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Land Use Spatial Optimization for Sustainable Wood Utilization at the Regional Level: A Case Study from Vietnam

Nguyen Dang Cuong [1,2,*], Köhl Michael [1,*] and Mues Volker [1]

[1] Institute for World Forestry, University of Hamburg, Leuschnerstr 91, D-21031 Hamburg, Germany; Volker.Mues@uni-hamburg.de
[2] Department of Silviculture, Thai Nguyen University of Agriculture and Forestry, Thai Nguyen 24000, Vietnam
* Correspondence: nguyendangcuong@tuaf.edu.vn (N.D.C.); michael.koehl@uni-hamburg.de (K.M.)

Abstract: Forest landscape restoration is a widely accepted approach to sustainable forest management. In addition to revitalizing degraded sites, forest landscape restoration can increase the supply of sustainable timber and thereby reduce logging in natural forests. The current study presents a spatial land use optimization model and utilizes a linear programming algorithm that integrates timber production and timber processing chains to meet timber demand trade-offs and timber supply. The objective is to maximize yield and profit from forest plantations under volatile timber demands. The model was parameterized for a case study in Thai Nguyen Province, Vietnam, where most forest plantations grow *Acacia mangium* (*A. mangium*). Data were obtained from field surveys on tree growth, as well as from questionnaires to collect social-economic information and determine the timber demand of local wood processing mills. The integration of land use and wood utilization approaches reduces the amount of land needed to maintain a sustainable timber supply and simultaneously leads to higher yields and profits from forest plantations. This forest management solution combines economic and timber yield aspects and promotes measures focused on economic sustainability and land resource efficiency.

Keywords: *Acacia mangium*; profit optimization; timber demand; linear programming

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1. Introduction

Between 1990 and 2015, the global annual net forest loss rate was 0.13% [1] and led to the worldwide search for more productive forest land use solutions and programs to motivate local people to use and manage their land in a more economical and environmentally friendly way [2]. Many international initiatives were launched focusing on the restoration of degraded land. The Bonn Challenge, for example, intends to restore 350 million hectares of deforested and degraded lands by 2030 [3] and the Asia-Pacific Economic Cooperation (APEC) aims to improve the forest cover of approximately 20 million hectares of all types of forests by 2020 [4].

In Vietnam, degraded land covers approximately 5.9 million hectares, or 41% of the total land area [5]. Several national Vietnamese restoration and reforestation efforts have been initiated to scale up the rehabilitation of degraded land, and to increase forest cover and wildlife habitats, such as the "Greening the Barren Hills Program" and "Five Million Hectare Reforestation Programme" [6,7]. The increase in forest area provides a larger timber supply, especially from planted forests. Currently, the area covered by forest plantations amounts to more than 3.5 million hectares and is estimated to reach 4.1 million hectares by 2020 [8]. Implementing the principles of sustainable development at the local level often encounters issues with contradictory stakeholder interests, which are likely to result in conflicts regarding the optimal use of land. Based on the principle of sustainable development and social sustainability, land use planning is often realized at the cost of a compromise between economic development and environmental conservation [9,10]. To achieve sustainable forest resource management and safeguard a sustainable timber supply, the long-term investment in planted forests requires significant planning and indepth understanding of governance practices [9]. Given the large selection of suitable land, afforestation and reforestation activities can foster resource utilization to meet an increasing global timber demand and mitigate CO_2 emissions by increasing forest carbon stocks and limiting the loss of natural forests.

Establishing forest plantations on currently unstocked land provides an opportunity to meet the growing demand for timber in Vietnam from domestic sources, while contributing to forest landscape restoration and protecting natural forests. This study provides an approach to efficiently select land for reforestation by incorporating site quality, growth projections, and the location of wood processing operations into the decision-making process. The approach offers a balance between long-term sustainable timber production and the demand for timber. At the same time, the optimization approach helps to reduce the amount of unnecessarily planted land.

There is a plethora of publications on multiple criteria demission making (MCDM) in the context of forest management. de Urbina et al. [11] provide a review of multi criteria and group decision making methods for decision making in forest management. From this multitude of methodological MCDM approaches, we have chosen to use linear programming (LP).

LP is a simple and flexible tool commonly used in land-use analysis as it can be combined with a GIS framework to optimize spatial land use allocation [12,13]. By combining LP and GIS, a model can be created that enables decision makers to analyze changes in the size and pattern of land use with regard to driving forces [14]. Linear programming models provide valuable insight into the relationship between decision variables and constraints in land use planning [15]. Previous studies demonstrated the usefulness of LP-based optimization methods to find suitable locations for strategic forest land use planning. Spatial bio-economic afforestation feasibility models were built to select bioenergy plantations to meet biomass demands needed for bioenergy based on the lowest wood supply costs and the break—even biomass yield [16,17]. Kalogirou [18] conducted land suitability assessment using linear programming to provide an economic evaluation of land for different types of agricultural crops and to select crops with the maximum income. Various multi-objective linear programming was applied by Santé and Crecente [19] to maximize gross margin obtained from land use allocation or by Shukla et al. [15] to maximize profit from a new allocation of land use in Spain.

Linear programming is often applied to select potential cut areas or to identify areas for wood supply. We extended on previous research on land optimization by focusing on wood demand and wood supply to achieve integration between wood production and wood processing chains. The aim of this work is to provide an integrated economic approach that identifies land suitable for forest plantations that also meets timber production goals and timber processing chain requirements. To this end, linear programming is used in combination with a GIS framework to create a land-use plan that maximizes profits from *A. mangium* plantations while maintaining a sustainable balance between timber demand and timber supply.

The main objective is to maximize the profitability of *A. mangium* plantations under different timber demands by integrating land use and resource utilization, which serve to reduce the area required for a sustainable supply of timber and to increase profits on the basis of the spatially explicit land-use optimization model. In this study, only the areas planned for production forests (commercial forests) are used for the optimization model. The areas earmarked for production forests include both planted and unplanted forest areas. Planted forest areas (forest areas) are areas planted with *A. mangium*. Unplanted forest areas are areas not planted with *A. mangium*, and these can be natural forests that grow very slowly and have a low biodiversity or are fallow.

2. Materials and Methods

2.1. Study Area and Species

2.1.1. The Study Area

Thai Nguyen Province, located in the northeast region of Vietnam (Figure 1), covers an area of approximately 350,000 ha. The total forest area is approximately 197,263 ha, of which 112,309 hectares are planned for production forests, 44,567 hectares for protection forests, and 40,387 hectares for special use forests. The elevation is between 50 m and more than 900 m a.s.l. The slope varies from 0 to over 35 degrees. Climate records show that the regional dry period lasts from December to February and the rainy season from May to October. The mean annual temperature is approximately 24°C, and the total annual precipitation is approximately 1700 mm [20].

