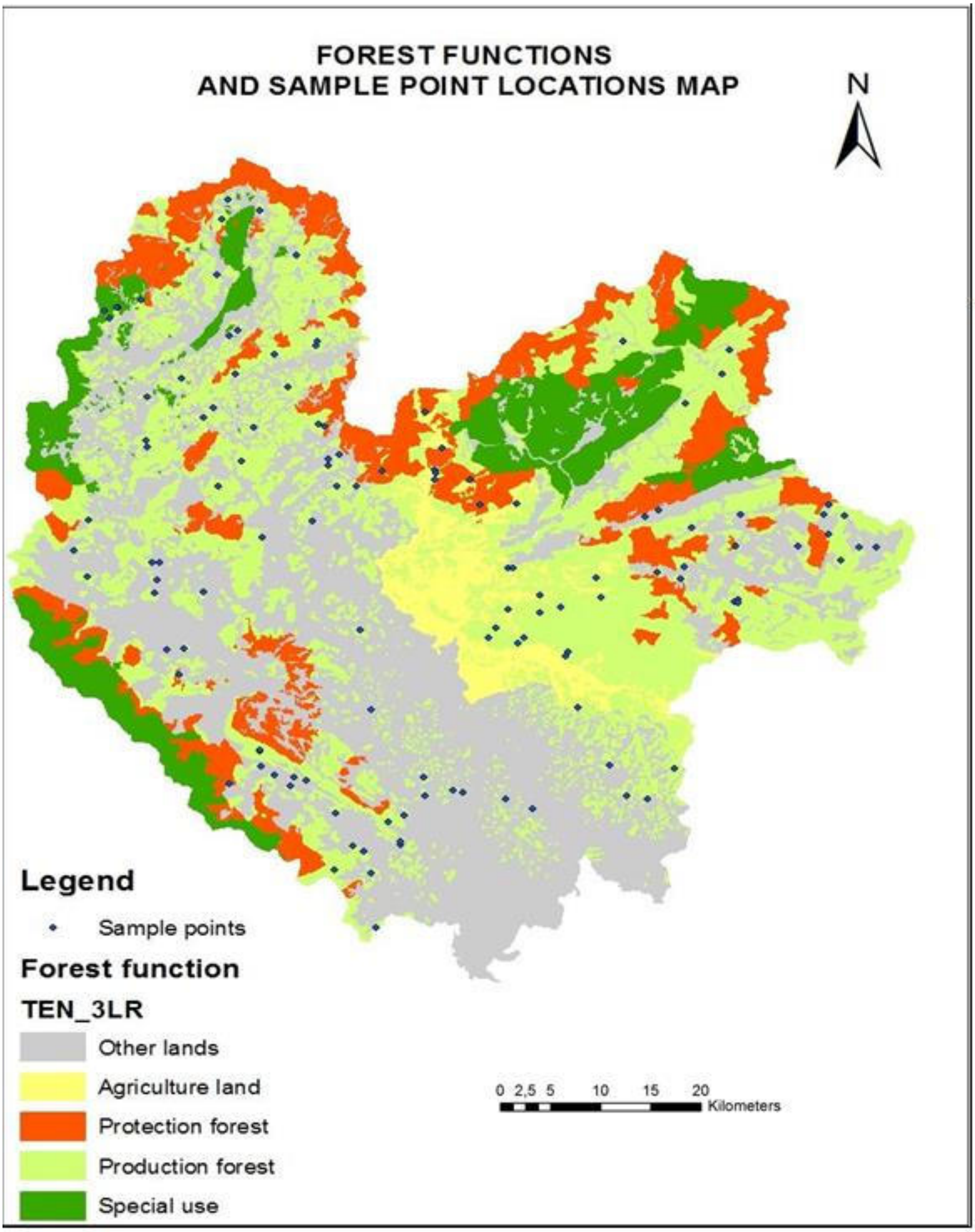


Figure 3.10 Map showing forest functions and selected sample points distribution

3.2.2.3 Design and location of sample plot

The center of plots that were representative for stands was located randomly by using the ArcGIS tool "Create random points" (ArcGIS 10.2.2). In the alternative stands, the center plot was located based on X, Y coordinates of the north, south, east and west. The x-coordinate is measured along the east–west axis; the y-coordinate is measured along the north–south axis. 152 single plots were captured cover the entire *Acacia mangium* distribution in the study area. All plots were established in production forests (Figure 3.10).

A concentric circular plot design was applied, with three different plot radii:

- r1 = 5.64 m for the tree with DBH > 0 cm
- r2 = 7.98 m for the tree with DBH > = 5cm
- r3 = 12.62 m for the tree with DBH > = 12cm

Concentric circular sample plots were established using three circular nested plots in various radii (Figure 3.11).

All stems with a diameter at breast height greater than 0 cm were recorded in the sub-plot with radius 5.64 m (r1). All stems with a diameter at breast height being equal to and greater than 5 cm were recorded in the sub-plot with radius 7.98 m (r2). All stems with a diameter at breast height being equal to and greater than 12 cm were recorded in the sub-plot with radius 12.62 m (r3). GPS 78S was utilized for positioning the center of plots. The slope gradient of a sample plot was measured using a Vertex transponder instrument. By going upwards from the plot center to a distance of 15m and downwards with a distance of 15m, the angles in degree were determined and the slope gradient of the sample plot was derived from the arithmetic mean of the two angles above. Based on this value, the slope distance for the circle radius was adjusted. The altitude of a sample plot in meters was collected using GPS.

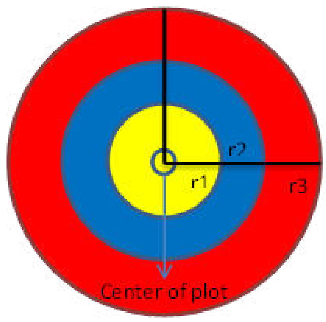


Figure 3.11 Creating scheme for concentric plot

All trees in a plot were measured with DBH at 1.3 m above the ground by using a diameter calliper. It is generally more complex to measure height than diameter. In addition, the measurement of height can be time consuming (Köhl et al. 2006; West 2015). Hence, the height of trees should be determined using predictions obtained by using a model that shows the relationship between tree height and diameter at breast height (DBH). In each plot, only the height of ten stems was recorded by using a RD criterion 1000 laser instrument (Figure 3.12). The variances in terrain conditions can affect the estimation of volume. Therefore, it is very important to identify the position of DBH measurement. The measurement of diameter at breast height was carried out as follows (Figure 3.13).

Figure 3.12 RD Criterion 1000 instrument (Source: http://www.lasertech.com)

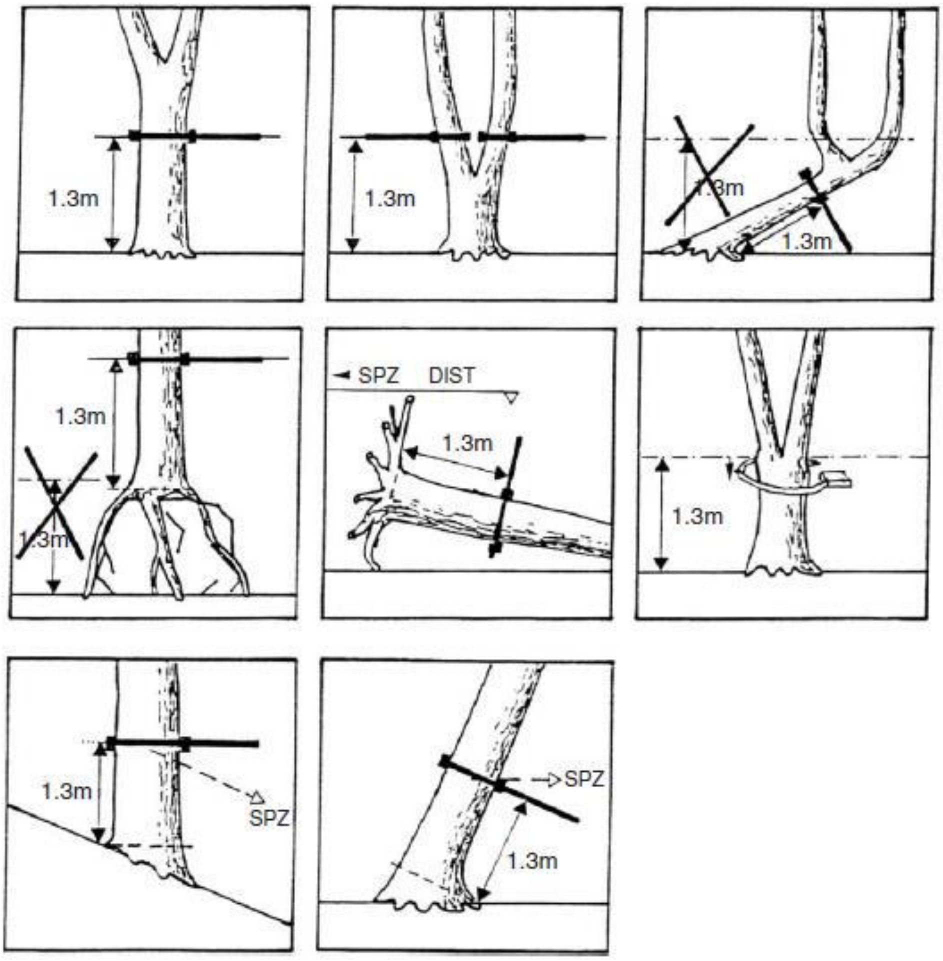


Figure 3.13 Regulation of measurement of DBH (Source: Köhl et al. 2006)

3.2.2.4 Calculation of stand variables

The relationship between tree height (h) and diameter at breast height (DBH) was built by linear models.

$$h = a \times DBH + b \quad \text{(equation 3.5)}$$

The models were established for 152 plots. These models were used to estimate the mean stand height (hg) by quadratic mean diameter (dg). The study utilized equation 3.7 to calculate the quadratic mean diameter and equation 3.8 to estimate hg.

$$d_g = \sqrt{[(40000/\pi)g/s]} \quad \text{(equation 3.6)}$$

where:

h: stand mean height (m)

d_g : quadratic mean diameter (cm)

g: basal area (m2/ha)

s: stocking density (stem/ha)

$$hg = a \times d_g + b \quad \text{(equation 3.7)}$$

Figure 3.14 Using GPS and diameter caliper in a forest survey

The volume of live stems per hectare was estimated using equation 3.9 based on the number stems per hectare, the basal area of the tree with quadratic mean diameter, stand mean height and tree form factor (f):

$$V = N \times (\frac{\pi}{4}) \times d_q^2 \times h \times f \quad \text{(equation 3.8)}$$

Where:

N: number of live trees per hectare

f: tree form factor (commonly used in Vietnam: 0.49 for *Acacia mangium*)

3.2.2.5 Adjustment of sample area at forest edges

Based on the central angle (C) and radius (BC and CA), the formula to find the area of the segment (AB) is described below (Oberg and McCauley 2012)

$$Area = \frac{R^2}{2} \times (\frac{\pi}{180}C - sinC) \quad \text{(equation 3.9)}$$

Where:

C: is the central angle in degrees

R: is the radius of the circle of which the segment is a part

Π: is Pi, approximately 3.142

Sin: is the trigonometric sine function

C is defined based on Edge 1 (CB) and Edge 2 (CA), both edges were measured by using compass. 56

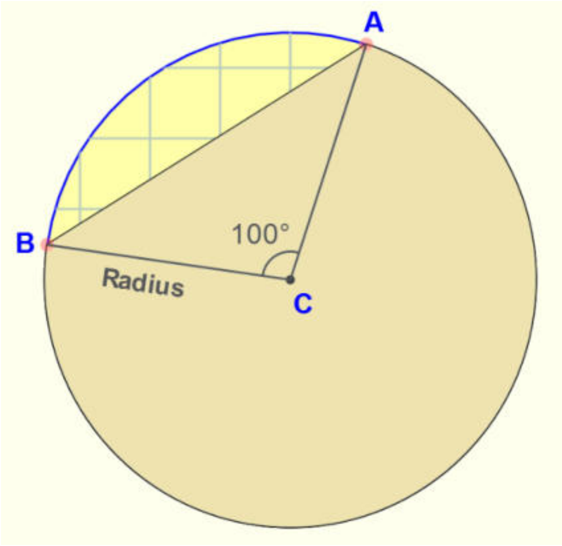


Figure 3.15 Calculate the segment area given the radius and segment's central angle

(Source:http://www.mathopenref.com/segmentarea.html)

If Edge 1 (CB) > Edge 2 (CA), C = 360 - Edge 1 (CB) + Edge 2 (CA)

If Edge 2 (CA) > Edge 1 (CB), C = Edge 2 (CA) - Edge 1 (CB)

For example, Edge 1 (CB) is 285° and Edge 2 (CA) 25°, then C = 360 – 285 + 25 = 100°

And if R = 7.98 m

$$Area = \frac{7.98^2}{2} \times (\frac{\pi}{180}100 - sin100) = 24.2152\ (m^2)$$

3.2.2.6 Modelling volume growth for suitability classes

The growth model is based on observations of growing stock volumes to predict the potential production of forest plantation. By using growth models, we can explore stand conditions and predict the harvesting time for maximal timber amount (Vanclay 1995). To model the growth curve, many studies have focused on empirical functions (Huu-Dung and Yeo-Chang 2012; Tewari et al. 2002; Tewari and Kumar 2005; Berrill 2004; Steward et al. 2014; Hong and Hung

2006). Generally, the overall shape of the curve is represented as a sigmoid shape (Burkhart and Tomé 2012).

The volume growth functions were examined by using Koft, Gompertz and Chapman – Richards (Pretzsch 2010) in SPSS software 22.0.

Koft (1939): $Vt = a_0 \times EXP(-a_1 \times A^{-a2})$

Gompertz (1825): $Vt = a_0 \times EXP(-a_1 \times EXP(-a_2 \times A)$

Chapman – Richards (1961- 1959): $Vt = a_0 \times (1-EXP(-a_1 \times A))^{a2}$

Parameters: a_0, a_1, and a_2 (asymptote, slope, and position of inflection point respectively)

V: is standing volume of live trees per hectare at age A, A ∈ (1, n)

e: is the base of the natural logarithms (e = 2.718)

The coefficient of determination (r^2) and Root mean square error (RMSE) were used to measure goodness-of-fit.

$$RMSE = \sqrt{\frac{\sum_1^n (\hat{Y}i - Yi)^2}{n}} \quad \text{(Equation 3.10)}$$

Where:

$\hat{Y}i$ is the estimated parameter on the ith observation

Yi is the field-measured parameter

$(\hat{Y}i - Yi)^2$ is square of the errors

After the growth curve was determined, the mean annual increment was allocated to respective suitability classes. A map of productivity was built based on a map of suitability.

3.2.3 Determination of optimal rotation as maximum sustained yield

When considering the optimal rotation age for production forests, two aspects are essential: the biological (maximum sustained yield) and economic rotation. In this study, from the management decision-making viewpoint almost all of the of *A.mangium* wood is used as raw material to produce woodchips for domestic and export use, for producing veneer and pallets, and or for furniture. Optimal forest rotation age is determined based only on timber production in a short rotation age, which estimates maximum sustained yield based on biology theory.

From a technical point of view, a rotation which maximizes average annual physical yield determines the optimal rotation age of a forest plantation stand, and occurs when the curves of the current annual increment (CAI) and the mean annual increment (MAI) meet (Strauss et al. 1990; Carlos and Betters 1995; Köhl et al. 2006).

The current growth curve model was identified as v(t), the CAI function is the first derivative of the growth curve and defined as $V'(t)$: Under the no thinning condition for a stand, MAI is defined as:

$$MAI = \frac{V(t)}{t} \quad \text{(Equation 3.11)}$$

The optimal rotation age is achieved when average productivity coincides with the marginal productivity, and when the mean annual productivity curve (MAI) and current annual productivity curve cross each other (CAI = $V'(t)$) (Carlos and Betters 1995; Borges et al. 2014). The optimal rotation age is given by the following equation:

$$V'(t) = \frac{V(t)}{t} \quad \text{(Equation 3.12)}$$

$V'(t)$: the first derivative of the growth curve

SPSS 22.0 programs were mainly used for computing forest stand data and diagrams.

3.2.4 Assessment of socio-economic aspects of *Acacia mangium* plantations

Questionnaires were formulated for local households growing *A.mangium* plantations on land planned for production forests, and for mills that used *A.mangium* wood as production material.

The questionnaire for the local households aims to provide information on the way the forest owners cultivate their plantations and the costs related to production and harvesting along with the actual timber price. Household information on the management of plantations is essential for the parameterization of a model on the development of forest plantations in the study area. This model helps to describe how an optimization of forest management takes into consideration its value added. The households are the actors who establish forest plantations and manage them. The assessment of their economic benefit is directly related to the households' motivation, and is a major driver of the entire reforestation process. Based on the list of households, 45 households were selected randomly using Microsoft Excel 2010. And then, 45 selected households were interviewed by a face to face approach.

The second questionnaire was developed for mills which produce woodchips as raw material for industrialized utilization purposes, veneer, and pallets. The questionnaires obtain information on timber demand, timber price at mill, minimal diameter timber used for producing, cost for machine and labor, predicted wood demand for next years, and the price of products. Based on a list of all mills, 15 mills producing woodchip, 16 mills producing veneer, and 19 mills producing pallets were chosen randomly. And then, 50 selected mills were interviewed by face to face approach.

Both surveys were conducted in November, December 2015 and January 2016. Surveys for questionnaires were conducted using practices from literature (Fink 2017). The questions in the questionnaire were asked in the exact order without skipping any questions. The three interviewers in the survey team were trained and guided during a pilot period in order to minimize errors and uncertainties in the interview results. The interview was face to face, and only adults of selected households and leader of mills were asked.

Production costs (US$/ha) for a *A.mangium* plantation includes site preparation, seedling, planting, fertilizing in the first year. Weeding is applied in the second year or the third year (silviculture cost) and management cost. Timber price was calculated using information obtained from local households.

Harvest cost consists of felling, cutting timber and loading cost. The unit of measurement was USD/ha. In this study area, the harvesting costs depends on the amount of timber per hectare, which was not equal for all forest locations and so it influenced the location decision in competition of locations – allocation between mills.

Transportation cost is the cost of transporting timber from the forest (stands) to the mill and is often a significant component in the cost to deliver the wood (US$/$m^3$/km). The data was processed and analyzed using the descriptive statistics method in Excel 2010.

Figure 3.16 Transport of timber from forest (a, b, c), interviewing local household (d), woodchip mill (e), veneer mill (f), Pallet mill (g, h)

3.2.5 Scenario simulation with geo-explicit optimization methods

Optimization of the land use in terms of an *A. mangium* plantation is an important task which can be addressed by combination of objective functions described in decision science (Nocedal and Wright 2006). The objective of the scenario analysis is to show how optimization models work to maximize household profit from growing plantations covering different input variables. The outcomes of the optimization model are performed using two different approaches. The process of application of optimization model shows how timber amounts are assigned to mills. Adjustment of transportation distance for calculations is represented in this section.

3.2.5.1 Geo-explicit optimization model

The purpose of the optimization model is to maximize a households' profit (profit = income). A framework of the optimization model is represented in Figure 3.17. According to the framework, potential land area was identified based on land use planning in study area. Only land planned for production forest is used for the optimization model. Land planned for protection forests and special use forests is excluded from the optimization. The land planned for production forest includes planted forest area and unplanted forest area (Non-planted). Planted forest areas (forested land areas) are lands covered by planted *A.mangium.* Un-planted forest areas mean lands which are not planted by *A. mangium*, those could be natural forests which generate negligible growth and hold low levels of biodiversity, or bare land (Figure 3.18).

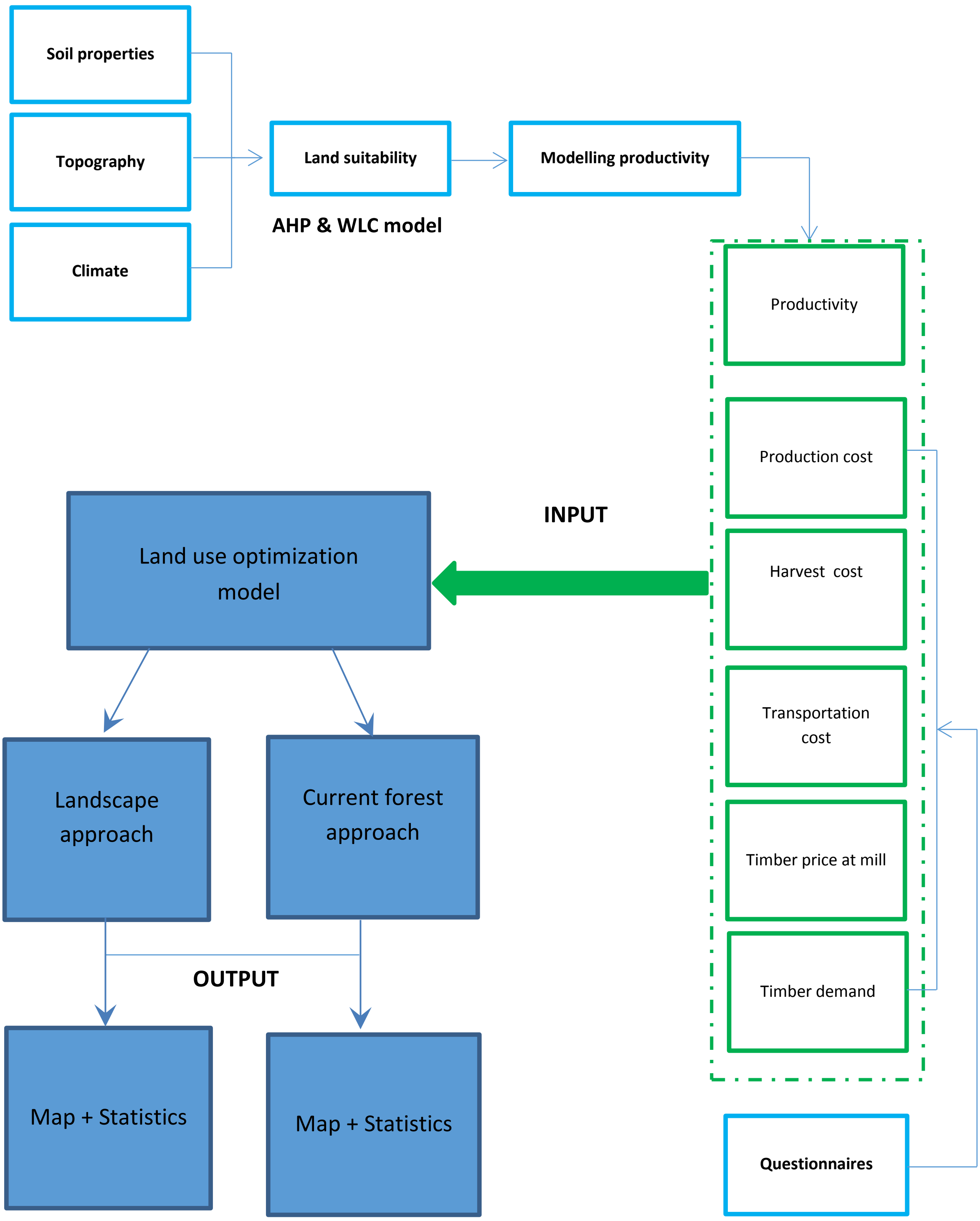


Figure 3.17 Framework of an optimization model

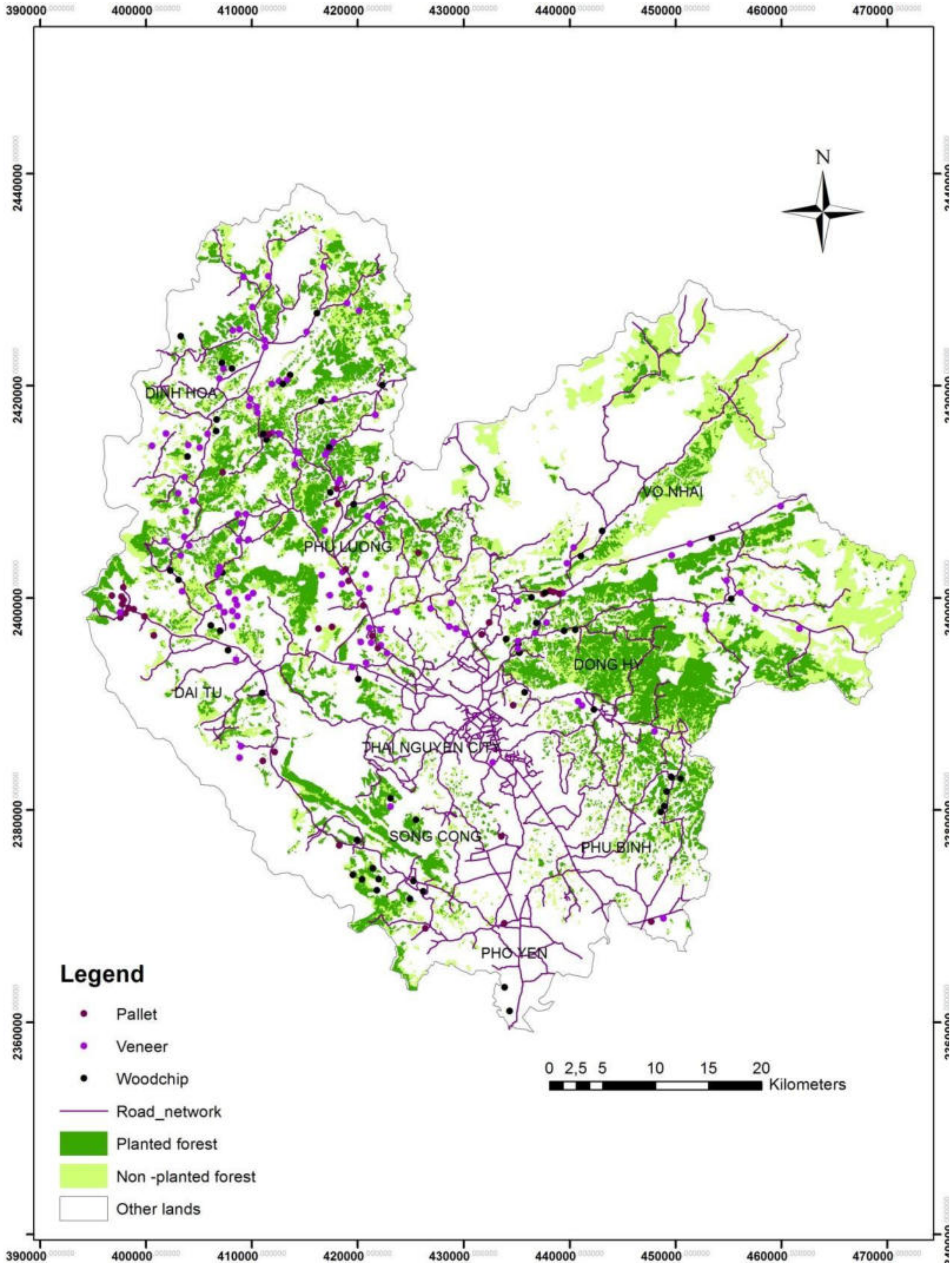


Figure 3.18 Map showing only the locations of land planned for production forest including planted forest and Un-planted forest areas (non-planted forest)

To generate possible additional income for the households, the objective of the optimization model must indicate suitable locations for planting forests in order to maximize household profit.

The objective function is defined as:

$$MaxP = max(\sum_{i=1}^{I} \sum_{j=1}^{J} P_j . Q_{ij} - \sum_{i=1}^{I} (C_{Ei} + C_{Si} + C_{Mi}). Q_i - \sum_{i=1}^{i} \sum_{j=1}^{J} U_{TR}. Q_{ij}. d_{ij} - \sum_{i=1}^{J} U_H . Q_i)$$

Sets:

I: the set of all parcels

J: the set of all mills

Parameters:

Q_{ij} : is the quantity of timber volume per parcel i and delivered to mill at location j in a year

Q_i : is the quantity of timber volume per parcel i

P_j: is the unit price for the sale of timber at mill j in $/m^3

C_{Ei}: is the unit cost for forest plantation establishment in $/ m^3 in parcel i

C_{Si}: is the unit cost for silviculture practice applied in in $/ m^3 in parcel i

C_{Mi}: is he unit cost for forest plantation management in $/ m^3 in parcel i

U_{TR}: is the unit cost for transport in $ /m^3 /km

d_{ij}: is the distance in km from parcel i to mill at location j

U_H: is the unit cost for harvesting in $/m^3

Constraints:

Subject to

$$\sum_i Q_i = \sum_j M_j \,;\ \forall\, i \in I, \forall\, j \in J$$

M_j: timber demand for processing per year in j^{th} mill.

This constraint shows the annual amount of timber harvested and shipped from parcels to mills must equal that of all mill's annual usage, and meet the demand of the processing facilities. If delivered timber amount of parcels (polygons) were sufficient to satisfy the demand of the nearest mill with its highest profit gained, timber from other parcels will be taken to the second closest mill to fulfill its wood demand. The process is continued until the timber demand of the final mill is sastified.

$$\sum_i Q_i \leq Q;\ \forall\, i \in I$$

This constraints the total timber amount allocated in parcels to the total timber amount available Q (land allocated to growing *A.mangium* plantation cannot exceed total forest land available).

The inputs to the objective function include potential productivity, production cost, harvest cost, transportation cost, timber demand, and timber price at mills. Production cost included establishment cost, silviculture cost, and management cost, which were derived from the household questionnaires. Transportation cost, harvest cost, timber price and timber demand were identified from the mill questionnaires.

To achieve a maximum households profit two approaches were considered when planting *A. mangium* in study area.

The landscape approach (_LA): this approach does not distinguish between currently planted forest areas and unplanted forest areas. Planted forest areas and un-stocked forest areas can be allocated to satisfy the timber demand of individual mills, irrespective of the actual land-use.

The current forest approach (_FO): this approach puts planted forest area as priority area to fulfill timber demand. If timber from the planted forest area is not sufficient to satisfy the demand, timber from unplanted forest area will be allocated until the demand of timber is fulfilled.

The application of optimization process to assign timber amounts to mills undergoes several steps:

- Step 1: Calculating potential timber supply of each parcel of land and timber demand of each mill.
- Step2: Calculating the most profitable supply relation between each parcel of land to individual mill.
- Step3: Allocating timber supply relation between each parcel of land to each mill based on highest profit, followed by parcels with lower profits until the demands for all mills are fulfilled.

If the timber supply from the land parcels was allocated to individual mills, three scenarios were realized.

- If the timber supply (volume) of parcel i is not sufficient to meet the demands of mill j where the highest profit for parcel i is obtained, the supply gap will be closed by timber from other parcels of land with respective profitability.
- If the timber supply (volume) of parcel i is equal to timber demand of the mill j where the highest profit of parcel i is obtained, the total timber of parcel i will only be assigned to this mill.
- If timber supply (volume) of parcel i is higher than the timber demand of mill j where the highest profit of parcel i is obtained, the surplus timber is allocated to the next profitable mill.

Outputs from the model were mapped and statistics show the allocation of forest to potential land areas, the profit obtained and the costs for growing *A. mangium* plantations in the study area.

3.2.5.2 Calculation of transportation cost in ArcGIS environment

The transportation cost was determined based on transport distance. Transport distance was designated by off-road distance and on-road distance.

Off-road distance corresponds to the transportation from the felling areas (plantation locations or parcels) to the nearest existing road (roadside). The off-road distance was considered to be a straight line distance by using Euclidean distance (km) in the Network analysis Arc toolbox of the ArcGIS environment. Therefore, a new road was built when no road was available for hauling timber from the forest plantation. A new road was constructed only once, and then it was considered as an existing road. We excluded the cost for building new roads and road maintenance costs. The skidding distance is underestimated.

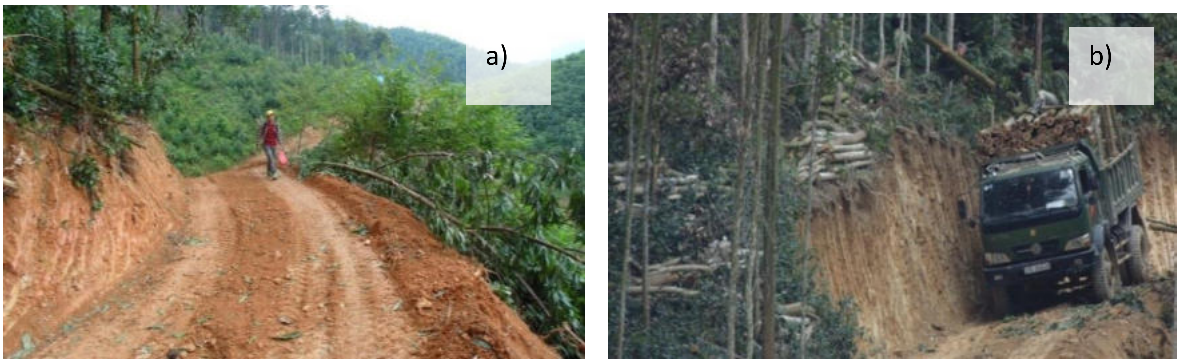


Figure 3.19 New roads were built to be accessible to timber delivered (a, b)

On - road transportation distance is the transport distance from the nearest point along the existing road to the mills, which was determined by using the closest facility tool in Network analysis Arc toolbox of the ArcGIS environment.

In order to reduce computation time due to the high number of medium and small size facilities, we used a model approach to approximate the transportation distance by correcting the direct distance between parcels of land and mills by a regression function that was developed based on a sample of 100 parcel - mill road distances. The result of the regression model is shown below.

$$transportation\ distance = 1.65 * [(x_i - x_j)^2 + (y_i - y_j)^2]^{1/2} \quad (R^2 = 0.81)$$

Distance included off-road distance and on-road distance.

x_i, y_i: are the geographic coordinates of the centroid of each parcel

x_j, y_j: are the geographic coordinates of the centroid of each mill

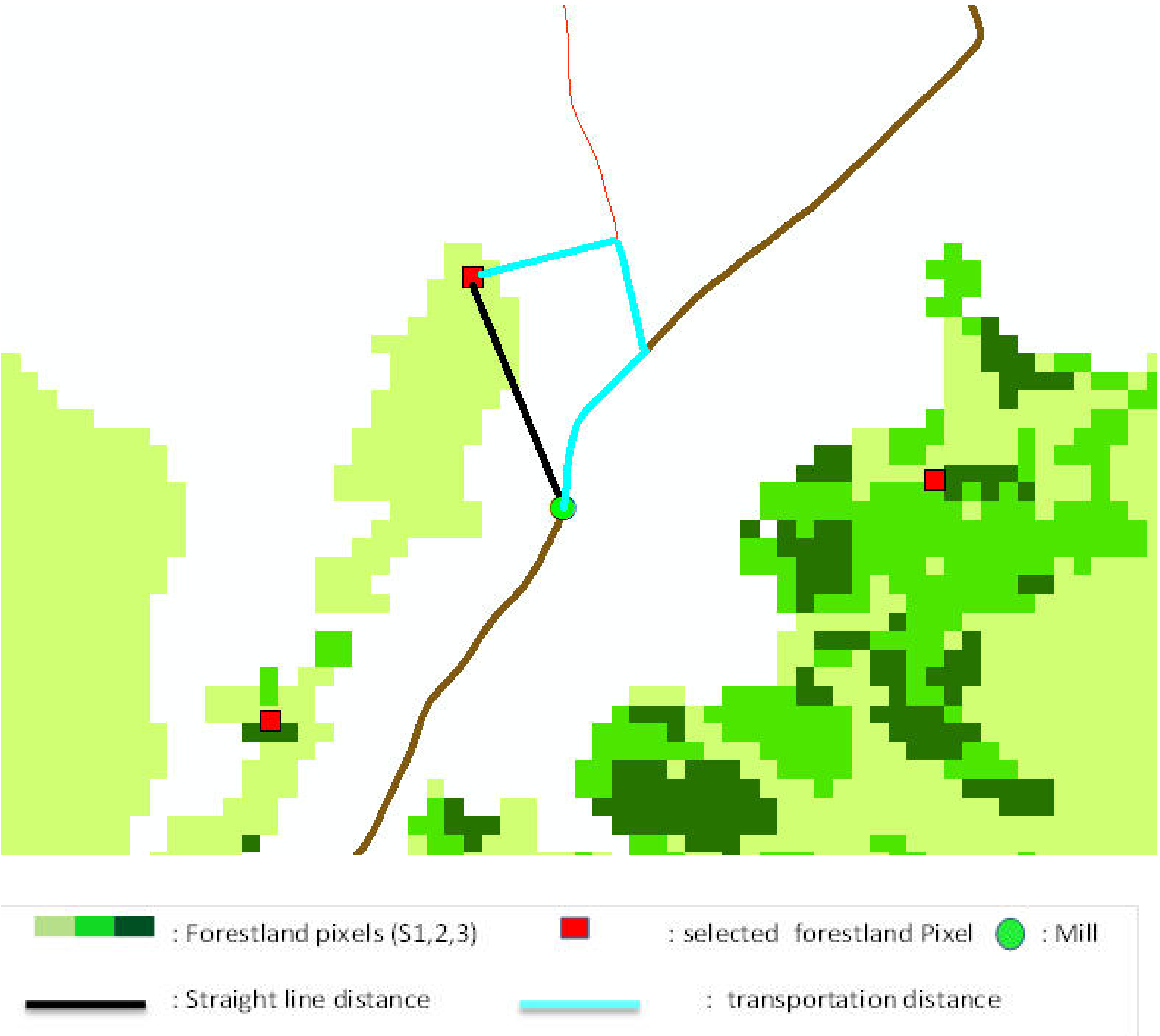


Figure 3.20 Difference between straight line distance and transportation distance

Based on the maps completed in previous steps, which include potential productivity map (m^3/parcel/year), transportation cost and the information of price at mill, the optimization algorithm identifies which parcels supply which mills. In each step, the parcel with the highest maximum profit per cubic meter is allocated to a respective mill until the demand for timber of each mill is reached.

