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An approach for the formulation of sustainable replanting policies in the Indonesian natural rubber industry

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Abstract

Rubber replanting is a key factor in sustaining natural rubber supplies because it replaces less productive rubber trees with fully productive ones. However, the time taken for rubber trees to become fully productive (approximately 6 years) can cause significant impacts on shorter-term rubber supplies. In addition, replanting can have environmental impacts, such as reduction of carbon stocks because immature trees convert less CO_2 than mature ones, and social impacts, such as reduced need for tappers, the highly skilled employees who harvest latex from rubber trees, during the immature phase of trees' lives. Early discussions with Indonesian natural rubber stakeholders highlighted a demand for methods and tools that allow the consideration of these impacts when formulating replanting policies. This paper proposes an approach to support the formulation of sustainable replanting policies in the Indonesian natural rubber supply network that allows users to consider trade-offs between three factors: economic, social and environmental. The approach uses the composite indicators method to represent the impacts of replanting on the sustainability of the supply network. These indices are used to drive computer simulations with a view to finding optimal replanting policies for given situations. The approach is illustrated through an application to the formulation of sustainable replanting scenarios in the Langkat, Deli Serdang, Asahan, Simalungun and South Tapanuli Districts at North Sumatera Province Indonesia.

Keywords: Sustainable supply network, replanting, Composite indicators, Dynamic programming, Natural Rubber

Highlights

- Rubber trees have three lifecycle phases: immature, productive, less productive
- The balance of trees in a supply network is managed with replanting quotas
- Replanting quotas and policies impact all three dimensions of sustainability
- Sustainability impacts of quota allocations are quantified using composite indices
- These indices are used in network simulations to find optimal allocation quotas
- The simulations use a novel hybrid approach to integrate the three dimensions
- Simulation results identified different optimal quota allocations for each district

1. Introduction

Natural rubber is an important material because it is renewable and has good elasticity properties. Global demand for natural rubber is increasing because many products, such as tyres, industrial equipment, medical and laboratory devices, use it. To support the future economic sustainability of the natural rubber industry, it is important to secure future natural rubber supplies to meet future customer demands. In addition, customers and other industry stakeholders are increasingly concerned by the environmental sustainability of raw materials such as rubber and, social sustainability in the regions of the world where such materials are produced. Meeting these conflicting demands requires strategic planning from stakeholders in the natural rubber supply network. Rubber tree replanting is a critical point in the lifecycle of rubber plantations, and so wider rubber supply networks, because it replaces less productive, aging, rubber trees with young ones that will be more productive once they have matured. For this reason, replanting is regarded as a key activity to sustain rubber supplies by the Sustainable Natural Rubber Initiative (SNR-i)[1]. Despite the importance of this activity, however, there are few approaches in literature to support replanting decisions and the one approach that does exist, (Manisri and Pichitlamken, 2017), proposes a hybrid simulation model to support natural rubber planting decisions but is focussed on pricing and oversupply. This paper contributes by developing a hybrid approach for supporting natural rubber replanting decisions that take account of all three aspects of sustainability. The approach has been evaluated using the Indonesian rubber industry as a case study and has the potential to be developed into an industry strength methodology once it has been tested in a range of different situations and by different users.

Indonesia has the world’s largest rubber plantation area and produces around 25% of global natural rubber supplies. Its natural rubber supply network includes a range of players including rubber plantation farmers, latex suppliers and primary processors who convert latex into crumb rubber, rubber smoke sheet and highly concentrated latex (Sitepu et al., 2016). These players are geographically dispersed across Indonesia’s territory. The allocation of replanting quotas to specific districts is a strategic decision that influences future rubber supply (a longer term impact) and requires capital investment. However, although it ensures supplies in the longer term, replanting brings significant negative impacts to the shorter term sustainability of the supply network. This paper focusses on three of these impacts, which were identified through discussions with Indonesian natural rubber industry stakeholders in North Sumatera:

i) reduction in short term supplies because of non-production in the immature phase of rubber trees’ lifecycles after replanting [economic sustainability],

[1] SNR-i is part of IRSG, an international study group with a focus on rubber. Members of this organisation include producers of natural rubber from several countries including Indonesia, Malaysia and Thailand.

ii) reduction in global carbon stocks because of the removal of mature trees [environmental sustainability], and
iii) reduction in demand for workers who harvest latex from the trees (tappers) because their services are not required within the immature phase [social sustainability].

These discussions highlighted a need for improvements so that these shorter-term impacts could be taken into account in the formulation of replanting policies for the longer term. Although, there are other impacts of replanting, such as reduction of suppliers' income and declining population of suppliers, these impacts were selected because they were identified as key factors that disturb the stability of the natural rubber supply network and so the supply of rubber. To address this need, an approach was proposed to assist decision makers in making trade-offs between these three sustainability impacts when formulating replanting policies. The approach was evaluated through application to a case study based in the Indonesian natural rubber industry across several districts in North Sumatera Province.

In Section 2 we review literature with a focus on planning sustainable supplies of agricultural products at the sourcing stage of agricultural supply networks. The methodology and research process used in this research are outlined in Section 3 and, in Section 4, the life cycle of rubber plantations is introduced and replanting outlined as a critical point in rubber plantations' life cycles. Section 5 introduces a trade-off and optimisation tool for formulating sustainable replanting policies. The tool was evaluated through a series of experiments that used real world data from selected districts in North Sumatera Province. This experimentation generated rubber replanting allocation quotas for selected districts, which are outlined in Section 6. In the final section, conclusions are summarized together with the limitations of the study and potential future work.

2. Sustainable supplies in agricultural industry supply networks

This section introduces a review of literature on planning for sustainable supplies at the sourcing stage of agricultural supply networks. Recent approaches used by researchers to support the planning of sustainable supplies are reviewed with a view to identifying models for trade-offs between the three objectives of sustainability (economic, social and environmental) used in making decisions related to supply networks. To achieve these objectives, this section is divided into three sub sections: recent approaches for planning sustainable supplies (Section 2.1), trade-off models for planning sustainable supplies (Section 2.2), and dynamic programming for planning sustainable supplies (Section 2.3).

2.1. Planning sustainable supplies at the sourcing stage

In agricultural industries, establishing optimal supplies for downstream organizations in the supply network depends on production from upstream sources such as farms and plantations. Tsolakis et al. (2014) define this as a strategic decision and major component in configuring supply networks in agricultural industries where the goal is to maximise supply. However, in rubber supply chains, what constitutes optimal supply also depends on factors that affect the longer term sustainability of the industry. It is not possible to plan for all future events when determining optimal sourcing in the network, but it is necessary to define an appropriate direction, which requires comprehensive insights and good forecasts of future situations in the supply network, such as the ability to predict future natural rubber supply volumes. Moreover, he asserts that optimal sourcing should be achieved without generating adverse effects to surroundings such as reducing community welfare and increasing emissions.