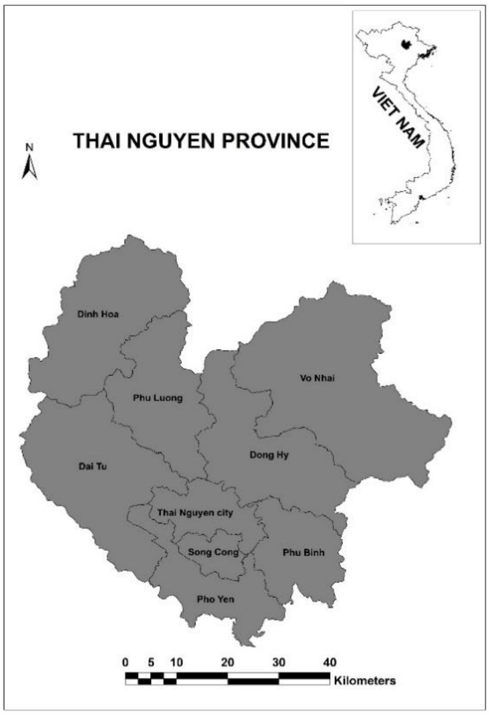

Figure 1. Map showing the study area.

2.1.2. The Study Species

The present study focuses on areas intended for production forests (commercial forests), which supply timber for processing in mills. The species studied is *A. mangium* Willd, also known by its local name Keo tai tuong, and one of the fastest-growing tree species in Vietnam [21]. According to Harwood and Nambiar [22], the total area of acacia plantations (e.g., A. auriculiformis, *A. mangium*, and hybrids of *A. auriculiformis* and *A. mangium)* in Vietnam in 2013 was around 1.1 million hectares. With an area under cultivation of 600,000 hectares, *A. mangium* is the most widely planted species in North Vietnam. In the study area, almost the entire harvested timber of *A. mangium* is used to produce woodchips, veneer, and pallet products. Figure 2 shows the distribution of 215 wood processing mills (37 pallet, 119 veneer, and 59 woodchip mills) and the distribution of non-planted and planted areas.

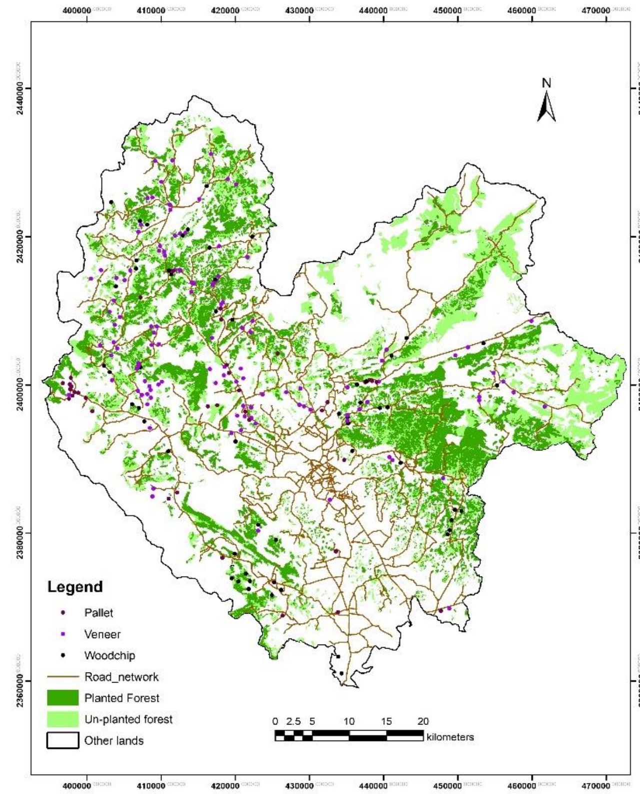

Figure 2. Map showing distribution of 215 wood processing mills and distribution of un-planted areas.

2.2. Description of the Land Use Optimization Model

The purpose of the optimization model in this study is to maximize owners' forest profit (profit = income) based on an objective function. The objective function is defined as:

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

where

MaxP: maximal profit

I: the set of all parcels

J: the set of all mills

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

P_j: is the unit price for the sale of timber at mill j in US dollars m^{-3}

C_{Ei}: is the unit cost for forest plantation establishment in US dollars m^{-3} in parcel i (the ith parcel)

C_{Si}: is the unit cost for silviculture practice applied in in US dollars m^{-3} in parcel i

C_{Mi}: is the unit cost for forest plantation management in US dollars m^{-3} in parcel i

U_{TR} : is the unit cost for transport in US dollars m^{-3} km^{-1}

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

U_H : is the unit cost for harvesting in US dollars m^{-3}

Constraints:

Subject to

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

M_j: annual timber demand for processing in mill J.

This constraint shows that the annual amount of harvested timber supplied to all mills must correspond to the annual consumptions of all mills. When the delivered timber of parcels (forest stands) is sufficient for the first mill and the profit is the highest, timber from other parcels is taken to the second nearest mill to cover the required timber demand. The process was carried out to the final mill to cover the total amount of timber used.

$$\sum_{i} Q_i \leq Q; \ \forall \, i \in I$$

The timber amount available from parcel I, Q_i, cannot exceed the available total timber amount Q.

Two approaches were considered to maximize household profits: (1) the landscape approach (_LA) does not distinguish between planted and unplanted forest areas. Both planted and unplanted forest areas have the same priority to be allocated to the timber demands of the individual mills. (2) The current forest approach (_FO) considers planted forest areas as priority areas to meet timber demands. If the planted forest areas do not supply enough timber to satisfy the demand, unplanted forest areas will be afforested until the demand is saturated. The framework of land use optimization model is presented in Figure 3.

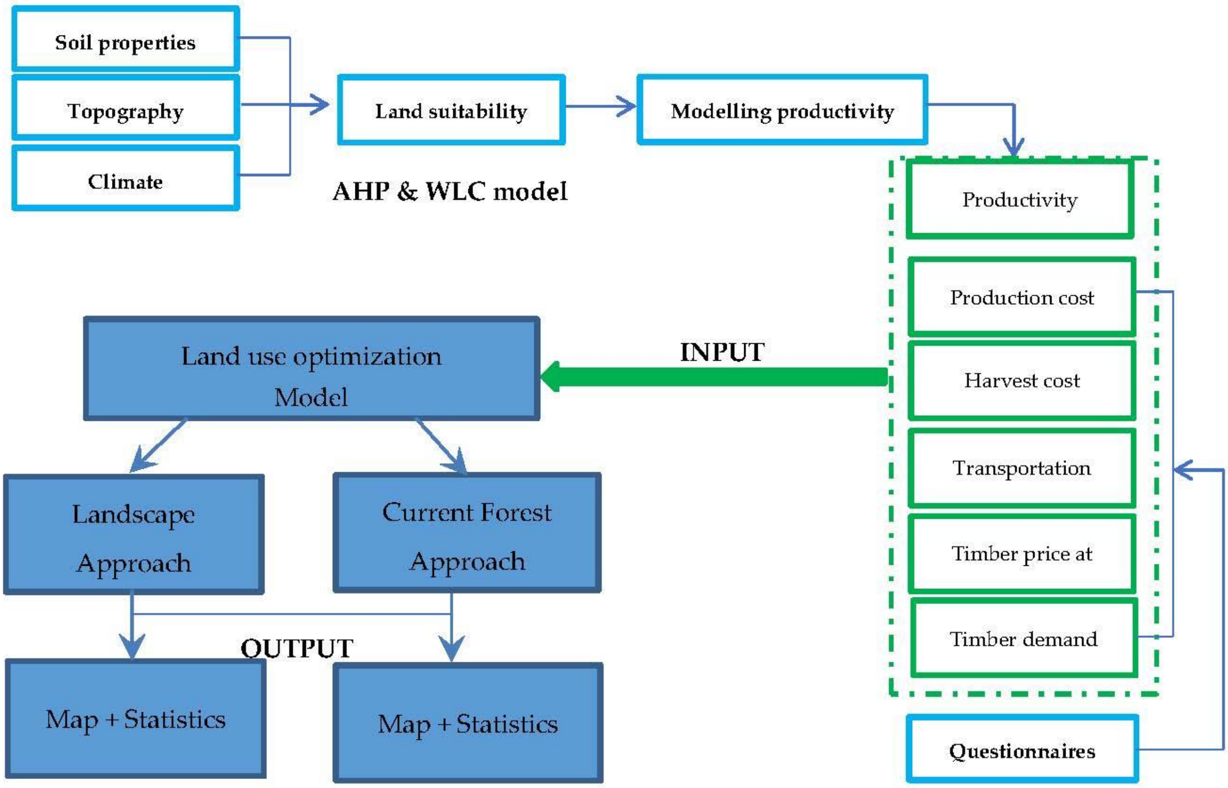

Figure 3. Framework of the land-use optimization model.