As the quality of forest sites varies across the study area and timber demand for individual mills differs, it is necessary to verify that all the selected land parcels have a sufficient timber supply to support the demand of all mills. The parcel – allocation was realized using an algorithm developed and programed in *Microsoft Visual Basic*. The suitability assessment is a fundamental source for making decisions regarding land-use allocation. By means of the ArcGIS environment a map of the respective areas for *A.mangium* plantations was generated with respect to both, the land-use structure and spatial distribution of parcels.

3.2.6 Scenario analysis

Scenarios have been defined by varying rotation lengths, economic conditions, and changes in the optimization model's constraints. The profit from growing a plantation is calculated based on an objective function. Interest rate (r) has not been included in the calculation. The optimization results are given in terms of land area allocated to meet timber demand, total costs, and total household profit earned. The scenario analysis is analyzed in terms of household's income.

The different scenarios are defined as follow:

Business as usual (BAU): This represents the basic results of current practices. In this scenario, the values of the independent variables used in optimization model are calculated when a forest plantation is harvested at age 7 years in line with local households' preference. Although biologically the optimum rotation age varies according to suitability class, the productivity value used in the optimization model was determined when a forest plantation was harvested at 7 years in all three suitability classes.

Different rotation periods (ROT): varying harvesting age is analyzed to indicate different profit gains at different harvest ages. Total profit and total land area allocated to meet timber demands were derived via an optimization model for different rotation ages (5, 6, 7, 8, 9, 10, 11, and 12 years). Then, the annual profit generated per hectare is defined by dividing the total profit obtained by the total allocated forest area and the productive years. The profit per hectare per year (US $/ha/year) is calculated for different rotations to determine the economically optimum rotation age.

Based on the economically optimum rotation age, other scenarios are assumed and analyzed such as different economic scenarios, related to changes in the optimization model's constraints.

Economic scenarios (ECO) show the change in household profits as well as the allocated land area by the assumption of variations in timber demand, timber prices and costs. Specifically, ECO_demand identifies scenarios with variations in timber demand. Two sub-scenarios were defined:

- Eco+ with increased timber demand by 20%; 30%; 40%; and 50%.
- Eco- with decreased timber demand by 30%

ECO_price identifies scenarios with assumed variations in timber prices based on the mills centralized and distance between mills and forested plantations density in reality.

ECO_Cost identifies scenarios with assumed variations in costs. Variations in silviculture cost and harvest costs were analyzed according to the roughness of the terrain.

Scenarios related to the change in demand constraints in the optimization model are Mill_new, Mill_coop and Con_.

Mill_new: Number of existing mills was increased by adding new mills. This scenario showed the change in household profit gains by adding three new larger mills. Three new mills were larger in capacities and randomly located within the study area. The total timber demand of the three new mills was assumed to equal the timber demand of all existing mills, and thus resulted in doubling the timber demand.

Mill_coop: Cooperation among mills was assumed when existing smaller mills were replaced by a lower number of larger mills, but the total timber demand remained unchanged.

Con: this scenario realizes environmental interests. In spite of meeting required timber demands, several sections of the potential forest land areas were allocated as “nature conservation” areas, where no logging takes place. This made statistically measurable contribution to the total profit obtained. This contribution was used to calculate a “shadow price”, which is the difference of the total profit obtained compared to the scenario when an economically optimum rotation age was applied. This scenario quantifies the cost for the establishment of nature conservation areas.

Forest growth varied according to suitability classes across the study area. For all scenarios, productivity values for all three suitability classes were considered in the calculation process of the optimization model.

4 Results

This chapter is divided into three parts. The first part provides results of the questionnaires on household forest activities, on mills and assignment of ecological factors according to suitability classes (section 4.1). The second part (section 4.2) describes results regarding the studied species' growth, growth function and assignment of productivity to suitability classes. The third part (section 4.3) provides results from the optimization procedure for the defined scenarios and puts them in the context of sustainable forest management. Additional scenarios are analyzed based on changes in the constraints of optimization model.

4.1 Results of questionnaire

This section covers results of forest activities of households, characteristics of different mill types and the assignment of ecological factors to different suitability classes. Information of household survey shows the status of growing *A. mangium* plantations by households in the study area. Information of the questionnaire also was used to calculate planting and other costs. Information regarding timber demand, timber price, various products, etc was obtained from the sawmills survey. The classification of different suitability classes based on ecological factors was made in consultation with forestry experts. The information from household and sawmill survey as well as expert consultations was used in the optimization framework.

4.1.1 Result of questionnaires on forest activities of households

A total of 45 questionnaires were elaborated, collected and evaluated for descriptive statistics. Descriptive statistics are presented in Table 4.1.

Table 4.1 Descriptive statistics on the size and spatial situation of the household questionnaire (Exchange rate: 1 USD = 22000 VND)

Attribute	N	Minimum	Maximum	Mean
Acacia area [ha]	45	0.5	10	2.04
Distance to road [m]	45	10	5000	757.4
Harvest age [years]	45	5	7.5	6.6
Stumpage price [USD/m^3]	35	39	55	48
Establishment cost [USD/ha]	45	256	420	316
Silviculture cost (Weeding) [USD/ha]	45	36	273	103
Harvest cost [USD/m^3]	38	6.5	11.0	8

As can be seen from Table 4.1, the average area planted with *A. mangium* is approximately 2ha. The typical plantation consists of a single stand. The average distance from planted forests to roads is 757 m. Forest owners plan to harvest their plantations at the age of 5 to 7.5 years with an average of 6.6 years.

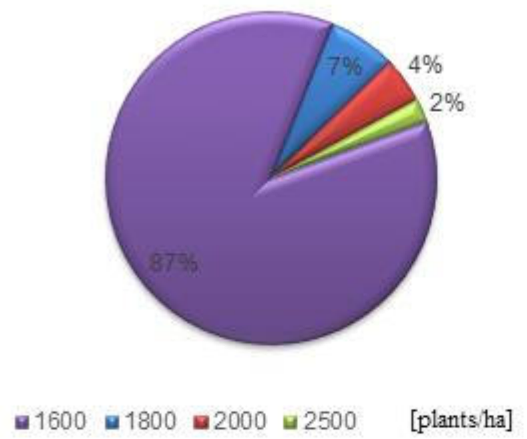


Figure 4.1 Planting density of *A.mangium* in Thai Nguyen province

Production costs consist of establishment cost (site preparation, seedling, planting, fertilizer in the first year), silvicultural cost (weeding applied almost twice in the second year or third year). Average of 60 USD/year/ha was calculated based on the decision on labor input in afforestation and forest protection and development of the Ministry of Agriculture and Rural Development for management cost (MARD, Decision No. 38/2005/QD-BNN).

Site preparation is a process of removing vegetation, tilling and excavating planting holes. The participating households stated that among the four planting densities applied, 1600 stems/ ha was the most common for this species accounting for 87%, followed by 1800 stems/ha, 2000 stems/ha and 2500 stems/ha accounting for 7%, 4% and 2% respectively (Figure 4.1). The planting density of 1600 stems/ha was applied as proposed by Thai Nguyen Forestry department for planting in mono-specific stands, and others densities were applied based on the forest owners.

According to the household questionnaire, planting takes place in the beginning of the rainy season. About 84% of the households planted their plantations in March, and 16% of households planted in April. More than 90% of the households replaced mortality one month after planting by adding 10% more seedlings. Fertilizer was applied to the stands to increase productivity. All of households applied fertilizer for their plantations with a mean of 100 gram per seedling in the first year.

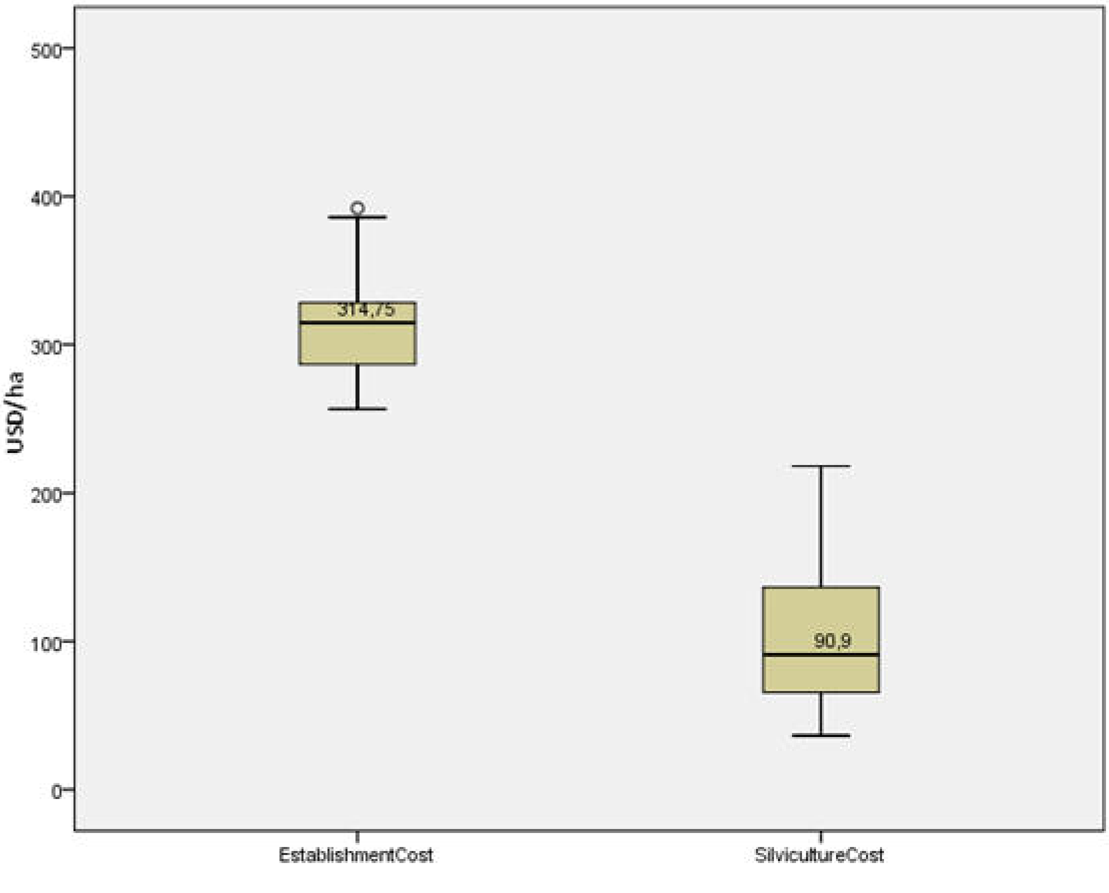


Figure 4.2 Establishment cost and silviculture cost derived from questionnaire

Table 4.1 and Figure 4.2 shows that establishment costs ranged from 256 USD/ha to 420 USD/ha. Silviculture practices were implemented such as weeding. The benefits of weeding including grass control, shrub and some branch pruning to limit negative effects on the growth of the plantation and encourage stems to grow more valuable with straight stems (Beadle et al. 2007). During the field study, a majority of the households conducted weeding twice in the second year (89%), 11% weeded in the third year. The cost for weeding ranged from 36 USD/ha to 273 USD/ha.

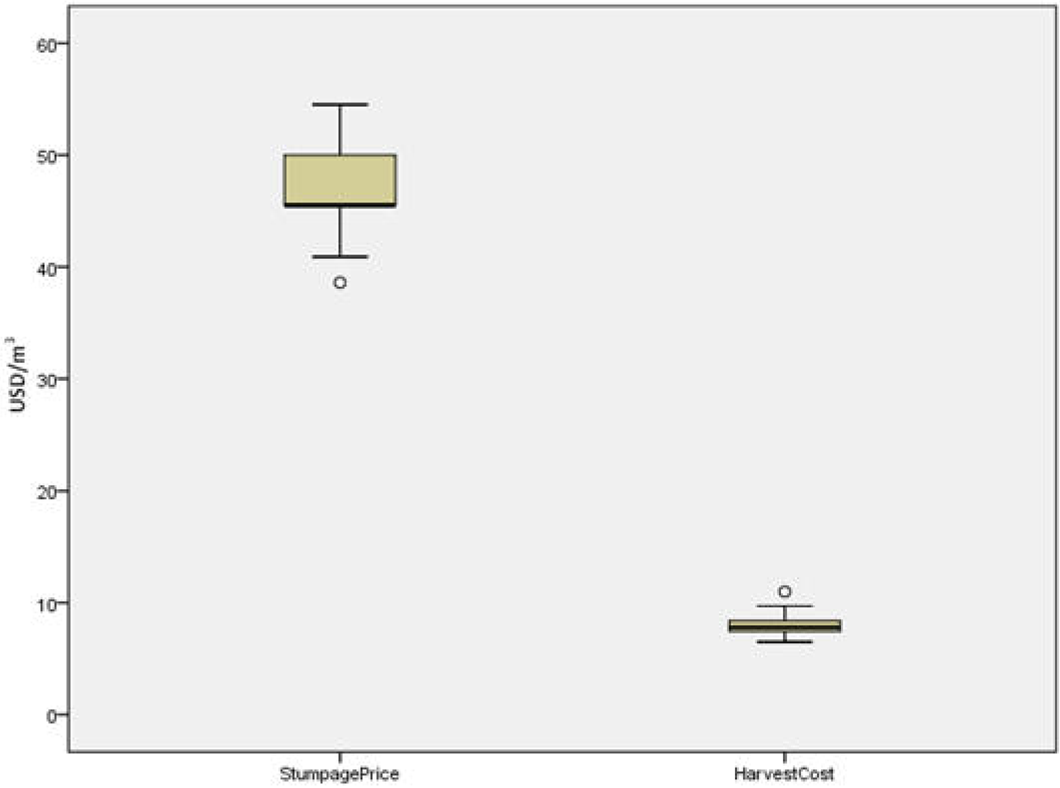


Figure 4.3 Stumpage price and harvest cost derived from questionnaire

Table 4.1 and Figure 4.3 show that harvest cost was calculated according to the number of days allocated per hectare or to the price per m^3 after being loaded to trucks. According to the results of the survey, on average, a team of 5 people is engaged in harvesting, performing jobs like felling, cutting and skidding to the road. The minimal cost for harvesting was 6.5 USD/m^3, the maximal cost 11 USD/m^3. The stumpage price ranged from 39 USD/m^3 (min) to 55USD/m^3 (max).

4.1.2 Results of questionnaires on sawmills

A survey was also conducted in 50 mills. 15 of the mills produce woodchips as raw material for industrialized utilization purposes, 16 produce veneers, and 19 mills produce pallets.

Table 4.2 Characteristics of mills derived from the questionnaires

Attribute	Obs.	Mean	Std.Dev	Min	Max	SE	95%CI
Price of wood at mill							
Woodchip (USD/m^3)	15	55.6	2.70	51.9	58.4	0.70	±1.50
Veneer (USD/m^3)	16	53.6	3.67	48.7	58.4	0.92	±1.93
Pallet (USD/m^3)	19	52.3	4.58	48.7	55.2	1.05	±1.12
Demand for wood							
Woodchip (m^3/year)	15	7061.6	2267.9	3360	10500	585.6	±1255.9
Veneer (m^3/year)	16	3945.4	1731.1	1890	8400	432.8	±922.4
Pallet (m^3/year)	19	2037.7	1091.6	907	5460	250.4	±526.2
Labor							
Woodchip (people/mill)	15	7.4	3.2	5	15	0.8	±1.8
Veneer (people/mill)	16	7.2	3.9	3	20	1.0	±2.1
Pallet (people/mill)	19	6.1	5.4	2	21	1.2	±2.6
Cost for labor							
Woodchip (USD/day)	15	53.4	26.5	27.3	118.2	6.9	±14.7
Veneer (USD/day)	16	58.7	37.2	23.2	181.8	9.3	±19.8
Pallet (USD/day)	19	48.9	39.6	13.6	143.2	9.1	±19.1
Finished product							
Woodchip (dry ton/day)	15	19	5.5	9	30	1.43	±3.1
Veneer (m^3/day)	16	11.9	4.3	4.9	19.6	1.1	±2.3
Pallet (m^3/day)	19	4.4	1.9	2.5	10.5	0.4	±0.9
Trade price							
Woodchip (USD/dry ton)	15	110	7.3	91	118.2	1.9	±4.1
Veneer (USD/m^3)	16	98.2	4.2	91	104.6	1.0	±2.2
Pallet (USD/m^3)	19	111.2	18.8	91	149.1	4.3	±9.1

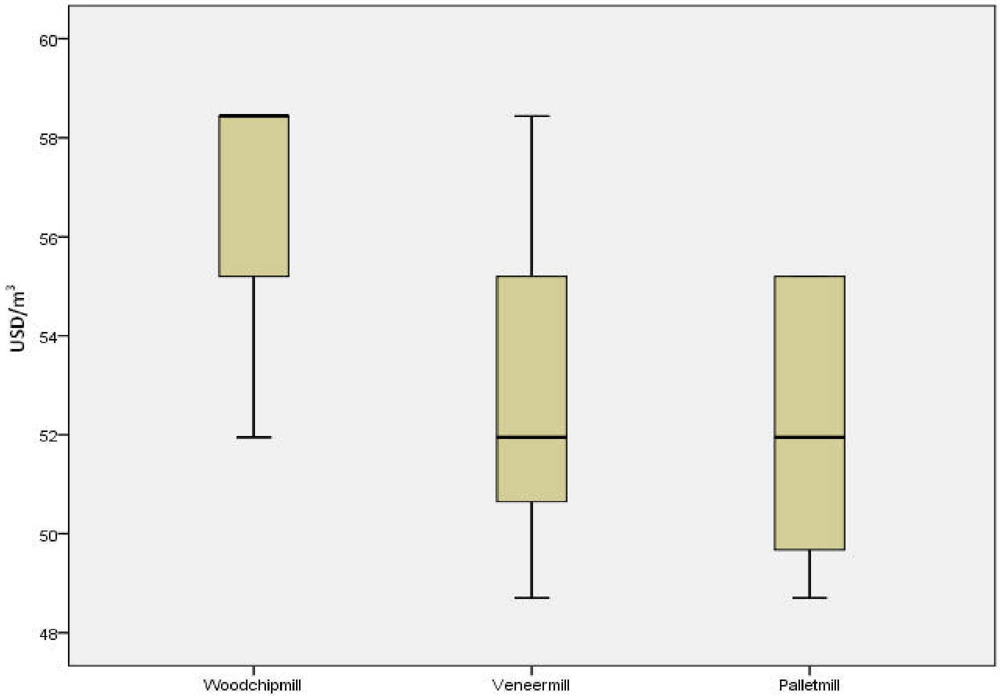


Figure 4.4 Different timber prices at mills according to mill types

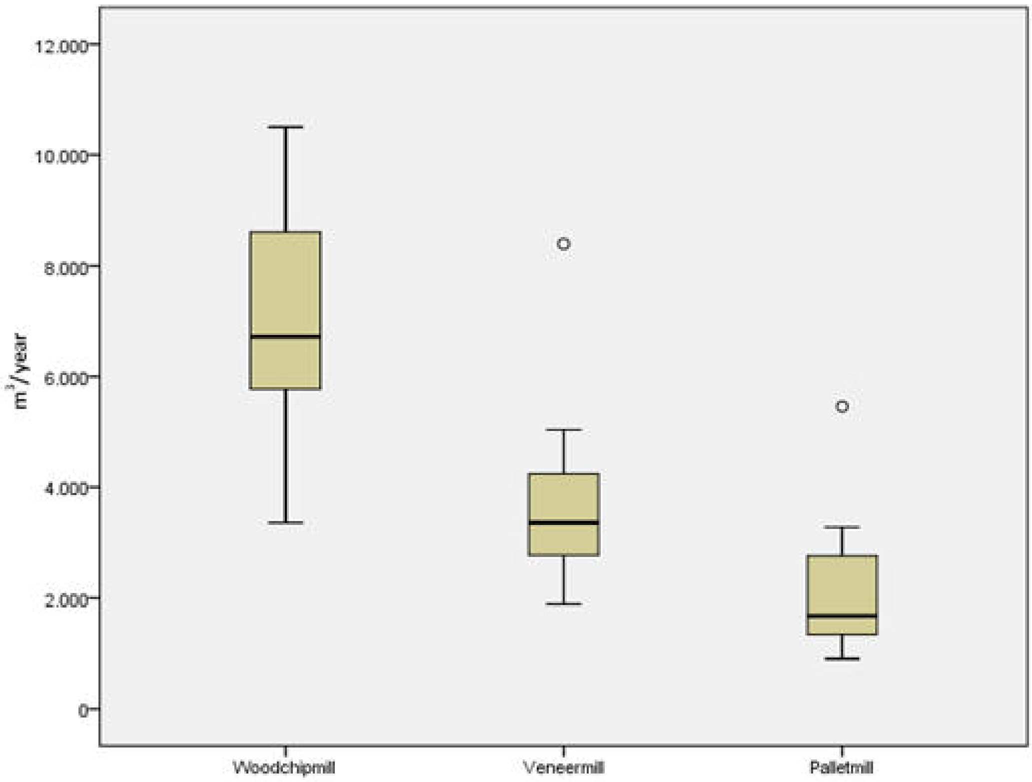


Figure 4.5 Different timber demands according to mill types

Table 4.2, Figure 4.4 and Figure 4.5 show that the price of wood at mills, with the average price of wood being the highest when forest stands are harvested at age 6 or 7 years old (including wood with diameters from 3 to 25 cm). Prices are highest for woodchip mills (56.6 $\$/m^3$), followed by veneer mills and pallet mills with average prices of 53.6 $\$/m^3$ and 52.3 $\$/m^3$ respectively. The wood demand of chip mills was largest with 7061.6 m^3/year, 3945.4 m^3/year for veneer mills and 2037.7 m^3/year for pallet mills.

The production quantity and labor cost varied depending on the number of people working in mills. Generally, all of mills were medium sized or small sized, employing on average 4 and 12 persons.

Information on transportation cost was also provided by the mill survey. Transportation is one part of the wood supply chain. The cost of transporting timber from the forest (stands) to the mill is often a significant component of the cost of wood. In this study, transportation cost was considered as the cost for carrying timber from the stand to the mill. Out of 50 mills, information obtained from 31 mills showed that the mean transportation cost was 0.3 USD per cubic meter per km.

The responses from mills show that *A. mangium* timber is mainly processed for medium value products such as woodchip, veneer and pallet. The result shows that the minimal diameter utilized in varying according to the type of product. All mill types buy timber with various diameters (3-25cm), which explains why forest owners usually harvest their plantation at an age around 7 years when the stems regularly have diameters below 25 cm. According to the survey, no timber from *A. mangium* plantations is supplied for furniture production. The main wood source for furniture comes from individual trees that are being grown as scattered trees near local households.

Pallet mills, in particular, need larger sizes of wood than the woodchip and veneer mills. Pallet mills pay a lower price for timber, and as a result, forest owners currently prefer to sell timber to woodchip mills.

4.1.3 Assignment of suitability classes for *Acacia mangium*

Based on consultations with forestry experts, four different suitability classes were identified: (i) highly suitable, (ii) moderately suitable, (iii) marginally suitable, and (iv) unsuitable class.

Ecological factors were allocated to respective suitability classes through consultation of four forestry experts. The results are presented in Table 4.3.

Table 4.3 Parameters for determining suitable classes by experts

Site condition	**Forestry land suitability**			
	Highly suitable (S1)	**Moderately suitable (S2)**	**Marginally suitable (S3)**	**Unsuitable (UN)**
Soil type	Fk, Fp, D	Fs, Fa, Fv	Fq, Rk, Ha	Karst
Soil depth [cm]	≥ 100	≥ 70 - 100	≥ 50 - 70	50
Elevation [m]	< 200	200 – 400	400 – 700	>700
Slope gradient [degree]	0 - 15	15 - 25	25 – 35	>35
Mean annual rainfall [mm/year]	2000 – 2400	1500 – 2000	1300- 1500	< 1300
Score of each variable category for land suitability assessment	**4**	**3**	**2**	**1**

The information in Table 4.3 shows that the best growth of *A. mangium* is found on sites with soil types such as Fk, Fp, D, soil depth larger than 100 cm, elevation less than 200m, slope gradients between 0 and 15 degree, and mean annual amount rainfall above 2000 mm.

Table 4.4 Matrix of pair-wise comparison of all attributes by forestry experts

Acacia mangium	**Soil properties**	**Topography**	**Climate**	**Weight**
Soil properties	1	2.20	3.00	0.556
Topography	0.45	1	1.70	0.272
Climate	0.33	0.59	1	0.172

Table 4.5 Weights of ecological parameters in land suitability assessment

Factor	Weight 1	Parameter	Weight 2	Overall weight = (W1 *W2)
Soil property	0.556	Soil types	0.31	0.172
		Soil depth	0.69	0.384
Climate	0.172	Rainfall	1	0.172
Topographic	0.272	Elevation	0.29	0.079
		Slope	0.71	0.193
Sum				**1**

By using aggregation individual judgments (AIJ) with geometric mean approach, the following judgment matrix given by four forestry experts was developed. The overall weights of attributes in the land suitability assessment for *A. mangium* species are given in Table 4.4 and Table 4.5. These tables show that soil properties are the most important factor, followed by topographic and climate factors. To create a map of land suitability, each input raster layer was weighted according to its proportional influence given the constraint that the sum of the percentage influence weights for all the raster map (factors) is equal to 1. The consistency analysis (Table 4.4) was performed using the normalized matrix and the factor weights. The results illustrate that the Consistency Index (CI) for paired factors concerning the impact of different factors to land suitability is 0.003 (0.3%) and Consistency Ratio (CR) were 0.005, which is smaller than 10% threshold proposed by Saaty (1980). The consistency made in the judgment is therefore considered to be acceptable.

WLC technique enables each criteria map to be multiplied by their weight. The raster calculator tool in ArcGIS environment, which is based on the principle of WLC, was utilized to combine weighted raster inputs. Table 4.6 and Figure 4.6 illustrate defined land suitability of the study area for *A. mangium*. The map was masked with the area planned for forest production in the study area.

Table 4.6 Land suitability class for *Acacia mangium*

Suitability class	Highly Suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable	Total
Area (ha)	27158	73227	6537	5388	112309
%	24.18	65.20	5.82	4.80	100

The result indicatsthat indicates that forest land with respect to potential suitability for forest plantations with *A. mangium* is assigned to suitability classes including “Highly suitable”, “Moderately suitable”, “Marginally suitable”, and “Unsuitable”. A map of suitability locations for growing *A. mangium* is represented in Figure 4.6.

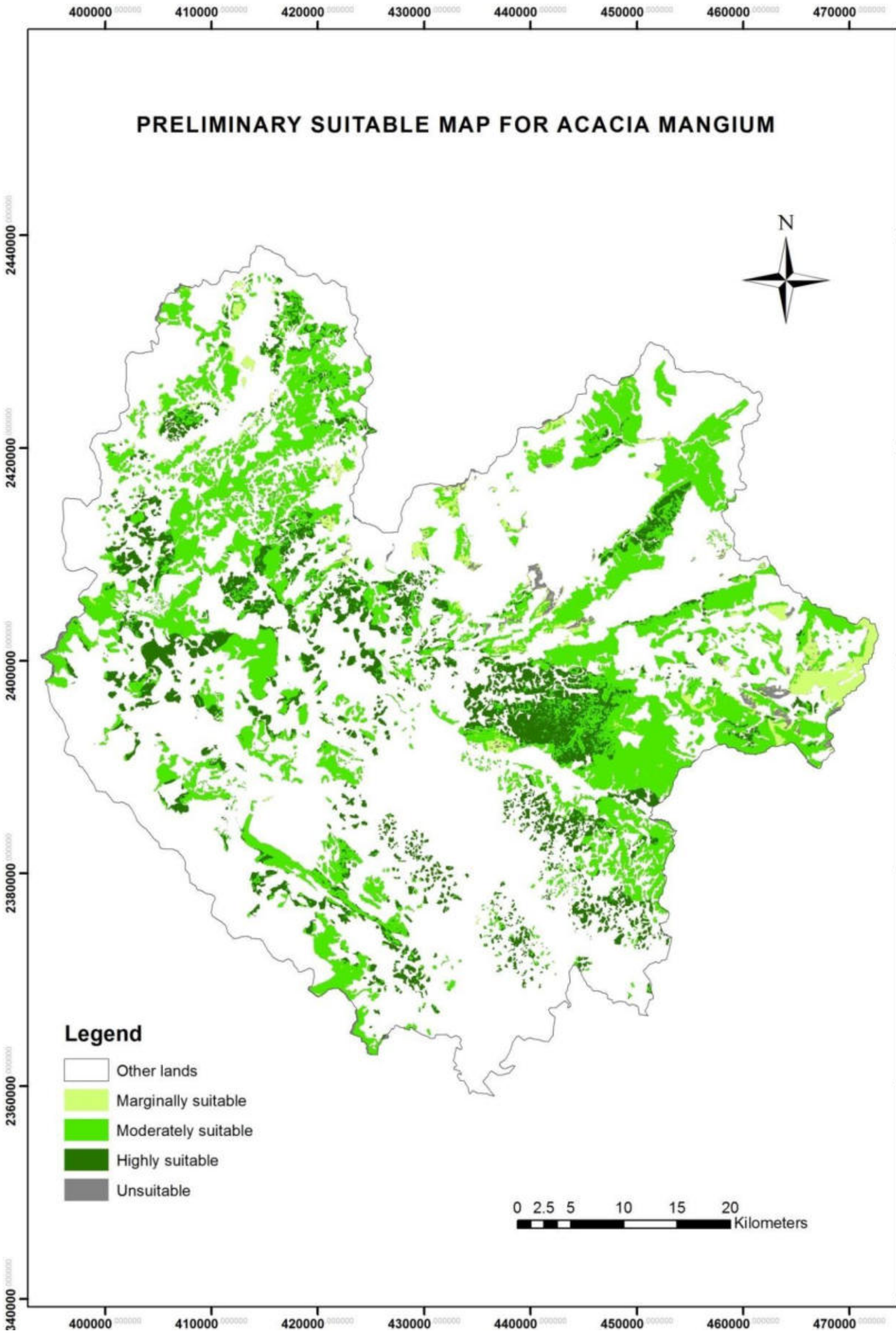


Figure 4.6 Map of suitability locations for growing *A. mangium*

4.2 Growth of *Acacia mangium*

The growth of the *A. mangium* was determined by the diameter frequency distribution, along with the growth of forest plantations in different sites. The diameter distribution shows a maximum of the majority of stems per hectare for different suitability classes in different ages. This information is useful to determine harvest age. The general picture of different growth in various suitability classes is supported by variables calculated. Finally, growth models were built, and applied to the three suitability classes.

4.2.1 Number of trees per hectare – diameter classes distribution according to suitability classes

Diameter distribution reflects the number of trees according to diameter classes. Blue, green and orange colored bar charts show diameter distribution in highly suitable class (S1), moderately suitable class (S2) and marginally suitable class (S3). Figure 4.7 (a) and (b) show that the highest number of trees are mainly located in the diameter classes of 6cm – 7.5cm and 7.5cm – 9cm in 1 to 3 years old *A. mangium* plantations.