Hence, three dimensions of sustainability need to be considered in the planning process. This is challenging because the supplies that are a consequence of the planning process depend on the lifecycle stages of the trees in the plantations and the distribution of trees' ages across the network. To address these challenges, numerous models and tools have been proposed to support decision making for optimal sourcing. For example, Bouchard et al. (2016) proposed an integrated model for forest planning that consists of a forest management model and a logistics model. Natural growth and the spatial distribution of trees in forests are captured by their forest management model while their logistics model captures the flow of timber through several processes after harvesting. Zhai et al. (2014) introduced bi-level programming with a genetic algorithm to support planning for fast growing plantations. This model consists of a higher level programme to capture the age structure of the plantation and a lower level programme as a model to maximize economic benefits from harvesting. Ahumada and Villalobos (2011) introduced a planning model for planting tomatoes and peppers considering traditional factors such as price, inventory cost and transportation cost. Furthermore, they improved a previous model by capturing uncertainty factors in the planning model for planting tomatoes and peppers (Ahumada et al., 2012). Each of these approaches focus on assessing one or at most two dimensions of sustainability whereas this paper considers three dimension of sustainability in formulating replanting policies for the Indonesian natural rubber industry.

In the natural rubber industry, optimal sourcing means ensuring a steady supply of rubber across the long term. Achieving this depends on finding an optimal quota of planting for new plantation areas and replanting for existing plantation areas. However, neither the allocation of replanting quotas nor the total area for replanting is considered in current practice. Current approaches for planning replanting focus on the use of high quality seeds and improvement of plant density measured as the total number of rubber trees/hectare (SNR-i). In addition, the majority of available models for the planning of sourcing in literature are intended for fast growing plants, such as tomatoes and peppers, which have different characteristics to slower growing plants such as the trees used in the natural rubber industry. In this context, this paper contributes to the source planning field for tree-based products such as rubber by introducing an approach that supports the formulation of sustainable tree replanting policies using the Indonesian natural rubber industry as a case study.

2.2. Trade-off models for planning sustainable sourcing

The incorporation of sustainability in supply network planning processes is challenging because it requires decision-making processes that balance the three dimensions of sustainability. In practice, planners are unable to improve all dimensions concurrently because improving one dimension can have detrimental effects on other dimensions. As a result, planners make compromises across the sustainability dimensions when making strategic decisions. For example, in the natural rubber industry, a three way trade-off between customers' needs for a steady flow of rubber, an industry need to improve its environmental sustainability and rubber plantation owners' needs to maintain their financial sustainability are required in designing replanting programmes (Sitepu et al., 2016). To address this issue, many studies have investigated and proposed trade-off models. Mathematical modelling has been used for this purpose by a number of authors. (Longinidis and Georgiadis, 2013) report the use of multi objective mixed integer non-linear programming with Pareto optimality to achieve compromises between financial performance and credit solvency in designing supply networks under economic uncertainty. A similar approach was used by (Zhang et al., 2014) to enable trade-offs between three sustainability indicators in chemical business supply networks: total cost, greenhouse gas emissions and lead time. Furthermore, their model used environmental data from company lifecycle assessment reports. However, mathematical models do not provide flexibility for planners to prioritize different dimensions in different circumstances, e.g., based on current conditions of the network and requirement from stakeholders such as regulators. In some supply networks, due to environmental damage, stakeholders and regulators push planners to prioritize environmental indicators over other indicators.

Hassini et al. (2012) proposed the use of the composite indicators method for assessing the sustainability of supply networks. This method provides a single performance indicator value, a composite index, which is calculated from a collection of performance and sub-performance indicators that span multiple sustainability dimensions. In Hassini et al's framework, indicators and sub-indicators are determined by planners in the supply network. Furthermore, planners are given flexibility to determine weightings for each indicator based on the degree of interest. Moreover, it is straightforward to link composite indices across different models used in applications such as lifecycle assessment and process simulation. Composite indices are widely used in fields such as economics, engineering, healthcare and agriculture (Rogge, 2012). Flexibility for planners and the ability they offer to aggregate information from different indicators into a single value are the main reasons for the popularity of this method. Some example implementations of the composite indicators method can be seen in (Areal and Riesgo, 2015; Badea et al., 2011; Tajbakhsh and Hassini, 2014; Zhou et al., 2010). These examples show implementations in different fields and apply a range of methods for the normalization, weighting and aggregation of indicators into a composite.

The use of the composite indicators method offers several advantages for the consideration of sustainability. For example, in this research they opened opportunities for stakeholder participation in the selection of indicators to be used and the allocation of weightings. Applications of the composite indicators method to enable trade-offs across the three sustainability dimensions are sparse in literature, particularly around the planning of sourcing in agricultural industries; this paper demonstrates its use in the formulation of sustainable replanting policies for natural rubber.

2.3. Dynamic programming for the planning of sustainable sourcing

Dynamic programming was developed as an optimisation tool and is based on Bellman's principle of optimality (Bellman, 1972) which argues that problems whose resolution require decisions to be made at different levels or stages must be solved by an interrelated series of decisions (Hillier and Lieberman, 2001). In essence, Bellman's principle requires the division of problems into sub-problems where optimal solutions are defined sequentially for each sub-problem.

Dynamic programming has been widely used in a range of sectors. For example in the transportation sector, Otto and Boysen (2014) used dynamic programming to define locations for stops in public transportation networks. In the energy sector, Fan et al. (2016) used dynamic programming to define allowance levels for trading and energy consumption based on a personal carbon trading scheme and in the medical sector Astaraky and Patrick (2015) investigated the use of dynamic programming for multi resource surgical scheduling. In the agricultural sector, Diban et al. (2016) used dynamic programming to identify the best times for replanting by considering CO_2 emissions during the life time of palm oil trees.

Dynamic programming offers an effective approach for optimizing complex networks (Tripathy et al., 2015). However, in supply networks, implementations of dynamic programming are rare (Seuring, 2013). For example, Brandenburg et al. (2014) found that dynamic programming had only appeared in one paper, (Hu and Bidanda, 2009), where the focus is on the whole lives (from raw material to disposal) of consumer products, such as electronic goods, with short lifecycles. In contrast, this paper applies the composite indicators and dynamic programming methods as a trade-off and optimisation tool for use in the planning of the supply of a raw material, rubber, used in a range of end products and lifecycle lengths.