2.3. Input Variables

2.3.1. Productivity

We estimated productivity using a preliminary land suitability map through site-specific growth modelling. According to Cuong (2019) [23], four suitable classes were assigned to the land area: (1) highly suitable (S1), (2) moderately suitable (S2), (3) marginally suitable (S3), and (4) unsuitable (UN). Volume growth was assessed in three suitability classes, S1, S2, and S3. *A. mangium* plantations will be harvested at age 6 years according to forest owners' preferences and *A. mangium* plantations tend to show increased mortality at ages over 6 years. Based on the volume growth function, productivities of *A. mangium* at age 6 were assigned (S1 = 149.3 m^3 ha^{-1}, S2 = 127.3 m^3 ha^{-1}, and S3 = 103.6 m^3 ha^{-1}).

2.3.2. Production and Harvest Cost

Information on forest management practices, and on costs related to management and harvesting, were collected from local households in personal interviews using a questionnaire. Based on the list of households owning an *A. mangium* plantation, about 1% (45 households) of the total were randomly selected and interviewed face-to-face. The production cost for an *A. mangium* plantation was separated in the first year for site preparation, seedling, planting, and fertilizing. Weeding (grass control, shrub, and branch pruning) is applied in the second or third year (silviculture cost). Since forest owners generally live far from their forests, the annual payment for forest protection, which is considered a management cost, was calculated as per Decision No. 38/2005/QD-BNN on the use of labor in afforestation, forest protection, and development of the Ministry of Agriculture and Rural Development. Forest owners bear this cost for forest keepers. Harvest costs involve felling, cutting, and loading costs. The respective survey was conducted in November and December 2015. The questions in the questionnaire were asked in the exact order without skipping questions. For each interviewed household, the content questionnaires concentrated on the current social-economic condition, and forest-related activities such as establishment cost, silviculture cost, management cost, and harvest cost. The three interviewers of the survey team were trained and guided during a pilot phase, so as to minimize errors and uncertainties in the survey results.

2.3.3. Transportation Cost, Timber Price, and Timber Demand

A second questionnaire survey was developed to assess transportation cost, timber prices, and timber demand for mills that produce veneer, pallets, and woodchips as raw materials for industrial use. Fifteen mills producing woodchips, 16 mills producing veneer, and 19 mills producing pallets were randomly selected and interviews were made face to face. This survey was conducted in December 2015 and January 2016. It was conducted in a manner similar to the survey used to collect information from local households, and likewise included a training and a pilot phase.

2.4. Optimization Process for Allocating the Amount of Timber to Mills

The process of timber allocation to the mills takes place in four steps:

Step 1: Calculating the potential timber supply of each parcel of land (each forest stand)

Step 2: Defining the timber demand of each individual mill

Step 3: The allocation of forest stands (parcels) to mills based on the lowest transport and timber costs

Step 4: The supply for individual mills ensured by the interactive allocations of the most profitable stands to the mills

Timber supply from the land parcels was allocated to individual mills, three scenarios were realized:

If the timber supply 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 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 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.

The land-use spatial optimization model was developed using a linear programming algorithm developed and programmed in Microsoft Visual Basic for use in conjunction with an ArcGIS environment. Microsoft Visual Basic is a programming language that enables users to build desirable models for objective functions. In this study, the objective function is to maximize profit by balancing wood supply and wood demand. The results of the model were mapped and statistics were calculated showing the allocation of forests to potential land areas, the profit achieved, and the costs for the cultivation of *A. mangium* plantations in the study area.

2.5. Scenario Analysis

(1) The majority of Vietnamese acacia plantations are not certified by forest management certification systems such as FSC or PEFC, which hinders exports to North America and Europe. Vietnam is one of the largest exporters of timber and wood-based products, woodchip, and veneer to China [24]. According to information provided from local mills, the amount of wood-based products exported to China fluctuates. In addition to changing market developments, the mills' demand for timber can vary. For these reasons, a scenario called ECO_demand with five sub-scenarios was defined, which, in comparison with the current demand for timber, shows a different development in demand. ECO_demand − 30%: timber demand of all individual mills was assumed to decrease by 30% (673,063 m^3 $year^{-1}$).
(2) ECO_demand + 20%: Timber demand of all individual mills was assumed to increase by 20% (1,153,823 m^3 $year^{-1}$).
(3) ECO_demand + 30%: Timber demand of all individual mills was assumed to increase by 30% (1,249,975 m^3 $year^{-1}$).
(4) ECO_demand + 40%: Timber demand of all individual mills was assumed to increase by 40% (1,346,127 m^3 $year^{-1}$).
(5) ECO_demand + 50%: Timber demand of all individual mills was assumed to increase by 50% (1,442,279 m^3 $year^{-1}$).

For the ECO_demand scenario, the mean values of the attributes are similar to the scenario input variables selected for the business as usual (BAU) scenario, only the wood demand was adjusted for the respective sub-scenarios.

3. Results and Discussion

3.1. Questionnaires on Forest Activities of Households and Mills

3.1.1. Forest Activities of Households

A total of 45 questionnaires were collected and evaluated for descriptive statistics (Table 1).

Table 1. Descriptive statistics of households.

Attribute	N	Minimum	Maximum	Mean
Acacia area [ha]	45	0.5	10	2.0
Distance to road [m]	45	10	5000	757.4
Harvest age [years]	45	5	7.5	6.6
Establishment cost [USD ha^{-1}]	45	256	420	316
Silviculture cost (weeding) [USD ha^{-1}]	45	36	273	103

The average area planted with *A. mangium* is approximately 2 ha. The average distance from planted forests to roads is 757 m. Forest owners plan to harvest their plantations at the age of 5–7.5 years with an average of 6.6 years. The production costs comprise the establishment cost (site preparation, seedling, planting, fertilizer in the first year) and the costs for silviculture (weeding in the second year or third year, usually twice). The average of 60 US dollars $year^{-1}$ ha^{-1} was calculated by the Ministry of Agriculture and Rural Development for management costs related to the use of labour in afforestation, forest protection, and development.

The foundation costs ranged from USD 256 ha^{-1} to USD 420 ha^{-1}. During site preparation, the vegetation is removed and holes are dug for planting. Planting then takes place at the beginning of the rainy season. About 84% of households planted their plantations in March and 16% of households planted in April. The forest department of Thai Nguyen University recommends a tree density of 1600 trees per hectare, but forest owners often use different tree densities. More than 90% of households replant dead seedlings one month after planting. All households fertilized their plantations in the first year to increase productivity, with an average of 100 g per seedling.