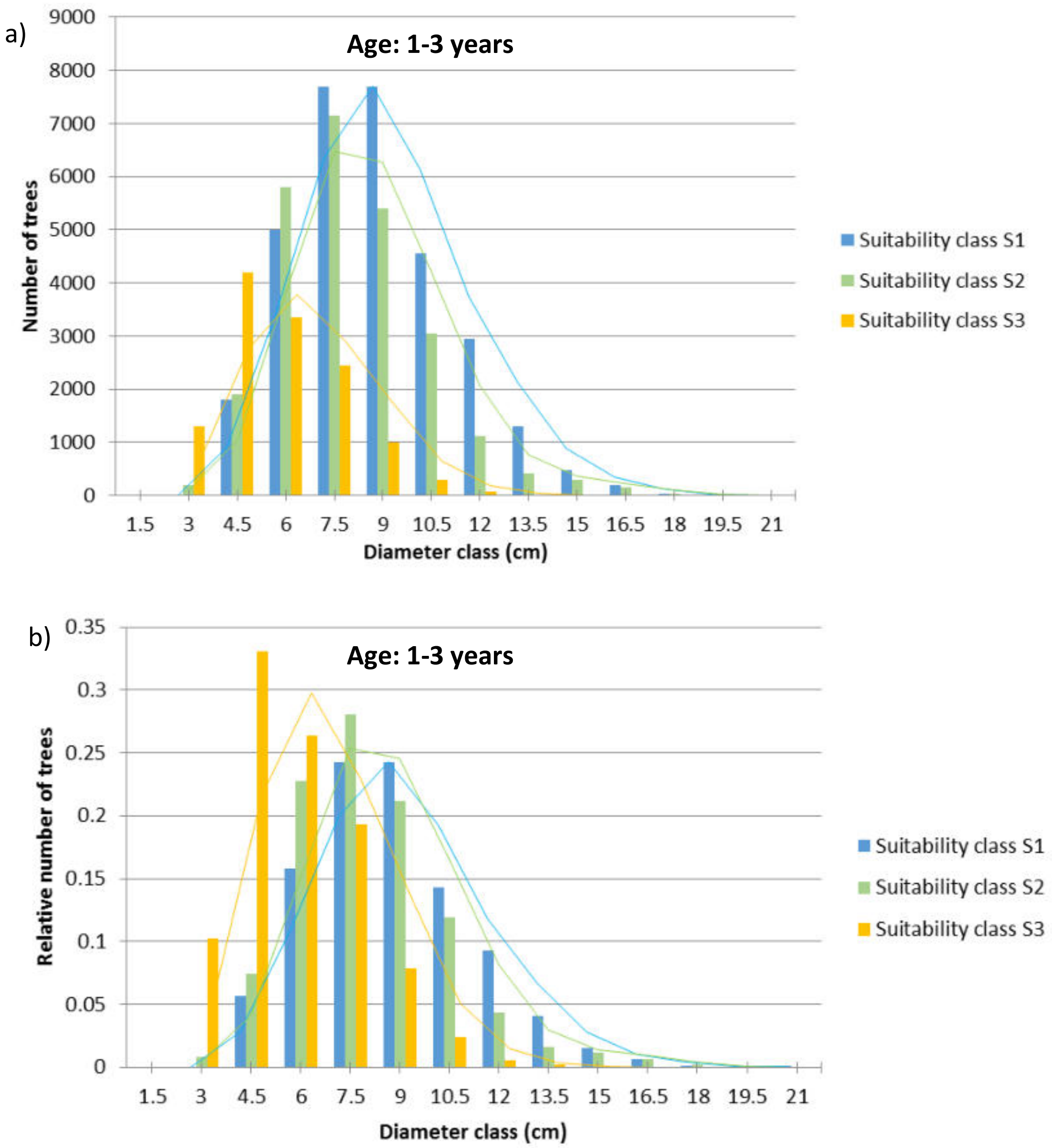


Figure 4.7 Distribution of number of trees (S1: 14 plots, S2: 12 plots, S3: 5 plots, calculated per hectare) in different suitability classes. a) Absolute number of trees and b) Relative number of trees according to diameter classes

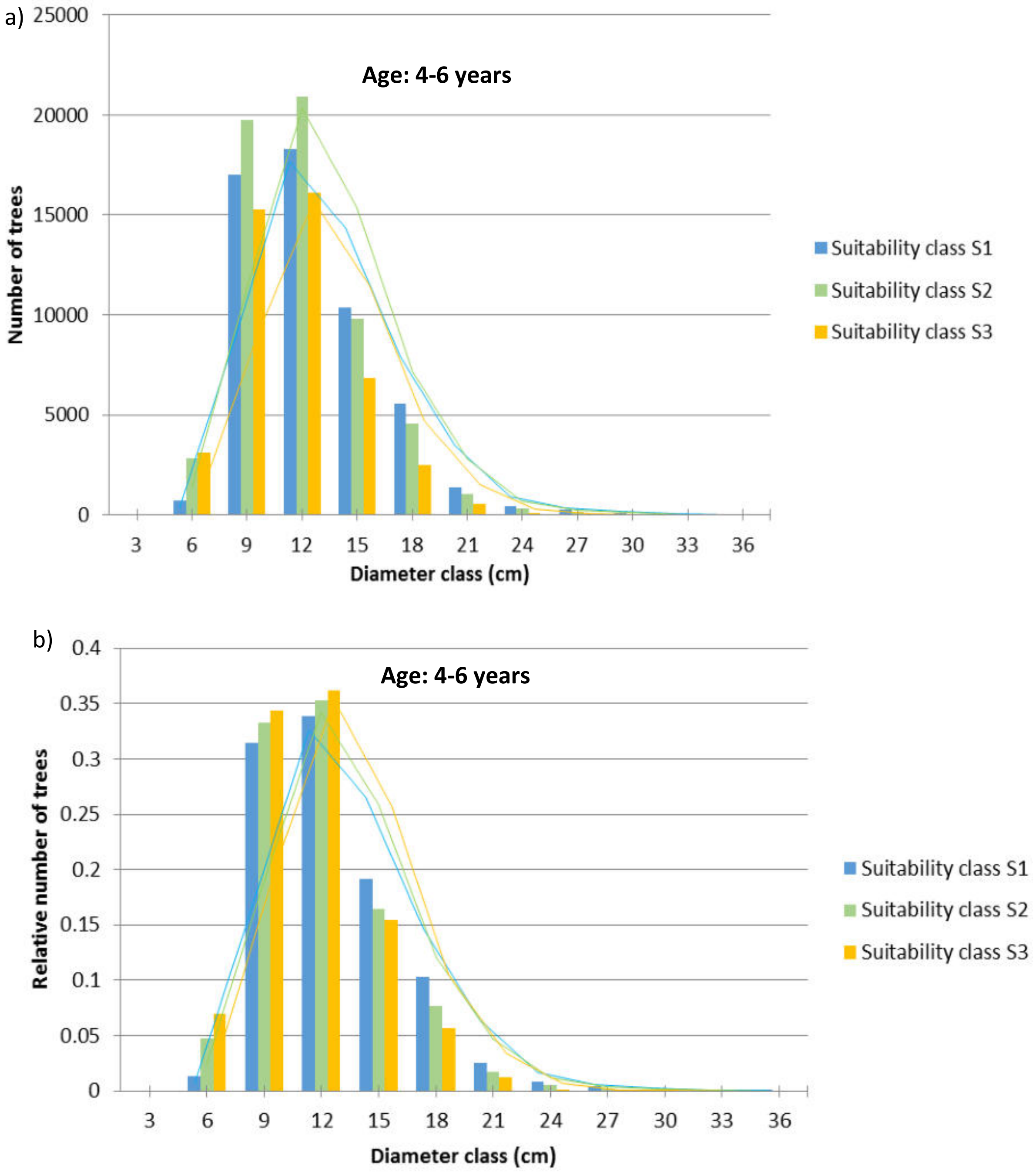


Figure 4.8 Distribution of number of trees (S1: 29 plots, S2: 31 plots, S3: 25 plots, calculated per hectare) in different suitability classes. a) Absolute number of trees and b) Relative number of trees according to diameter classes

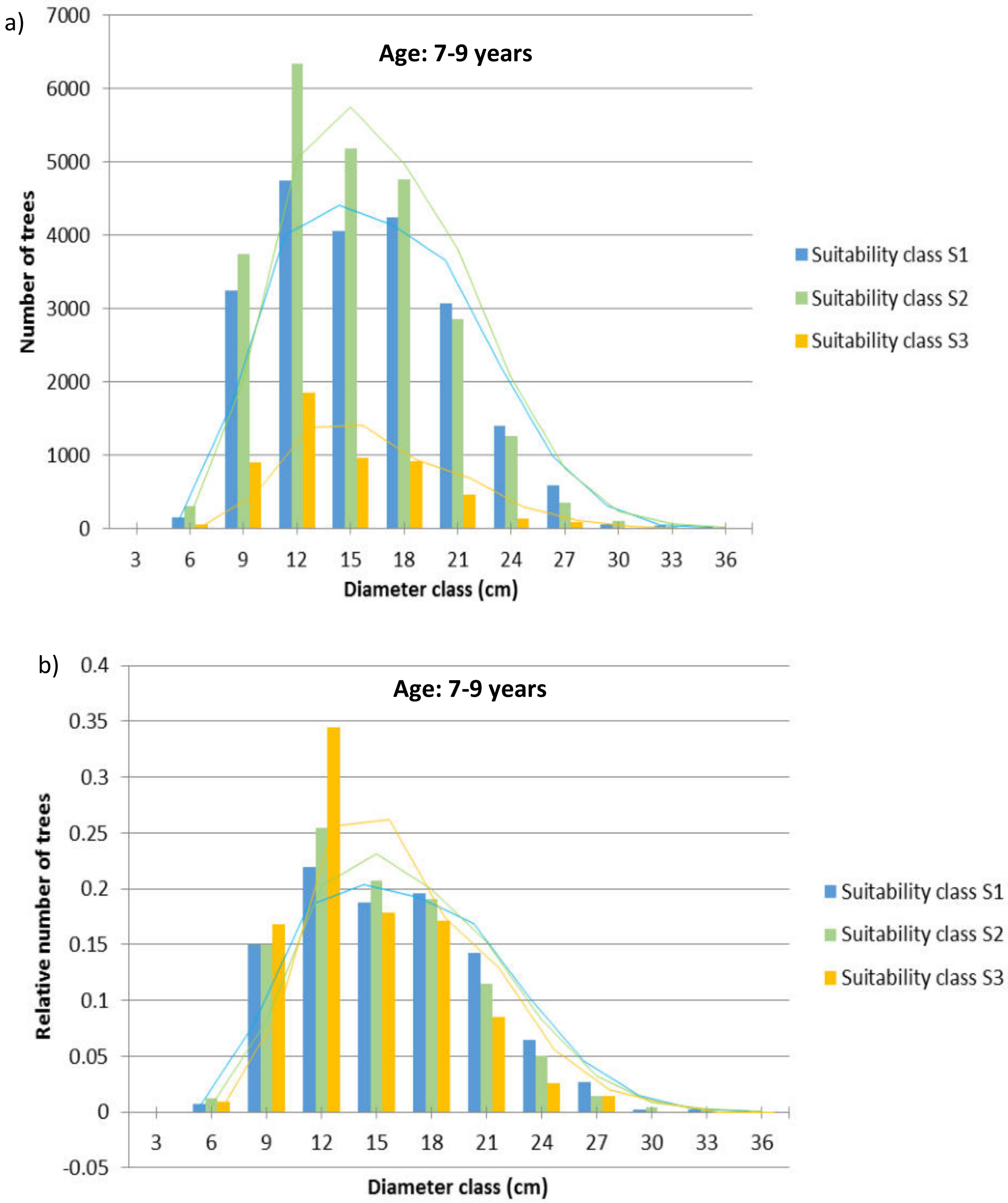


Figure 4.9 Distribution of number of trees (S1: 14 plots, S2: 17 plots, S3: 3 plots, calculated per hectare) in different suitability classes. a) Absolute number of trees and b) Relative number of trees according to diameter classes

a)

b)

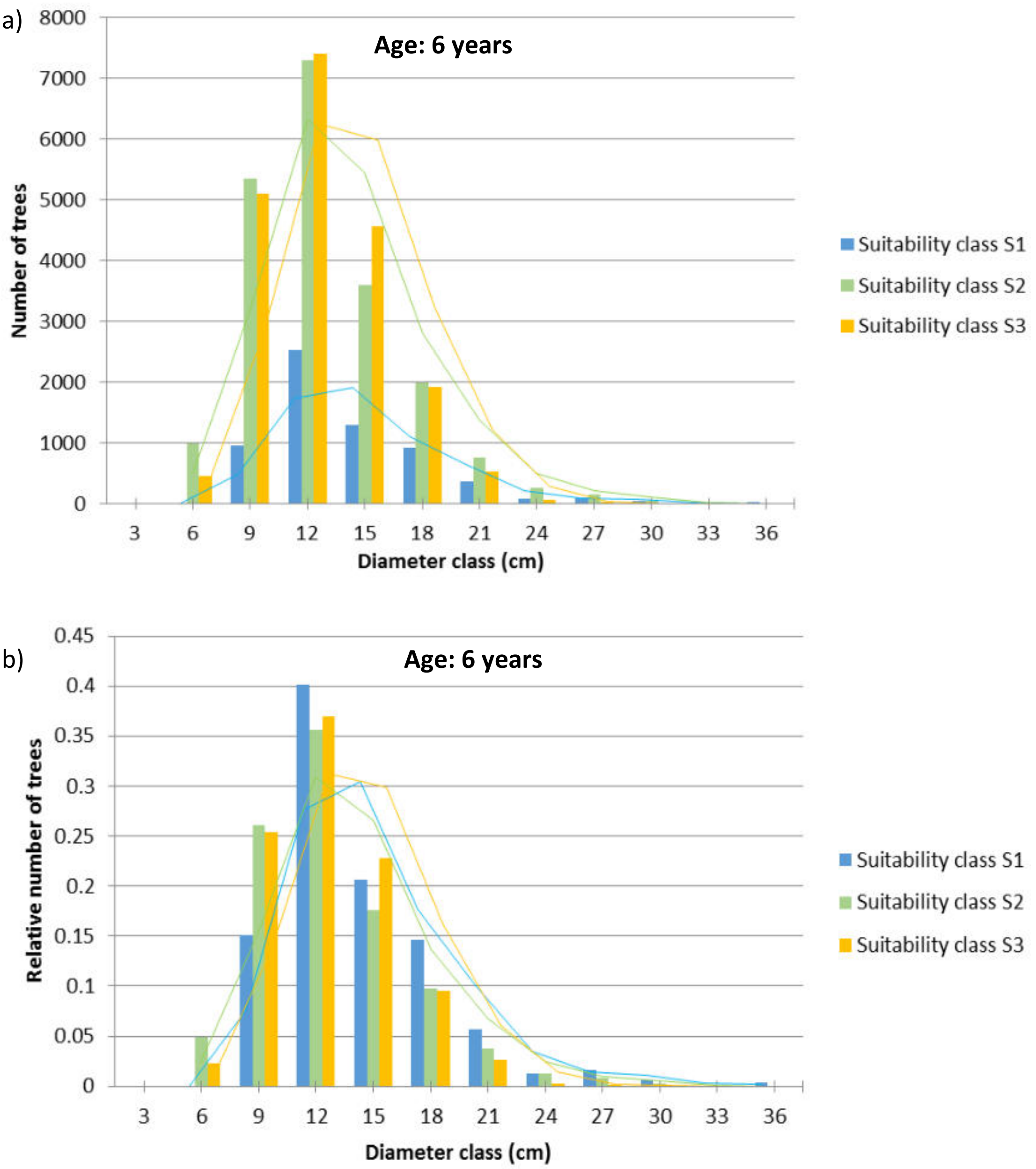


Figure 4.10 Distribution of number of trees (S1: 4 plots, S2: 11 plots, S3: 12 plots, calculated per hectare) in different suitability classes. a) Absolute number of trees and b) Relative number of trees according to diameter classes

In comparison, in older stands at age 4 to 6 years the number of stems is larger on the diameter classes of 9 – 15cm (Figure 4.8 a and b). The number of individuals with diameters of 21 - 27cm plantation stands at age 7 to 9 years (Figure 4.9 a and b) was significantly higher than that of plantation stands at age 4 to 6 years (t =56.12, α = 0.05). If the local households harvest their plantations at age 6 years, stands in different suitability classes were close to a mature stage at the same diameter due to the skewness of distribution, which shows a trend towards the symmetry (Figure 4.10 a and b). Hence, the harvest of plantation stands at age 6 years is just as effective for supplying the need for small timber. At this age, the largest number of trees is between 9 and 15 cm. These figures show that *A. mangium* plantations can be transfered to higher diameter dimensions in longer rotation cycles.

In general, the distribution of trees in different diameter classes seems to approximate the normal distribution in all suitability classes. Among the three suitability classes, a larger number of trees in the higher diameter classes is seen in suitability classes S1 and S2 compared with S3, which clearly shows the diameter growth in S1 and S2 was greater than that in S3.

4.2.2 Stand variables according to suitability classes

The calculation results presented in Table 4.7 illustrate that the average number of trees per hectare found in S1 (1823 trees/ha) and S2 (1837 trees/ha) are similar, while the number of trees per hectare in S3 is larger (1905 trees/ha).

Table 4.7 Summary results of calculation of stand variables

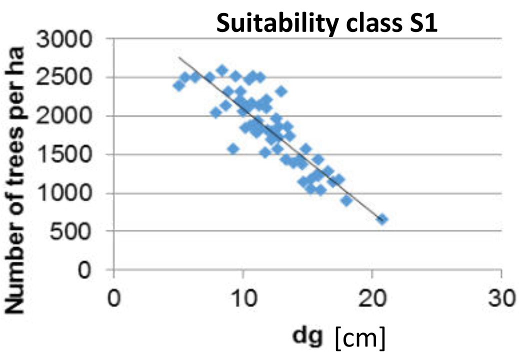
Suitability class	**Statistics**	**Variables**					
		Age	Stocking density (trees/ ha)	Basal area (m^2/ha)	Quadratic mean diameter (d_g, cm)	Mean stand height (h_g)	Volume (m^3/ha)
Highly suitable S1	Min	1	660	4.8	5.0	5.6	13.1
	Max	9	2590	30.6	20.8	17.0	235.6
	Average	5	1823	19.5	12.0	12.6	125.7
Moderately suitable S2	Min	1	920	5.2	5.7	4.7	12.2
	Max	9	2590	34.5	18.9	16.9	262.2
	Average	5	1837	18.3	11.5	11.8	112.3
Marginally suitable S3	Min	1	1000	2.6	3.6	3.0	3.8
	Max	9	2800	27.5	14.7	15.1	173.5
	Average	5	1905	14.7	10.0	10.5	81.8

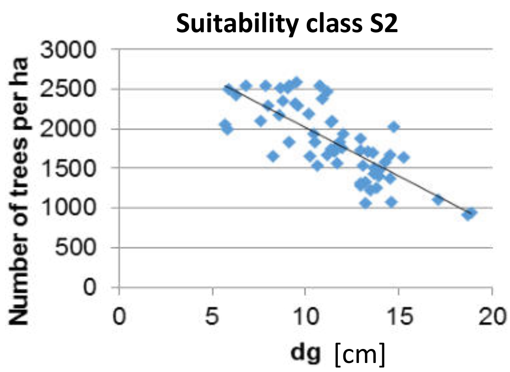
With regard to basal area, the largest basal area per hectare was found in S1 (19.5 m^2/ha), followed by S2 (18.3 m^2/ha), and S3 (14.7 m^2/ha). The average values of stand wise quadratic mean diameter in S1 (12cm) was slightly higher than in S2 (11.5cm) and S3 (10cm). Similarly, highest mean stand height mean (12.6m) was found in S1, compared to S2 and S3 with 11.8m and 10.5m respectively. The relationships between quadratic mean diameter (d_g) and number of tree per hectare (n) in three suitability classes are described by three negative linear functions, which show the relationships between dg and n for the three suitability classes:

S1: $n = -133.915 \times dg + 3432.959$ ($r^2 = 0.752$; $P < 0.05$)

S2: $n = -121.521 \times dg + 3230.95$ ($r^2 = 0.596$; $P < 0.05$)

S3: $n = -127.163 \times dg + 3176.512$ ($r^2 = 0.666$; $P < 0.05$)





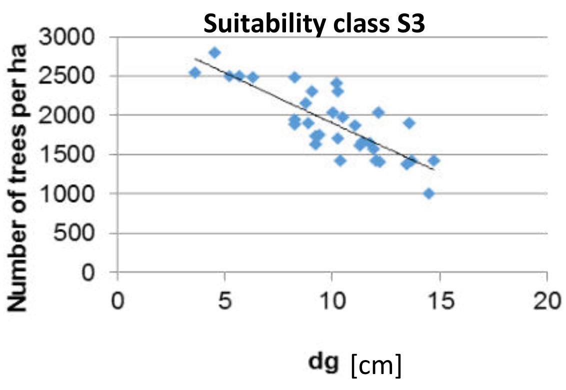


Figure 4.11 Relationship between quadratic mean diameter and number of tree per hectare in different suitability classes

Figure 4.11 shows that mean diameter and number of trees per hectare are negatively correlated, which explains why higher numbers of trees are found in stands with smaller trees and vice versa. This holds true for all three suitability classes.

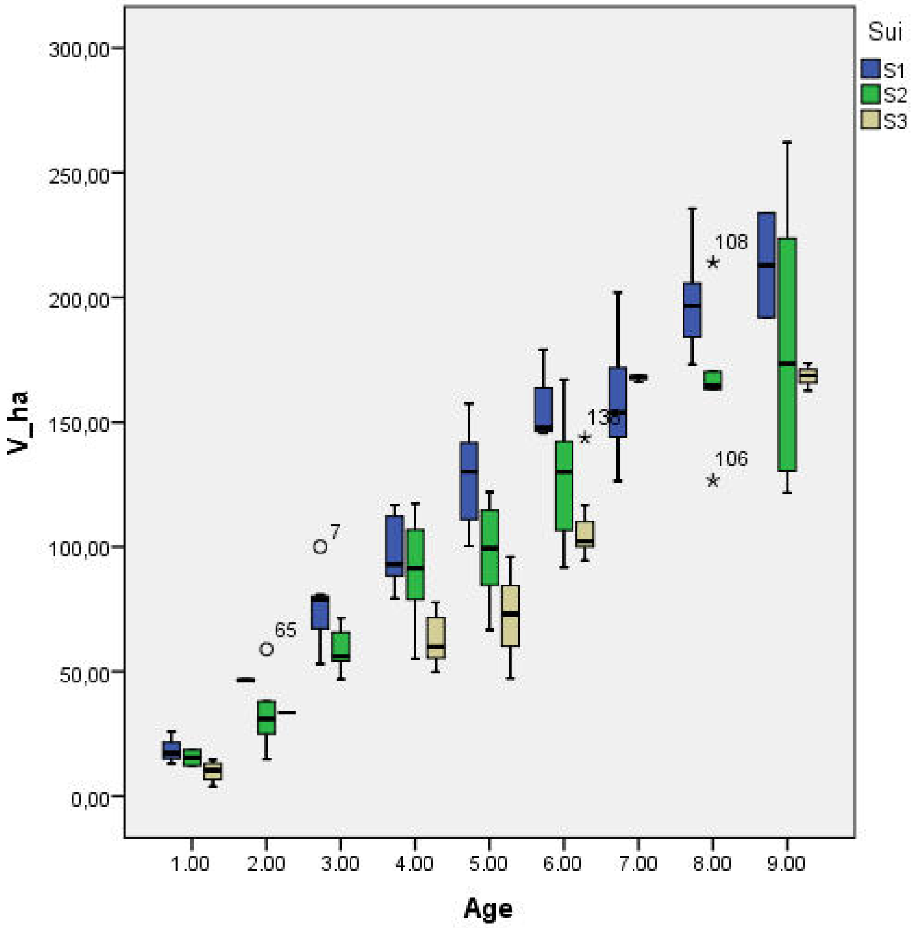


Figure 4.12 Distribution of volume per hectare over age by different suitability classes

Timber volume is of superior interest for forest owners and forest managers (Vanclay 1992). Table 4.7 shows that volume of stands ranges from 13.1 m^3/ha to 235.6 m^3/ha in S1, 12.2 m^3/ha to 262.2 m^3/ha in S2, and 3.8 m^3/ha to 173.5 m^3/ha were witnessed in S3. Volume growth was considerably affected by site quality derived three suitability classes. Figure 4.12 demonstrated that the effect of different suitability classes on volume growth is significant (Kruskal–Wallis test, $\chi 2$ = 15.74, P = 0.000). The volume of stands varies not only by age, but also by suitability class. Over all stand ages 1 to 9 years, volume per hectare of stands in S1 showed the highest number of volume per hectare with a mean of 125.7m^3/ha. S2 and S3 revealed lower volume per hectare with a mean of 112.3 m^3/ha and 81.7m^3/ha, respectively.

4.2.3 Growth function

Three models are utilized to fit volume growth curves to observed data. The relationship between observed and estimated volumes is qualified by the coefficient of determination (r^2) and the root mean square error (RMSE). Table 4.8 shows that all models provided sufficient r^2 values. Differences of r^2 and RMSE between models are negligible.

Table 4.8 The fitted models for tested species

Suitability class	Function	r^2	RMSE	Number of plots
S1	Koft	0.873	18.23	59
	Gompertz	0.870	18.49	59
	Chapman-Richards	0.872	18.26	59
S2	Koft	0.766	26.10	60
	Gompertz	0.766	26.09	60
	Chapman-Richards	0.766	26.08	60
S3	Koft	0.926	11.73	33
	Gompertz	0.926	11.68	33
	Chapman-Richards	0.926	11.70	33

As the r^2 and RMSE do not show considerable differences between the three tested models, the Koft function was selected for reasons of simplicity. As the volume growth function for further analysis and for building a map of the potential productivity. The Koft-functions for the three suitability classes are:

$V\ (S1) = 5488.675 \times EXP\ (-5.662 \times A^{-0.252})$

$V\ (S2) = 2225.187 \times EXP\ (-5.242 \times A^{-0.338})$

$V\ (S3) = 479751.862 \times EXP\ (-10.945 \times A^{-0.145})$

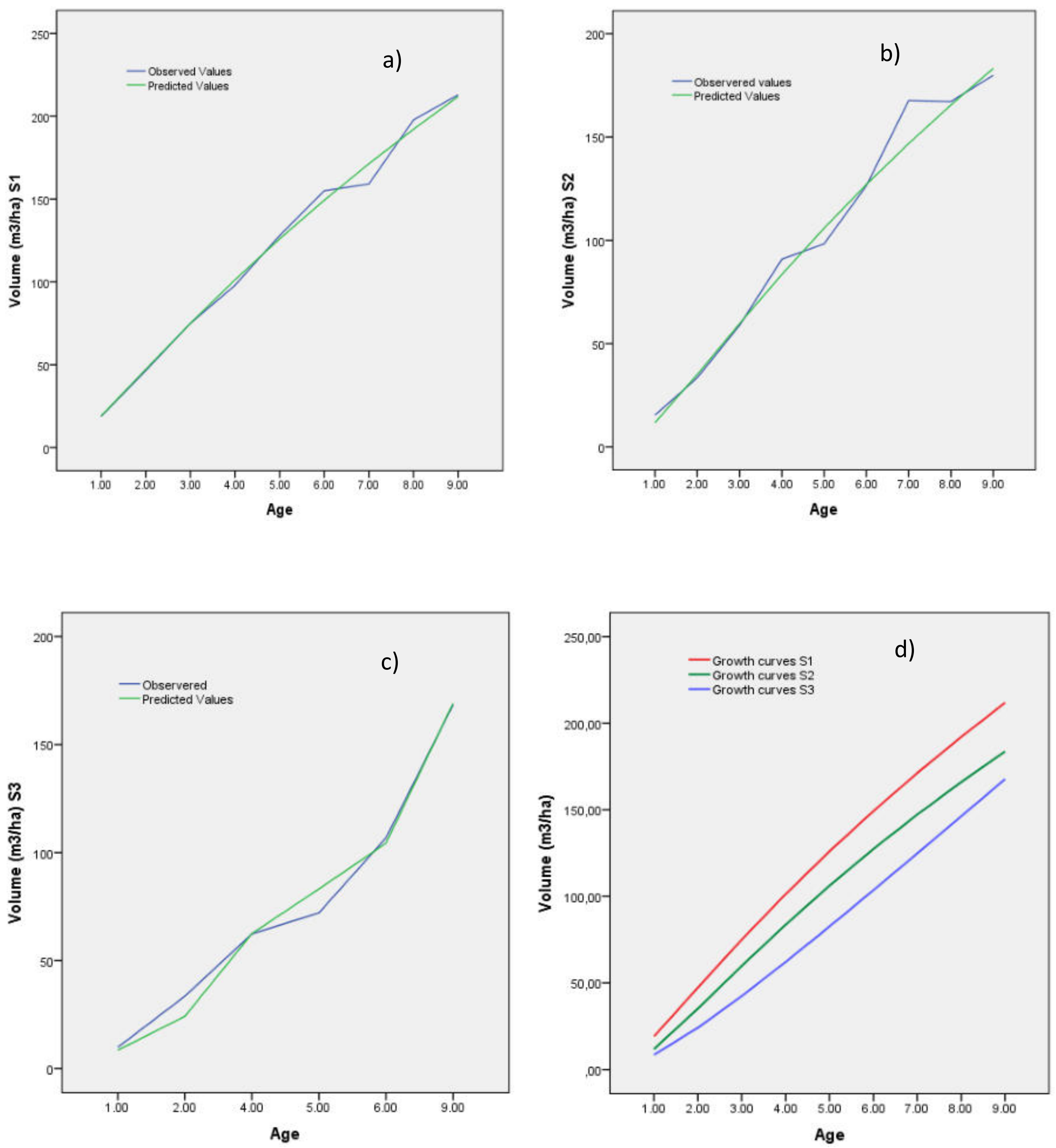
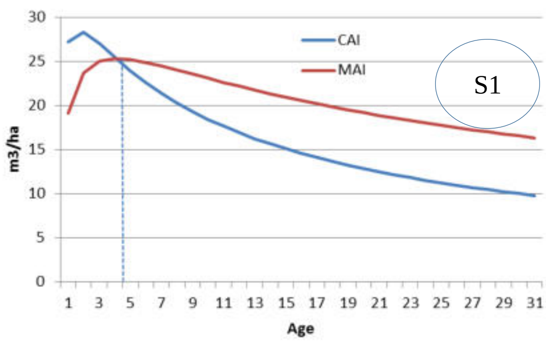
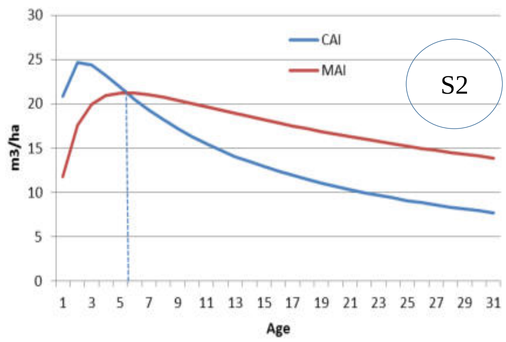


Figure 4.13 Volume growth curves for tested species in three suitability classes (a: S; b: S2, c: S3) and growth functions for the suitability classes (d)

As can be seen from Figure 4.13 a, b, c, the performance of the models clearly reflects the change of volume growth according to age for all suitability classes and plantation ages. The shapes of the volume curves indicate clear differences between the best and the worst suitability class (Figure 4.13 d), which clearly shows difference in volume growth of stands with respect to bio-physical factors.

The volume growth functions in S1, S2, S3 indicate that the biological optimal rotation age depends on site quality. The optimal rotation age was 4 years for plantations in S1, 5 years in S2 and 22 years in S3. The pattern is illustrated in Figure 4.14. The optimal rotation is realized where the mean growth and the current growth are equal.





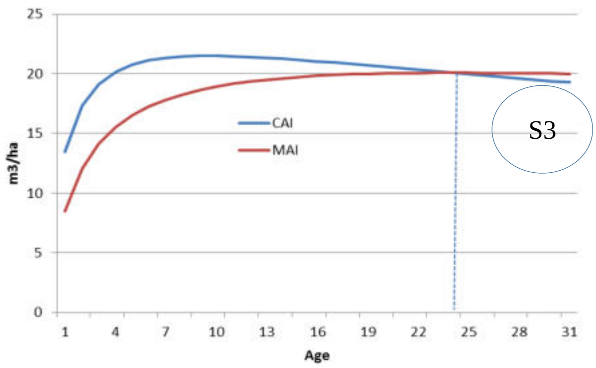


Figure 4.14 Biological optimum to gain the maximization of the sustainable yield (CAI: current annual increment, MAI: Mean annual increment), (S1: highly suitable, S2: Moderately suitable, S3: Marginally suitable)

The maximum sustainable yields found are of 25.32 m^3/year for S1, 21.23 m^3/year for S2 and 20.07 m^3/year for S3. Based on the volume growth functions, productivity (m^3/ha) or annual productivity (m^3/ha/year) is assigned to each suitability class. A map of potential productivity at age 6 years is presented in the Figure 4.15.

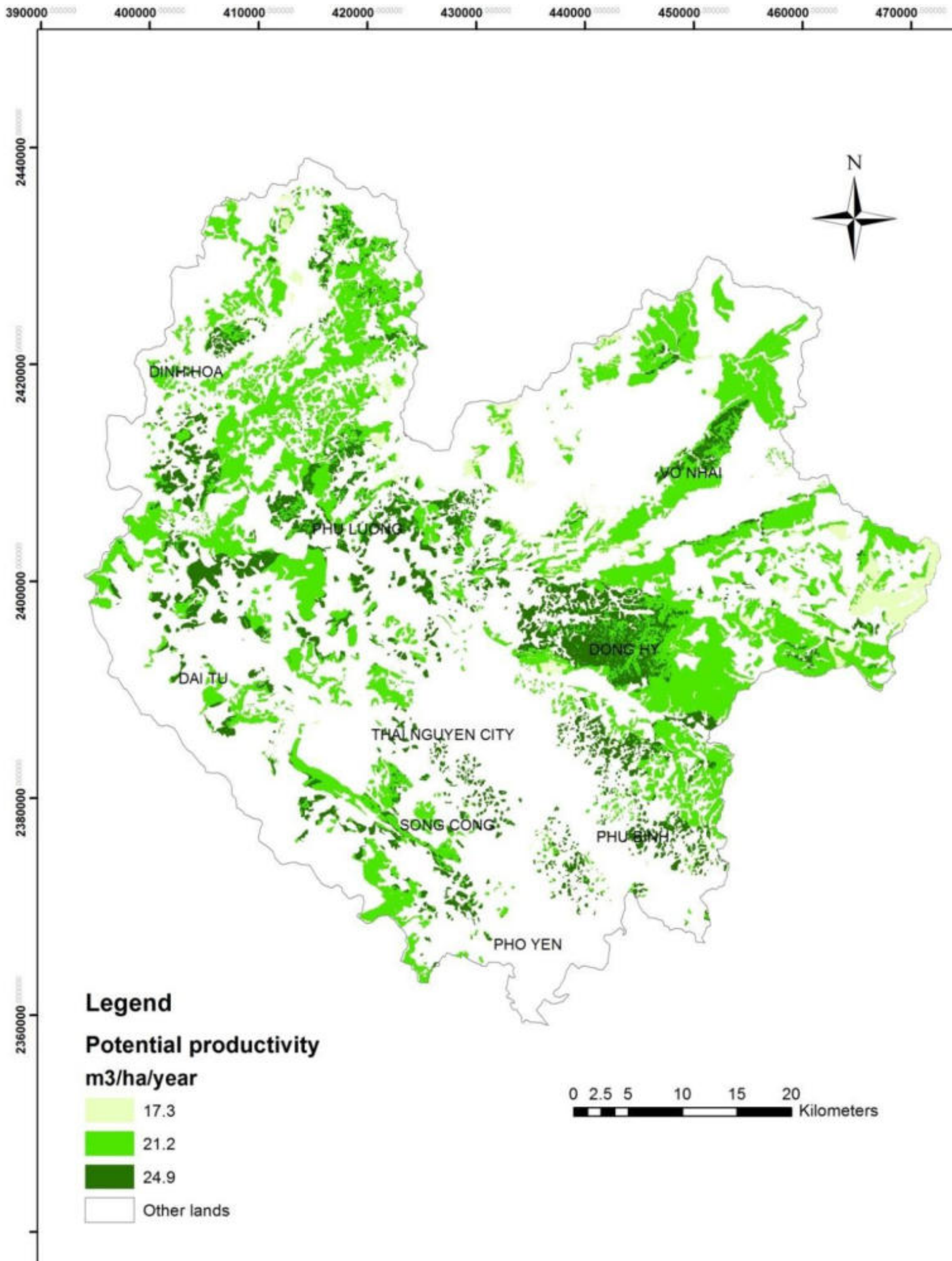


Figure 4.15 Map showing productivity for *A. mangium* plantations at age 6 years on the land area planned for production forest

4.3 Scenario results

This section presents the results of the optimization model used in order to maximize household profit. There scenarios analyzed are: (see 3.2.6)

- BAU: represents the basic results of current management practices. In this scenario, the values of independent variable used in optimization model are calculated when forest plantation is harvested at age 7 years.
- ROT: is analyzed to indicate different profits achieved according to different rotation ages and optimal rotation age. The result of optimal rotation age is used for comparision with other scenarios.
- ECO: This scenario analyses shows the change of households' profit obtained by assumed variations in timber demand (ECO_demand), in timber price (ECO_price) and in costs (ECO_cost).
- Mill_new, Mill_coop: are scenarios incorporated change of optimization model's constraints by changing mill capacities. In Mill_new additional mills are added to the set of existing mills. In Mill_coop the existing mills with low capacities are replaced by three new mills with larger capacities.
- Con_: is a scenario realizing environmental interest

The scenario analyses have been performed under the two approaches "Landscape Approach" and "Current Forest Approach", which are described in the section 3.2.5

4.3.1 BAU (Business As Usual)

The objective of this scenario is to study the effects of current management practices on outcomes of the optimization model such as profit achievement, costs, and land area allocated to meet timber demand. In this scenario, *A. mangium* plantations are harvested at age 7 years according to forest owner's preference (actual practice). Mean values of attributes were used in the optimization process (Table 4.9). The outcomes are total profit, costs, total area needed, and forested area used to fulfill timber demand. The values selected for attributes are given in Table 4.9.

Table 4.9 Value selected for attributes in the optimization model

Attribute	Mean	Min	Max
Establishment cost (USD/ha)	316	256.4	419.8
Silviculture cost (USD/ha)	103	36.3	272.7
Annual management cost (USD/ha/year)	60	-	-
Harvest cost (USD/m^3)	8	6.5	11
Transportation cost (US$/$m^3$/km)	0.3	0.26	0.43
Price at Pallet mills (US$/$m^3$)	52.3	48.7	55.2
Price at veneer mills (US$/$m^3$)	53.6	48.7	58.4
Price at woodchip mills (US$/$m^3$)	55.6	51.9	58.4
Timber demand of each pallet mill (m^3/year)	2038	907	5640
Timber demand of each veneer mill (m^3/year)	3945	1890	8400
Timber demand of each woodchip mill (m^3/year)	7062	3360	10500
Annual timber demand (m^3/year) of all mills (including 215 mills: 37 pallet mills, 119 veneer mills, and 59 woodchip mills)	961519	-	-
Number of parcel of land	42168	-	-
Number of mills	215	-	-

Table 4.10 demonstrates the allocation of the demand for timber (961519 m^3 per year or 6730633 m^3 in 7 years) for different mill types. The allocated area (area of annual harvest) needed to meet timber demands (for the Landscape Approach was 2 % lower (6134 ha/year) than for the Current Forest Approach (6259 ha/year). The difference is caused by the differences in productivity. The productivity of the allocated area to meet timber demand of the Landscape Approach (average productivity 26.1 m^3/ha/year) is higher than that of the Current Forest Approach (average productivity 25.6 m^3/ha/year). Similarly, the costs found of the

Landscape Approach are 11.3% lower than the Current Forest Approach (i.e., 11.59 million US$/year compared to 13.07 million US$/year).