3. Research methodology

This section outlines the methodology and research process that were used to develop and evaluate the approach for supporting the formulation of replanting policies in the Indonesian natural rubber industry. Formulating replanting policies involves a range of activities including selection of seeds, selection of rubber tree age to be replanted, selection of rubber plantation locations and allocation of quotas for land to be replanted. Replanting policy in this paper refers to a policy for allocating quotas of land to be replanted (in hectares).The natural rubber industry has a number of key characteristics that differentiate it from other agricultural industries. Specifically, differences can be observed in the lifecycle of rubber trees, and methods for harvesting, processing and the distribution of the latex that they produce. A deep investigation was required to capture interactions between key players and their behaviours in the supply network. To achieve this, the case study approach was selected as the research methodology because it enables a phenomenon to be explored within its real life context (Yin, 2017). In this paper, the phenomenon to be investigated was the process of making replanting decisions, as these have a critical effect on productivity across the lifecycles of rubber plantations, which in turn affects rubber supply and the wider network.

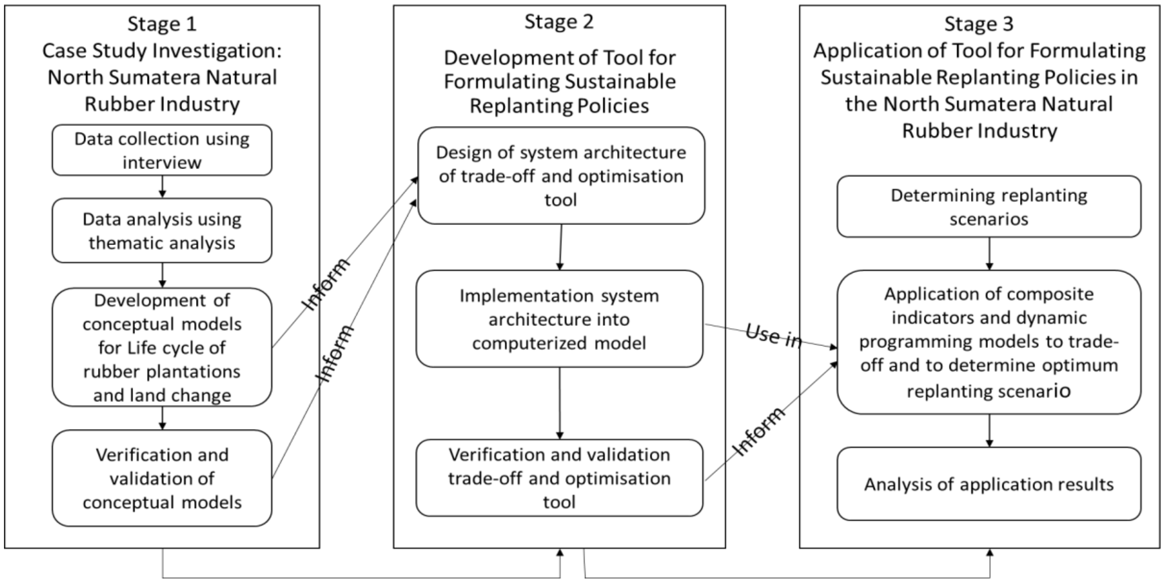

Fig 1. Research processes in developing trade-off approach

Figure 1 shows the research process that was used. It started by interviewing stakeholders in North Sumatera Province on the lifecycles of rubber plantations and current replanting practices. Rubber smallholders, rubber researchers and academics in North Sumatera were interviewed between October and December 2015 at this stage. Information gained from the interviews, such as how rubber smallholders cultivate their plantations and how replanting practices are currently applied, was used to build a conceptual model of rubber plantations' lifecycles in North Sumatera Province. This conceptual model was then verified and validated with a panel of experts that consisted of academics from University of Sumatera Utara, researchers from Sungai Putih Rubber Research Centre and representatives from the Indonesian association of rubber primary processors. The main criticisms from the expert panel lay in the inability of the conceptual model to capture the impact of external factors such latex price, fertilizer price and seed price on replanting decisions. These criticisms were addressed by conducting a quantitative survey which is reported elsewhere (Sitepu, 2018). Results from this stage are reported in Section 4.

In the second stage, the research focused on the development of the tool for the formulation of sustainable replanting policies. It began with the design of a system architecture for the trade-off and optimisation tool. In this system architecture, composite indices are used to inform trade-offs between replanting impacts and dynamic programming is used to determine optimal replanting scenarios based on these impacts. The system architecture was implemented using Microsoft Excel and resulted in a computational model that was verified by evaluating whether it followed the required steps for implementing the composite indicators and dynamic programming methods (Areal and Riesgo, 2015; Diban et al., 2016). Results from this stage are outlined in Section 5.

In the third stage, the focus of the research was on the evaluation of the tool by applying it using real world data from North Sumatera Province. This stage began by postulating replanting quota scenarios and assessing their sustainability impacts using a simulation model that is reported elsewhere (Sitepu et al., 2016). The sustainability impacts of the alternative replanting allocation quotas were translated into composite indices. These, in turn, were used in further simulations where alternative replanting quota scenarios were produced. The experiments resulted in recommendations to stakeholders in North Sumatera Province regarding allocation of replanting quotas to targeted districts in this province. Results from this stage are described in Section 6.

4. Case study: Indonesian natural rubber industry

Based on information from interviews, rubber smallholders in North Sumatera currently farm their plantations for 30 years, which is one production cycle, and then decide whether to keep the existing rubber trees (which results in lower production rates), replant the rubber trees (which incurs higher costs), or switch to other crops. Plantation areas can be categorised according the age of the trees: immature areas, productive areas, and less productive areas. Immature plantation areas comprise recently planted rubber trees that have not yet matured and less productive plantation areas comprise aging trees. Figure 2 shows a causal loop diagram of the lifecycle of rubber plantations and land change in the Indonesian natural rubber industry.

It can be seen from Figure 2 that rubber trees in immature plantation areas vary in age from 0 to 6 years. Productive plantation areas in North Sumatera can be divided into five phases based on the ages of the rubber trees: 6-10 years, 10-15 years, 15-20 years, 20-25 years, and 25-30 years. This categorization highlights the different productivity levels at each phase. Rubber trees are expected to achieve their highest productivity in phases 2 and 3. After this, productivity remains stable at phase 4, and starts to decrease at phase 5. Unproductive plantation areas are areas where the trees are over 30 years old. At this final stage, rubber smallholders generally make the decision to replant their land. Old plantation areas are those within which owners have decided not to replant. A combination of the variables in Figure 2 (represented by the ovals) can be used to represent the lifecycle of rubber plantations. Dynamic changes in the composition of plantation areas within the network can thus be captured through analysing these variables.

The composition of rubber plantation areas is affected by three variables, all measured in hectares: the availability of land for new plantation areas, the total replanting carried out by smallholders, and the total occurrence of crop switching. The availability of new plantation areas refers to new pieces of land that have been made available by smallholders. New plantation areas increase the total area of immature production. The total replanted area is given by the rubber smallholders who have decided to replant their land. The decision of smallholders to replant their land is reflected in the proportion of replanting. Not all smallholders with less productive plantations will decide to replant these areas. Replanting interventions comprise forms of intervention taken by stakeholders to change old plantation areas into immature areas. This is a part of the government's programme to rehabilitate old plantation areas in order to sustain the natural rubber supply.