Silviculture practices such as weeding were implemented. Weeding including grass control, and shrub and branch pruning is applied to limit the mortality of seedlings and to promote the value increase of logs with straight stems [25]. Most of the households (89%) conducted weeding twice in the second year, while 11% weeded in the third year. The cost for weeding ranged from USD 36 ha^{-1} to USD 273 ha^{-1}.

Harvest costs were calculated according to the number of working days per hectare, or to the price per m^3 after loading on trucks. On average, a team of five people carried out the harvesting operations, such as felling, cutting, and skidding to the road. The cost of harvesting was between USD 6.5 m^{-3} and USD 11 m^{-3}.

3.1.2. Processing Mills

A survey was also conducted at 50 mills. Fifteen of the mills produce woodchips as raw material for industrial use, 16 produce veneers, and 19 mills produce pallets.

Table 2 shows that the highest average prices are for woodchip mills (56.6 US dollars m^{-3}), followed by veneer mills (53.6 US dollars m^{-3}), and pallet mills (52.3 US dollars m^{-3}). At 7061.6 m^3 $year^{-1}$, the wood demand of chip mills is the highest, followed by veneer mills (3945.4 m^3 $year^{-1}$) and pallet mills (2037.7 m^3 $year^{-1}$).

Table 2. Mean timber price and demand and their descriptive statistics.

Attribute	Obs.	Mean	Std. Dev	Min	Max	SE	95%CI
Timber price at mill							
Woodchips (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
Timber demand							
Woodchips (m^3 $year^{-1}$)	15	7061.6	2267.9	3360	10,500	585.6	±1255.9
Veneer (m^3 $year^{-1}$)	16	3945.4	1731.1	1890	8400	432.8	±922.4
Pallet (m^3 $year^{-1}$)	19	2037.7	1091.6	907	5460	250.4	±526.2

Transport is part of the timber supply chain. The cost of transporting timber from the forest (stands) to the mill is often an essential component of the total timber costs. In this study, transport costs are considered as the cost of carrying timber from the stand to the mill. Of the 50 mills surveyed, 31 provided information on transport cost. The average transport cost was 0.3 US dollar m^{-3} km^{-1}.

3.2. Scenario Results

The optimization model was executed to show the allocation of potential land areas, the cost of growing *A. mangium* plantations, and the profit obtained for different scenarios. The BAU scenario assumes that *A. mangium* plantations are harvested at the age of 6 years according to the preference of forest owners and to satisfy the annual wood demands of all mills. In ECO_demand scenarios, the same rotation period of 6 years is assumed. The wood requirement varies, which means that the provision of an increasing or decreasing wood demand can be analysed. Both scenarios were implemented using two approaches—the landscape approach (_LA) and the current forest approach (_FO).

3.2.1. BAU

The objective of the BAU analysis was to implement the actual *A. mangium* management practice of harvesting timber at age 6. In this scenario, the mean values of the attributes presented in Table 3 are selected as input values for the optimization.

Table 3. The value of attributes used for the optimization model.

Attribute	Mean	Min	Max
Establishment cost (USD ha^{-1})	316	256.4	419.8
Silviculture cost (USD ha^{-1})	103	36.3	272.7
Annual management cost (USD ha^{-1} $year^{-1}$)	60	-	-
Harvest cost (USD m^{-3})	8	6.5	11
Transportation cost (USD m^{-3} km^{-1})	0.3	0.26	0.43
Price at pallet mills (USD m^{-3})	52.3	48.7	55.2
Price at veneer mills (USD m^{-3})	53.6	48.7	58.4
Price at woodchip mills (USD m^{-3})	55.6	51.9	58.4
Timber demand of individual pallet mill (m^3 $year^{-1}$)	2038	907	5640
Timber demand of individual veneer mill (m^3 $year^{-1}$)	3945	1890	8400
Timber demand of individual woodchip mill (m^3 $year^{-1}$)	7062	3360	10,500
Annual timber demand (m^3 $year^{-1}$) of all mills (Total 215 mills, of which 37 pallet mills, 119 veneer mills and 59 woodchip mills)	961,519	-	-
Number of parcels of land (Forest stand)	42,168	-	-
Number of mills	215	-	-

Table 4 shows the annual timber volume of 961,519 m^3 (in total, 5,769,114 m^3 in six years) supplied to individual mills in the study area. The annual timber harvest area required to meet the timber demand was lower under the landscape approach (7053 ha $year^{-1}$) than under the current forest approach (7217 ha $year^{-1}$). The difference is based on varying productivity rates; with average annual productivity at 22.7 m^3 ha^{-1} for the landscape approach and 22.2 m^3 ha^{-1} for the current forest approach. For the entire rotation period of six years, a total of 5,769,114 m^3 was needed to meet the timber demand for all mills. This corresponds to an *A. mangium* plantation area of 42,318 hectares under the landscape approach and 43,303 hectares under the current forest approach. Under the landscape approach, 17,924 hectares were currently planted in the forest, leaving a deficit of 24,394 ha, which need to be afforested in the 6 years of the first rotation (4066 ha/year). Under the current forest approach, the required *A. mangium* plantation area of 43,303 hectares has already been planted. However, from the second six-year cycle onwards, the entire area allocated must be replanted to meet the same timber demand.

Table 4. Key statistics for the landscape approach and the current forest approach (PA: pallet mills, VE: veneer mills, WC: woodchip mills).

Approach	Category	Total Profit (million USD $year^{-1}$)	Total Costs (million USD $year^{-1}$)	Land Area Allocated (ha $year^{-1}$) [1]	Demand (m^3 $year^{-1}$)
Landscape approach (_LA)	**Total**	**38.13**	**12.03**	**7053**	**961,519**
	PA	2.80	0.98	559	75,406
	VE	18.21	5.91	3484	469,455
	WC	17.12	6.05	3010	416,658
Current forest approach (_FO)	**Total**	**36.68**	**13.43**	**7217**	**961,519**
	PA	2.55	1.22	573	75,406
	VE	17.24	6.85	3570	469,455
	WC	16.89	6.28	3074	416,658

[1] Land area includes both planted and unplanted forest area.

In addition, the landscape approach resulted in lower total costs for timber procurement (USD 12.03 million pa^{-1}) compared to the current forest approach (USD 13.43 million pa^{-1}). The total profit of the landscape approach (USD 38.13 million pa^{-1}) was thus 3.96% higher than that of the current forest approach (USD 36.68 million pa^{-1}).

According to simulation results, the distribution of profit, cost, and area for both approaches varied depending on the total amount of timber demand by the different types of mills. Owing to the higher demand for wood, veneer mills accounted for the largest share, followed by woodchip and pallet mills. The annual wood demand of all mills was 961,519 (m^3 pa^{-1}). Although the average timber demand on a per-mill basis is the highest for woodchip mills (7062 m^3 pa^{-1} mill^{-1} compared to 3945 m^3 pa^{-1} mill^{-1} for veneer mills and 2038 m^3 pa^{-1} mill^{-1} for pallet mills), the total timber demand of the veneer mills was higher than that of the others mills, due to their large number (37 pallet mills, 119 veneer mills, and 59 woodchip mills).