As a result, the total profit was different between the Landscape Approach and the Current Forest Approach. Specifically, the total profit achieved for the Landscape Approach (38.48 million US$/year) was 3.96% higher than that of the Current Forest Approach (36.95 million US$/year).

According to the simulation results, distribution of profit, cost, and area allocated with both approaches varies according to total amount of timber demand from different mill types. As a result of the mills survey, the highest share belongs to veneer mills due to the higher timber demand, followed by woodchip mills and pallet mills. Annual timber demand of all mills is 961519m^3/year. Although the average timber demand by mills is dominated by woodchip mills (7062 m^3/year/mill compared to 3945 m^3/year/mill and 2038 m^3/year/mill of veneer and pallet mills respectively), the total timber demand of veneer mills is highest due to the larger number of veneer mills (37 pallet, 119 veneer and 59 woodchip mills).

Table 4.10 Results for the Landscape Approach and the Current Forest Approach (PA: pallet mills, VE: veneer mills, WC: woodchip mills)

Approach	Category	Total Profit (Mil.US$/year)	Total Costs (Mil.US$/year)	Land area allocated (ha/year)	Demand (m^3/year)
Landscape approach	**Total**	**38.48**	**11.59**	**6134**	**961519**
	PA	2.83	0.94	486	75406
	VE	18.39	5.69	3025	469455
	WC	17.27	4.96	2623	416658
Current forest approach	**Total**	**36.95**	**13.07**	**6259**	**961519**
	PA	2.55	1.22	494	75406
	VE	17.37	6.68	3091	469455
	WC	17.04	5.16	2674	416658

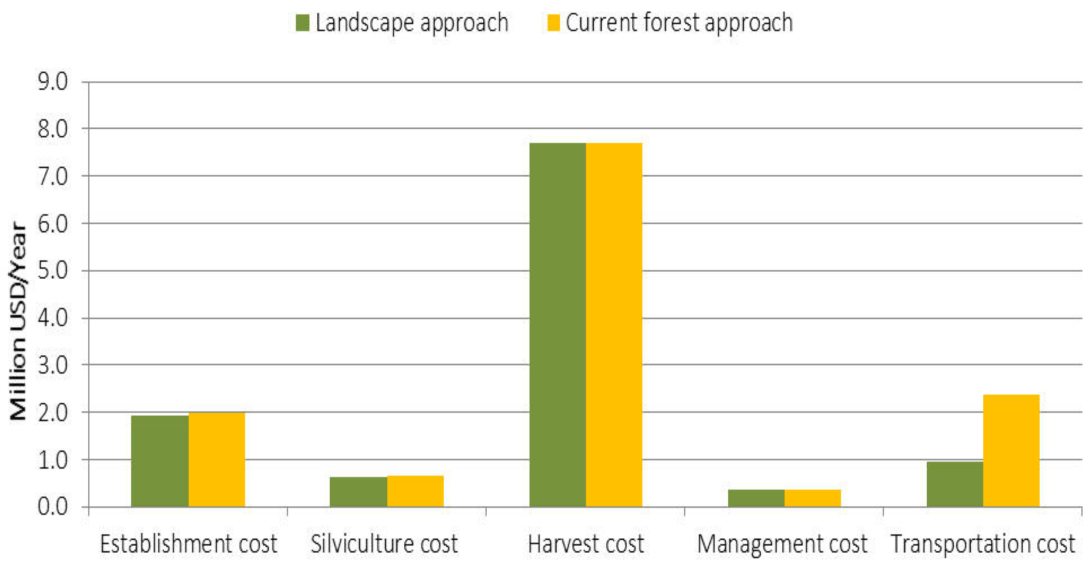


Figure 4.16 Difference in cost components for the _LA approach and the _FO approach

Between the Landscape Approach and the Current Forest Approach, cost components in the Landscape Approach were slightly lower than in the Current Forest Approach, except for harvest cost. Harvest cost was calculated by $/ m^3, while there was the same amount of timber demand under both approaches (Figure 4.16). Transportation cost substantially decreased by 60% (1.4 million US$/year) for *A. mangium* plantations under the Landscape Approach in comparison with the Current Forest Approach.

Figure 4.17 shows distinct differences in the allocation of plantation areas for two approaches. Under the Landscape Approach larger areas of current plantations are not utilized due to the allocation of concurrently unplanted forest areas to meet the same timber demand.

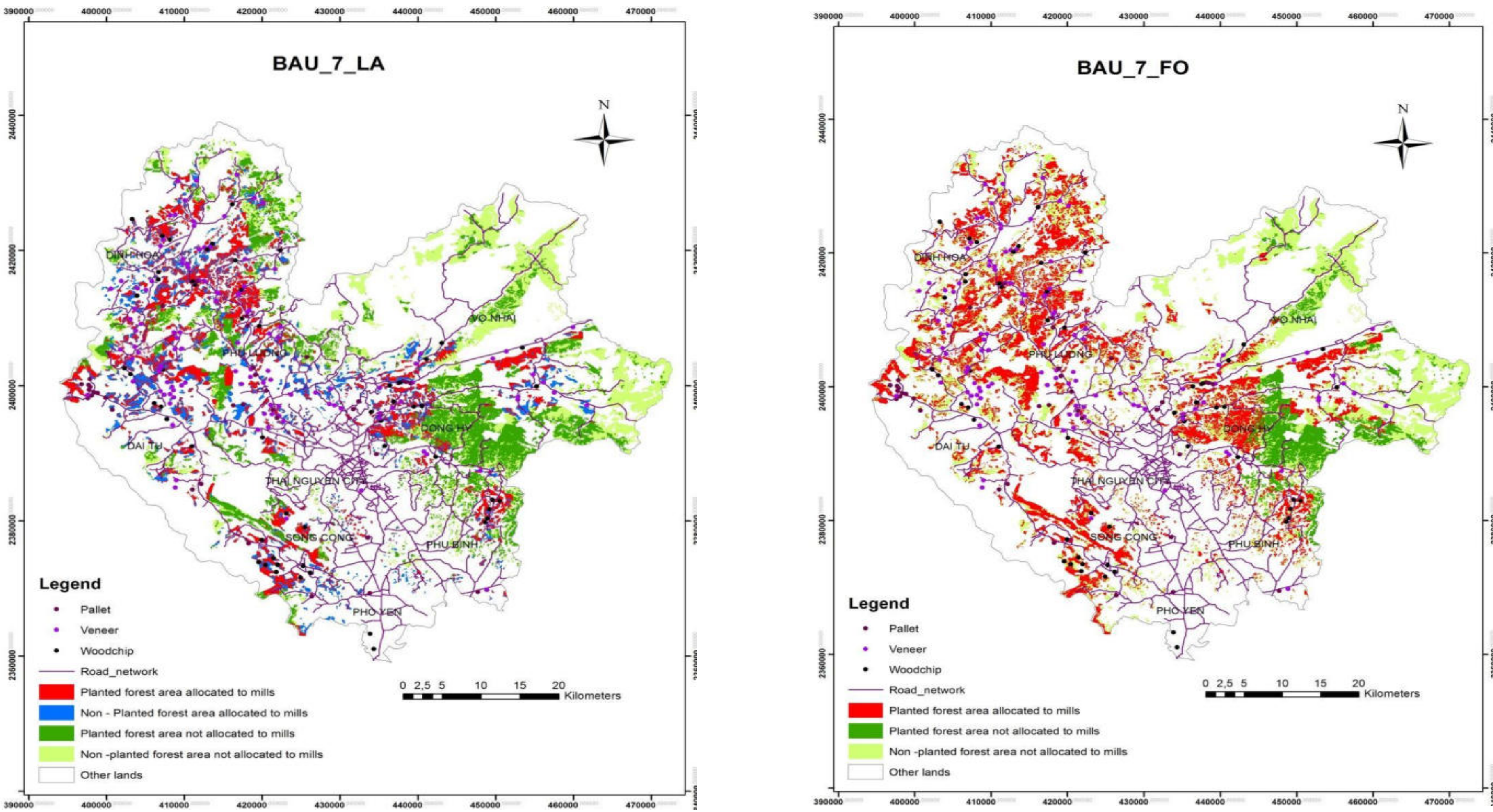


Figure 4.17 Maps showing land area allocated under the Landscape Approach (_LA) and the Current Forest Approach (_FO) for *Acacia mangium* at age 7 years

4.3.2 Rotation ages

The objective of this scenario (ROT) is to maximize profits by adjusting rotation ages, and indicate optimal harvest ages for achieving the highest annual profit for growing a plantation. Mean values of attributes which are used in the optimization model execution were described in Table 4.9. The difference in profit achieved is shown for various ages from 5 years to 12 years for both the Landscape Approach (_LA) and the Current Forest Approach (_FO). The profit is calculated using the optimization model described in section 3.2.5. The results indicate variations in household profits due to different rotation lengths (Figure 4.18).

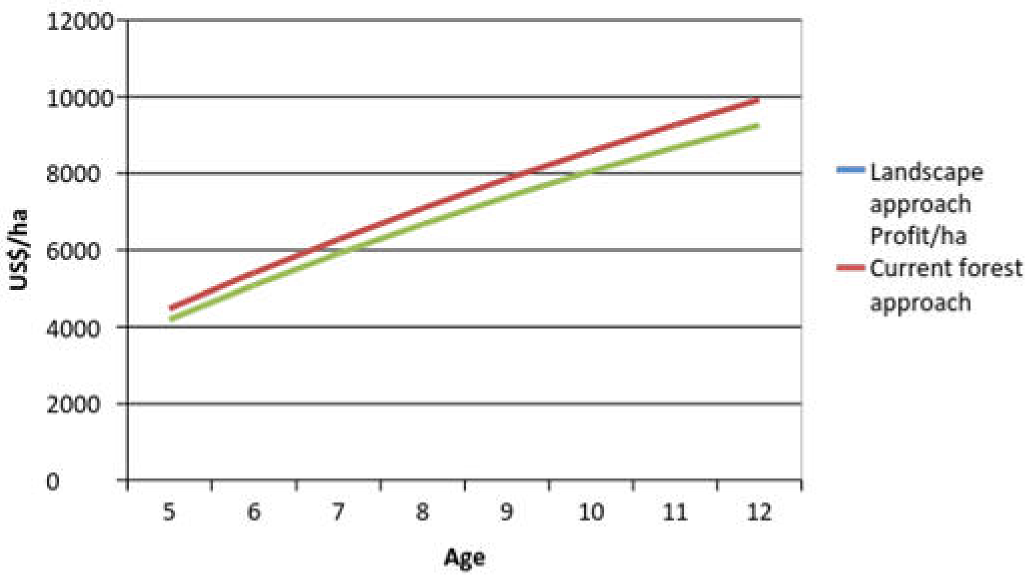


Figure 4.18 Profit per hectare by age for *A. mangium* plantations

Figure 4.18 shows the increase in profit per hectare from age 5 to age 12 for both approaches. The profit per hectare of the Landscape Approach is higher than that of the Current Forest Approach. The optimization model starts at age 5, since no households prefer to harvest their forest plantation earlier. Profit per hectare increased continuously with the age of forest plantations from 4479 US$/ha at age 5 to 9922 US$/ha at age 12 for the Landscape Approach and from 4191 US$/ha at age 5 to 9257 US$/ha at age 12 for the Current Forest Approach.

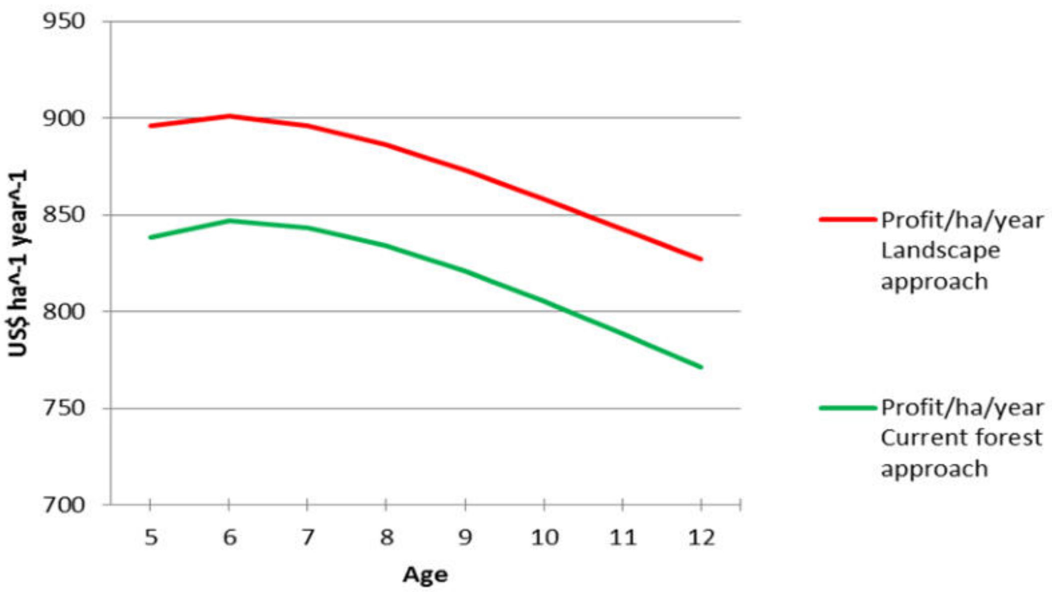


Figure 4.19 Profit per hectare per year by age for *A.mangium* plantation

Figure 4.19 indicates that the highest annual profit (US$/ha/year) is realized for *A.mangium* plantations at age 6 years. Starting with a considerable increase from 5 years to 6 years, the annual profit reached a peak at 901 US$/ha/year and 847 USD US$/ha/year at age 6 years for the Landscape Approach and the Current Forest Approach respectively, followed by a significant decrease from 896 US$/ha/year (at age 7 years) to 827 US$/ha/year (at age 12 years) for the Landscape Approach and from 843 US$/ha/year to 771 US$/ha/year for the Current Forest Approach.

Table 4.11 Land area allocated for the Landscape Approach and the Current Forest Approach for harvesting *A. mangium* plantation at age 6 years

Approach	Total land area allocated (ha/year)	Planted forest area allocated (ha/year)
Landscape Approach	42318	24394
Current Forest Approach	43303	43303

(Total land area includes planted forest areas and unplanted forest areas)

A rotation period of 6 years is considered as the optimal harvest age for a *A. mangium* plantation in the study area. For the first cycle of 6 years, the required timber production of

5769114 m^3 (961519 m^3/ year) is realized on 42318 ha (7053 ha/ year) for the Landscape Approach and 43303 ha (7217 ha/year) for the Current Forest Approach. For the Landscape Approach 24394 ha (4066 ha/year) of already planted areas need to be supplemented by new plantations on 17924 ha (2987 ha/year) to meet the timber demand. Under the Current Forest Approach the entire all 43303 ha are already planted land. However, from the second cycle of 6 years onwards, the total land area allocated would need to be replanted to meet the required timber demand.

This study shows the outcomes of the optimization model when a forest plantation is harvested at 6 years of age, which is named as "ROT_6". The map of land area allocated for growing *A. mangium* plantations with rotation periods of age 6 years is shown in Figure 4.20. Both planted forest areas (red color) and unplanted forest areas (blue color) are allocated to individual mills for the Landscape Approach, while only planted forest areas (red color) are allocated to individual mills for the Current Forest Approach to meet the same demand for timber.

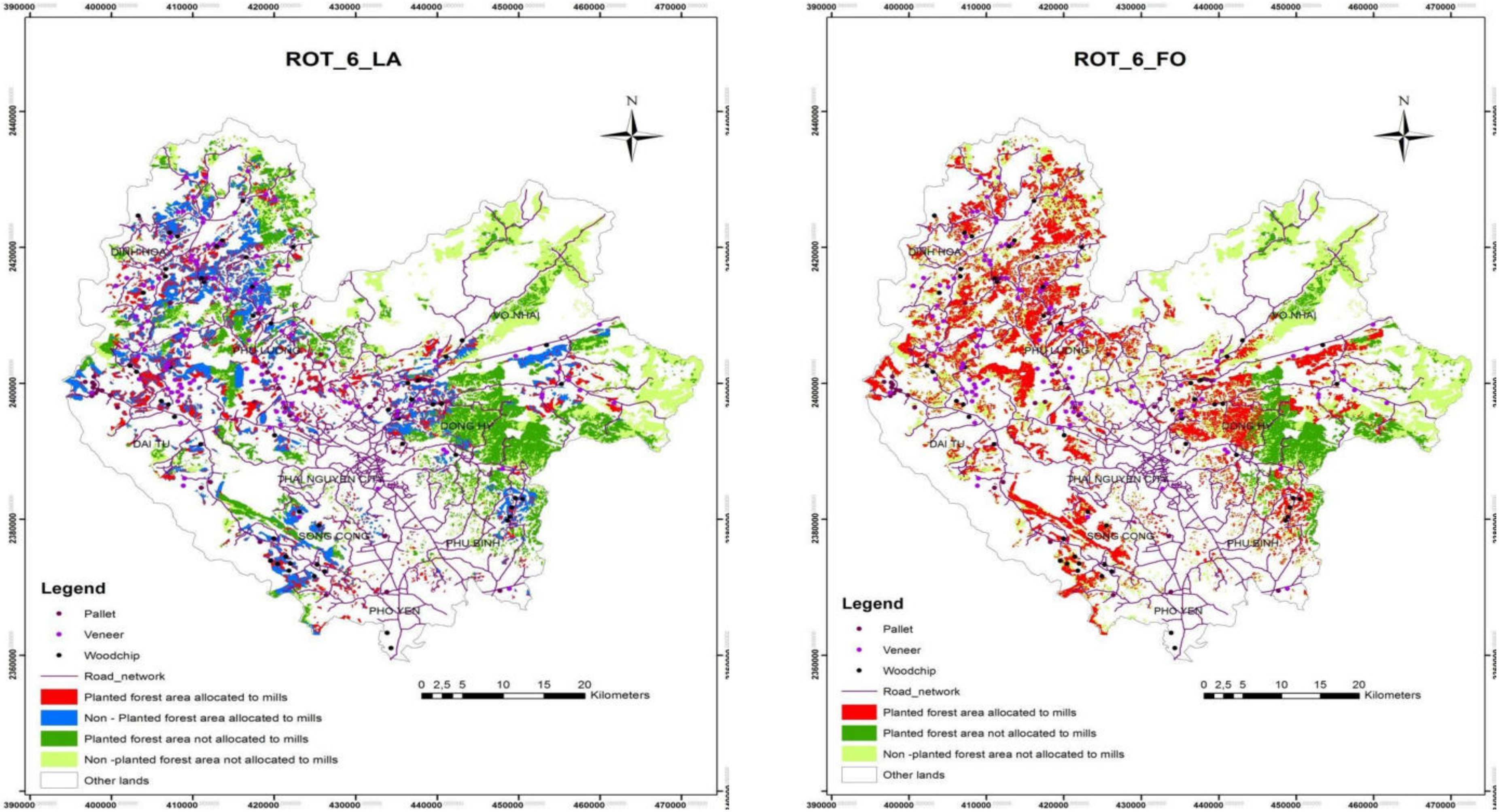


Figure 4.20 Maps showing land area allocated under the Landscape Approach (_LA) and the Current Forested Approach (_FO) for *Acacia mangium* at age 6 years

4.3.3 ECO (economic scenario)

The objective of these scenarios is to study the impact of changes in economic conditions on outcomes of the optimization model such as total profit, allocated land area to meet the timber demand, and costs. These scenarios were analyzed by changing economic conditions such as timber demand (ECO_demand), timber price (ECO_price) and costs (ECO_cost) for A.*mangium* plantations. The rotation age is set at 6 years for *A. mangium* plantations (economically optimal harvest age). Economic scenarios correspond to the objective function of economic aspect representing decisions regarding forest owners (households) and mills. These scenario analyses were also performed under two approaches: the Landscape Approach (_LA) and the Current Forest Approach (_FO).

4.3.3.1 ECO_demand

This scenario shows the variation in timber demand that has an influence on the outcome of the optimization model such as profit, costs, and total land area allocated. In this assumption, changes of timber demand are assumed for all mill types simultaneously. The outcomes of these scenarios are compared with the outcome of "ROT_6" (*A. mangium* plantations harvested at age 6 years, economically optimal harvest age). For all "ECO_demand" scenarios mean values of attributes are used in the optimization model execution (Table 4.9), except for timber demand; productivity was assumed for *A.mangium* plantations on 6 – year rotation. The five timber demand scenarios are:

(1) ECO_demand-30%: Timber demand of all individual mills is assumed to decrease by 30 percent.
(2) ECO_demand+20%: Timber demand of all individual mills is assumed to increase by 20 percent.
(3) ECO_demand+30%: Timber demand of all individual mills is assumed to increase by 30 percent.
(4) ECO_demand+40%: Timber demand of all individual mills is assumed to increase by 40 percent.

(5) ECO_demand+50%: Timber demand of all individual mills is assumed to increase by 50 percent.

Firstly, the effects of simultaneous change in timber demand for all mill types on profit, costs, total land area allocated, and planted forest area are analyzed. Specifically, average profit per hectare per year varied and is shown in Figure 4.21.

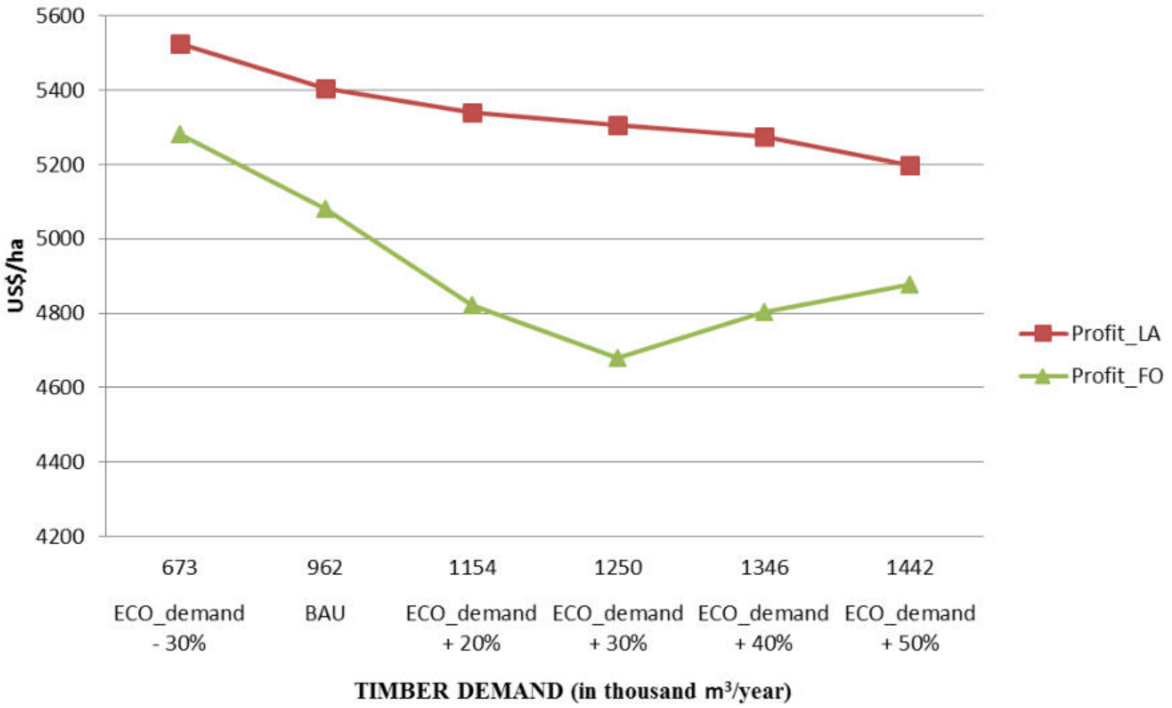


Figure 4.21 Difference in household profit achieved by the Landscape Approach and the Current Forest Approach according to variations in timber demand

There is a clear difference in the average profit obtained by the Current Forest Approach compared to the Landscape Approach. The average profit obtained for the Landscape Approach is higher than that of the Current Forest Approach. The difference is due to the fact that in the Landscape Approach all highest profit parcels are chosen from the available potential land areas without differentiating between planted forest areas and unplanted forest areas, while the Current Forest Approach is implemented by selecting planted forest parcels in advance to meet the timber demand, followed by unplanted forest parcels. This enabled the model execution to determine the highest profit parcels including both planted forest area and unplanted forest area at the same time for the Landscape Approach. For the Current Forest

Approach all planted forest areas are selected before the plantation areas are extended by currently unplanted forest areas to close the gap under insufficient timber supply.

As can be seen from Figure 4.21, the average profit per hectare decreased continuously when timber demand was assumed to increase by 20%, 30%, 40%, and 50% for the Landscape Approach. Because the most profitable areas were allocated to individual mills, hence, the increase of timber demand led to a significant increase of areas with lower profit gains due to lower potential productivity or higher costs, especially transportation cost.

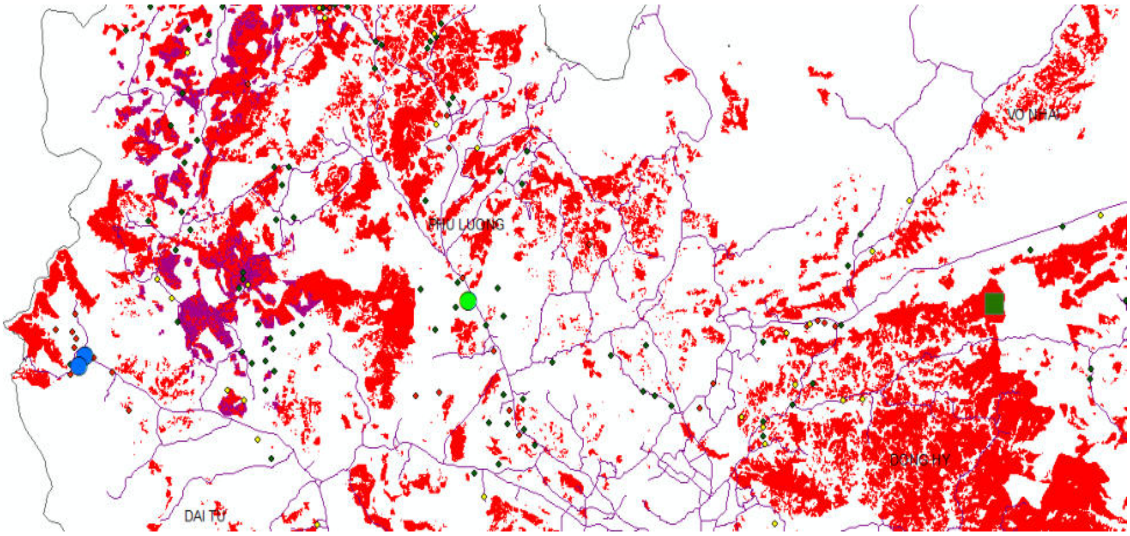
In the Current Forest Approach, the average profit per hectare reached a low of 4679 US$/ha at "ECO_demand+30%", followed by a slight increase when timber demand increased by 40%, and 50%. The main reason for this phenomenon is the fact that almost all the planted forest area (56991 ha) was used to meet the timber supply in the Current Forest Approach. Table 4.12 clearly shows that when timber demand was predicted to increase by 20%, 92% of the total planted forest area was allocated to individual mills (52197 ha). Any further increase in timber demand leads to the extension in to unplanted forest areas, which makes use of higher profit supply points. This results in higher profits obtained as well as lower total costs, especially in transportation cost when timber demand was assumed to increase by 40% and 50% (Figure 4.21, Figure 4.23). For example, there was no need for unplanted forest areas to be used to meet timber demand when timber demand increased by 20%. However, unplanted forest areas started to be used when timber demand increased by 30%, but here only 244 ha unplanted forest areas are used to contribute to the enhancement of the total profit or profit per ha. A larger amount of timber from unplanted forest area (4450 ha and 13114 ha) is used for individual mills when timber demands increase by 40 % and 50%. This results in higher profits under "ECO_demand+40%" and "ECO_demand+50%" compared with the profit obtained from "ECO_demand+30%".

Table 4.12 Total forested area allocated in different timber demand amount over 6 years in the Current Forest Approach (_FO)

Scenario	Total land area allocated (ha)	Unplanted forest area allocated (ha)
ECO_demand-30%	30043	0

ROT_6	43303	0
ECO_demand+20%	52197	0
ECO_6_demand+30%	56749	244
ECO_demand+40%	60972	4450
ECO_demand+50%	69603	13114

Moreover, under the Current Forest Approach the average profit per hectare obtained was lower when demand increased by 30% than for an increase of 40% and 50%. This effect is due to the assignment of timber amount to mills by the optimization model (Section 3.2.5). Timber supply points (land parcels) were shifted among mills, which causes an increase in transportation costs and a substantial reduction in profit achieved. Figure 4.22 offers a clear example of the process used to assign timber supply to mills that has an effect on transportation cost and profit per cubic meter. Specifically, when timber demand increases by 30%, the timber source of parcel 41119 would be delivered to mill 0 (pallet) and 7 (pallet), the profit per cubic meter gained is 13.7 and 13.5 US$/m^3 while transportation costs are 24.5 and 24.6 US$/m^3, respectively. Otherwise, if timber demand increases by 40%, the timber source of parcel 41119 is shifted to mill 141 (pallet), and resulting profit per cubic meter gained is 24.1 US$/m^3 and the transportation cost was 14.1 US$/m^3. This explains the special phenomenon that under a timber demand increase by 30%, the profit gain is lower and transportation costs are higher in comparison with the situation under an increased timber demand by 40% and 50%.

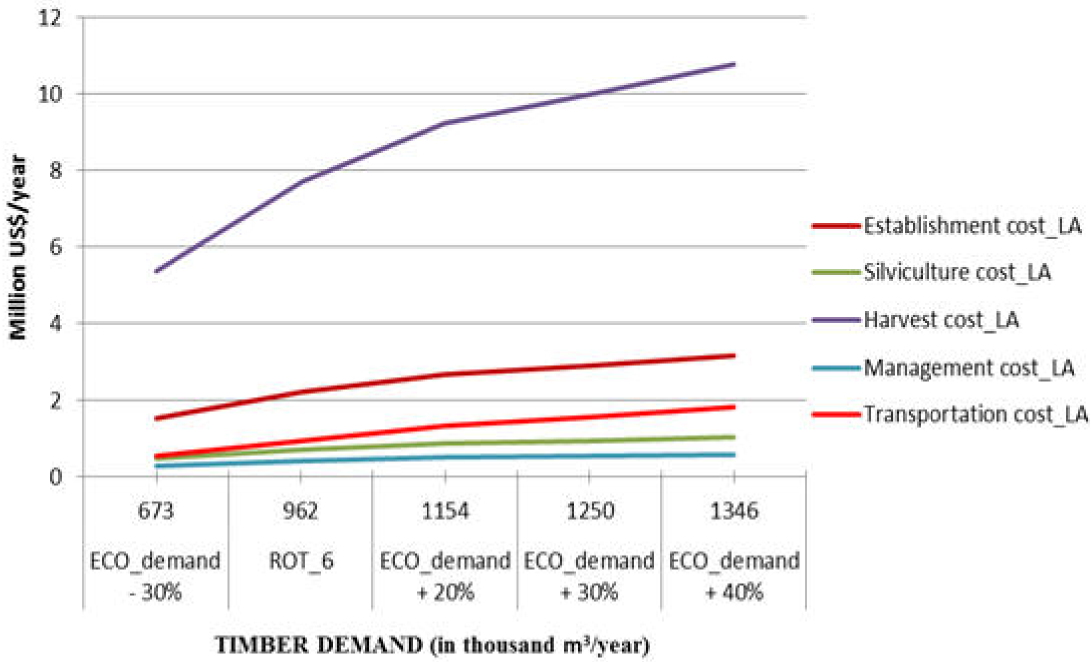


: Selected parcel of land (41119) : mill 141 : mill 0 and mill 7

: Transport network Parcels of land (Forest land area)

Figure 4.22 The effect of timber demand on profit/m^3 and transportation cost/m^3

a)



b)

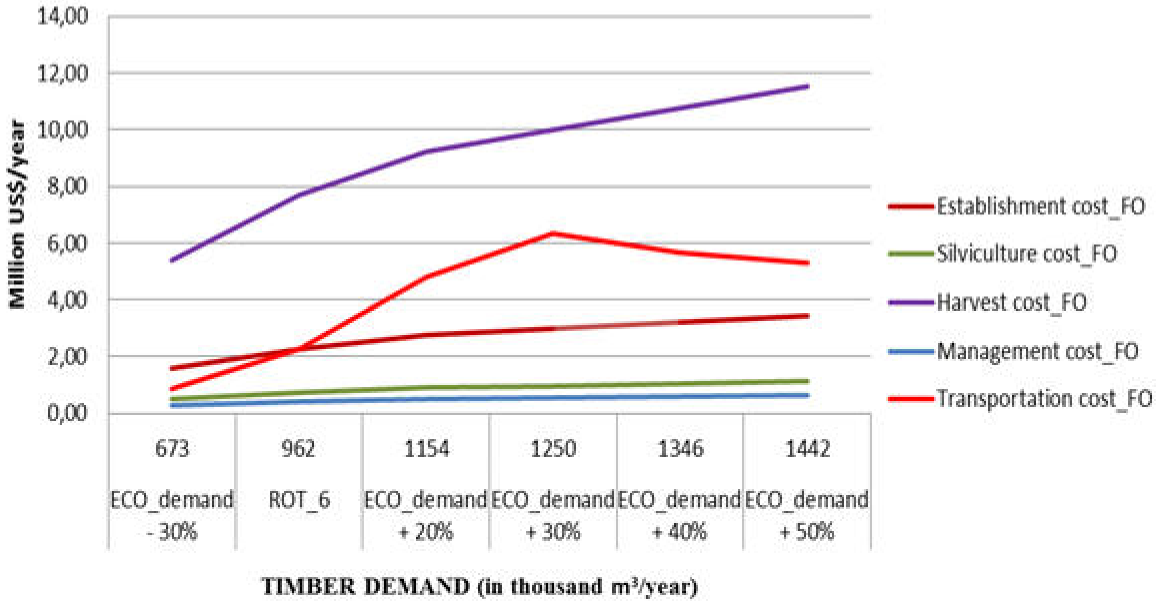


Figure 4.23 Change in costs in the Landscape Approach (a) and the Current Forest Approach (b) based on timber demand variations

Figure 4.23 shows a clear upward trends in total costs when timber demand increases. Of those, harvest cost exceeded other costs. Total harvest cost was calculated based on the timber amount harvested, hence, the total harvest cost increases according to the increase in timber demand. Transportation cost slightly increases continuously with increasing timber demand under the Landscape Approach, while under the Current Forest Approach this cost rose considerably until timber demand increases by 30%, and then started to decrease as timber demand increases by 40% and 50%. This is due to the fact that under an increase in timber demand of 40% and 50% a greater amount of previously unplanted forest areas is used than under timber demand increased by 30%.

In addition, assumptions of timber demand changes by mill types are implemented. Here, increases or decreases were allocated separately and alternately to each mill type. In the following twelve sub-scenarios for variations in timber demand for each mill type are presented. For all twelve sub-scenarios the mean values of attributes are used in the optimization model execution (Table 4.9); productivity was assumed for *A. mangium* plantations on 6 – year rotation.