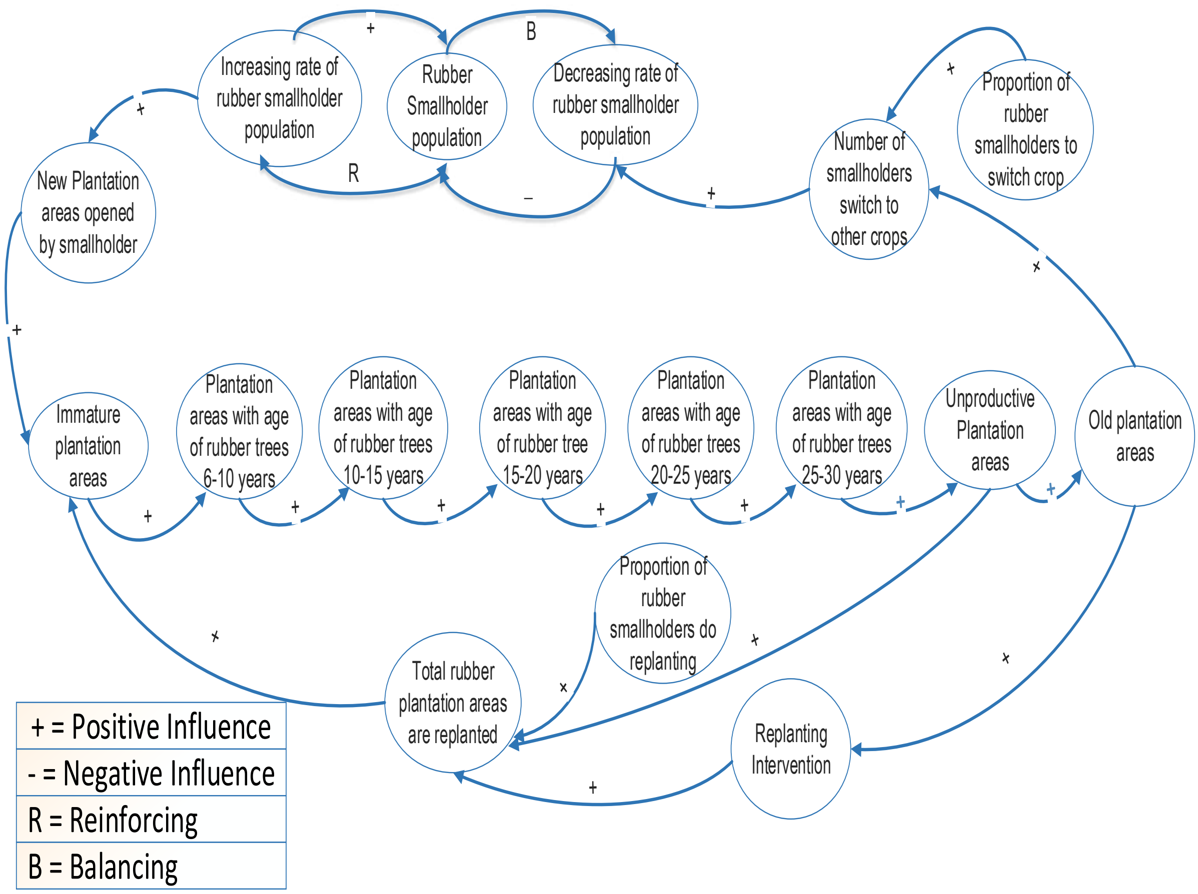

Fig 2. Lifecycle of Rubber Plantations and Land Change Causal Loop Diagram.

One of the main areas producing natural rubber in Indonesia is North Sumatera Province. A discussion with stakeholders in this province indicated a reduction of natural rubber supply from some districts. This was because many rubber plantation areas were entering their less productive phase at a similar time and plantation owners were switching crops. Every district in this province has a different total plantation area, each with its own distribution of rubber trees at different lifecycle stages, meaning that the total of immature, productive and less productive areas is different in each district. As a result, the capacity of plantations to supply natural rubber varies between districts. Future supply from each district depends on the total immature area that will enter the productive stage after six years. In order to sustain natural rubber supplies from Indonesia, an innovation in determining allocation of replanting quota was considered necessary. Learning from the situation in this province, if rubber replanting quotas are not planned effectively then the rubber supply could reduce significantly due to many plantation areas entering their non-productive phase at the same time. This reduction has the potential to influence downstream, customer, industries who use Indonesian rubber as a raw material.

The case study covers three sustainability goals: maximising future rubber supplies, balancing the required population of tappers who harvest latex and maximising carbon stocks. Each aspect is quantified in a different way. Firstly, future supplies depend on new rubber trees that are currently planted and are expected, after five years, to produce natural rubber for a further 20-25 years. Future supplies (quantified as an annual production volume, kg/year) can be calculated by multiplying the total number of rubber trees in given plantation areas with a production rate that varies based on the ages of the rubber trees. Replanting is one way to replace old rubber trees, with limited productivity, with new rubber trees that with have full productivity after their immature phase. However, replanting introduces immature areas, which, in turn, do not require tappers. The population of tappers (quantified as the number of people needed to work as tappers) is calculated by multiplying the productive area (i.e., the area occupied by trees aged 6-30 years) with the availability of tappers to tap the productive trees. Thirdly, the impact on carbon stocks (quantified as the total amount of carbon are stored inside rubber trees, kg/year) is calculated by multiplying the total number of rubber trees at each lifecycle phase with the capacity of rubber trees at that phase to store carbon. Replanting replaces old rubber trees with new ones that have a lower carbon storage capacity. To consider these three sustainability goals, with their different units and measurement methods, in the formulation of sustainable replanting policies needs tools to support trade-offs across these competing goals.

5. Trade-off and optimisation tool for the formulation of sustainable replanting policies

This section introduces a software tool for the formulation of sustainable replanting policies. The purpose of the tool, which determines optimal allocations of replanting for each district within the network, is to assist stakeholders in the natural rubber industry to consider the three sustainability impacts of replanting when formulating replanting policies. Each district has a different composition of rubber plantation areas, which means that decisions on the allocation of rubber replanting affect the future composition of rubber plantations which, in turn, particularly for the productive areas, influences the livelihoods of plantation owners and workers, and the total production of natural rubber.