For the two BAU scenarios with the landscape approach and the current forest approach, Figure 4 shows the map of areas for which a cultivation of *A. mangium* plantations with a rotation time of six years was assigned. In addition to the planted forest areas (in red and green), the unplanted areas (in blue and light green), as well as the locations of the mills and the road network, are also shown. For the landscape approach (left map), both planted and unplanted areas were assigned to the mills. For the current forest approach (right map), only planted areas were assigned to the mills. The allocation shown covers the wood requirements of the individual mills in both cases. It can be clearly seen that the selected areas for the landscape approach are aggregated in a smaller region around the mills, which is why the transport distances are shorter.

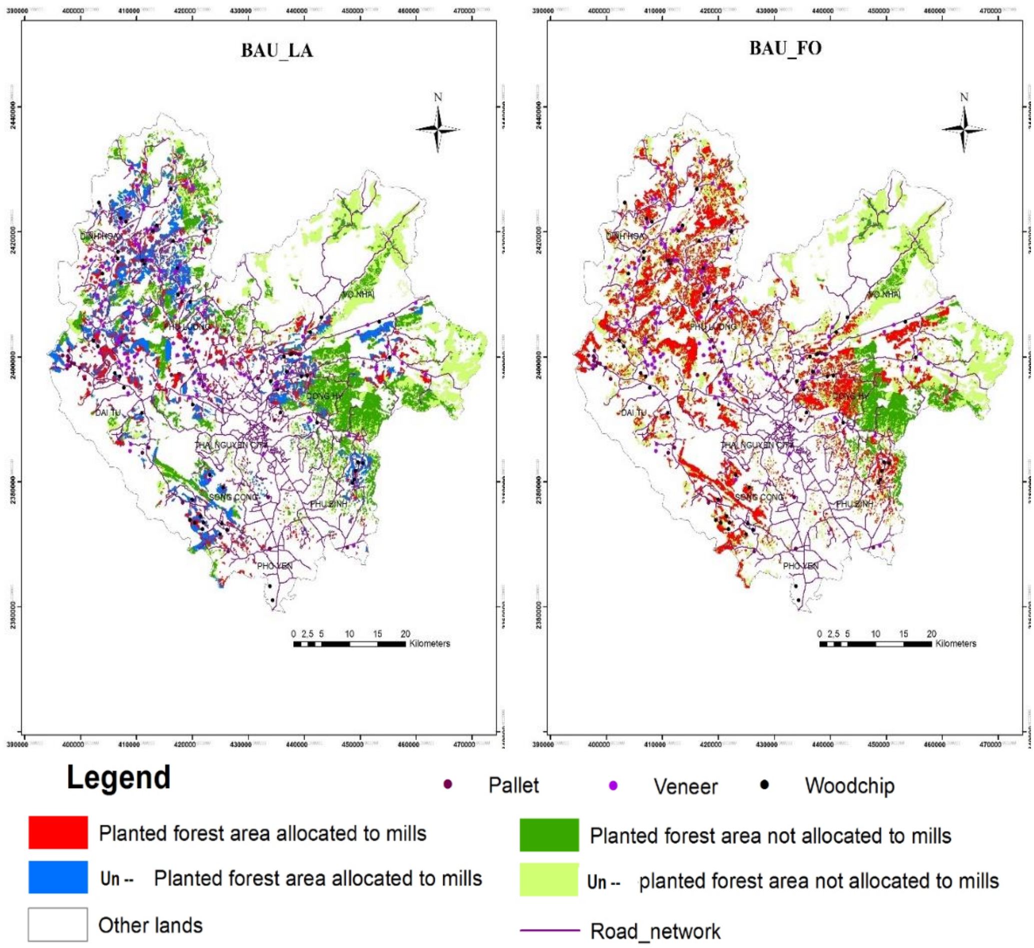

Figure 4. Maps showing the land area allocated for A. *mangium* plantations under the landscape approach (_LA) and the current forest approach (_FO).

3.2.2. The Impact of Timber Demand on the Allocation of Plantations

The effects of changing timber demand for all individual mills on profit, costs, total allocated land area, and total planted forest area are analysed. Figure 5 shows the annual average per hectare profit for the five sub-scenarios. The average profit under the landscape approach was generally higher than that of the current forest approach. This is because of the allocation of plantation areas to the mills. While the current forest approach uses the current allocation of plantations and only assigns additional areas for plantations if there is a shortage of timber, the landscape approach allows an optimal allocation of plantation areas, which ensures a significant increase in economic efficiency.

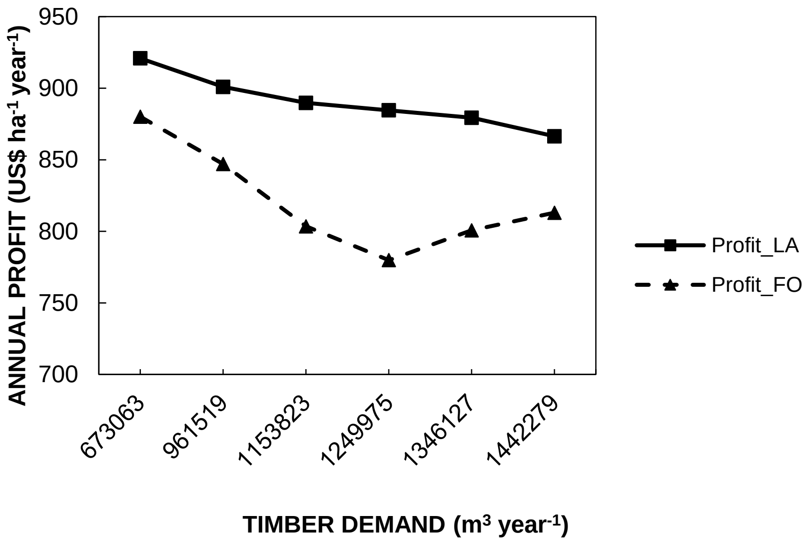

Figure 5. Household profits achieved by the landscape approach and the current forest approach.

Assuming an increase in timber demand from 20% to 50%, the landscape approach results in a consistent decrease in average profit. With low wood consumption, the optimization approach ensures that all plantation areas are placed on productive sites. As the demand for wood increases, areas with lower productivity are also selected, leading to observed losses in profits.

Under the current forest approach, the average profit per hectare decreased with increasing timber demand and reached a minimum of 4679 US dollars ha^{-1} for a 30% timber demand increase (ECO_demand+30%), followed by a slight increase. This development is replaced by a moderate increase in profit when timber demand is assumed to increase from 40% to 50% (ECO_demand +40% and ECO_demand +50%). This effect is caused by the selection of all planted areas for supply in sub-scenarios ECO_demand −30% and ECO_demand +20%. For the sub-scenario ECO_demand+30%, 244 hectares have to be planted additionally to satisfy the timber demand (Table 5). Any further increase in the timber demand necessitates the afforestation of larger areas of currently unplanted areas. These additional areas are allocated to sites that are more productive and are located closer to the mills. This increases the yield with lower transport costs and thus the overall profit.