(1) ECO_demand_PA-30%: Timber demand is assumed to decrease by 30 percent only in pallet mills and the timber demand of different mill types remained unchanged

(2) ECO_demand_PA+20%: Timber demand is assumed to increase by 20 percent only in pallet mills and the timber demand of different mill types remained unchanged

(3) ECO_demand_PA+30%: Timber demand is assumed to increase by 30 percent only in pallet mills and the timber demand of different mill types remained unchanged

(4) ECO_demand_PA+40%: Timber demand is assumed to increase by 40 percent only in pallet mills and the timber demand of different mill types remained unchanged

(5) ECO_demand_VE-30%: Timber demand is assumed to decrease by 30 percent only in veneer mills and the timber demand of different mill types remained unchanged

(6) ECO_demand_VE+20%: Timber demand is assumed to increase by 20 percent only in veneer mills and the timber demand of different mill types remained unchanged

(7) ECO_demand_VE+30: Timber demand is assumed to increase by 30 percent only in veneer mills and the timber demand of different mill types remained unchanged

(8) ECO_demand_VE+40%: Timber demand is assumed to increase by 40 percent only in veneer mills and the timber demand of different mill types remained unchanged

(9) ECO_demand_WC-30%: Timber demand is assumed to decrease by 30 percent only in woodchip mills and the timber demand of different mill types remained unchanged

(10) ECO_demand_WC+20%: Timber demand is assumed to increase by 20 percent only in woodchip mills and the timber demand of different mill types remained unchanged

(11) ECO_demand_WC+30%: Timber demand is assumed to increase by 30 percent only in woodchip mills and the timber demand of different mill types remained unchanged

(12) ECO_demand_WC+40%: Timber demand is assumed to increase by 40 percent only in woodchip mills and the timber demand of different mill types remained unchanged

Change of the average profit by variation in timber demand for specific mill types is presented in Table 4.13 and Table 4.14.

Table 4.13 Change of profit with various timber demands for specific mill types under the Landscape Approach, 6 – year rotation

Scenarios	**Profit US$/ha**	**Profit_PA US$/ha**	**Profit_VE US$/ha**	**Profit_WC US$/ha**
ROT_6	5406	5004	5227	5687
ECO_demand_PA – 30%	5417	5080	5301	5687
ECO_demand_PA + 20%	5396	5025	5285	5768
ECO_demand_PA + 30%	5393	5004	5227	5687
ECO_demand_PA + 40%	**5388**	4974	5225	5687
ECO_demand_VE – 30%	5475	4978	5225	5687
ECO_demand_VE + 20%	5362	4965	5225	5687
ECO_demand_VE + 30%	5341	4988	5179	5687
ECO_demand_VE + 40%	**5321**	4941	5162	5687
ECO_demand_WC – 30%	5426	4920	5143	5687
ECO_demand_WC + 20%	5386	4978	5187	5639
ECO_demand_WC + 30%	5378	4968	5172	5619
ECO_demand_WC + 40%	**5369**	4920	5154	5602

Table 4.14 Change of profit with various timber demands for specific mill types under the Current Forest Approach, 6 – year rotation

Scenarios	Profit US$/ha	Profit_PA US$/ha	Profit_VE US$/ha	Profit_WC US$/ha
ROT_6	5082	4459	4828	5494
ECO_demand_PA – 30%	5118	4595	4851	5496
ECO_demand_PA + 20%	5057	4457	4797	5494
ECO_demand_PA + 30%	5045	4416	4791	5493
ECO_demand_PA + 40%	**5031**	4345	4789	5492
ECO_demand_VE – 30%	5228	4728	5011	5496
ECO_demand_VE + 20%	4937	4333	4619	5494
ECO_demand_VE + 30%	4861	4337	4507	5493
ECO_demand_VE + 40%	**4776**	4229	4399	5493
ECO_demand_WC – 30%	5145	4574	4962	5607
ECO_demand_WC + 20%	5004	4328	4684	5413
ECO_demand_WC + 30%	4951	4343	4577	5367
ECO_demand_WC + 40%	**4906**	4253	4490	5332

(Profit: profit obtained by timber allocated to all mills; Profit_PA, Profit_VE and Profit_WC: profit obtained by timber allocated to pallet mills, to veneer mills, and to woodchip mills)

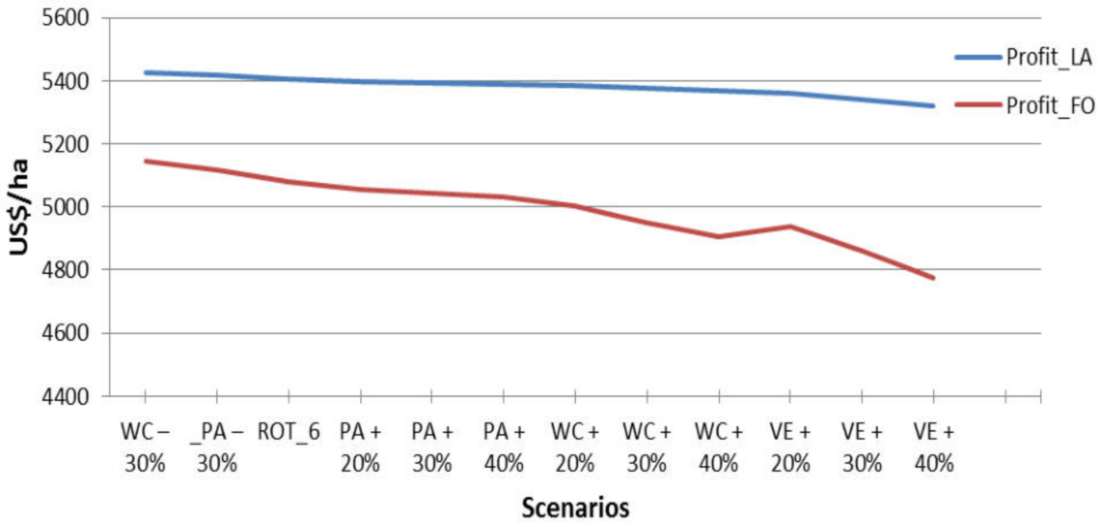


Figure 4.24 Change in profit per hectare for the Landscape Approach (blue color) and the Current Forest Approach (red color) when timber demand is changed for specific mill types

Generally, the profits achieved show a downward trend with increasing timber demand from any mill type (Figure 4.24, Table 4.13, and Table 4.14). The increase of timber demand had a smaller effect on profit per hectare when timber demand was assumed to increase from pallet mills in comparison with veneer mills and woodchip mills. For example, under the Landscape Approach the total profit achieved is 5388 US$/ha when timber demand increases by 40% in pallet mills and 5321 US$/ha and 5369 US$/ha when timber demand increases by 40% in veneer mills and woodchip mills, respectively. Similarly, under the Current Forest Approach the profit is 5031 US$/ha when timber demand increases by 40% in pallet mills and 4776 US$/ha and 4906 US$/ha when timber demand increases by 40% in veneer mills and woodchip mills, respectively. This is caused by the fact that there are fewer pallet mills and there is a lower timber demand from pallet mills, compared with veneer mills and woodchip mills, which leads to higher profit found in pallet mills when timber demand increased by the same percentage.

With regard to profit obtained by timber to be delivered to each mill type, the profit obtained from woodchip mills is higher than that from veneer mills and pallet mills, as the timber price at woodchip mills is higher in comparison with other mill types. In addition, the percentage of profit reduced by timber demand was assumed to increase separately in each mill type under the Landscape Approach was lower than that under the Current Forest Approach. For example, under the Landscape Approach timber demand was assumed to increase by 40% in three mill types, 1.7% “ECO_demand_VE+40%”, 1.7% “ECO_demand_WC+40%” and 0.8% “ECO_demand_PA+40%” lower profit is obtained compared with “ROT_6” (usual demand for timber). In comparison, under the Current Forest Approach 6% “ECO_demand_VE+40%”, 3.5% “ECO_demand_WC+40%” and 1% “ECO_demand_PA+40%” lower profit is obtained compared with “ROT_6”.

Spatial areas expanded according to timber demand are shown in Figure 4.25, Figure 4.26, Figure 4.27, Figure 4.28, and Figure 4.29.

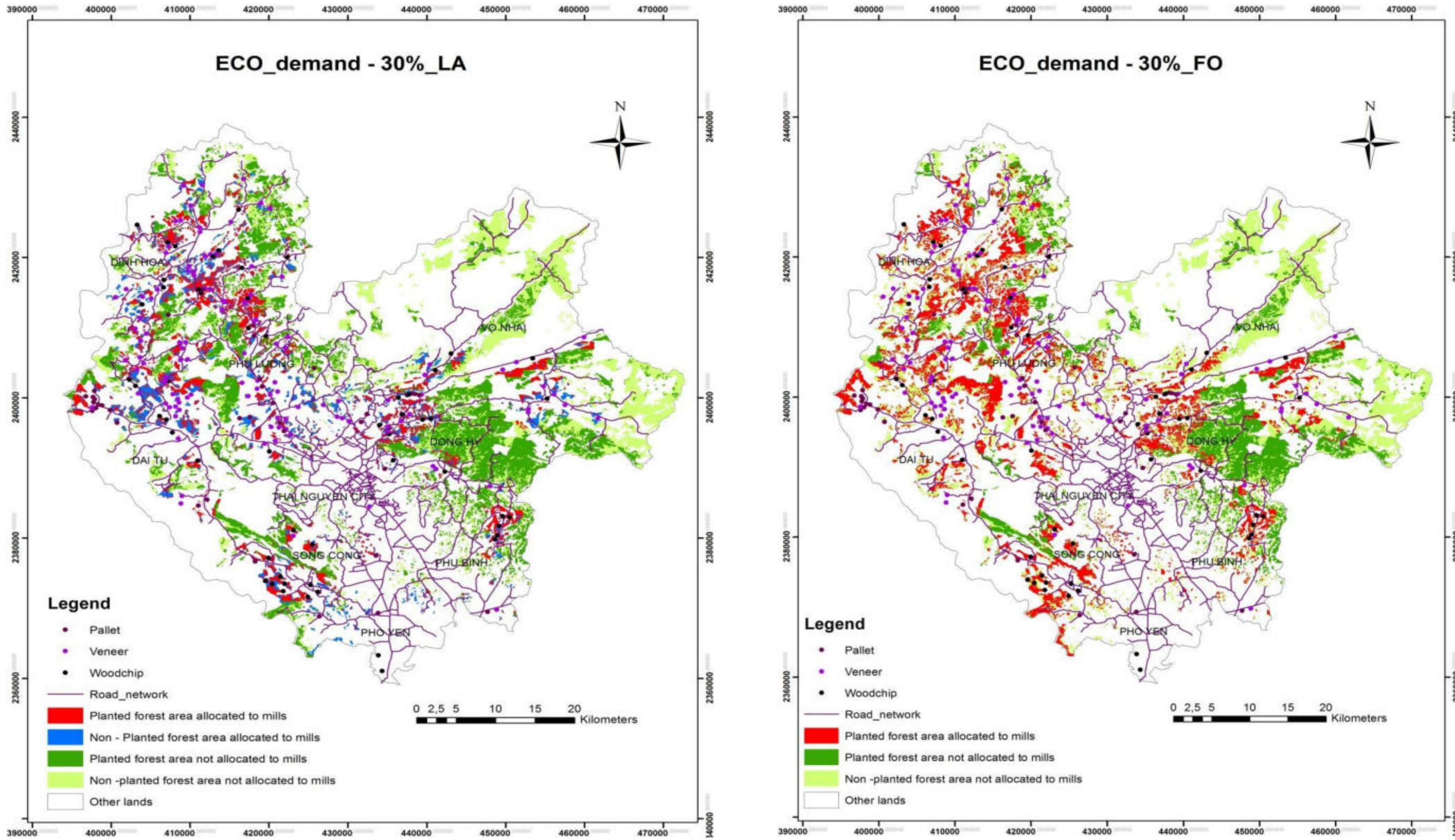


Figure 4.25 Maps showing the distribution of land area allocated by decreasing timber demand 30% on 6 – year rotation

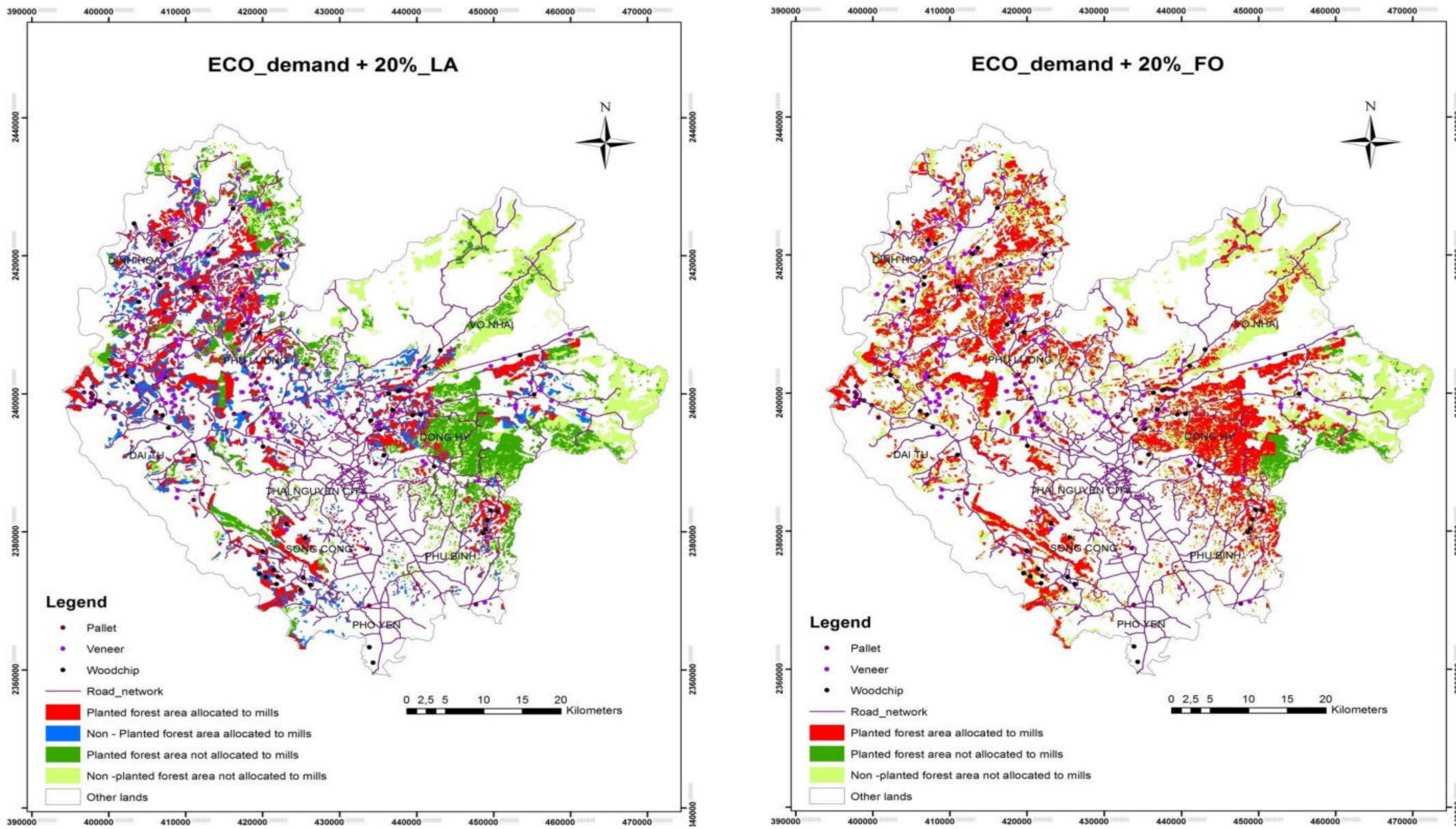


Figure 4.26 Maps showing the distribution of land area allocated by increasing timber demand 20% on 6 – year rotation

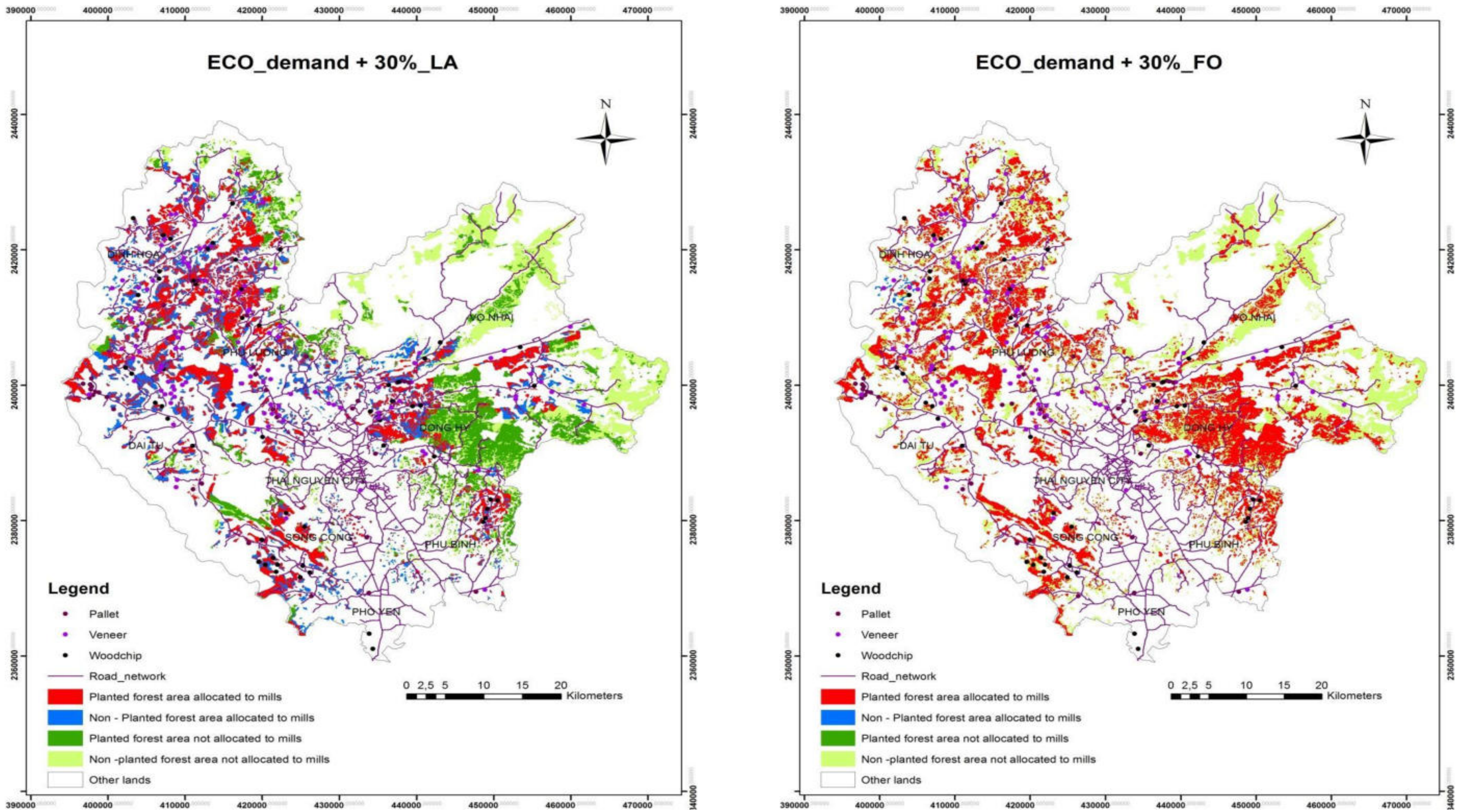


Figure 4.27 Maps showing the distribution of land area allocated by increasing 30% timber demand on 6 – year rotation

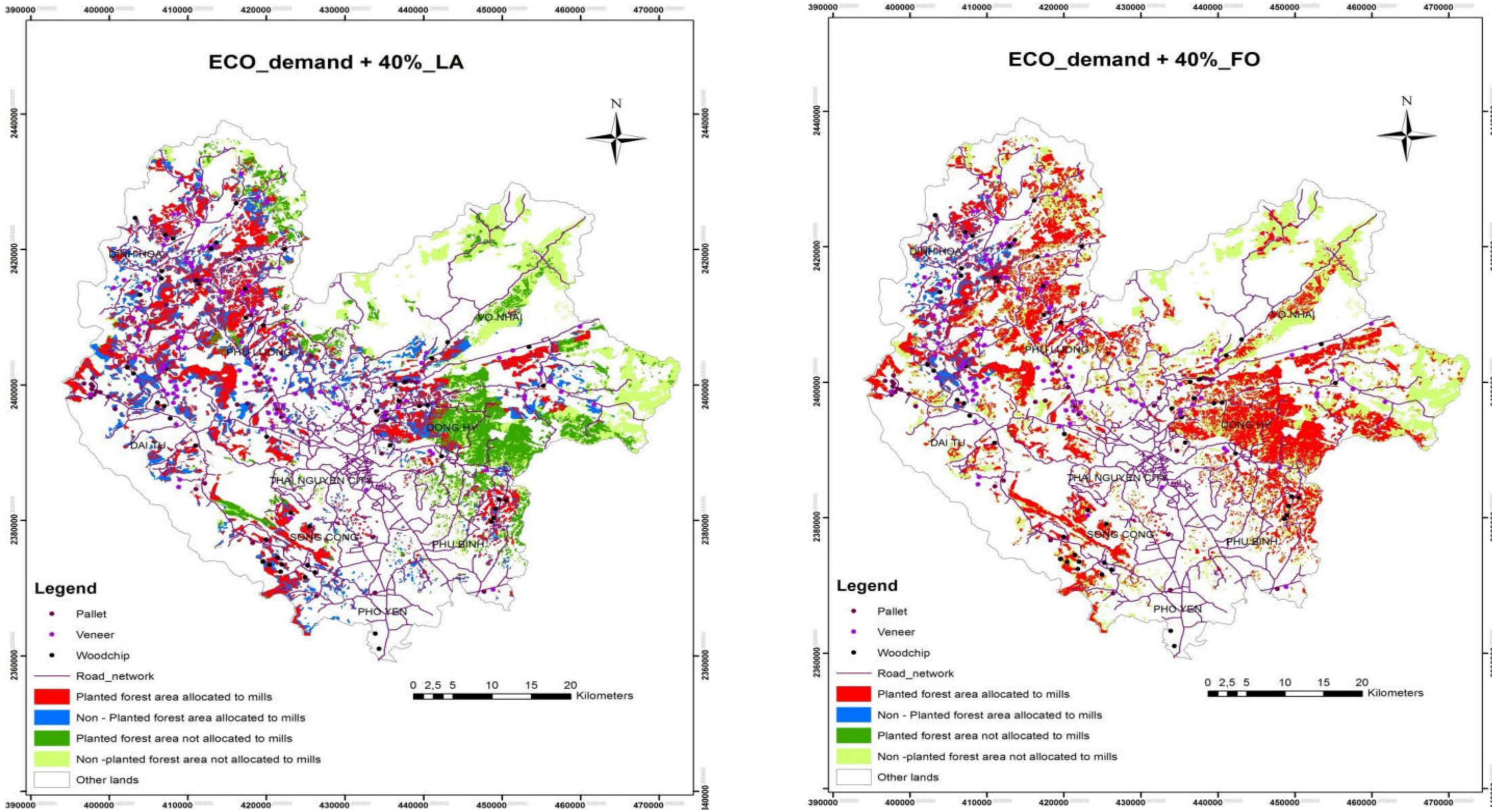
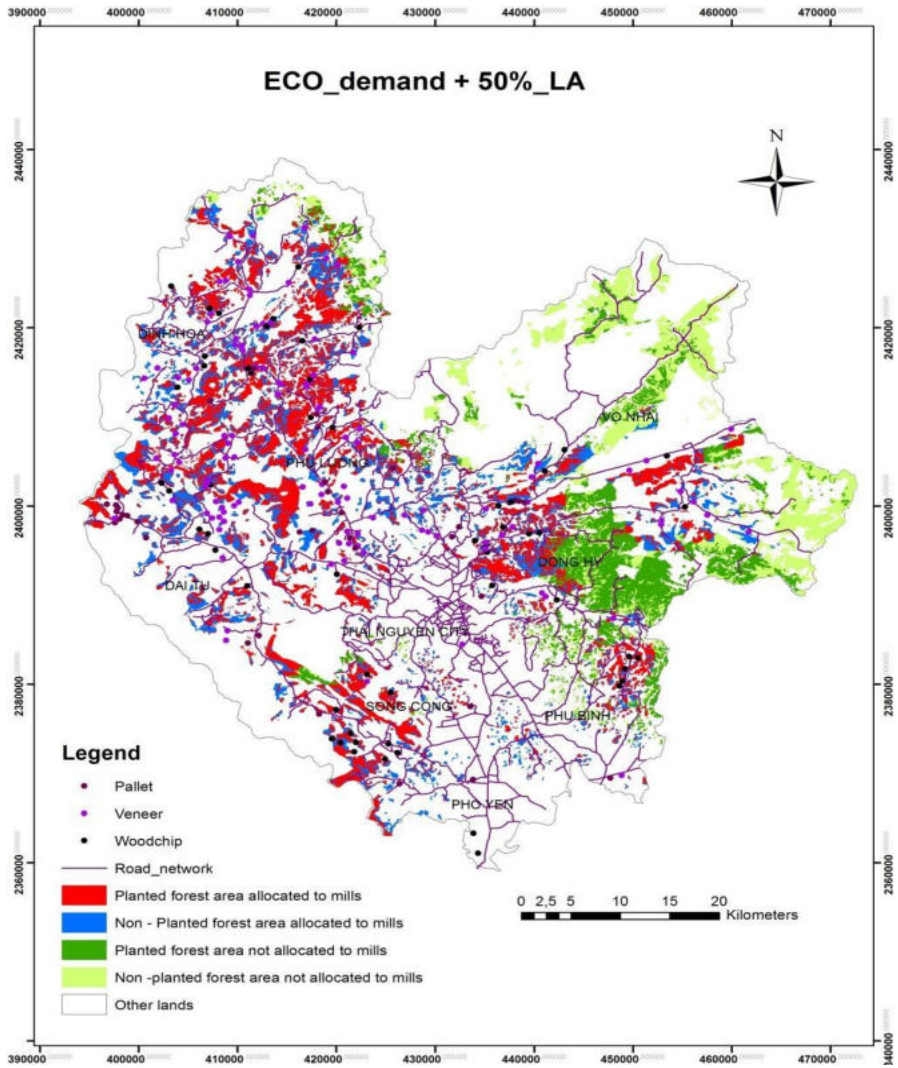


Figure 4.28 Maps showing the distribution of land area allocated by increasing timber demand 40% on 6 – year rotation



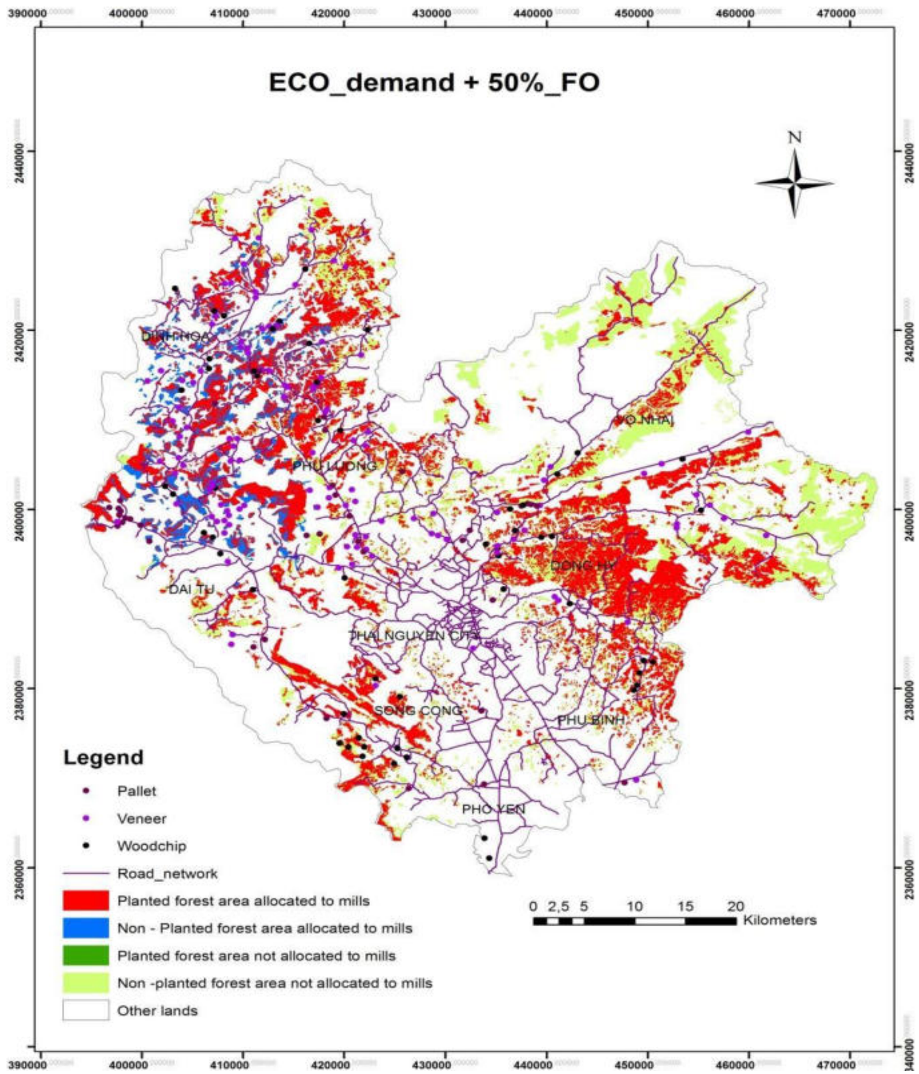


Figure 4.29 Maps showing the distribution of land area allocated by increasing timber demand 50% on 6 – year rotation

4.3.3.2 ECO_ price

The scenario "Eco_price" is run under the assumption that timber prices vary within sub-regions and timber price is assumed to be equal at all mill types. Mean values of attributes are used in the optimization model (Table 4.9), except for timber price.

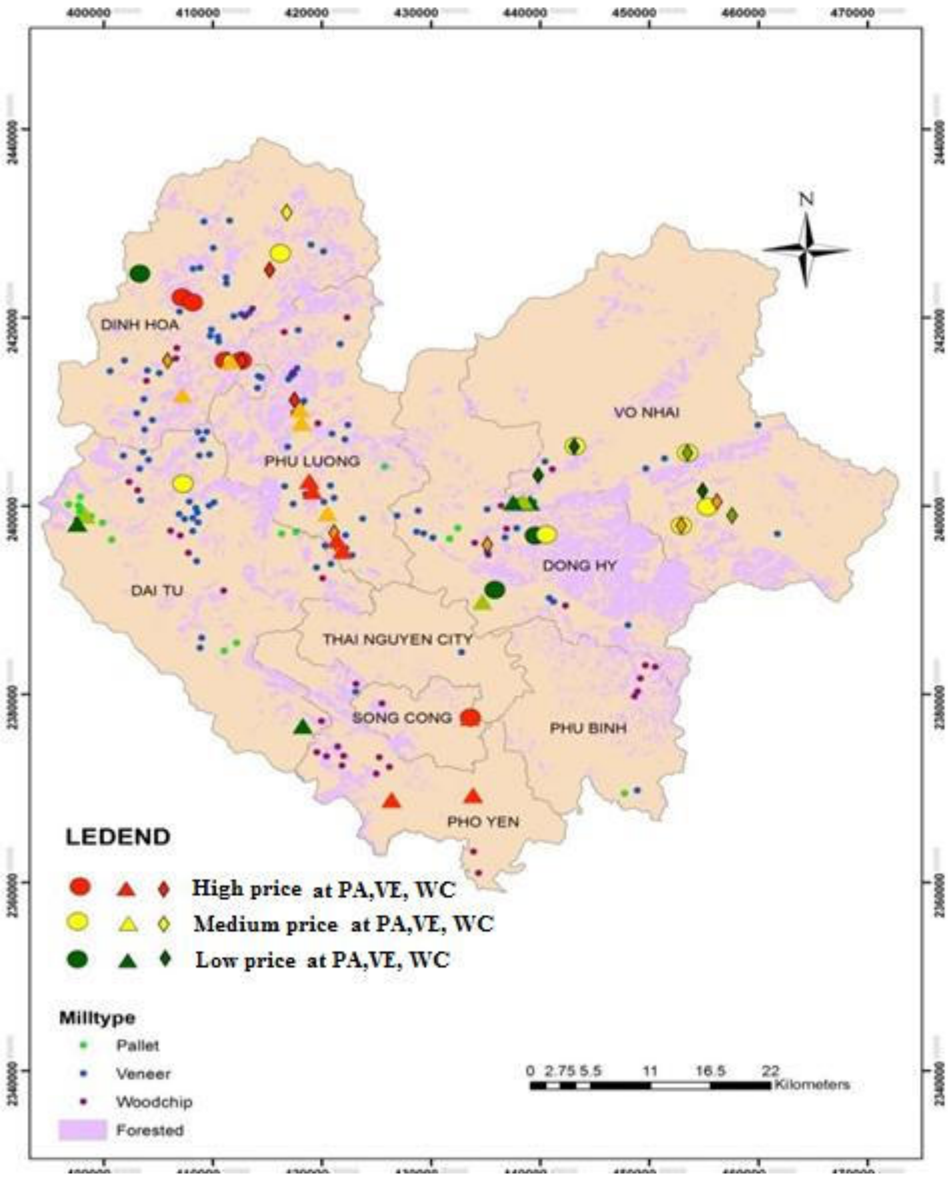


Figure 4.30 Map showing various timber prices at mills

The difference in timber price is assumed by the centralized mills and the distance between mills and planted (forested) plantations density (Figure 4.30). We assumed that timber in the

Dinh Hoa and Phu Luong districts is purchased at a higher price by all mill types due to higher number of mills (higher competition in timber source). Pho Yen, Thai Nguyen City and Song Cong is assumed to have higher prices because of their distance from the timber source (higher transportation cost). The scenario analyses is performed under the two approaches: the Landscape Approach and the Current Forest Approach, which is described in Section 3.2.5. The outcomes of these scenarios are compared with the outcome of "ROT_6" (*A. mangium* plantations harvested at 6 years, economically optimal harvest age). Timber price in "ROT_6" is calculated based on timber price derived from mill survey for different mills and presented in Table 4.9. Four sub-scenarios were defined. All scenarios use mean values of attributes are used in the optimization model (Table 4.9); productivity was assumed for *A. mangium* plantations on 6 – year rotation. The four sub-scenarios are:

(1) ECO_price_523: Timber price is assumed to be equal to 52.3 US$/$m^3$ for all mill types.

(2) ECO_price_536: Timber price is assumed to be equal to 53.6 US$/$m^3$ for all mill types.

(3) ECO_price_556: Timber price is assumed to be equal to 55.6 US$/$m^3$ for all mill types.

(4) ECO_ price_dif: The higher timber price is assumed to be 57.1 US$/$m^3$, 55.6 US$/m^3 and 53.8 US$/$m^3$ at woodchip mills (WC), veneer mills (VE) and pallet mills (PA) respectively when mill types are located in Dinh Hoa, Phu Luong, Song Cong, Pho Yen, Thai Nguyen City (sub-regions). The lower price is assumed to be 54.4 US$/$m^3$, 51.6 US$/m^3 and 49.5 US$/$m^3$ at woodchip mills (WC), veneer mills (VE) and pallet mills (PA) respectively when mill types are located in Dai Tu, Vo Nhai, Dong Hy, Phu Binh (Table 4.15). These prices are calculated based on average value of timber price derived from mill survey according to sub-regions.

Table 4.15 The timber price at mill types varied according sub-regions

Scenarios (change of timber price)	**Distinctive districts (sub-regions)**	**Timber price at mill types**		
		WC	**VE**	**PA**
ECO_ price_dif	Dinh Hoa, Phu Luong, Song Cong, Pho Yen, Thai Nguyen City	57.1	55.6	53.8
	Dai Tu, Vo Nhai, Dong Hy, Phu Binh	54.4	51.6	49.5
ROT_6	Whole area	55.6	53.6	52.3
ECO_ price_523	Whole area	52.3	52.3	52.3
ECO_ price_536	Whole area	53.6	53.6	53.6
ECO_ price_556	Whole area	55.6	55.6	55.6

Table 4.16 and Figure 4.31 show that identical timber prices are assumed for all mill types at levels of 52.3 US$/$m^3$ “ECO_price_523” and 53.6 US$/$m^3$ “ECO_price_536”, the total profit or profit/ha of them are slightly less than that of “ROT_6”, while the assumption of 55.6 US$/$m^3$ “ECO_price_556” to be equal to all mill types shows higher total profit or profit/ha compared with ROT_6. A simple reason is higher timber price (55.6 US$/$m^3$) assumed equally to all mill types in “ECO_price_556”, while lower or equal timber price was assigned to different mill types in “ROT_6” (Table 4.15). This holds true for both approaches.