Figure 3 shows the overall system architecture of the trade off and optimisation tool, which includes the establishment of composite indices and their use, through dynamic programming, to generate optimal replanting scenarios. The composite indicators method provides a mechanism of trading-off between sustainability impacts of replanting. Dynamic programming is used to generate optimal replanting scenarios for each district by considering sustainability impacts of replanting. A more optimal replanting scenario for the network has a higher composite index value than a less optimal one. Composite indices produced from the composite indicators method become an input for the dynamic programming. This is represented by the arrow from the composite indicators box to dynamic programming box in Figure 3.

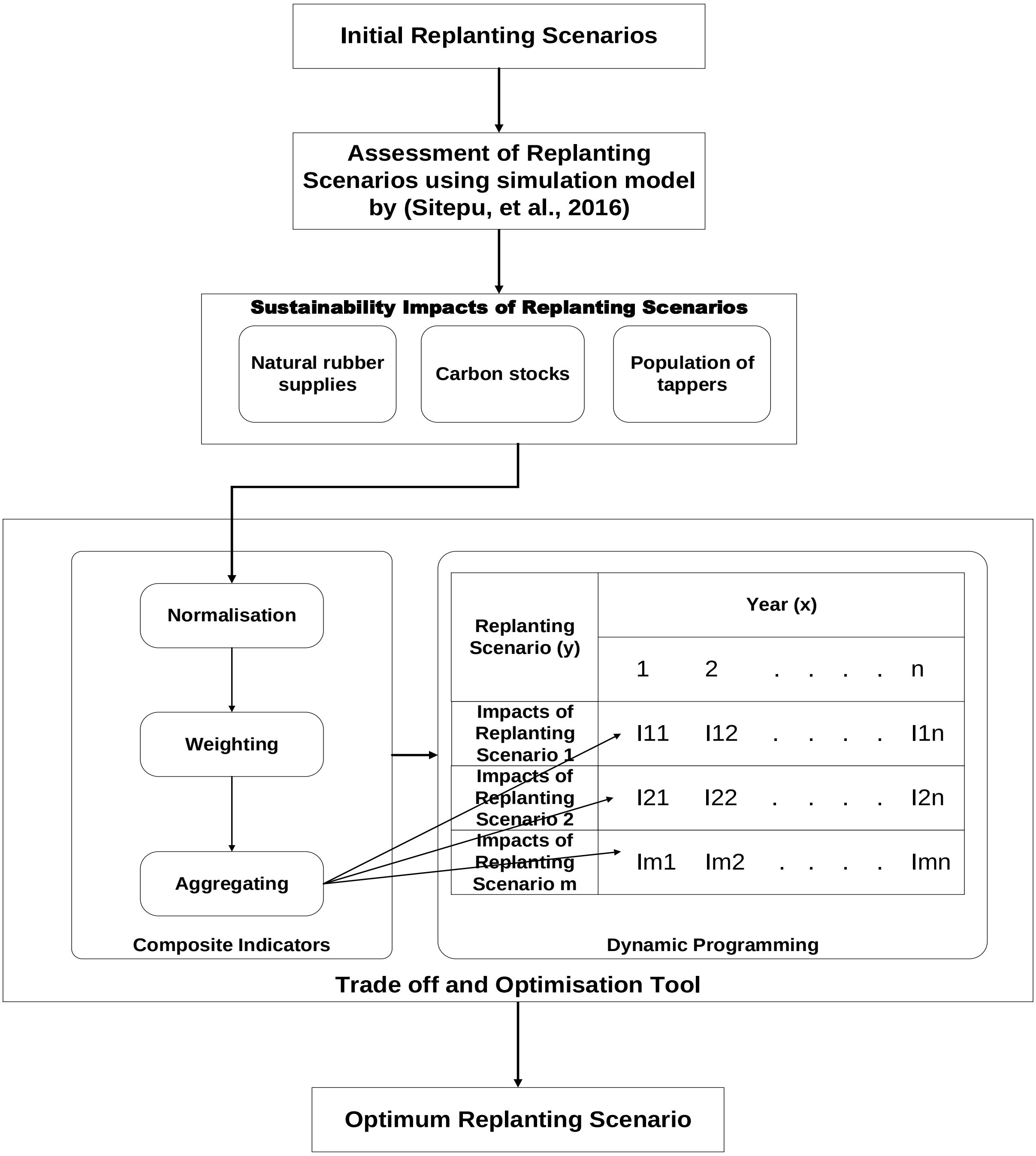

Fig 3. System Architecture of Trade-off and Optimisation Tool.

This study used an adaptation of Sargent's steps for building a verified and validated simulation model (Sargent, 2013). Sargent divides verification and validation steps for simulation models into four categories: the validation of the conceptual model, the verification of the computerized model, operational validation, and data validation. Early equations and functions were verified by testing those equations and functions with manual calculations, in order to confirm the applicability of the composite indicators method in supporting trade-offs for sustainability dimensions and indicators, and the applicability of dynamic programming in generating the optimal allocation of replanting quota. This was followed by removal of errors and verification that focused on whether the model followed the required steps for the composite indicators and dynamic programming methods. For example, in the composite indicators method, normalizing, weighting, and aggregating are the main steps that are carried out sequentially. Verification was carried out to check whether the model had run these steps sequentially. At the final stage, operational validation was carried out by testing the tool with different inputs. This was then continued by comparing results from the trade-off and optimisation tools with results from the manual calculations.

5.1. Composite Indicators method for comparing sustainability impacts

As outlined in Section 4, each of the three sustainability indicators in the case study is quantified in a different way. As a result, for trade-offs to be made, a way of quantifying each so that it can be compared with the others was needed. Composite indices were used for this purpose. Composite indices were calculated using the composite indicators method and used as input for the dynamic programming and to provide trade-offs between replanting impacts. To achieve this, the use of the composite indicators method requires three steps to process measurement data and information from different indicators and sub indicators into a single index (Areal and Riesgo, 2015; Zhou et al., 2010). The following three steps were used to calculate the composite indices.

5.1.1. Normalizing

Normalizing changes the units of individual indicators and sub indicators into a common unit. Distance to reference model was developed for normalizing the values of the indicators (Zhou et al., 2010). This method can be applied when indicators or sub-indicators have reference values. In this research, these values were determined from measurement experience, stakeholder reports, local and international regulations (see Table 1). Equations 1 and 2 show the normalization methods used for indicator and sub-indicators with positive impact (Equation 1) and with negative impact (Equation 2).

$$N_{i,j,a,b} = \frac{V_{i,j,a,b}}{V_{i,j,b}^{reference}} \quad (1)$$

$$N_{i,j,a,b} = \frac{V_{i,j,b}^{reference}}{V_{i,j,a,b}} \quad (2)$$

Where $V_{i,j,a,b}$ is the value for indicator (i) from the group of sustainability dimension (j) which is an impact resulting from rubber replanting scenario (a) for area/district (b). $V_{i,j,a,b}^{reference}$ is the reference for indicator (i) under dimension (j) and district (b).