The total profit depends on a number of cost factors. Figure 6 shows a clear upward trend in total cost under increased timber demand. Harvesting costs are the biggest cost factor and increase continuously with the amount of timber provided. The same applies to the cost component establishment costs, management costs, and silvicultural costs, which increase with the increase in the underlying areas. The situation is different with transport costs. Under the landscape approach, the optimization algorithm selects areas with regard to site productivity and distance to mills. With increasing demand for wood, areas necessarily selected are located further away from the mills, resulting in a continuous increase in transport costs. Under the current forest approach, all currently planted areas are selected first. As the demand for wood increases, so does the transport distance and thus also transport costs. If the currently planted areas alone are no longer sufficient to meet the timber demand (i.e., from ECO_demand +30% onwards), additional areas must be afforested. The optimization algorithm selects currently unplanted areas that are closer to the mills. This reduces the average transporter distance and, in turn, transportation costs.

Table 5. Total forested area allocated for different timber demands under the current forest approach (_FO).

Scenario	Total Land Areas Allocated (ha)	Planted Forest Areas Allocated (ha)	Un-Planted Forest Areas Allocated (ha)
ECO_demand − 30%	30,043	30,043	0
BAU	43,303	43,303	0
ECO_demand + 20%	52,197	52,197	0
ECO_demand + 30%	56,749	56,505	244
ECO_demand + 40%	60,972	56,522	4450
ECO_demand + 50%	69,603	56,489	13,114

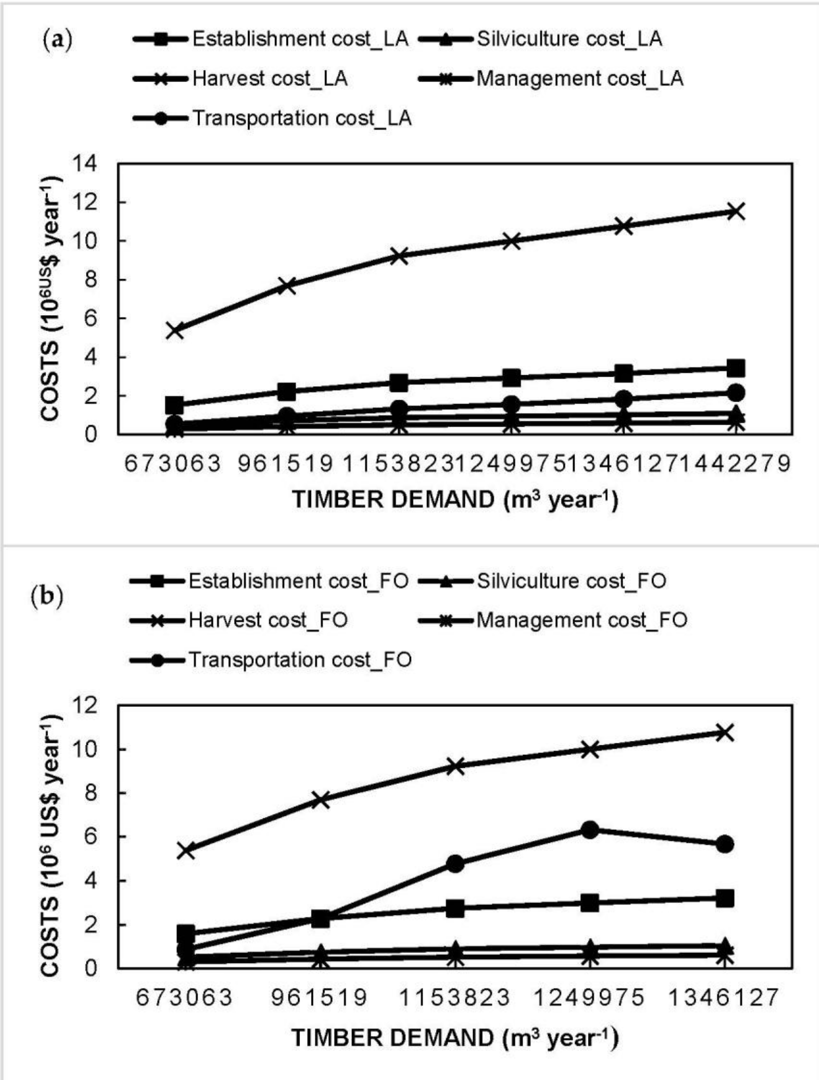

Figure 6. Change in cost components under the landscape approach (**a**) and the current forest approach (**b**) for different timber demands according to variations in timber demand.

In summary, the optimization algorithm selects those areas that maximize the profit for timber supply. The landscape approach does not require any consideration of existing plantation areas. Thus, the optimization has an effect on every level of the timber demand. Under the current forest approach, the influence of optimization only comes fully to bear when new areas have to be reforested. Therefore, profit maximization is only achieved with a delay. The spatial allocation of plantation areas is shown in Figures 7–11 for different levels of timber demand.

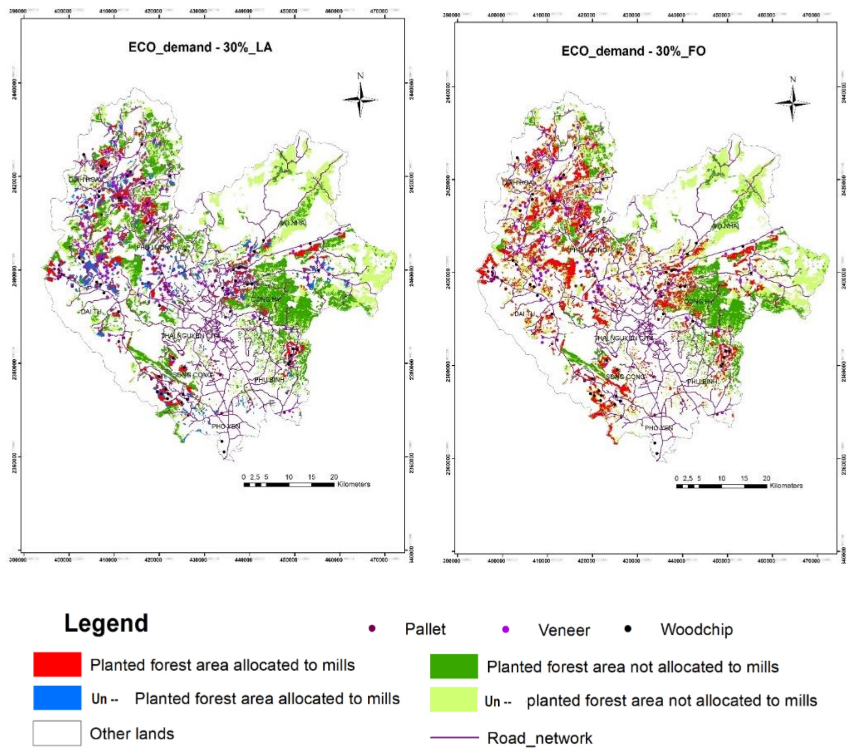

Figure 7. Spatial distribution of land area allocated by decreasing timber demand 30% under the landscape approach (_LA) and the current forest approach (_FO).