In addition, there is little difference in profit obtained between “ECO_ price_dif” and “ROT_6”. Profit obtained of “ECO_ price_dif” (5389 US$/ha) is 0.3% less than that of “ROT_6” (5406 US$/ha) for the Landscape Approach, while profit obtained of “ECO_ price_dif” (5048 US$/ha) is 0.7% less than that of “ROT_6” (5082 US$/ha) for the Current Forest Approach. This difference mainly comes from the effect of transportation cost. A 2% higher transportation cost is found in “ECO_ price_dif” compared with “ROT_6” for the Landscape Approach, while a 9% higher transportation cost was found in “ECO_ price_dif” compared with “ROT_6” for the Current Forest Approach (Figure 4.32). Moreover, the land area allocated in “ECO_ price_dif” is slightly higher than that in “ROT_6” for both approaches, which partly leads to lower profit obtained in “ECO_ price_dif” (Table 4.16).

Table 4.16 Differences in cost, profit and land area allocated for growing plantations with variations in timber price on 6-year-rotation

Approach	Scenarios	Total costs (Million US$/year)	Total profit (Million US$/year)	Land area allocated (ha/year)
Landscape Approach (_LA)	ROT_6	3209	38.13	7053
	ECO_price_536	3074	37.42	7059
	ECO_price_523	3074	36.17	7059
	ECO_price_556	3074	39.35	7059
	ECO_price_dif	3274	38.07	7064
Current Forest Approach (_FO)	ROT_6	7601	36.68	7217
	ECO_price_536	8250	36.45	7221
	ECO_price_523	7368	36.01	7225
	ECO_price_556	7368	37.93	7225
	ECO_price_dif	7368	34.76	7225

Figure 4.31 Profit per hectare obtained by timber prices at mills on 6 – year rotation

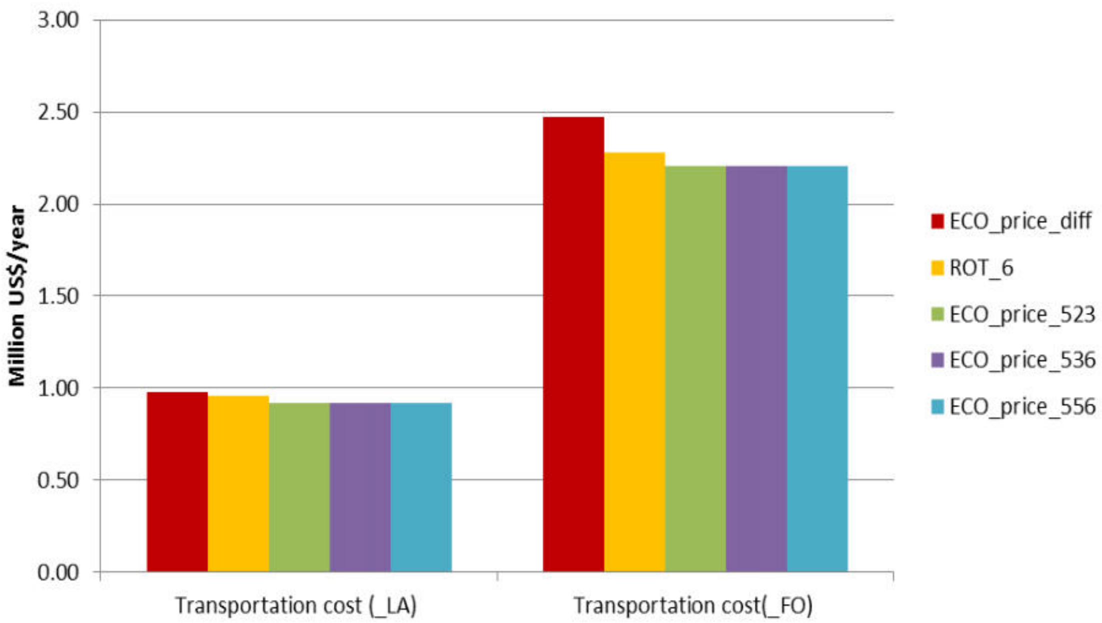


Figure 4.32 Transportation cost varied according to timber price for the Landscape Approach and the Current Forest Approach

Maps showing land area allocated according to variations in timber price and equal timber price assumed are shown in Figure 4.33, Figure 4.34, Figure 4.35, and Figure 4.36. All maps also show that unplanted forest areas did not need to be used to meet timber demand for the Current Forest Approach.

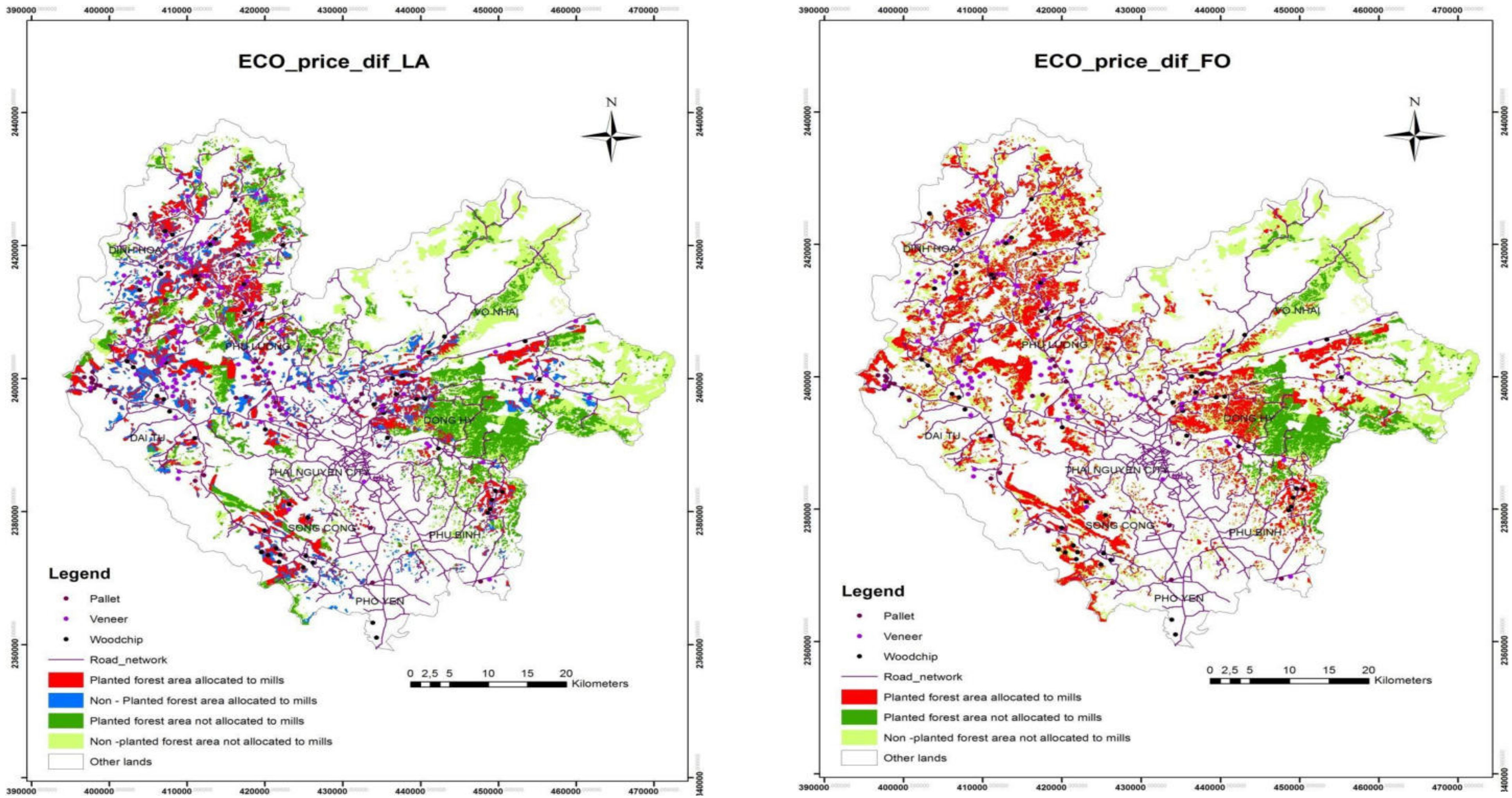


Figure 4.33 Maps showing the distribution of land area allocated by variations in timber price according to sub-regions on 6 – year rotation

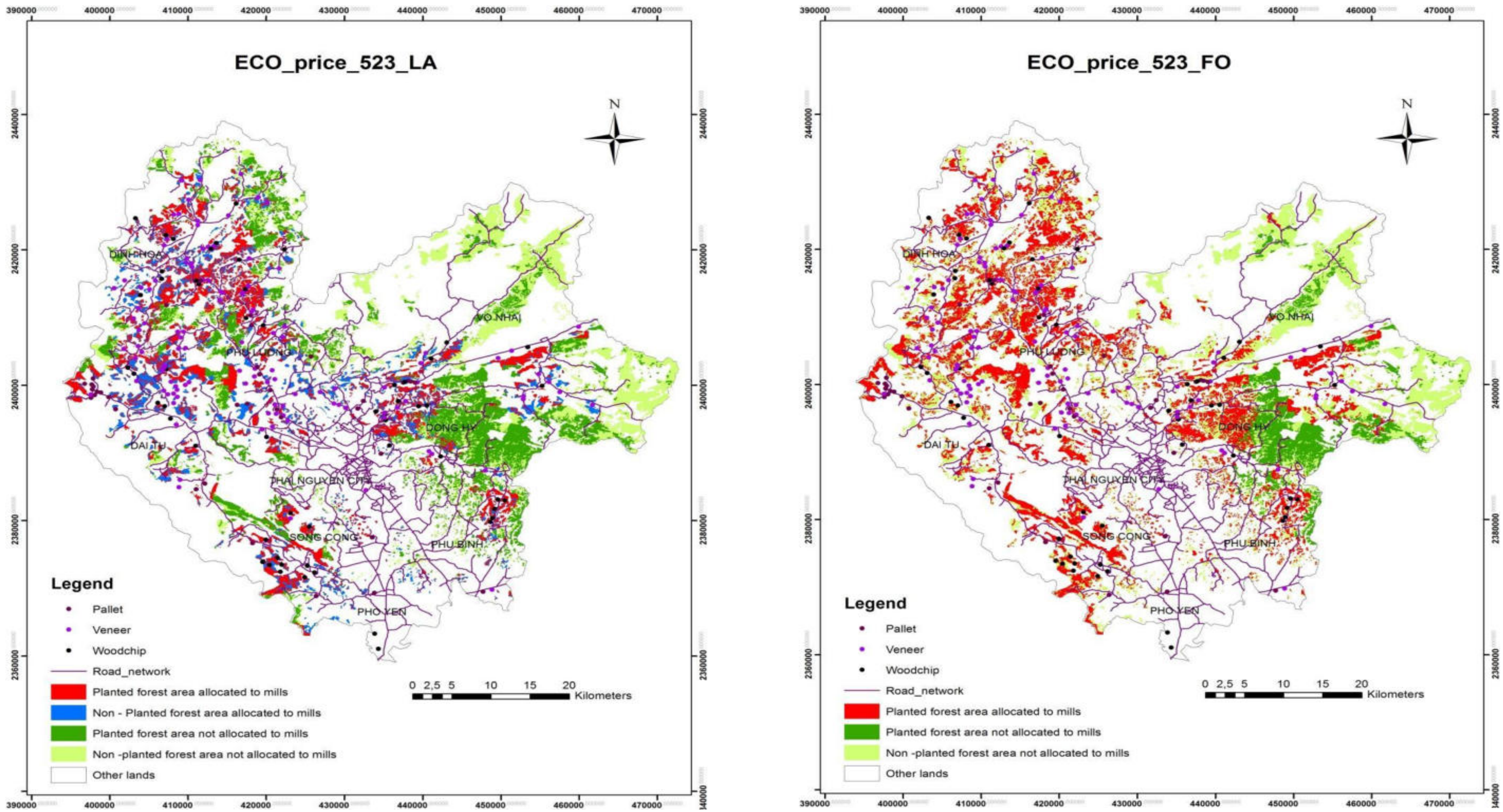


Figure 4.34 Maps showing the distribution of land area allocated by assumption of equal timber price 52.3$/m^3$ to mills on 6 – year rotation

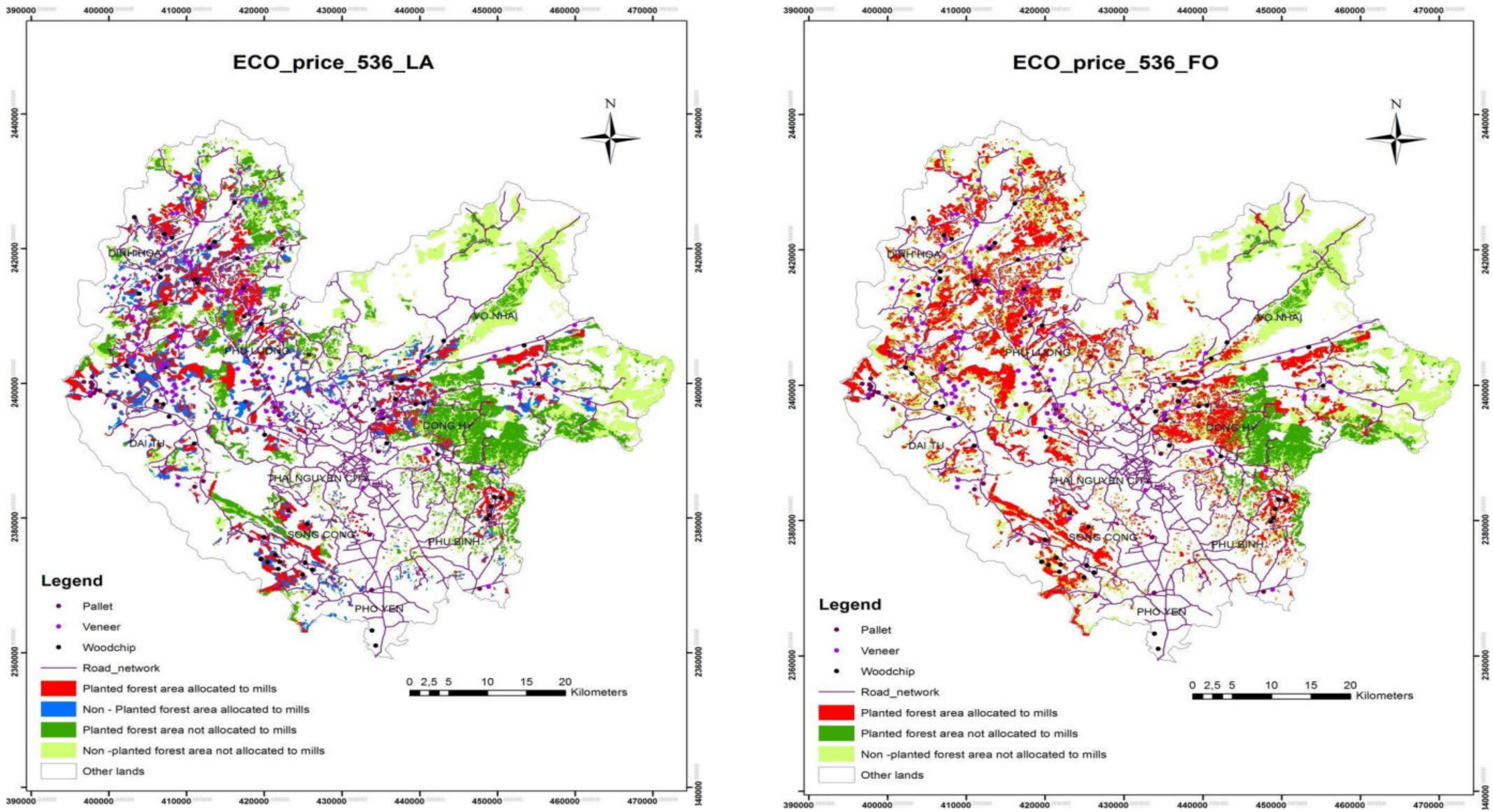


Figure 4.35 Maps showing the distribution of land area allocated by assumption of equal timber price 53.6$/m^3 to mills on 6 – year rotation

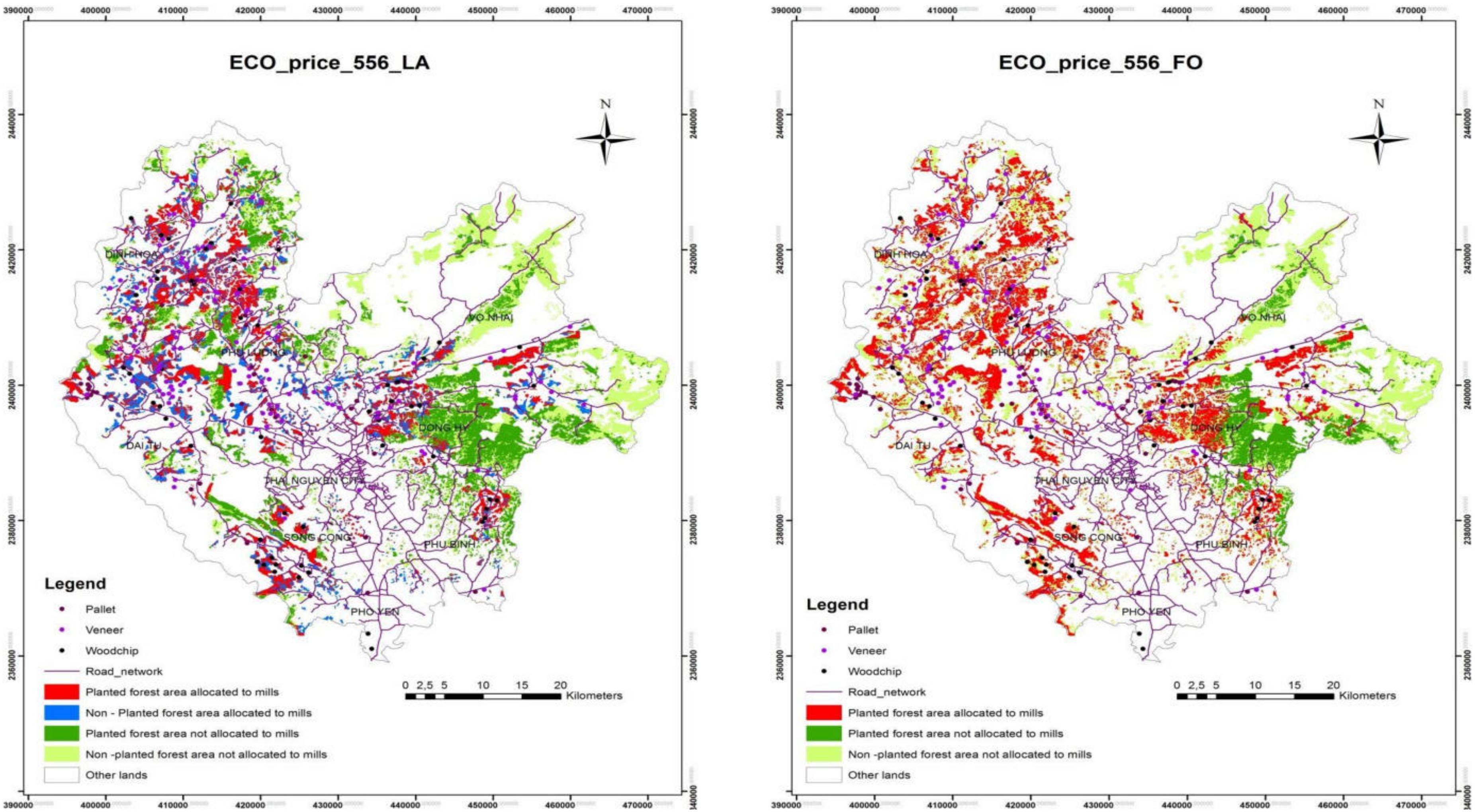


Figure 4.36 Maps shows the distribution of land area allocated by assumption of equal timber price of 55.6$/m^3 to mills on 6 – year rotation

4.3.3.3 ECO_ cost

The objective of the "ECO_cost" scenario is to study the impact of cost changes on outcomes such as profit, costs and land area allocated. Harvest cost and silviculture cost are assumed differently according to various elevations above sea level. This attribute is linked to the roughness of the terrain, and is obtained on actual observation and questionnaires from the mills. The scenario analysis is performed under the two approaches: the Landscape Approach and the Current Forest Approach, which are described in Section 3.2.5. Mean values of attributes are used in the optimization model execution (Table 4.9), except for harvest cost and silviculture cost, productivity was assumed for *A.mangium* plantations on 6 – year rotation. The outcomes of these scenarios are compared with the outcome of "ROT_6" (*A.mangium* plantations harvested at 6 years age, economically optimal harvest age). Harvest cost and silviculture cost in "ROT_6" are average values calculated from the mill survey and presented in Table 4.9. The three costs change sub-scenarios:

(1) ECO_Harcost: Harvest cost is assumed to vary according to different elevations above sea level.

(2) ECO_Silcost: Silviculture cost is assumed to vary according to different elevations above sea level.

(3) ECO_HarSilcost: Harvest cost and silviculture cost are both assumed to vary according to different elevations above sea level.

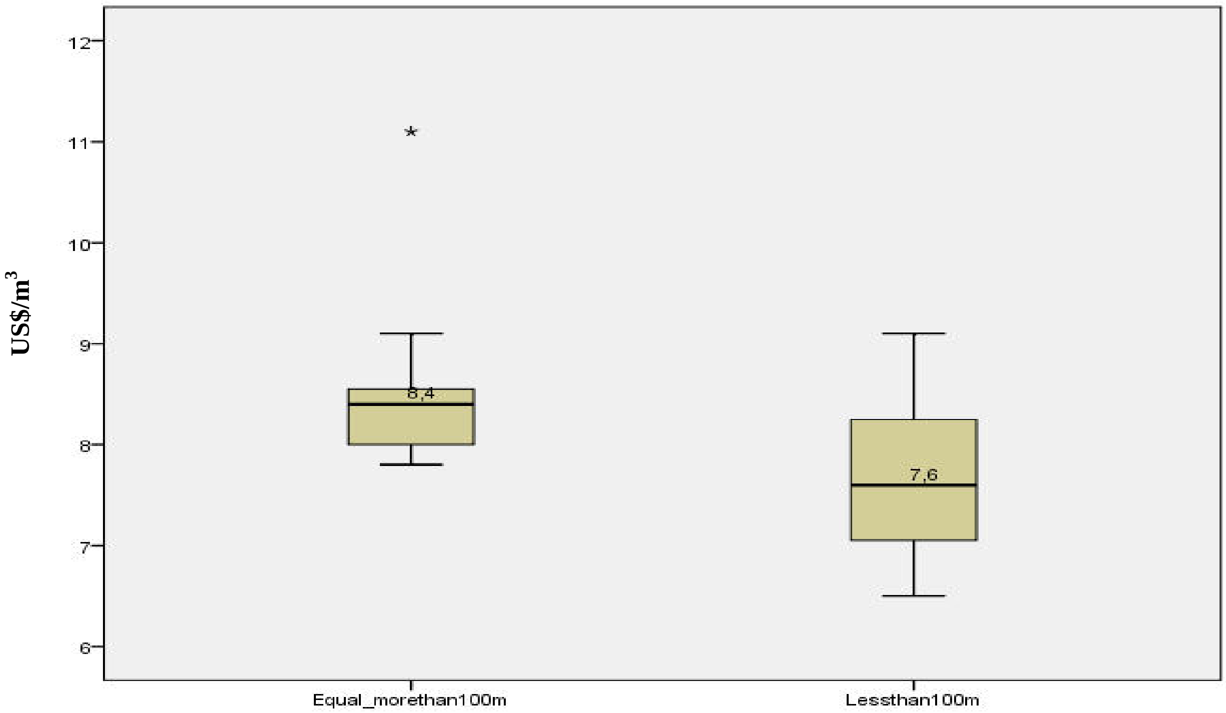


Figure 4.37 Distribution of harvest cost in different altitude

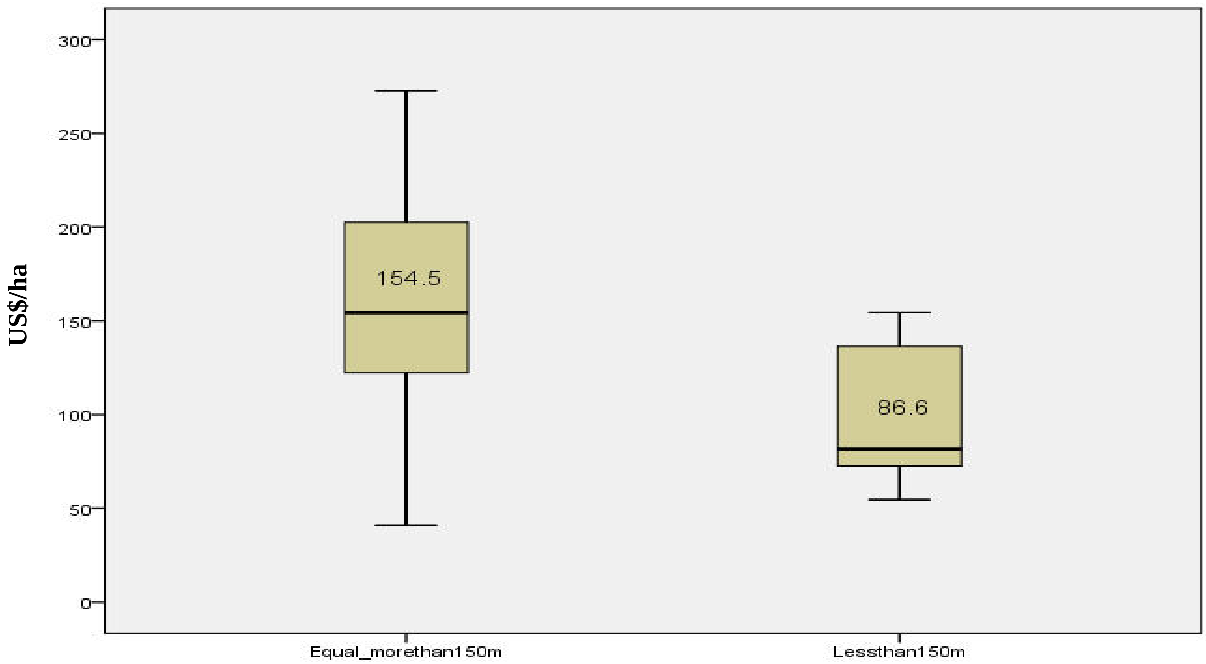


Figure 4.38 Distribution of applied silviculture cost in different altitude

The different harvest cost and silviculture cost are examined by means of by t-tests. Harvest costs are significantly affected by altitude (t = 3.89, p = 0.0003) (Figure 4.37) when 2 groups were found ($\geq 100m; < 100m$). Altitude had a statistically significant effect of on silviculture cost (t = 3.14, p = 0.009) (Figure 4.38) when this cost was divided into 2 groups ($\geq 150m; < 150m$).

Table 4.17 Costs, profit and area varied by change of cost on 6 years rotation

Approach	**Scenarios**	**Costs (US$/ha)**	**Profit (US$/ha)**	**Land area allocated (ha/year)**
Landscape Approach (_LA)	ROT_6	1706	5406	7053
	ECO_Silcost	1704	5412	7049
	ECO_Harcost	1710	5412	7043
	ECO_HarSilcost	1706	5416	7043
Current Forest Approach (_FO)	ROT_6	1907	5082	7.217
	ECO_silcost	1913	5075	7.216
	ECO_harcost	1925	5061	7.221
	ECO_HarSilcost	1928	5063	7.214

For the Landscape Approach, the profit of "ECO_Silcost" (5412$/ha), "ECO_Harcost" (5412$/ha) and "ECO_HarSilcost" (5416$/ha) are slightly higher than that of "ROT_6" (5406$/ha) (Table 4.17). The land areas allocated to meet a timber demand of 961519 m^3/year were slightly lower for "ECO_Silcost", "ECO_Harcost" and "ECO_HarSilcost" than that of "ROT_6", while total costs changed only marginally.

In contrast, for the Current Forest Approach, profit of “ECO_Silcost” (5075$/ha), “ECO_Harcost” (5061$/ha) and “ECO_HarSilcost” (5063$/ha) are slightly lower than that of ROT_6 (5082$/ha). Nevertheless, the opposite values is true of total costs. Meanwhile, land areas allocated to “ECO_Silcost”, “ECO_Harcost” and “ECO_HarSilcost” are slightly different than that of “ROT_6”.

In general, the assumption of varying cost will respect to elevation does not have much of an influence on the outcomes for both scenarios, the Landscape Approach and the Current Forest Approach. Maps of these scenarios showing land area allocation are presented in Figure 4.39, Figure 4.40, and Figure 4.41. For the Current Forest Approach, unplanted forest area does not need to be used to meet timber demand in these scenarios.

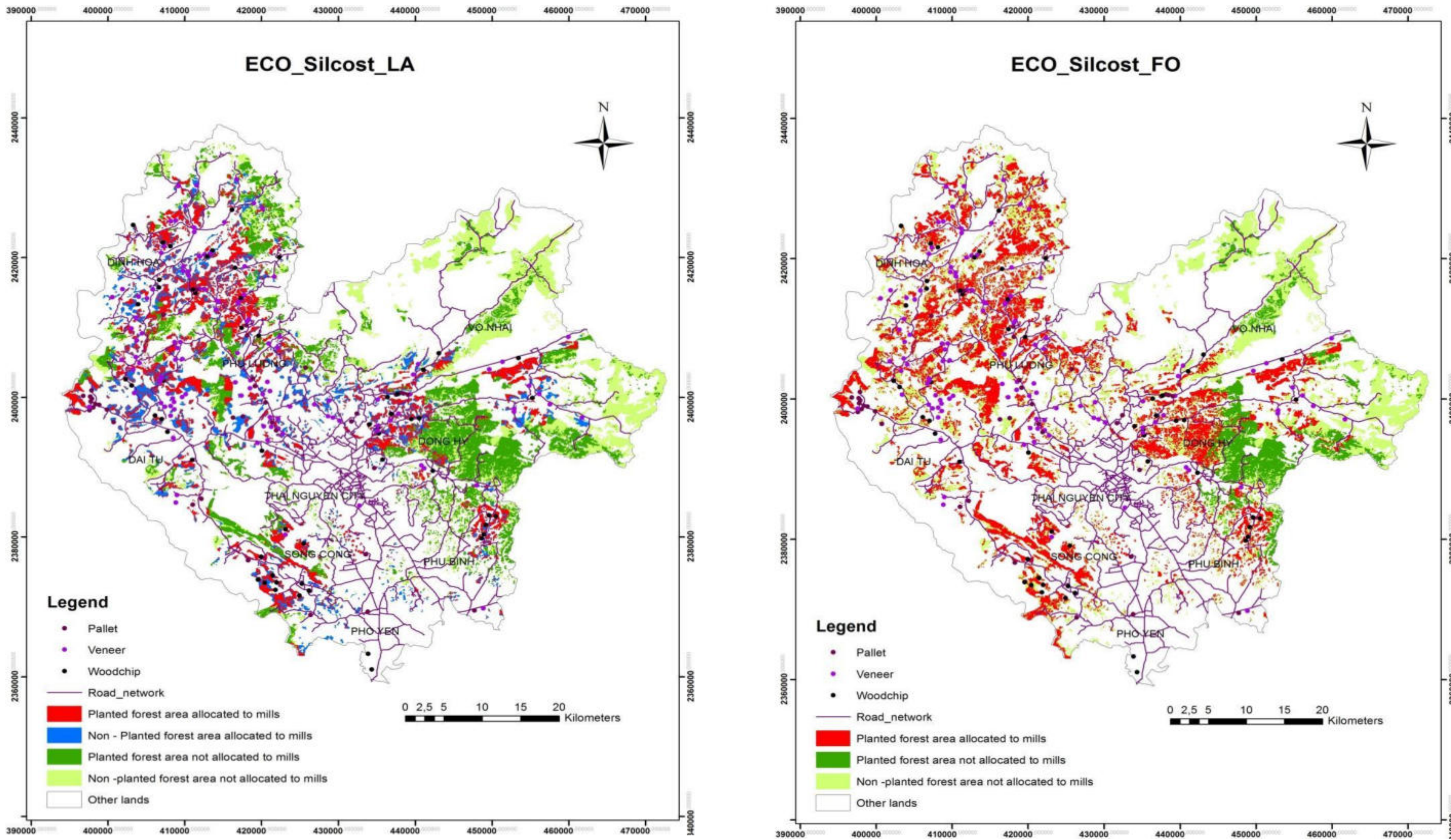


Figure 4.39 Maps showing the distribution of land area allocated by assumption of siviculture cost change on 6 – year rotation

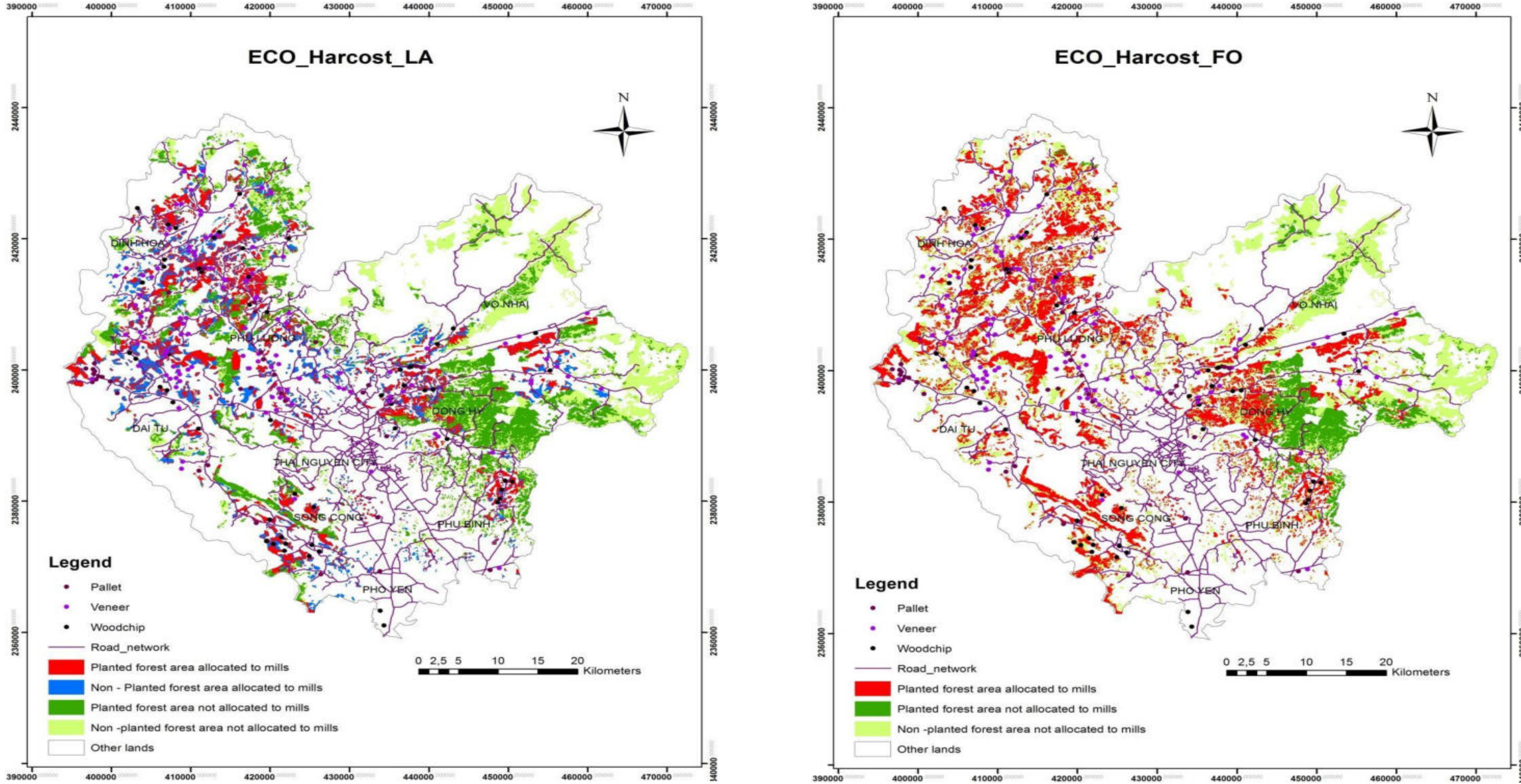


Figure 4.40 Maps showing the distribution of land area allocated by assumption of harvest cost change on 6 – year rotation

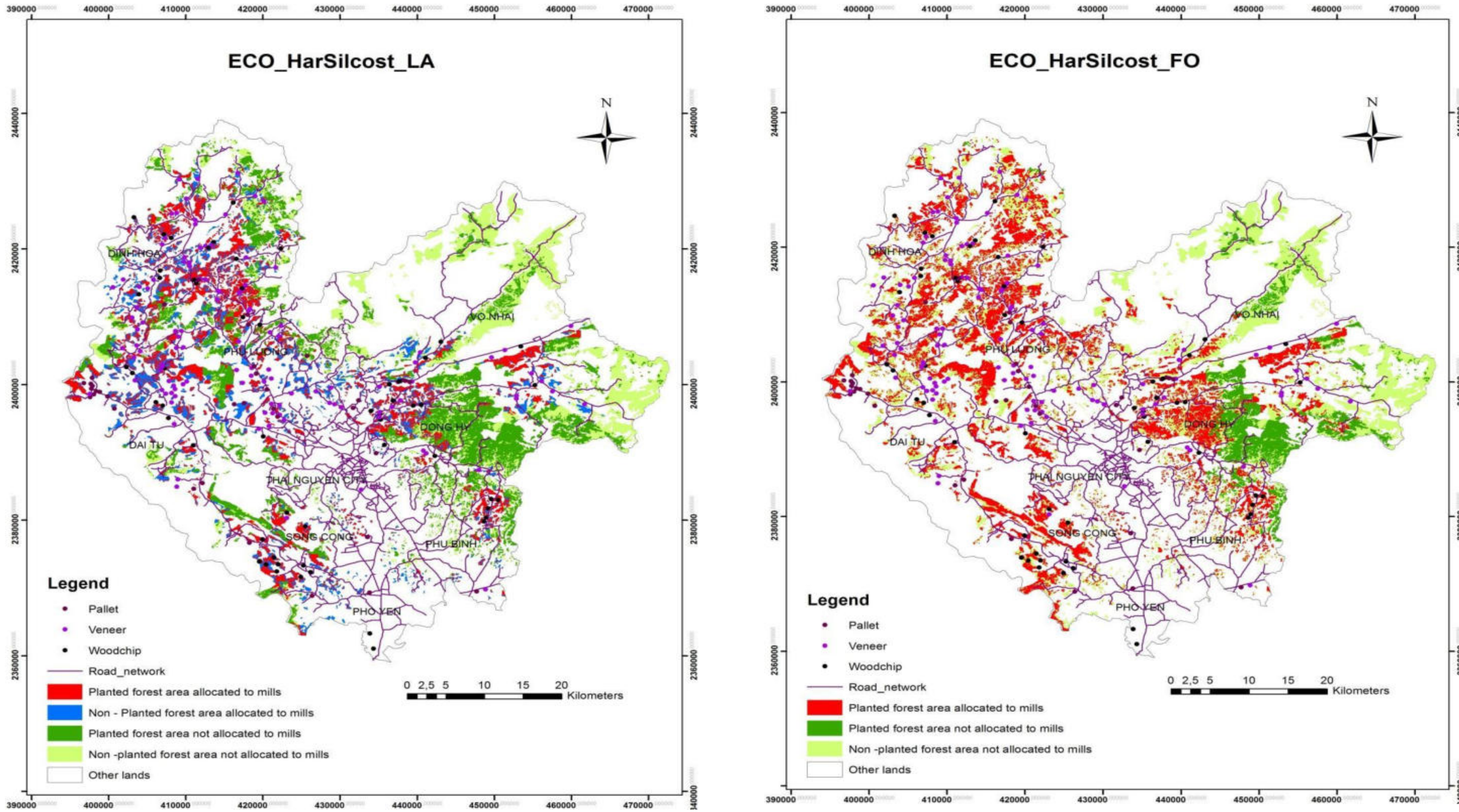


Figure 4.41 Maps showing the distribution of land area allocated by concurrent changes of silviculture and harvest costs on 6 years rotation

4.3.4 Mill_new and Mill_coop

In the current sub-scenarios the number of existing mills is changed by adding new mills "Mill_new" or by replacing existing smaller mills by a lower number of larger mills "Mill_coop". The scenario analyses is performed under the two approaches: the Landscape Approach and the Current Forest Approach, which are described in Section 3.2.5. Mean values of attributes are used in the optimization model execution (Table 4.9). The outcomes of these scenarios were compared with the outcome of "ROT_6" (*A. mangium* plantations harvested at 6 years of age, economically optimal harvest age).