5.1.2. Weighting

Weighting assigns weights to the normalised indicators and sub-indicators. The weights used reflect the importance of individual indicators within the formulation of replanting policies. This step offers planners the flexibility of adjusting the prioritisation given to specific indicators and so sustainability dimensions.

A budget allocation process was developed to assign weights to indicators and sustainability dimensions. This method requires the participation of experts in assigning weights. The purpose of this method is to capture specific local requirements that can be identified from current environmental, economic, or social conditions and regulations. Experts are people who are able to inform the requirements and details of the conditions of an operation owing to a long history of involvement in those operations. A disadvantage of this method is that the weights of indicators or sub-indicators may not be transferable to other types of industries or regions.

5.1.3. Aggregating

Composite indices were constructed from hierarchies of sub-indicators and indicators. Firstly, an index value for each indicator was calculated by aggregating the values of its sub-indicators. These indicator values were then aggregated to calculate the value of the composite index. This step is key for making trade-offs because it provides a balancing between indicators or sub-indicators where poor performance of one indicator can be balanced by the high performance from other indicators. A linear aggregation model was used in this step. In this method, each composite indicator is defined by summing the weighted values of each indicator. The aggregation method is shown in Equations 3 and 4.

$$I_{SI\ j,b} = \sum_{i=1}^{n} N_{i,j,a,b} \,.\, w_{i,j,b} \quad (3)$$

$$w_{i,j,b} = 1$$

$$w_{i,j,b} \geq 0$$

$$I_{sust.impact} = \sum_{j=1}^{n} I_{SI\ j,b} \cdot w_{j,b} \quad (4)$$
$$\sum w_{j,b} = 1$$
$$w_{j,b} \geq 0$$

Where $I_{sust.impact}$ is the composite index that reflects the impact of replanting for area/district (b) and replanting scenario (a), $I_{SI\ j,b}$ is the impact of replanting into specific dimension of sustainability (j) for district (b), $w_{j,b}$ is the weight of sustainability dimension (j) for district (b), and $w_{i,j,b}$ is the weight of indicator (i) under sustainability dimension (j) for district (b).

5.2. Dynamic Programming for Optimizing Allocation of Replanting

Decisions related to replanting for the Indonesia natural rubber industry are sequential decisions (e.g., establishing a replanting quota for year 1 influences the replanting quota for years 2 and 3). Dynamic programming is an effective method to solve optimization problems with sequential decisions (Fan et al., 2016) because it uses transformation functions that link the current and previous stages of the system under investigation. For this reason, dynamic programming was used to make trade-offs between different replanting quota scenarios for a given district in order to identify the optimal replanting scenario, i.e., the one that generates the best replanting impacts for the sustainability of the supply network. To identify the optimal scenario, composite indices for each scenario were compared using Bellman's optimality principle (Bellman, 1972). Following this principle, the replanting scenarios problem was divided into different stages based on the total number of target years, as shown in Figure 4 where it can be seen that the optimal value in the current stage is influenced by the optimal value in the previous stage.

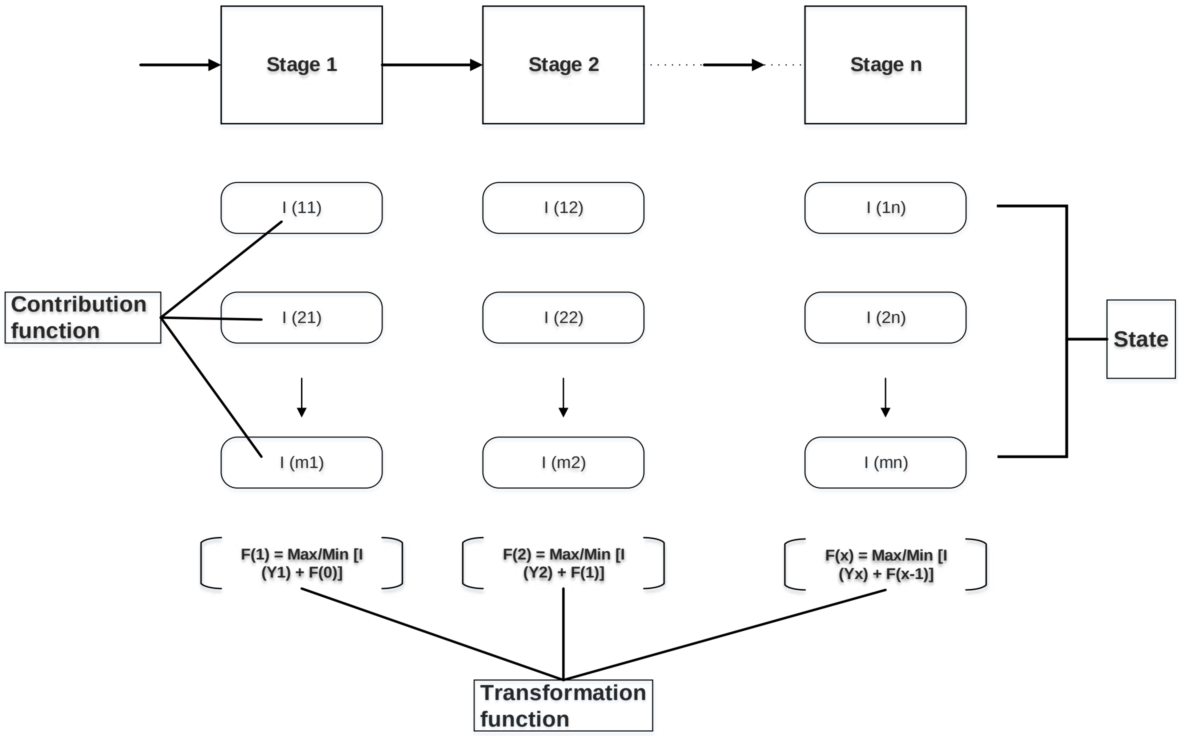

Fig 4. Dynamic Programming applied to replanting scenarios.

Based on Figure 4, dynamic programming includes the following.

- Stage (x) represents a sub-problem in a given scenario: in this case the year when a replanting quota is to be implemented.
- State (y) represents decision variables related to the problem for each stage: in this case, the replanting quota quantified in hectares.
- Bellman's contribution function, is used to generate a value, $I_{sust.impact}$, representing the sustainability impact, for each state, y, at a given stage, x. In this case, this value is generated by the composite indicators method (see Figure 3) based on values from simulation model (Sitepu et al., 2016).
- The Transformation function is used to define an optimal value for each stage.

$$f_x^{**}(y_x) = Max\left[I_{sust.impact}(y_{x-1}, y_x) + f_{x-1}^{**}(y_{x-1})\right] \quad (5)$$
$$x = 1,2,3,4, \ldots, n \ (n = number\ of\ years)$$

where $f_x^{**}(y_x)$ is the optimal replanting impact for replanting quota (y) at stage x. $I_{sust.impact}(y_{x-1}, y_x)$ is the replanting impact for replanting quota (y) at year x. $f_{x-1}^{**}(y_{x-1})$ is the optimal replanting impact for replanting quota (y) at stage x-1. This function is recursive and there are two recurrent processes: forward formulation and backwards formulation. In forward formulation the process is started from the first stage while in backward formulation the process is started from the last stage. This paper uses the forward formulation.