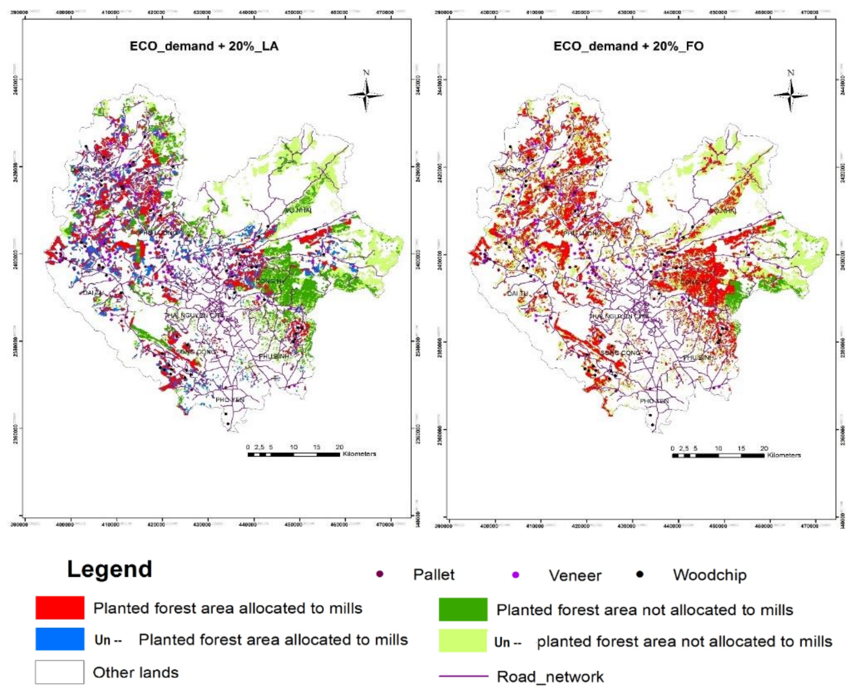

Figure 8. Spatial distribution of land area allocated by increasing timber demand 20% under the landscape approach (_LA) and the current forest approach (_FO).

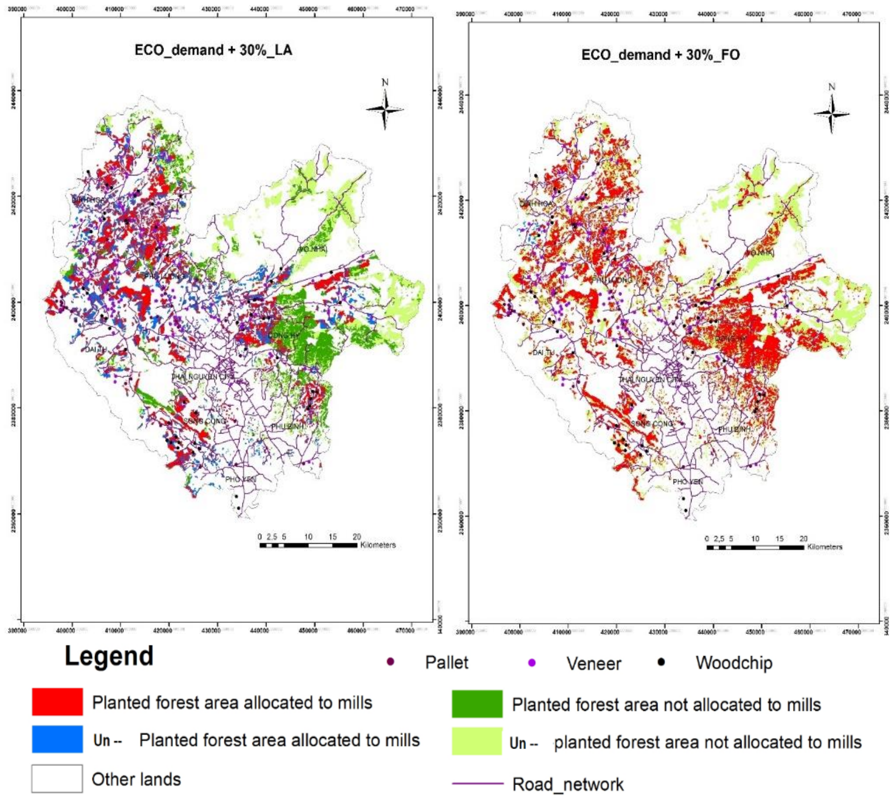

Figure 9. Spatial distribution of land area allocated by increasing timber demand 30% under the landscape approach (_LA) and the current forest approach (_FO).

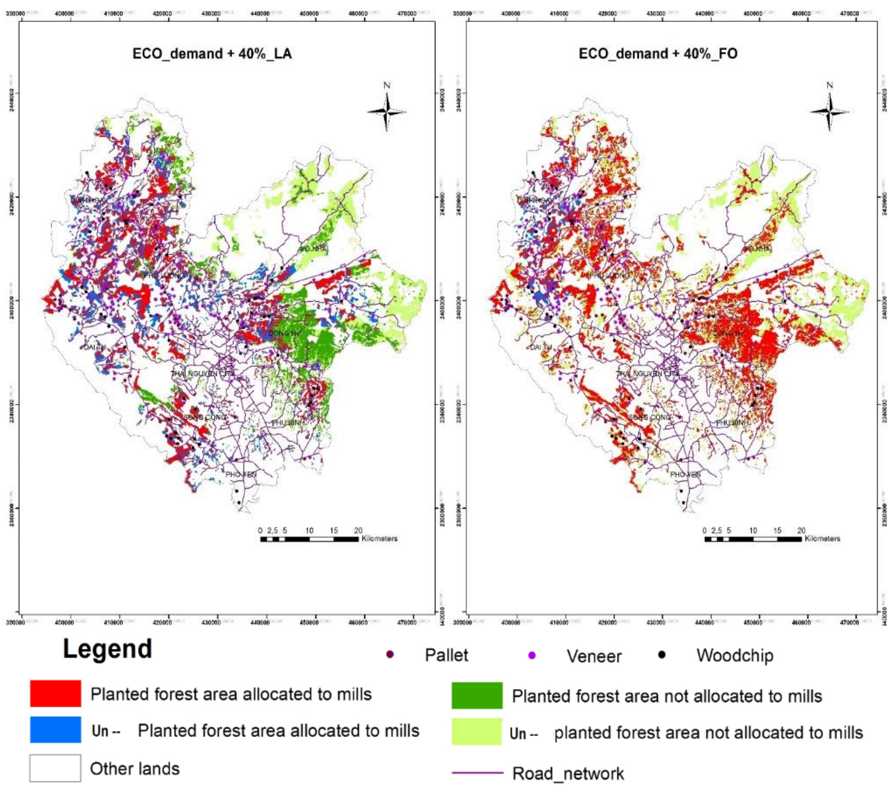

Figure 10. Spatial distribution of land area allocated by increasing timber demand 40% under the landscape approach (_LA) and the current forest approach (_FO).