4.3.4.1 Mill_new

Sub-scenario "Mill_new" is concerned with the change of household profit obtained by adding 3 new larger mills to the existing 215 mills. The 3 new larger mills were randomly located in the study area. The total timber demand of the 3 new mills was assumed to be equal to the timber demand of all existing mills. Therefore, the total timber demand was assumed to be two times higher than that of "ROT_6". Each new mill consists of three types of products (veneer, pallet, and woodchip) and it was named VPW. The timber price at the new mills was assumed to be similar to the timber price of the woodchip mill (55.6 US$/m^3). Timber demand and timber price of this scenario are shown in Table 4.18. This scenario is analyzed on 6-year rotation.

Table 4.18 Distribution of timber demand and timber price at mills

Mills	Timber demand (m^3/year/mill)	Timber price at mill (US$/m^3)
Pallet	2038	52.3
Veneer	3945	53.6
Woodchip	7062	55.6
VPW (including veneer, pallet, woodchip)	320506	55.6

For the Landscape Approach the profit for “Mill_new” (4918 US$/ha) is significantly smaller than that of “ROT_6” (5406 US$/ha) (Table 4.19). This is caused by lower total costs. Total costs for “Mill_new” are 20% higher than that of “ROT_6”, which was mainly attributable to transportation cost. On average, transportation cost from forest stands to mills under the “Mill_new” sub-scenario is 4.2 times higher than “ROT_6”.

The outcomes of the Current Forest Approach show the same trend as the Landscape Approach. Profit for “Mill_new” (4872 US$/ha) is considerably lower than that of “ROT_6” (5082 US$/ha). However, total costs for “Mill_new” are only 10% higher than that of “ROT_6”, and average transportation cost for “Mill_new”(4.5 US$/$m^3$) are 1.9 times higher than that of “ROT_6” (2.4 US$/$m^3$).

Total costs and transportation cost increased significantly in the “Mill_new” sub-scenario in comparison with ROT_6 due to an increasing timber demand. Timber demand in the “Mill_new” sub-scenario was doubled, which resulted in higher land area allocated to meet timber demand and higher cost for timber transport from farther locations. This was reflected in the lower profit achieved in the “Mill_new” scenario compared with “ROT_6” for both approaches.

Table 4.19 Different costs, profits and land area allocated for growing plantations by adding new mills on 6-year rotation

Approach	**Scenario**	**Profit (US$/ha)**	**Costs (US$/$m^3$)**	**Transportation costs (US$/$m^3$)**	**Land area allocated (ha/year)**
Landscape Approach	Mill_new	4918	15.8	4.2	14440
	ROT_6	5406	12.5	1.0	7053
Current Forest Approach	Mill_new	4872	16.1	4.5	14447
	ROT_6	5082	14.0	2.4	7217

Figure 4.42 provides details about land area allocated. For the Current Forest Approach not only land area to be close to mills, but remote areas are also used to meet timber demand. Under the Landscape Approach the majority of land area are allocated closer to mills.

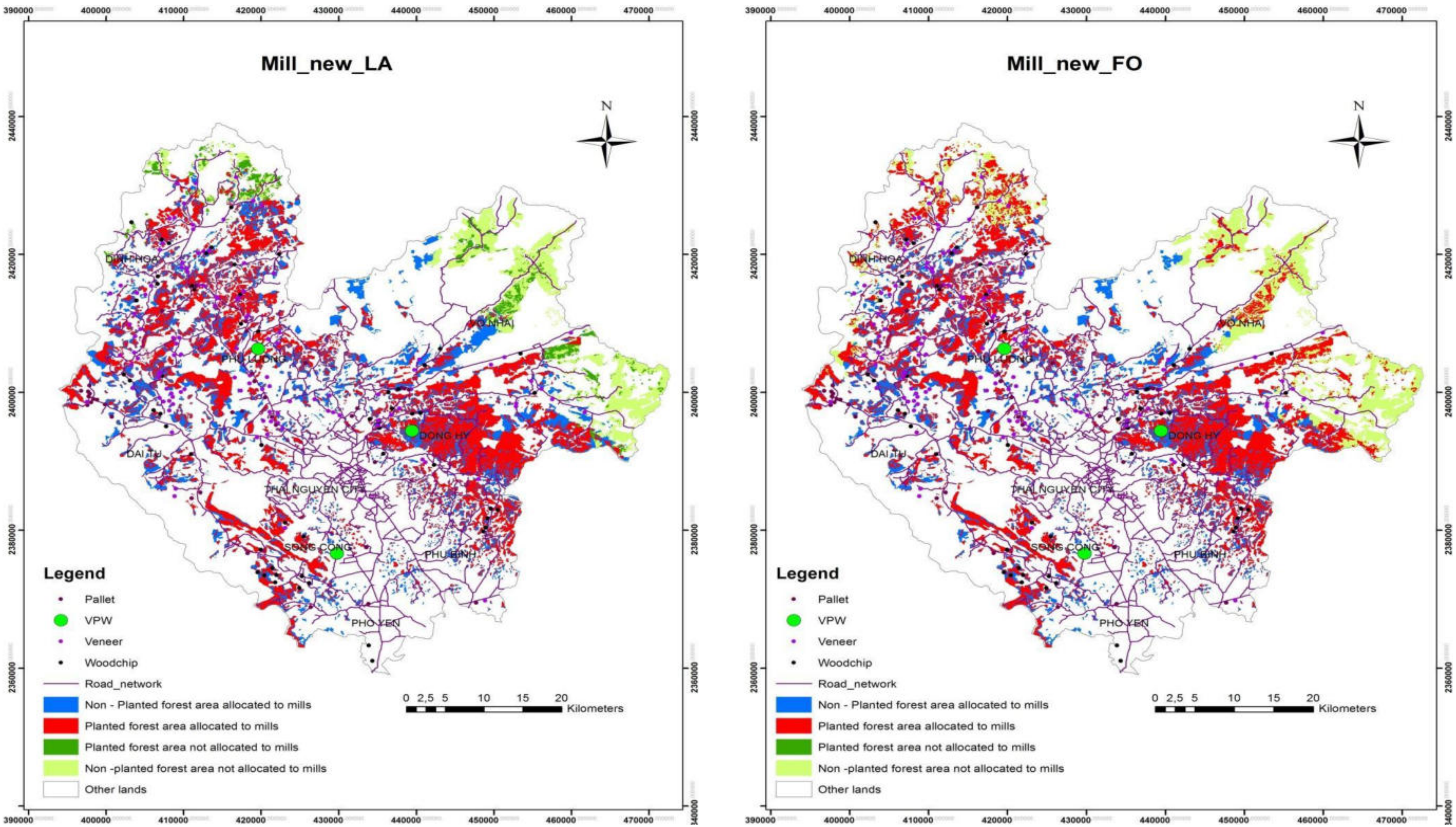


Figure 4.42 Maps showing land area allocated by adding 3 new mills

4.3.4.2 Mill_coop

The scenario "Mill_coop" focuses the change in household profit gains by assuming cooperation among mills. The objective of this scenario is to study the possibility of cooperation among mills according to sub-regions in study area. This scenario only evaluates the change of household profit if existing mills with lower capacities are replaced by a smaller number of higher capacity mills. The cost for the installment of larger mills is not considered.

In this scenario, 215 existing smaller mills were replaced by 24 larger mills with regard to mill types (pallet, woodchip, and veneer). Thai Nguyen province includes 9 sub-regions. Three mills types were representatively allocated to each sub-region in study area, excluding Thai Nguyen City where the majority of land is assigned for urban development. The location of the 24 larger mills was assumed to be based on 24 existing locations (Figure 4.43).

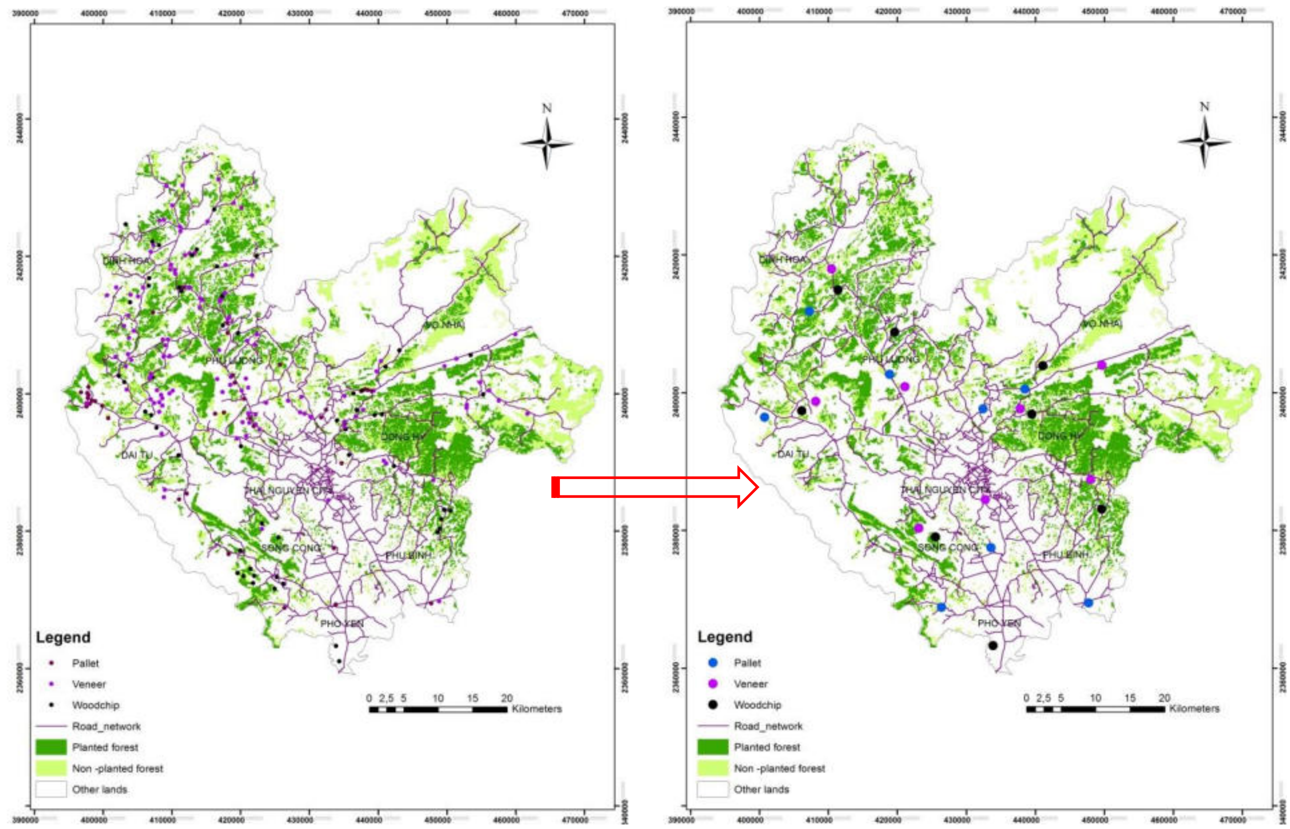


Figure 4.43 Replacement of 215 existing mills by 24 larger mills

The economy of scale concentration process of larger mills could not only provide better opportunities to decrease input costs and increase production units, but would also alter the possibility of increased efficiency with a link between farmers and businesses. For example, cooperation between small mills and larger mills can result in an increase in production. A larger mill can use specialized machinery with higher capacity and power, which can generate more profit.

In this assumption, mean values of attributes are used in the optimization model execution (Table 4.9). The outcomes of these scenarios are compared with the outcome of "ROT_6" (*A.mangium* plantations harvested at 6 years, economically optimal harvest age). Timber demand from the 24 larger mills is equal to that of the 215 smaller mills.

In order to meet a sufficient amount of timber (961519 m^3 per year), the capacity is distributed to 24 bigger mills according to sub-regions. The price of timber at mill types complies with the price in "ROT_6" (Table 4.20).

Table 4.20 Distribution of timber demand and price at mills

Mill types	**Timber demand (m^3/year/mill)**	**Timber price (US$/$m^3$)**
Pallet	18777	52.3
Veneer	36347	53.6
Woodchips	65066	55.6

In addition, the total land area allocated under "Mill_coop" was slightly lower than that of "ROT_6" for both approaches. This indicates that the land area allocated to the "Mill_coop" generates a higher productivity than that of "ROT_6".

Table 4.21 shows that the replacement of 215 smaller mills by 24 bigger mills results in lower profit gains and an increase in costs for both approaches. For the Landscape Approach, profit for the "Mill_coop" (5276 US$/ha) is nearly 2.4% lower than that of "ROT6" (5406 US$)/ha. This is mainly due to transportation costs, because the lower number of mills results in longer transportation distances. Therefore, the results show that total costs of "Mill_coop" (13.7

US$/m^3) are about 8.4% higher than that of “ROT6”(12.5 US$/m^3). Transportation cost of “Mill_coop”(2.2 US$/m^3) is 54% higher than that of “ROT6”(1 US$/m^3). The total land area allocated to meet the same amount of timber demand remains unchanged (7053 ha for “ROT_6”and 7039 ha for “Mill_coop”).

Similarly, for the Current Forest Approach, the profit of “Mill_coop”(4932 US$/ha) is 3% lower than that of “ROT6” (5082 US$)/ha, while total costs of “Mill_coop”(15.3 US$/m^3) is 9% higher than that of “ROT6”(14.0 US$/m^3). Especially, transportation cost of “Mill_coop” (3.8 US$/m^3) is 37% higher than that of “ROT6”(2.4 US$/m^3) and total land area allocated changes insignificantly (7217 ha/year for “ROT_6”and 7192 ha/year for “Mill_coop”).

In addition, total land area allocated to the “Mill_coop” is slightly lower than that of “ROT_6” for both approaches. This indicates that land area allocated under “Mill_coop” generates higher productivity than that of “ROT_6”.

Table 4.21 Different costs, profits and land area needed by taking into consideration larger mills on 6-year-rotation

Approach	Scenarios	Profit US$/ha	Costs (US$/m^3)	Transportation costs (US$/m^3)	Land area allocated (ha/year)
Landscape Approach	ROT_6	5406	12.5	1.0	7053
	Mill_coop	5276	13.7	2.2	7039
Current Forest Approach	ROT_6	5082	14.0	2.4	7217
	Mill_coop	4932	15.3	3.8	7192

Figure 4.44 and Figure 4.45 show the differences between the “Mill_coop” scenario and “ROT_6” scenario regarding land area allocated to mills. Both scenarios show that land areas allocated are located close to mills. For the Landscape Approach, land area allocated to mills is similar for “Mill_coop” and “ROT_6”. For the Current Forest Approach the planted forest area allocated to the “Mill_coop” in the northwest is not used in contrast to “ROT_6”, while the larger planted forest areas located in the east are used by “Mill_coop” than used by “ROT_6”.

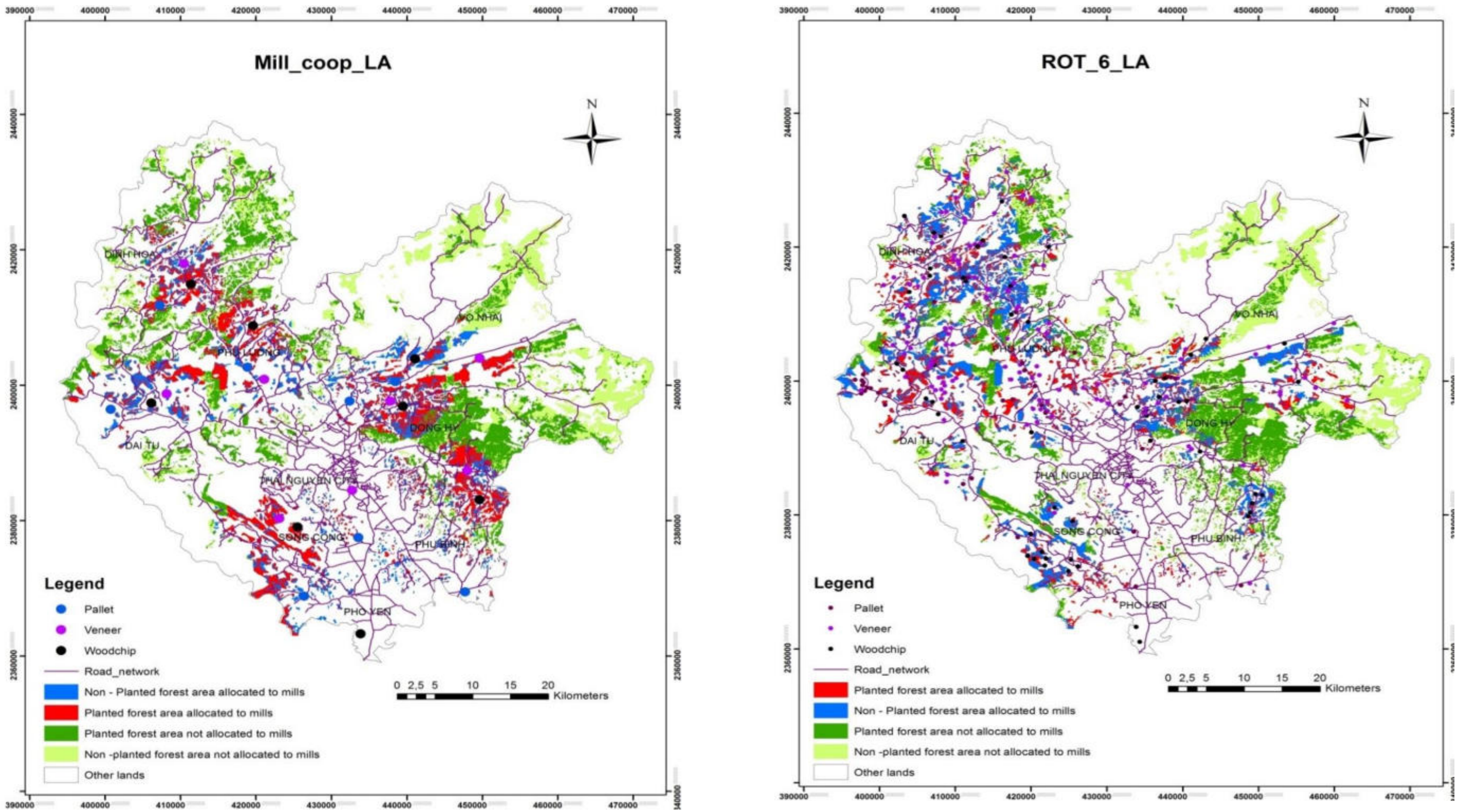


Figure 4.44 Maps showing a difference of in land allocated to mills between the Mill_coop scenario and ROT_6 scenario for the Landscape Approach

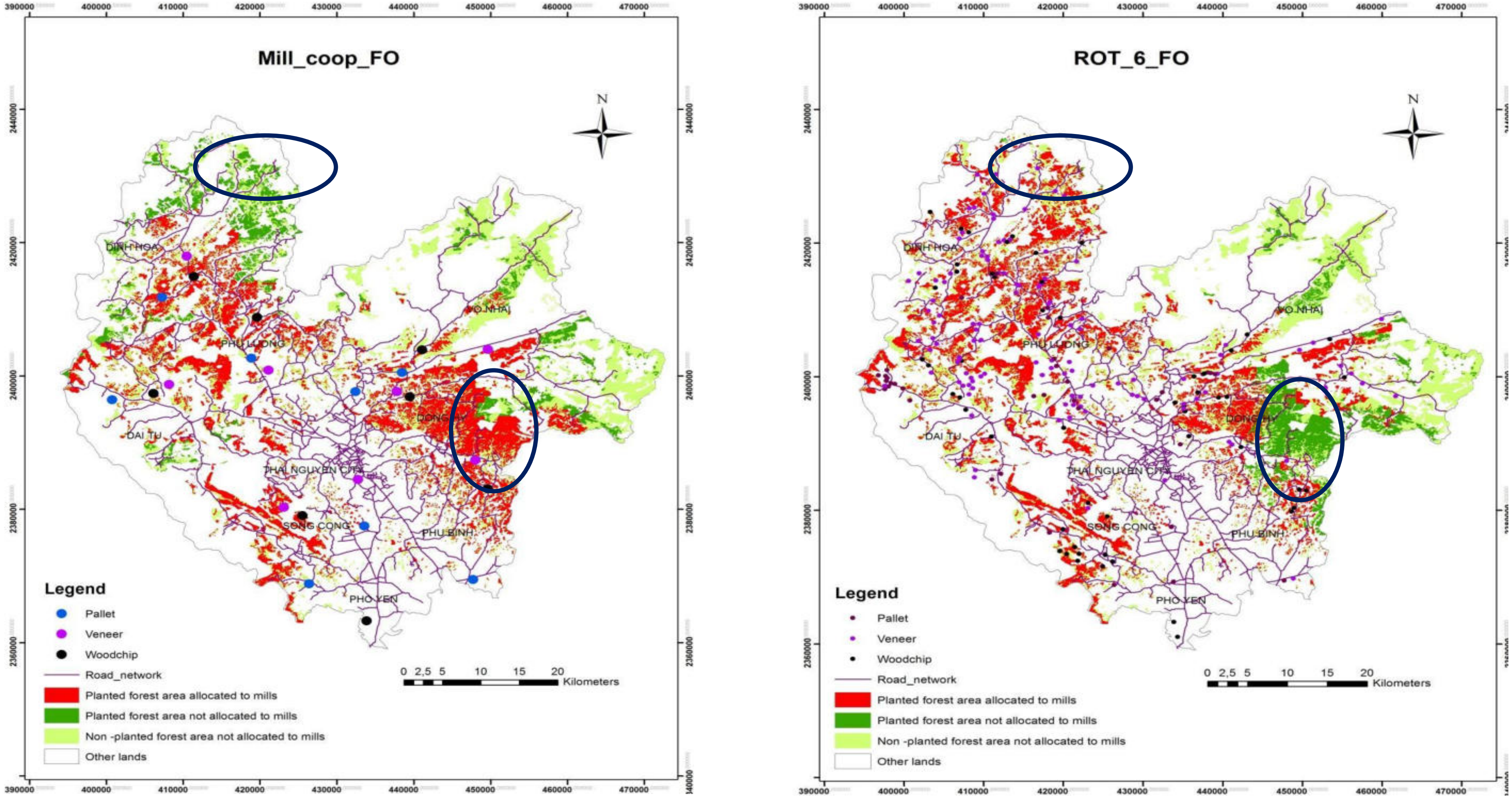


Figure 4.45 Maps showing a difference in land allocated to mills between Mill_coop scenario and ROT_6 scenario for the Current Forest Approach

4.3.5 Nature conservation area

A scenario concerned with environmental interests was considered and named as “Con_”. The objective of this scenario is to study the possibility of establishing nature conservation areas in the study area. This scenario shows a link between socio-economic developments with environmental interest by establishment of natural conservation areas.

Worldwide the amount of protected land area has increased from 1990 to 2010 (FAO 2010a). Forest plantations not only indirectly contribute to this increase by helping to reduce deforestation and forest degradation and thereby alleviating pressure on natural forests, but also adding value to the public (Pirard et al. 2016). Forest plantations can satisfy wood demand while at the same time meeting other values such as biodiversity conservation, or enhancement of carbon storage.

The scenario “ROT_6” showed the area allocated to the respective mills and the household profit obtained to meet the timber demand of 961519m^3/year. The scenario “Con_” shows that natural conservation areas can be established to enhance environmental services and functions and meet timber demands as in “ROT_6” simultaneously. In spite of meeting the requirement of timber demand for processing, the allocation of a subset of potential forest land area as “nature conservation” makes a contribution to the total profit obtained. This contribution was used to calculate “shadow price”.

Here shadow price is considered as the potential cost of strictly protecting forests as natural conservation areas. Shadow price is quantified as the difference in value of profit by excluding areas assigned as nature conservation areas between “ROT_6” and this scenario. The shadow price is defined as the sum of a decrease in profit obtained and additional costs for the establishment of the new forests where unplanted forest areas were considered as conservation areas and profit from commercial forest is excluded. The establishment of conservation areas means that harvesting and conversion of protected forest to commercial forest is no longer accepted. The shadow price provides useful information for policy makers, land-use planners, and development practitioners in designing strategies for protected area management in the study area.

Five locations are selected subjectively as nature conservation areas (Figure 4.46). They are located close to urban regions. The total of anticipated conservation areas is 905.4 hectares consisting of 2.9 hectares unplanted forest area and 902.5 hectares planted forest area It is extracted from the total potential land area planned for production forest. In conservation areas, no timber harvesting is permitted and their primary function is to supply environmental values.

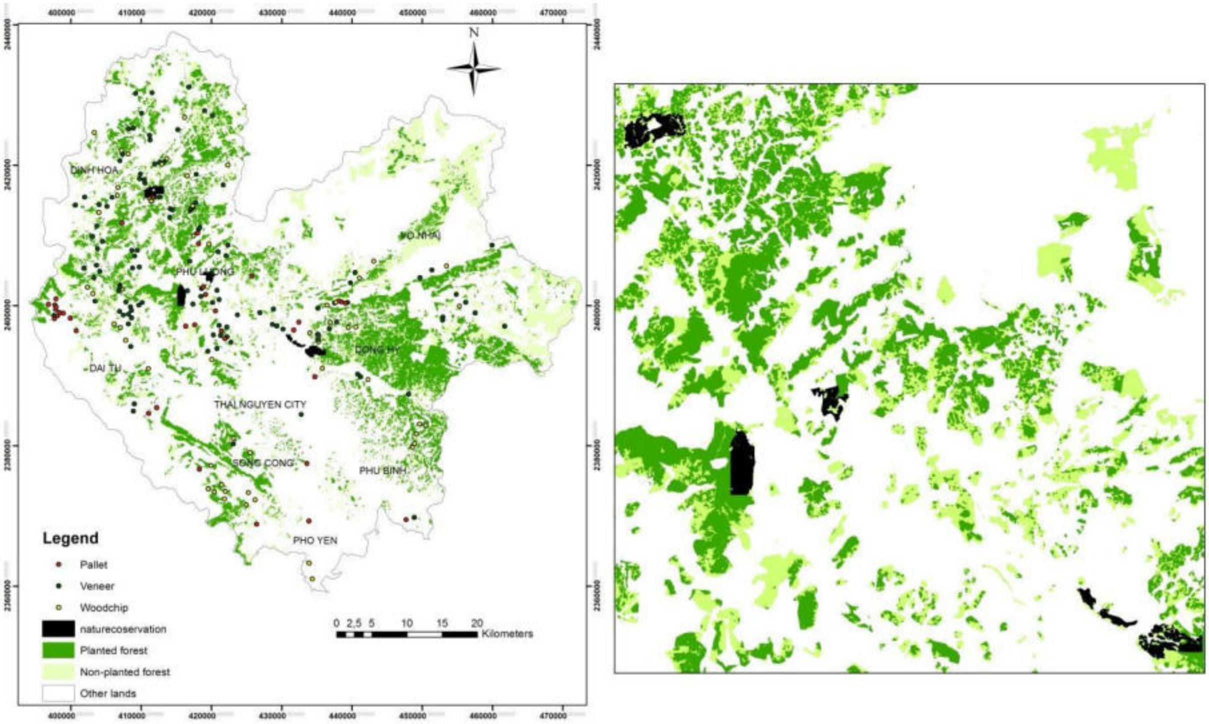


Figure 4.46 Maps showing 5 locations considered as nature conservation areas

The establishment cost for 2.9 hectares of new forest as a part of conservation efforts should be calculated as additional cost. Additional cost was 916.4 $ (2.9 ha * 316 US$/ha). Table 4.22 presents the shadow price of virtual conservation area establishment, where is calculated as:

For the Landscape Approach (excluding additional cost):

Shadow price_LA = (38125122 US$/year – 38103074 US$/year) = 22048 US$/year

For the Current Forest Approach (excluding additional cost):

Shadow price_FO = (36679885 US$/year – 36487515 US$/year) = 192370 US$/year

Table 4.22 The difference of total profit obtained between the basic timber demand and increase of 20%

Approach	**ROT_6 (US$/year)**	**Con_ (US$/year)**	**ROT_6 _demand+20% (US$/year)**	**Con_ _demand+20% (US$/year)**
Landscape Approach	38125122	38103074	45 519 502	45 488 072
Current Forest Approach	36679885	36487515	41 939 932	41 643 248

As discussed in Section 4.3.3.1 "ECO_demand", profit gains are highly sensitive to changes in timber demand. The model indicates that the profit from growing forest plantations decreases when timber demand increases. Therefore, the decrease in profit by increasing timber demand by 20% leads to the increase of the shadow price for both approaches. The shadow price is shown below by increasing timber demand by 20%.

The shadow price is calculated for the Landscape Approach by adding 20% timber demand and excluding additional cost:

Shadow price_LA = (45519502 US$/year – 45488072 US$/year) = 31431 US$/year

The shadow price is calculated for the Current Forest Approach by adding 20% timber demand and excluding additional cost:

Shadow price_FO (41939932 US$/year – 41643248 US$/year) = 296684 USD$/year

As a result, when timber demand increased by 20%, the shadow prices are nearly 1.4 and 1.5 times higher for the Landscape Approach and the Current Forest Approach than those for "ROT_6".

However, local officials could consider forming nature conservation areas in other locations where the shadow price is calculated to be zero. Because those areas are not necessarily used to fulfill timber demand, they are generally located in remote area. For example, for 1600 hectare designated as nature conservation areas the shadow price is estimated to be zero, except for additional for establishment of new forests in unplanted forest areas (Figure 4.47).

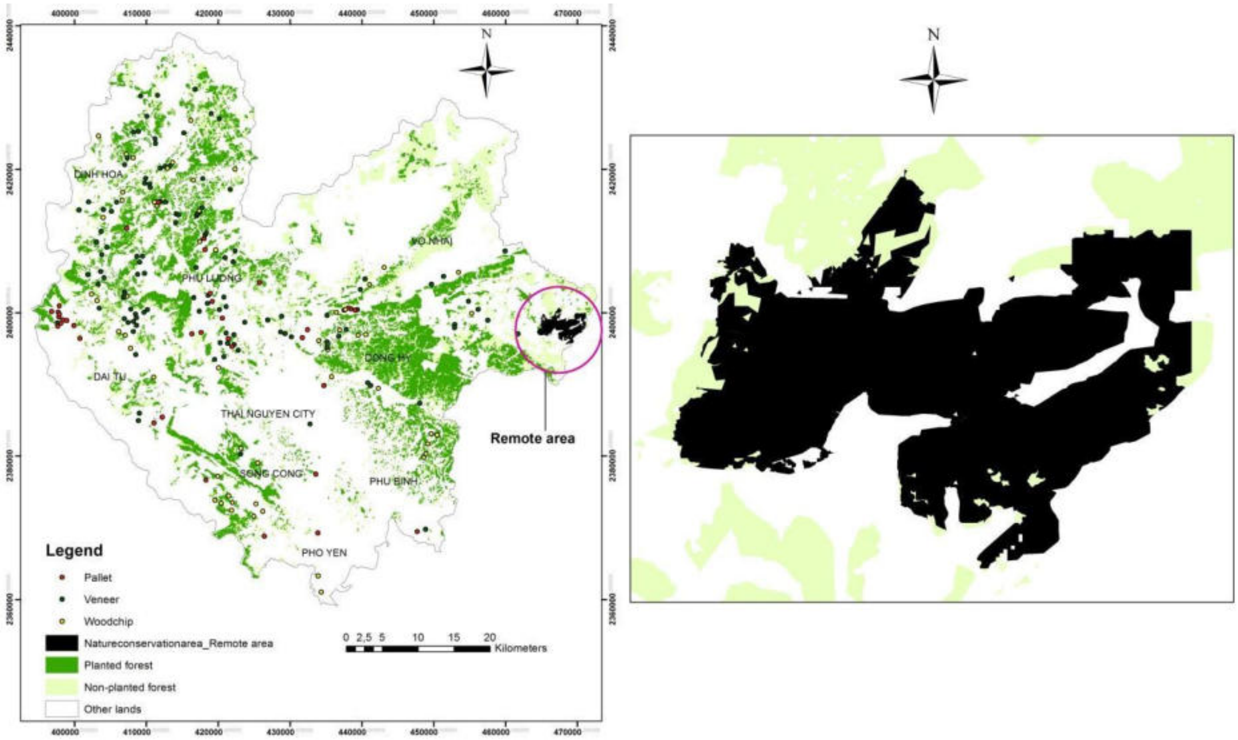


Figure 4.47 Map showing a possible solution to form nature conservation areas in remote area

In conclusion, the shadow price (opportunity cost) of areas eligible for nature conservation provides important information for planning and developing strategies for protected forest management for the sake of environmental values. The results show that shadow prices are highly sensitive to changes in timber demands. Here, the shadow price is considered as a maximum opportunity cost and local government's willingness to accept to identify desirable forest areas for nature conservation. By using the optimization model, the socio-economic requirements and needs with the environmental protection perspective of the local people living in research area could be combined.