These two methods were implemented using Microsoft Excel to form the trade-off and optimisation tool shown in Figure 3.

6. Evaluation of the trade-off and optimisation tool

The tool was applied to a case study supporting stakeholders in the North Sumatera natural rubber industry to formulate sustainable replanting policies. A replanting intervention is a program to replant less productive plantation areas by providing replanting funds for rubber smallholders. Funds had been allocated by central government to a number of provinces who have natural rubber plantations. It was the main job of the provincial government to allocate these replanting funds for districts under its territory. However, the current approach to replanting fund allocation does not consider the impact of fund allocation on sustainability in the targeted districts. The tool was used to support the provincial government to allocate these funds.

6.1. Design of Replanting Quota Scenarios

Application of the tool began by designing alternative replanting quota scenarios with an expert panel consisting of representatives from the primary processor association (GAPKINDO), Sungai Putih Rubber Research Centre and Industrial Engineering Department, University of North Sumatera. Replanting quota scenarios consisted of selecting the targeted districts, determining rubber replanting intervention scenarios, and determining the composite indices and a target value for each index.

The selection of target districts started by defining a list of districts based on the total less productive plantation areas in each district and other factors such as infrastructure condition, support or partnership from local government, human resources in each district, the availability of technology for replanting and the method for replanting. Selection was necessary due to the limited rubber replanting allocation. Based on this evaluation, five districts were selected as targets for the replanting programme: Langkat, Deli Serdang, Asahan, Simalungun and South Tapanuli. Replanting intervention scenario designs were based on discussions with expert panels. Replanting intervention scenarios were defined from between 0-1000 Ha per year, in increments of 100Ha. This was based on the allocations of replanting interventions for several districts of North Sumatera Province in previous years. Hence, there were 10 simulation experiments for each targeted district to assess the impact of replanting intervention scenarios from 0-1000 Ha per year.

The next step was to determine the sustainability indicators to be considered in identifying the optimal replanting scenario. Six indicators were selected based on discussions with the expert panel: future natural rubber supply and the population of rubber smallholders with immature land for the economic dimension; carbon stock and CO_2 sequestration levels for the environmental dimension; and the populations of rubber smallholders and tappers for the social dimension. Future natural rubber supply is an important indicator since the current reduction of supply in North Sumatera Province has disturbed the stability of other key players such as primary processors. Rubber smallholders with immature land are more susceptible to bankruptcy due to lack of income from the rubber plantation within its immature phase. Hence, it is important to maintain the population of rubber smallholders with immature land. However, if the number of rubber smallholders with immature land is too high then this risks causing difficulties for government to support them. On the other hand, if the number of smallholders with immature land is too low then future supply might be disturbed. Carbon stock and CO_2 sequestration levels are environmental benefits from the rubber plantation and influence air quality and wider climate concerns. It is important to manage these environmental indicators to maintain the quality of the environment within the district. Furthermore, the population of rubber smallholders and tappers reflects the impact of rubber plantations in providing jobs for people in latex production.

After selecting indicators, a target level for each indicator was assigned, reflecting the level that is desired to be achieved by the natural rubber industry. The target for each indicator was used as a reference to convert assessment results into the composite index. Due to the different conditions in each targeted district, different targets were set for each indicator for each district. The target values for each indicator in each district, shown in Table 1, were determined by discussion with the expert panel.

Table 1.

Reference values for normalization.

District	Ref for supply (Kg)	Ref for Immature Smallholder Population (People)	Ref for Carbon Stock Level (Ton C)	Ref for CO2 sequestration (Ton CO2 e)	Ref for Smallholder population (People)	Ref for stepper population (People)
Langkat	30,000,000	2,200	4,000,000	200,000	22,000	45,000
Deli Serdang	6,000,000	600	550,000	70,000	5,500	6,500
Asahan	6,000,000	1,500	550,000	30,000	8,000	6,500
Simalungun	12,500,000	900	1,200,000	65,000	9,500	13,500
South Tapanuli	18,000,000	3,500	1,800,000	100,000	30,000	20,000

6.1.1. Sustainability Impacts of Replanting Quota Scenarios

The trade-off and optimisation tool requires initial data showing the sustainability impacts of the replanting quota scenarios. Replanting intervention impacts data generated from simulation models (Sitepu et al., 2016) were used as initial data. The data consisted of replanting impacts for the five targeted districts. Changes to the values of indicators for the five targeted districts as a result of replanting interventions are shown in Figure 5. The data consists of values for each of the six indicators (future natural rubber supply, population of smallholders with immature areas, carbon stock level, CO_2 sequestration level, population of rubber smallholders and population of tappers). Figure 5 shows the replanting impacts on natural rubber supply for the five targeted districts used in the evaluation of the trade-off and optimisation tool.