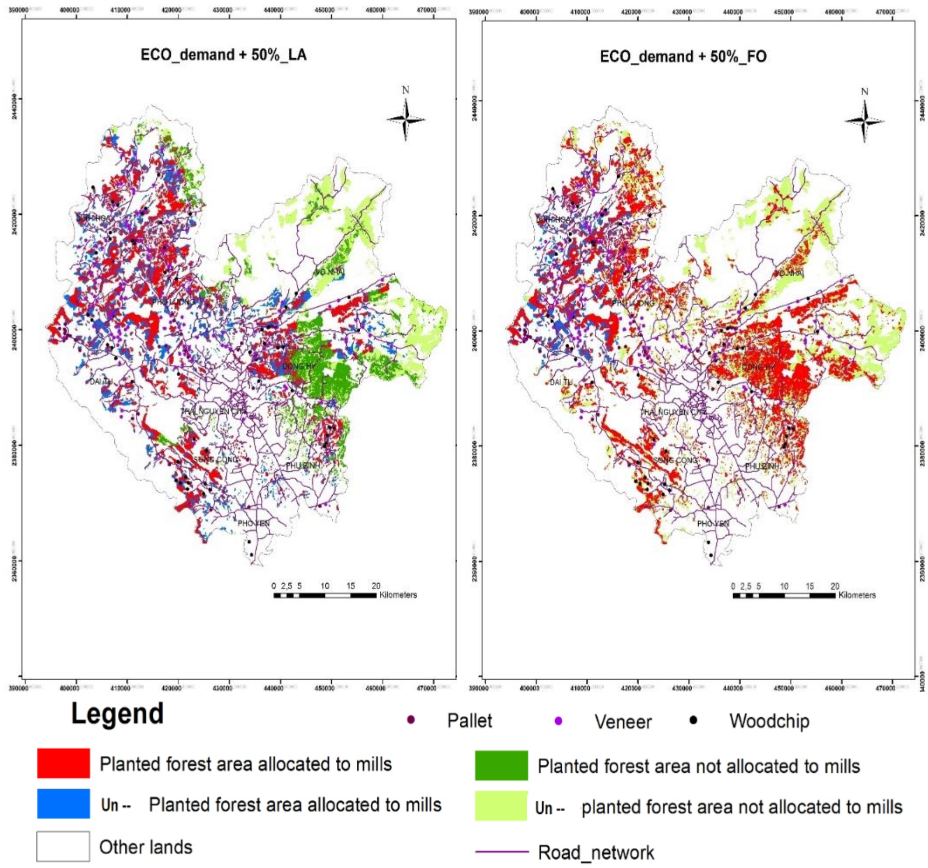

Figure 11. Spatial distribution of land area allocated by increasing timber demand 50% under the landscape approach (_LA) and the current forest approach (_FO).

The simulation study shows that the landscape approach, which does not take into account the current distribution of plantation land, generally results in minimized costs and reduced land requirements. However, the forest approach is easier to implement in reality, since forest owners who currently operate A. mangium plantations are hardly persuaded to manage other areas.

Timber demand was defined as a major cause for the expansion of forest plantations [26,27]. The expansion of plantation areas is often uncoordinated and therefore does not exploit the potential increase in profits. In particular, aspects such as site productivity and distance to the wood-processing industries are not sufficiently considered when new plantations are established. An optimization approach was developed to allow rational decisions to be made regarding the location of new plantation areas. The decision to establish new plantations is based on the timber demand of individual mills, the distance to mills, and the productivity of potential sites. The optimization model applied in the study indicated that the parcels with the highest profits were selected to serve forest plantation expansion.

Forest plantations can satisfy wood demand, while at the same time meeting other values such as biodiversity conservation, by reducing harvesting activities in natural forests. The benefits of planted forests for biodiversity are discussed controversially with respect to their design and management [28]. In this study, the method applied indicated that unplanted areas with low biodiversity values and low timber volumes can be afforested by acacia plantations to meet timber demands, but can lead to forests with low biodiversity. On the contrary, according to designated ecological functions and use purposes in Vietnam, areas planned for forest lands are classified into three categories: special use forest, protection forest, and production forest. This study focuses on land planned for production forests. Increasing timber supply by new forest plantations reduces pressures on protected forests in Vietnam [29–32].

The current model using linear programming provides a straightforward and flexible approach for a single objective, to assess trade-offs between multiple criteria and foster participatory decision making. The current approach may be extended to multi criteria decission making. Garcia-Gonzalo et al. [33] built an innovative decision support system including multi-objective linear programming. Borges et al. [34] constructed decision maps for forest ecosystem management based on the feasible goals method. Further approaches are presented by de Urbina et al. [11]. However, solving the objective function through linear programing and embedding the results in a GIS framework made it possible to visualize efficient solutions for land use planning in a mapped format. It provides an initial transparent approach to assess trade-offs between stakeholders from the forest and timber sector, which can be extended to a multiple criteria decision making tool.

The results of the study raise several issues that need to be discussed. Firstly, timber parcels assigned to mills vary and are shifted among mills, leading to higher transportation costs and substantially lower profits. For example, when the timber supply 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 mills. However, if the timber supply of parcel i is less than or equal to timber demand of the mill j, the total timber of parcel i will only be assigned to the mill with the highest profit.

Secondly, more timber demand would lead to a reduction in profits. The principle of execution model in order of the highest profit of parcel i would be selected in advance, followed by parcels with lower profits until the timber demand of all the mills is fulfilled. Increase in timber demand leads to a significant increase in the area with lower potential productivity and higher costs. Transportation costs in particular increase considerably when timber demand increases. This cost noticeably depends on the geographical distribution of mills and harvest areas [35]. The transportation cost should be included in an economic efficiency evaluation to avoid overestimating the yield value and economic return in forest evaluation [17]. Besides, the back-haulage flow of timber has not been used to reduce transport costs. Here, only transportation costs from a wood pickup location to a customer site are considered. [36].

Thirdly, the model was built to include the total timber needed in six years. Therefore, in fact, land areas must be planted to meet timber demand in six years, with annual land areas being 7053 ha under of the landscape approach and 7217 ha under the current forest approach, and forest plantation would be only harvested in the next six years to achieve the highest profit. Therefore, only a certain proportion of parcels would deliver timber in the first year of the second rotation.

Finally, the economic efficiency of forest plantations should be calculated based on net present values (NPV) rather than average annual profits. The NPV regarding the receipts, payment, rotation, and interest rate represents the comparison between cost and benefit and helps decision makers consider whether or not they should invest in plantations [17,37,38]. In this research, interest rate (r) has not been included in the calculation, which drives the optimal length of biological and economic cycles because it is volatile and must create artifacts. The optimization results are given in terms of land area allocated to meet timber demand; average annual profit could be accepted for decision making.

This optimization model enables cooperation between producers (forest owners) and consumers (mills), and fosters sustainable forest plantation management. Although Öhman et al. [38] applied a mathematical formulation (mixed integer programming) to meet demand for suitable habitat based on net present value maximization, the result of that research has not solved this issue. In fact, consumers want an ensured supply of sustainable timber, while producers are interested in a sustainable source of income. The link between these two requirements is usually the balance between wood supply and wood demand, and the price of the raw material. Both aspects are considered in the optimization approach presented, thus leading to a win–win situation for both producers and consumers. However, it must not be overlooked that the approach also presents some disadvantages for individual producers, in particular if their land is not of adequate site quality or too far away from consumers. If these producers are also to be involved in the sustainable production of wood, support measures may be necessary. Especially in this context, the optimization approach can be a valuable decision-making aid, by identifying profit deficits and thus providing starting points for support measures.

4. Conclusions

In the present study, a land use spatial optimization model is developed as an integrated economic approach, showing a combination between site productivity and economic factors, to generate value and integrate timber production and timber processing chains. The results showed that the landscape approach requires less land and less funding to produce the same amount of wood compared to the current forest approach (7053 ha year^{-1}/USD 12.03 million year^{-1} versus 7217 ha year^{-1}/USD 13.43 million year^{-1}). In contrast, the profit of the landscape approach is higher (USD 38.13 million year^{-1} versus USD 36.68 million year^{-1}). This optimization model enables the integration of land use and resource utilization approaches that serve to reduce the land area needed for a sustainable supply of timber and increase profit for both producers and consumers. The application of this optimization model can be extended to other species and areas in similar conditions.

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