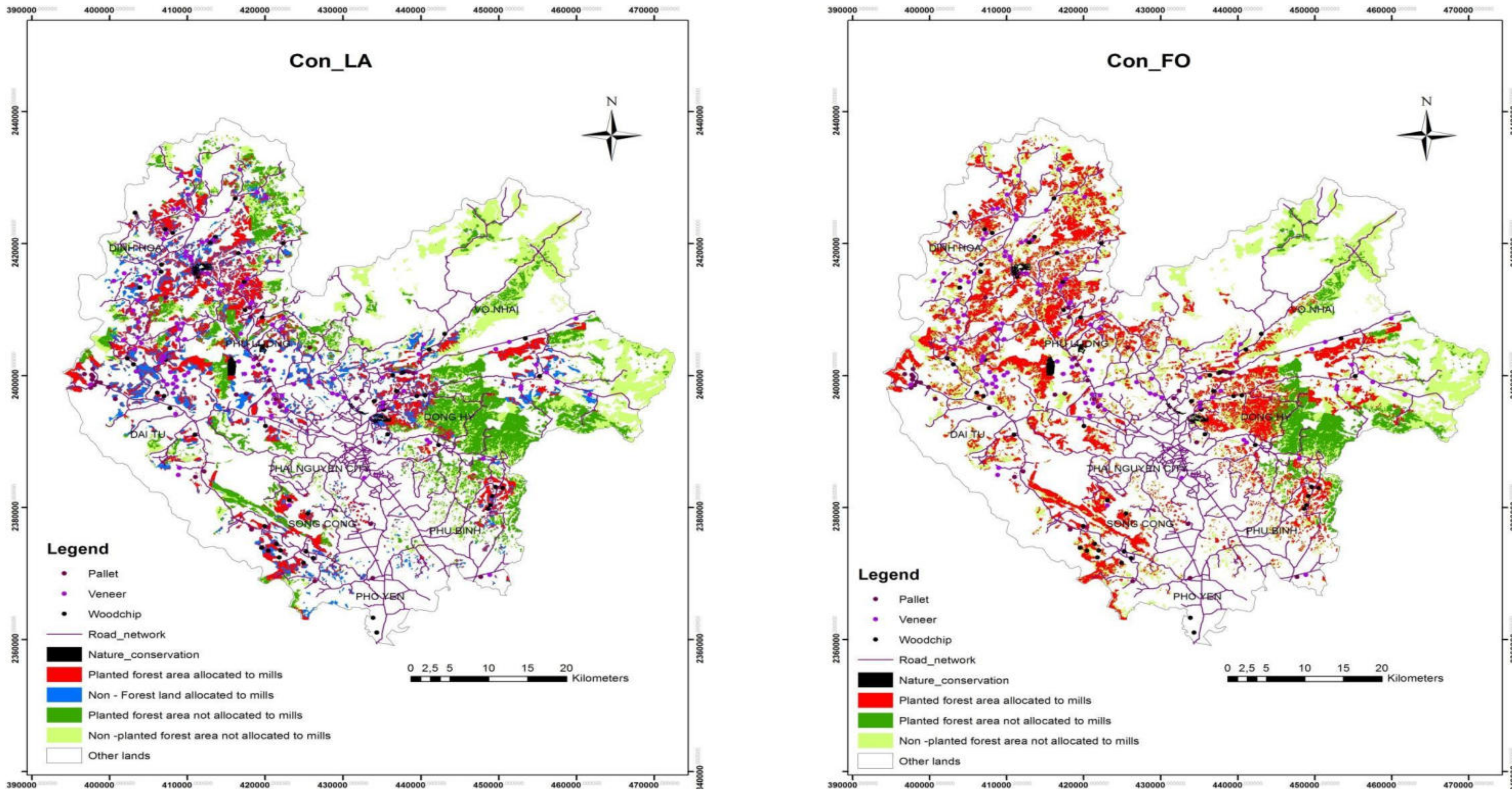


Figure 4.48 Maps showing land area allocated to mills considering nature conservation under usual timber demand

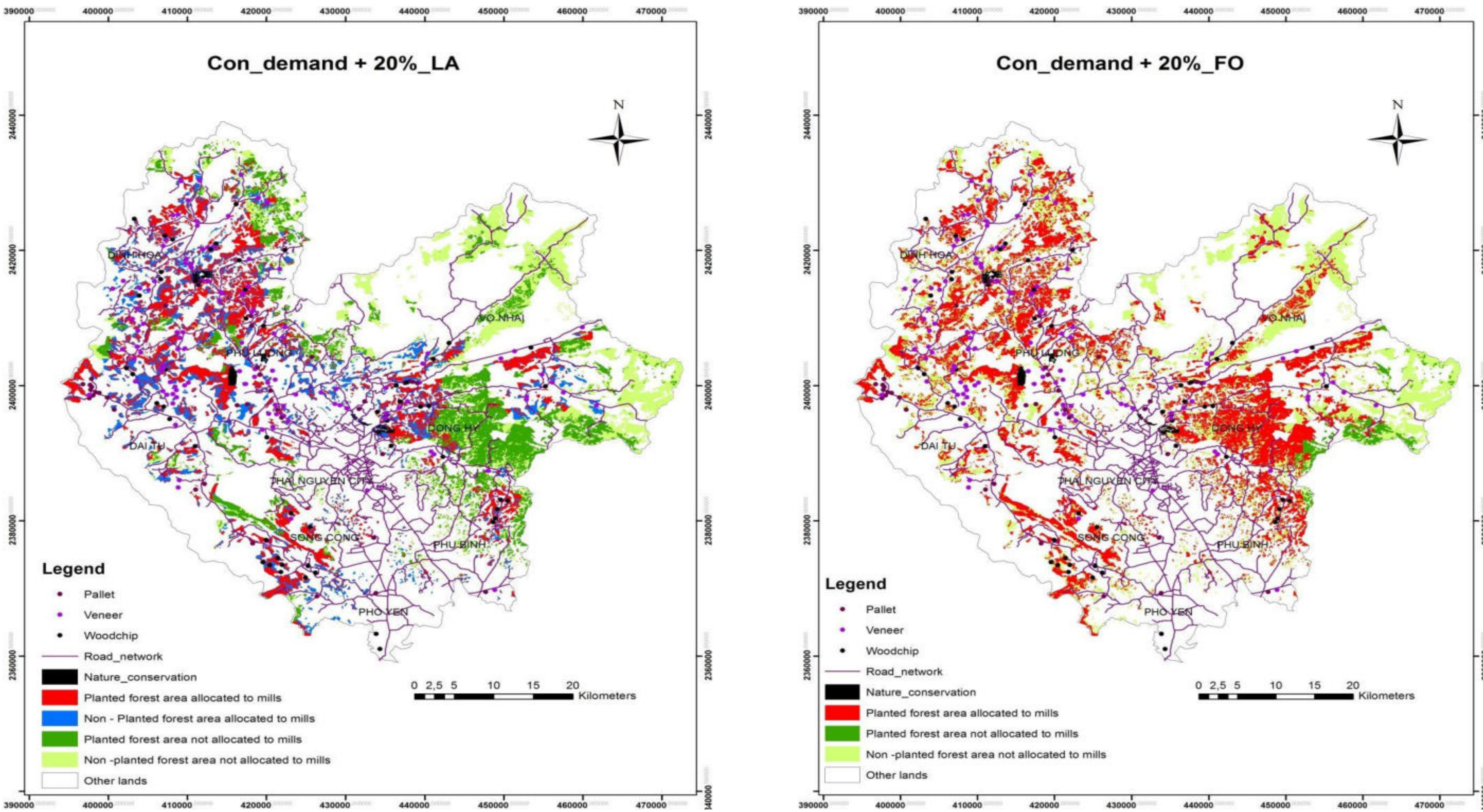


Figure 4.49 Maps showing land area allocated to mills when considering nature conservation by increasing timber demand by 20%

5 Discussion

5.1 Discussion of suitability and growth model

5.1.1 Land suitability assessment

The evaluation of land suitability is a major prerequisite for implementing sustainable forest management (SFM). Land suitability is assessed through the potential feasibility for defined uses. In this study, land suitability is evaluated for *A.mangium* plantations. Based on the availability of data, three ecological factors were utilized for a land suitability classification including soil factor (soil type, soil depth), topographic factor (elevation, slope), and climate factor (mean annual rainfall). Former studies showed that these factors considerably influence forest productivity (Huang et al. 2013; Fox 2000; Vance 2000; Corona et al. 1998; Laamrani et al. 2014). Land suitability serves to reflect different degrees of suitability. Linking site conditions with ecological requirements of *A.mangium*, four suitable classes were defined namely: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and unsuitable (UN). The classification based on FAO approach was verified by four experts who specialize in land use evaluation. This process of land suitability evaluation incorporates expert knowledge for a quick assessment of site feasibility for *A.mangium* plantations.

The land suitability classification according to FAO only predicts the potential and limitations of a site for forest plantations, and provides no information on the importance and ranking of individual factors. The AHP (Analytic Hierarchy Process) provides a systematic approach for simultaneously weighting multiple criteria. An integration of the FAO framework and the AHP approach in combination with GIS enables us to display and visualize the land suitability classes in a GIS environment, which is a prerequisite for the optimization of profitability. The results of the land suitability study guided the collection of field data in order to build a volume growth model.

In this study, 112309 ha of land area were used for planning a production forest. The land suitability assessment using GIS-analysis for growing *A.mangium* indicated that the suitable land area is approximately 10700 ha and the unsuitable land area is approximately 5400 ha. In the land area suitable for *A.mangium* plantations, the area assigned to suitability class S2 (moderately suitable, 68%) was dominant, followed by S1 (highly suitable, 26%) and S3 (marginally suitable, 6%).

In conclusion, the FAO framework is a useful tool for the evaluation of land suitability, while multi-criteria methods help determine the impact of individual factors on the site specific suitability (Santé-Riveira et al. 2008; Kangas et al. 2015). Based on the combined use of both, the suitable land is found with regard to favoring and constraining factors (Shi et al. 2008). The constraint of the AHP is subjective, driven by the expert's experience and preference in making decisions. The combination is not yet linked to socio-economic evaluation. In addition, soil properties used in the land suitability assessment applied are soil depth and soil type. Hence, the enhancement of the physical evaluation by involving more detailed soil characteristics such as organic matter content, soil reaction (pH) and soil fertility is recommended, and can essentially improve the determination of soil productivity.

In this study, assignment of the range of each factor to respective suitability class and AHP application for ranking of factors were implemented under the consultation of four forestry experts including Prof.Dr.Ngo Dinh Que[1], Prof.Dr. Do Dinh Sam[2], Dr. Nguyen Thi Thu Hoan[3] and Msc. Bach Tuan Dinh[4], who study forest growth, site condition requirements of trees and site needed feasibility studies, suitable forest site assessment for main tree species in Vietnam. All of four forestry experts were interviewed independently. The judgment of process was evaluated by each individual before grouping their preference. Prof.Dr.Ngo Dinh Que, Prof.Dr. Do Dinh Sam were interviewed in advance, followed by evaluations from the remaining experts who are local people. The judgment of process only ended when four experts achieved a common agreement.

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[1] The Vietnam Union of Science and Technology Associations
[2] The Vietnam Union of Science and Technology Associations
[3] Thai Nguyen University of Agriculture and Forestry (TUAF)
[4] Thai Nguyen Forestry department

5.1.2 Forest growth model and productivity

The volume growth model shows the performance of the three levels of suitability classes (excluding unsuitable class). Each suitability class resulted in a different sustained yield. The growth model in this study was developed based on data collected in the field on each suitability class.

The development of the forest growth model depends on potential availability of data. In the study area, permanent plots for fast growing species such as acacia or eucalyptus are not available. Hence, temporary plots assessed in stands of different age were grouped to develop chronosequence that are utilized to build the growth model. This approach was adopted from Hasenauer (2006), and forms the basis assessment of plots.

This study utilized empirical models including the Koft, the chapman Richard, and the Gormpert models adopted from (Hong and Hung 2006; Huu-Dung and Yeo-Chang 2012; Sein and Mitlöhner 2011) to develop the volume growth model. All three reflect volume growth well, but the Koft model obtained higher value of r^2 (coefficient of determination). Therefore, we selected the Koft model for calculating potential productivity and executing the optimization model for *A.mangium* plantations.

In term of volume growth, according to a volume growth curve, the volume per hectare was lower than reported in other studies (Torres Vélez et al. 2007; Sein and Mitlöhner 2011; Heriansyah et al. 2007). In the study area, weeding and fertilizing was carried out, but pruning and thinning have not yet been applied. Thinning practice can enhance the growth of a forest (Burkhart and Tomé 2012; Heriansyah et al. 2007). In a thinning regime, stand and individual stem volume can increase, and mortality residual trees can be significantly reduced in comparison with un-thinned stands (Kamo et al. 2009). When forest plantations become older, the thinning practice has considerable effect on stand growth. Appanah (2000) showed that the volume and diameter growth of thinned stands was higher than that in un-thinned stands. Besides, tree mortality was not considered in forest stand development in this study. When the age of a forest plantation increases, the number of live trees per hectare declines. In reality, under a self-thinning regime the number of surviving trees was higher on the less suitable sites

(Forss et al. 1996; Liang et al. 1991). This shows that growth of a forest plantation not only depends on site condition, but also can be significantly affected by intensive management.

In this study, the measure of stand volume growth is calculated from stem number, quadratic mean diameter and stand basal area, and is determined as yield – based measures of site productivity for each suitability class (given site) on un-thinned forest plantations. However, tree growth is sensitive to varying densities and thinning regimes (Weiskittel et al. 2011). Productivity can be increased by thinning given longer rotation periods. The stand volume growth model shows the current practice (i.e. no thinning). As *A.mangium* is implemented under short rotation, the use of a thinning regime is rendered unnecessary as thinning can lead to a reduction in total volume production under a short rotation.

5.2 Profitability maximization from growing forest plantations

A land suitability assessment has only indicated locations where forest plantations can achieve highest productivity potentially, but has not yet showed locations for growing plantations to achieve the highest profit in term of economic drivers. Therefore, optimal analysis based on the optimization model is used to take consideration of socio-economic factors in analyses to gain profitability maximization from growing plantations in line with meeting the trade-off between timber demand and timber supply. The study attempts to assess various profit gains according to different rotation ages, identify socio-economic factors impacting profit gains and present optimal land area needed to meet timber demand in order to achieve sustainable forest plantation management.

5.2.1 Optimal rotation age

Identification of optimal rotation age is to select the optimal time for harvest, followed by replanted forest. The optimal rotation age for production is affected by biological (maximum sustained yield) and economic aspects, which might lead to different optimal times depending on growth function for given species, management cost, stumpage price and interest rate (Clark 1987). In this study interest rate is not included in the calculation, which drives the optimal length of biological and economic cycles because it is volatile and must create artifacts.

Biologically optimum rotation age presents the time of maximum sustainable yield. The study showed biologically optimum rotation age varied according to suitability classes (4 years of age for *A.mangium* in a plantation in the highly suitable (S1), 5 years of age in the moderately suitable area (S2), and 24 years age in the marginally suitable area (S3)). Economically optimum rotation age represents the time need to generate the maximum revenue from growing a forest plantation. Excluding interest rate in calculation of economically optimal age rotation, 6 years of age is considered as optimal age rotation. In particular, the suitability map for growing plantations demonstrated that the majority of parcels of land allocated belonged to S1 and S2 under the usual timber demand, event when increasing timber demand 40%, this remained unchanged. For example, the majority of land area allocated to individual mills to meet usual timber demand could be reached by planting 98-99% of the available land of suitability class S1 and S2. Heriansyah et al (2007) pointed out that the economic optimum rotation is obtained later than the biological rotation for un-thinned stands. This result indicated that the economic optimum rotation is obtained one and two years later than biological rotation for *A.mangium* plantations under normal timber demand. A 2 year longer rotation period leads to higher income. There might be a change of economically optimal age rotation when timber demand is assumed to increase extremely due to more land area needed in S3 might be used to meet much higher timber demand.

In addition, *A.mangium* plantations mainly supply small sized wood to woodchip mills, pallet mills, and veneer mills in the study area. However, this species can supply larger sized wood to furniture mills where timber can be sold at a higher price if the forest rotation age is extended. Longer rotation periods can improve wood quality and wood utilization (Heriansyah et al. 2007). However, for this species longer rotation periods require a greater financial investment, which might be beyond the financial capacity of the local households in the study area.

5.2.2 Profitability maximization from growing plantation

The study enhanced the aspect of site productivity by economic considerations in order to enhance household income and include timber prices, timber demand and supply, and management and transportation cost through applying the optimization model. The optimization model was performed using two approaches:

1. The Landscape Approach: making no reference to the current allocation of planted forest
2. The Current Forest Approach: expanding on the current allocation of planted forest

A good land use plan can help increase productivity or reduce the area of land needed to meet timber demand. The more suitable forest site, the higher the forest productivity (Seifert 2014; Borges et al. 2014). Good land use planning can make use of higher productivity of forest land as well as decrease area required for the need of timber demand (Sedjo 1999; EWERS et al. 2009).

The study documented the growth of forest plantations using growth models. The growth of *A.mangium* plantations was calculated based on a growth model applying the Koft function. Productivity was assigned to each suitability class that was determined through land suitability assessment, and was considered as timber supply used the optimization model. Identification of different growth in different sites can help increase growth rate of plantation through growing on suitable land, the less area needed was required to meet the same timber demand (Fox 2000).

This optimization model, based on the objective function, enables locations for growing plantations to be identified that not only have lower costs, but also bring higher productivity on suitable land. The objective function is calculated based on different variables: productivity, timber demand, timber supply, and timber prices and cost components. The optimization model was conducted using linear programming. Application of linear programming in this study is regarded as an optimization technique to meet the requirements of different interest stakeholders such as households (forest owners), planners, and the owners of mills to find locations that maximize profitability for growing forest plantations.

Timber price and timber demand were assessed based on a questionnaire completed by mill owners. Timber is typically purchased from traders or brokers, who directly harvest forest plantations owned by households. Therefore, a part of the profit from forest plantations is transferred to them, which results in a reduction of household profit. Timber price at mills in this study includes transportation cost, harvest cost and timber price in the forest. Previous studies have shown that timber prices significantly influence farmers' decisions on planting

(Abt et al. 2010; Siregar et al. 2007). In this study, the centralization of mills and distance between mills and forested plantations could be considered factors that results in variations in timber price.

This study has proven that changes in timber demand affected profits achieved, costs expensed, and the land area allocated to grow forest plantations. Timber demand was defined as a major cause of expansion of forest plantation (FAO 2015a, 2009a). Recently, the need for timber increased considerably (PCT 2014) in the study area. The optimization model applied in this study indicated that the increase in timber demand leads to a significant increase in the area with lower potential productivity and higher costs. However, this study is only concerned with the timber supply to mills located in the study area. Further research will need to take into account timber demand from different mills which are located surrounding the study area

Cost components used in the optimization model consist of establishment cost, silviculture cost, management cost, harvest cost and transportation cost. Costs have significant effects on forest owners' decisions; especially, transportation cost play an important role in the decision to grow a forest plantation (Ying 2014; Yemshanov and McKenney 2008). Obviously, higher timber demand results in higher cost. Transportation cost in particular increases considerably when timber demand increases. However, this research uses a conservation approach to estimate the transportation cost. Off-road distance that is understood as a distance from forest stand to the nearest road where timber can be loaded on the truck has not been considered the cost for building new roads in calculation of transportation cost. In further research, the effect of terrain on harvest cost and transportation cost should be studied.

The optimization model developed enables cooperation between buyers (mills) and suppliers (households) with the aim of sustainable forest plantation management. Mills want to ensure a sustainable supply of timber from forest owners, while the forest owners want to avoid worrying about price instability. Good cooperation can ensure quality for both parties. When forest owners can convince purchasers that they are reliable suppliers, business will be conducted in a sustainable manner, which will bring more stable profits for the forest owners. This reliability may lead to more sustainable land use.

In addition, this approach can bring value added from the chain between timber product and timber processing for both households (e.g. by optimizing the rotation period) and industry (e.g. by ensuring a sustainable supply of timber for a competitive price). This is an holistic approach that will promote multi-functional forestry by allocating production and protection area, create employment and income and improve the competitive advantages of the forest and timber sector in the study area.

To conclude, the study developed the holistic approach that combines economic factors with site productivity, integrating timber production and timber processing chains. This results in two aspects:

(1) A reduction in the area needed to produce a desired quantity of timber for a sustainable supply, making the other land available for alternative uses or production
(2) The spatial allocation of plantation in order to reduce cost and thus increase the value add for the production, i.e. the processing chain. This makes plantation forestry as well as timber processing more rewarding from an economic perspective and helps to promote the forest and timber sector in Vietnam.

The approach is applied for *A.mangium*. The concept can be extended to other species in order to:

(1) Improve value added and income
(2) Maximize site productivity by taking into consideration the specific growth environment for diffident species
(3) Alter rotation periods to increase value growth
(4) Optimize forest management to produce timber assortments that highlight value adding is the production process.

6 Conclusion

Planted forests play an important role in meeting the rising demand for timber (FAO 2015b). In the long-term planted forest development requires a trade – off between socio - economic development and environmental conservation needs to achieve sustainable land management and development. This study provides a holistic approach showing a combination between site productivity and economic factors to generate value added and integrating timber production and timber processing chains.

The study indicates the biologically optimum rotation age based on the volume growth model and varied according to suitability classes, and economically optimum rotation age based on the optimization model for *A.mangium* species.

The study integrates land use and resource utilization approaches that serve to reduce the land area needed for a sustainable supply of timber, increase profit and add value, such as by creating employment for local people in contribution to hunger alleviation and bring additional environmental benefits.

This approach can bring potential benefits for sustainable development such as:

(1) This approach can contribute to energy and hunger balancing: Optimizing land use will respect to supply both food and renewable resource. Identification of optimal land area might demand land source for sufficient food and renewable resource efficiency consumption.

(2) The study provides an approach to optimizing land use in regions where land availability is limited and leads to conflict. The government encourages local people to grow several types of species in forest land including fast growing species (such as acacia and eucalyptus) and native tree species (such as melia, chukrasia, dracontomelon). By using this approach, the conflict among different land uses can be solved. Determination of spatial locations and land area for each land use is carried out, along with identifying possible alternative land use sources for other objectives such as protection.

(3) Improvement of land-use through applying this approach can reduce the land area used to generate the amount timber needed, which allocates the remaining land area for protection. For example, it is possible to extend rotation age for the remaining forest plantations to increase carbon stocks or allocate timber supply to intensively managed areas to meet timber demand, other remaining land areas where existing forest plantations do not need harvesting and can remain for the long term as natural forests.

Application of this optimization model can be extended to other species, areas, timber products, and other land uses such as agriculture crops, energy plant or palm oil. This approach is a tool that can contribute to the implementation of the Bonn Challenge that was launched in 2011 with the aim of restoring at least an additional 200 million hectares by 2030. Forest plantation establishment implemented with this approach can obtain this target and bring multiple benefits: economic, society, and conservation. All that is required is information on tree species, site productivity, rotation period, timber product, mill locations, and costs component. This model can take into account the value added to sustainable development.

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Appendix

Appendix 1: The result of growth models executed in SPSS

* NonLinear Regression.
MODEL PROGRAM ao=250 a1=10 a2=0.5.
COMPUTE PRED_=ao * EXP(-a1 / Age_V1 ** a2).

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
ao	19282,394	109243,575	-199474,092	238038,880
a1	6,850	5,332	-3,828	17,528
a2	,191	,218	-,245	,627

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	1128302,486	3	376100,829
Residual	19766,934	57	346,788
Uncorrected Total	1148069,420	60	
Corrected Total	169018,964	59	

Dependent variable: V1[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .883.

* NonLinear Regression.
MODEL PROGRAM ao=250 a1=10 a2=0.5.
COMPUTE PRED_=ao * EXP(-a1 / Age_V2 ** a2).

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
ao	2225,181	7176,625	-12145,764	16596,126
a1	5,242	2,523	,190	10,294
a2	,338	,368	-,398	1,074

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	889844,951	3	296614,984
Residual	40871,499	57	717,044
Uncorrected Total	930716,450	60	
Corrected Total	174420,822	59	

Dependent variable: V2[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .766.

```
* NonLinear Regression.
MODEL PROGRAM  ao=250 a1=10 a2=0.5.
COMPUTE  PRED_=ao * EXP(-a1  / Age_V3 ** a2).
```

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
ao	3418117,434	70429496,784	-140223788,281	147060023,148
a1	13,160	20,946	-29,559	55,879
a2	,132	,281	-,441	,706

ANOVA[a]

Source	Sum of Squares	df	Mean Squares
Regression	335996,536	3	111998,845
Residual	6577,934	31	212,191
Uncorrected Total	342574,470	34	
Corrected Total	87364,220	33	

Dependent variable: V3[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .925.

Appendix 2: Structure of household questionnaire

Introduction:
Hi, nice to meet you. My name is Nguyen Dang Cuong. I am conducting a PhD study at the University of Hamburg. I am interested in information on production costs and timber prices for *Acacia mangium* plantations.
The objective of this study is to improve the understanding of the selection of suitable locations for growing forest plantations, in this case *Acacia mangium* plantations.

The information that you give me will be used in my PhD thesis and published in English. I would like to record this interview using an audio recorder. That way, I can listen to the recording afterwards and make sure that I did not miss anything during the interview. Do you give me permission to record? [__] Yes [__] No

(Day/month/year):____
Province: Thai Nguyen District:
Commune: Village:
Interviewee Name: ___________________________________
Interviewer: ___________________________________
1. Are you the head of the household? [__] Yes [__] No
2. Do you have a forest plantation? [__] Yes [__] No
If yes, what are the species?

Species	Age	Hectare
Acacia mangium		
Acacia Hybrid		
Magnolia conifera		
Melia azedarach		
Styrax tonkinensis		
Eucalyptus		
Others		

3. What is the distance from the forest plantation boundary to the road? (Km)

4. What are the establishment and management costs (in the first year)?

Treatment	Material	Labor

	Unit/ha	VND/ unit	Day/ha	VND/ day
Site preparation				
Seedling				
Planting				
Fertilizing				

5. Do you apply any silvicultural activities from the second year until harvested? [__] Yes

[__] No

If yes:

5.1. Weeding

- What at age do you start weed control?

- How many times do you weed?

- How many days per ha? And how much do you pay for a day?

5.2. Fertilizing

- What at age do you fertilize?

- Which fertilizer do you use and how many kg do you fertilize per ha?)
- How many days do you need to fertilize for a hectare? And how much do you pay for a day?

6. When do you plan to harvest your plantation?

7. Which factors influence your decision to harvest the forest?

- Forest age [__]

- Timber price [__]

- Household's economic status [__]

- Decision of enterprises buying timber [__]

- Quantity timber (Yield) [__]

8. Harvesting costs

- How many days per hectare do you need to fell?

- How much do you pay for a day to fell?
- How many days per hectare do you need to cut timber (*pieces at standard length)*

- How much do you pay for cutting timber?

9. Do you know how much do you sell per m^3 timber at age of harvested year?

10. Transportation cost

- How much do you pay for transporting timber (1 m^3/ km) to the road head? (From the stumpage to the nearest road)

- What is the nearest sawmill from your plantation?

- How much do you pay for 1 m^3 timber transportation to mills for 1 km?

11. Did you receive support from the state to plant your plantation forest?

Support	**Unit/ ha (VND)**
- Subsidy:	
- Seedling	
- Fertilizer	
- Technical support	

12. Which factors are the main incentives for landowners to grow a forest plantation? Please list in descending order.

Factors	Ranks
Tax waiving	
Technical support	
Capital subsidy	
Timber price	
Others	

13. At what stage do you sell your wood?
- Standing trees [__]
- At road head [__]
- At mill gate [__]

14. Do you want to plant alternative tree species?

15. Which kind of tree species do you want to plant in the future?

16. If the government pays money to forest growers, are you willing to consider longer rotation periods? And reason?

17. The tenure of forest land
- Allocation [__]
- Leased [__]
- Contracted [__]

Appendix 3: Structure of mills questionnaire

Introduction:
Hi, nice to meet you. My name is Nguyen Dang Cuong. I am conducting a PhD study at the University of Hamburg. I am interested in information on timber price, transportation cost, your product types and the timer demand for processing *Acacia mangium*.
The objective of this study is to improve the understanding of the selection of suitable locations for growing forest plantations, in this case *Acacia mangium* plantations, under the optimization of forest management.

The information that you give me will be used in my PhD thesis and published in English. I would like to record this interview using an audio recorder. That way, I can listen to the recording afterwards and make sure that I did not miss anything during the interview. Do you give me permission to record? [__] Yes [__] No

Date of Interview (day/month/year):
Name of mill:
Location X:……………………..Y:…………
Interviewee name: ______________________________________
Interviewer: ______________________________________
1. Are you the head of enterprise/ household business? [__] 1. Yes [__] 2. No

2. Which tree species are main timber sources for processing?
- Acacia mangium [__]
- Acacia Hybrid [__]
- Magnolia conifer [__]
- Melia azedarach [__]
- Styrax tonkinensis [__]
- Eucalyptus [__]
- Others:

3. What kind of products do you produce?

4. What is the temporal horizon of your business?
5. The status of process
- Which unit do you use for selling (m^3 with air or without air, dry weight or wet weight?)

- Cost for labour:
+ How many people work in your mills and how much do you pay them?

+ Do your labors need lots of knowledge and experience in processing?

- Costs for machinery:
+ How many hours between machine repairs? How much do repairs costs?

+ Do you know the productivity of maximum machinery? Do you have enough timber for processing? If not, why?
6. Where do you sell your products and side products?
7. What are the dimensions and quality (classification) and price of your products?
8. Where, when, and who is doing the classification of your products?
9. Wood supply
- How many cubic meters does your mill need per month (year)?
- Which unit do you use for payment? (m^3 with air or without air, dry weight or wet weight?)

- Where do you buy timber (at street, at stand or at company)?
- Who is your counterpart (trader, forest owner)?
- . Do you buy *Acacia mangium* timber according to diameter class? [__] Yes [__] No
If yes: please specify the pricing system which applies to your particular case
   - Diameter between.........and ....with price at:
   - Diameter between.........and ....with price at:
   - Diameter between.........and ....with price at:
- Do you buy *Acacia mangium* timber according to diameter class? [__] Yes [__] No
- How much are you paying for 1 m^3 *Acacia mangium* timber (stumpage price or price at company)?
10. How does it cost for transporting 1 m^3 timber per kilometer? (by van/ truck to the mill)

11. Do you pay for transporting *Acacia mangium* timber to the mill according to distance?
[__] Yes [__] No
If yes: please specify the distance classes which apply to pay:

Distance	**VND / km**
< 5km	
5 – 10 km	
10 – 15 km	
15 – 20 km	
> 20 km	
…………	

12. How far away do considering buying wood (km) (at the farthest)? Why?

13. How much are you willing to pay for 1 m^3 of *Acacia mangium* timber at your door?

- The highest price:
- The medium price:
- The lowest price:

14. . In the next years, could you estimate how many cubic meters (m^3) your enterprise will need per year for processing? (What percent will your mill need?):

15. What is your perception of *Acacia mangium* in the future?

Appendix 4: Questionnaires for suitability classes determination for *A. mangium* and pair wise comparison

This interview is undertaken as part of a PhD research project conducted at the World Forestry Center, Biology Department, University of Hamburg, Germany.

The objective of this study is to improve the understanding of the selection of suitable locations for growing *A.mangium* plantations.

The aim of these questions is to evaluate the importance of ecological factors related to *A.mangium* growth. The ecological factors including soil, topographic and climatic factors are determined based on available data sources in the study area and the ecological requirements of tree species. The questions are designed to help experts in the assessment process by a combination between experts' judgments and AHP (Analytic hierarchy process).

The information that you provide will be used in my PhD thesis and published in paper in English. I would like to record this interview using an audio recorder. That way, I can listen to the recording afterwards and make sure that I did not miss anything during the interview. Do you give me permission to record? [__] Yes [__] No

Interviewee Name: ____

Institution: ____

Interviewer: ____

I. Assignment of ecological factors for suitability classes

1. Based on the FAO approach in land suitability assessment**,** how many suitability classes should be determined for growing *A.mangium* plantations in Thai Nguyen province?

2. Based on tree species requirements and site conditions, and classes of suitability determined as above; please assign ecological factors to respective suitability classes?

II. Pairwise comparison

Description of scale for pairwise comparison

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two factors contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one over the other.

5	Strong importance	Experience and judgment strongly favor one over the other.
7	Very strong importance	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Extreme importance	The evidence favoring one over the other is of the highest possible validity.
2,4,6,8	Intermediate values between adjacent scale values	Sometimes one needs to interpolate compromised judgment numerical

Source: (Saaty 2008)

For example:

a. Tick (x) in soil properties, which means ‘soil properties’ is more important than climate. If you say ‘more important’ with value of 3, which means ‘soil properties’ is 3 times more important than climate.
b. Similarly, Tick (x) in soil properties, which means ‘soil properties’ is more important than topography. If you say ‘more important’ with value of 5, which means ‘soil properties’ is 5 times more important than topography.
c. Tick (x) in climate, which means ‘climate’ is more important than ‘topography’. If you say ‘more important’ with value of 3, which means ‘climate’ is 3 times more important than topography.

	Soil properties	Climate	Topography
Soil properties	1	3	5
Climate	1/3	1	3
Topography	1/5	1/3	1

According to the results of a,b,c, we found what was wrong with this matrix? **The ratings are inconsistent.**

We know that Soil properties = 3 Climate and Soil properties = 5 Topography

As we say: 3 Climate = 5 Topography, which means Climate = (5/3) Topography. That is the reason why the judgment should be evaluated under careful consideration.

	Soil properties	Climate	Topography
Soil properties	1	3	5
Climate	1/3	1	**5/3**
Topography	1/5	**3/5**	1

1. Which factor is more important than the other? (Please tick x)

Soil properties	
Climate	

By how much?

1	
2	
3	
4	
5	
6	
7	
8	
9	

d.

2. Which factor is more important than the other? (Please tick x)

Soil properties	
Topographic	

By how much?

1	
2	
3	
4	
5	
6	
7	
8	
9	

3. Which factor is more important than the other? (Please tick x)

Climate	
Topography	

By how much?

1	
2	
3	
4	
5	
6	
7	
8	
9	

In soil properties:

4. Which criterion is more important than the other? (Please tick x)

Soil type	
Soil depth	

By how much?

1	
2	
3	
4	
5	
6	
7	
8	
9	

5. Which criterion is more important than the other? (Please tick x)

Elevation	
Slope	

By how much?

1	
2	
3	
4	
5	
6	
7	
8	
9	

From your judgment, please arrange the results as the following table:

	Soil properties	Climate	Topography
Soil properties			
Climate			
Topography			