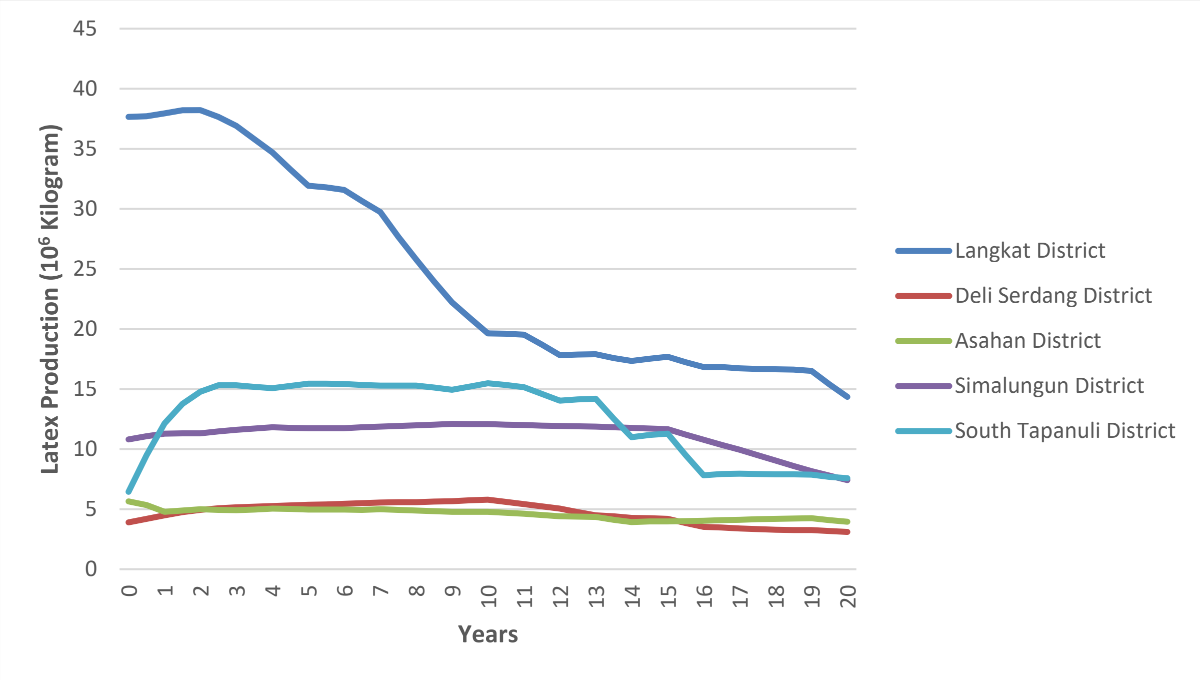

Fig 5. Data for level of supply generated by simulation model.

6.2. An Application of the Trade-off and Optimisation Tool

This section shows the results from applying the trade-off and optimisation tool to real world data from North Sumatera Province. This section is divided into two sub sections: applications of the composite indicators and dynamic programming methods.

6.2.1. Application of the composite indicators method

The purpose of this section is to demonstrate the application of the composite indicators method to translate replanting intervention impact data into composite indices for use in the dynamic programming method where optimal replanting quotas are identified.

Normalization Step

Distance to reference (Equation 3) was used to normalize the data, as described in Section 5. Table 2 shows the normalization results for the impact of the replanting intervention on Langkat District in Year 3, each expressed as a percentage of the target for the relevant indicator.

The future supply index compares latex production data from Years 7 to 12 in the simulation model (Figure 5) with the target supply for Langkat district (in Table 1).

Since rubber trees start to be productive six years after planting, latex production data in Years 7 through 12 reflects the impact of replanting intervention in Years 1 through 5. It can be seen that there was no significant difference in future supply if replanting rates between 0-600 Ha were applied in Year 3. Similar trends occurred for carbon stock index and CO_2 sequestration index. This was due to low levels of old plantation areas at Year 3 that could be replanted.

Table 2.

Normalization Result for Langkat District Year 3

Replanting Intervention (Ha)	Future Supply Index	Immature smallholder Index	Carbon Stock Index	CO_2 Sequestration Index	Smallholder's Population Index	Tapper's population Index
0	74	23	88	95	72	91
100	74	27	87	94	73	91
200	74	30	87	94	73	91
300	74	28	87	94	73	91
400	74	30	87	94	73	91
500	74	32	87	94	73	91
600	74	34	87	94	73	91
700	72	23	88	95	72	91
800	72	23	88	95	72	91
900	72	23	88	95	72	91
1000	72	23	88	95	72	91

Weighting and Aggregating Steps

The next important step is to assess trade-offs between the composite indicators by determining the weights of sustainability dimensions and indicators. In this case, weights were assigned using a budget allocation process in discussion with the expert panel by considering the current situation in North Sumatera Province. The weights of indicators can be used to balance the positive and negative impacts of replanting. Replanting has positive impacts such as ensuring the future supply, ensuring future carbon sequestration and maintaining the population of rubber tappers. However, replanting can also bring negative impacts, particularly for the shorter-term, such as reducing current supply capacity, decreasing the need for tappers and cutting carbon stocks.

The economic dimension with the future supply indicator was deemed to be more important than other dimensions, and so their indicators, due to the current situation in North Sumatera Province, which is facing a reduction of natural rubber supply. Furthermore, the increasing awareness of stakeholders with regard to environmental issues has contributed to increases in the importance of environmental dimensions and, since rubber plantations bring benefits to social communities across the supply network, social dimension indicators were set equal with the environmental dimensions. Table 3 shows the weights assigned to each of the sustainability dimensions and their indicators.

Table 3.

Weight for indicators and sub indicators.

Indicator	Weight	Sub Indicator	Weight
Economy	60%	Level of supply	60%
		Population smallholders with immature land	40%
Environmental	20%	Fertilizer rate	50%
		Carbon Absorption	50%
Social	20%	Population of smallholders	60%
		Population of Stepper	40%

The trade-off process was followed by aggregating the indices for the six indicators into a single composite index using the linear aggregation method described by Equations 3 and 4. It can be seen from Table 4 that without intervention (that is, in a scenario where 0 Ha are replanted) Langkat district faced a reduction of latex production.

Table 4.

Composite index result for Langkat district.

Replanting allocation	Composite Index				
	Year 1 (2016)	Year 2 (2017)	Year 3 (2018)	Year 4 (2019)	Year 5 (2020)
0	77	71	66	64	64
100	77	72	67	65	66
200	76	72	68	67	68
300	76	71	68	67	68
400	76	71	68	67	69
500	76	71	68	68	71
600	76	71	69	69	72
700	76	71	66	67	70
800	76	71	66	67	71
900	76	71	66	67	72
1000	76	71	66	68	73

In Year 1, it was expected that none of the replanting interventions could bring any positive impact to natural rubber supply network. A similar trend could be observed in Year 2, with only replanting interventions rates of 100 Ha and 200 Ha likely to produce a higher index than without replanting intervention. In Years 3 and 4, replanting interventions with rates between 200-600 Ha were likely to produce a higher index compared to other rates. In Year 5, higher replanting intervention rates such as 800-1000 Ha, produced a higher index compared to other rates of replanting intervention.

6.2.2. Application of Dynamic Programming

In the first step of the dynamic programming process, the problem was divided into a series of sub-problems or stages. In this case, there were five stages that reflected the number of years under consideration. Equation 5 was used to define the optimal allocation, i.e., the one with the highest index In Figure 6, the results of the dynamic programming are presented.

To analyse the dynamic programming results, a backtracking process was implemented. The purpose of this analysis was to define the optimal replanting quota scenario for each targeted year. This process involved selecting the highest index value from the previous stage that could be achieved with the remaining allocation. Starting from Stage 5, two replanting scenarios were found to have the highest index value in this stage: 500 Ha and 600 Ha. Hence, these allocations were selected for Stage 5 (Year 5). From the total 1,000 Ha replanting allocation for Langkat district, there were only 500 Ha and 400 Ha remaining allocation left for the Stage 4. In this stage, the highest index values (283 and 284) were achieved by allocating 200 Ha. From this calculation, there were only 200 Ha and 300 Ha allocations left for the Stage 3.

The next step involved checking the highest index value for the total allocation of 200 Ha and 300 Ha at Stage 3. For the allocation of 300 Ha, the highest index value was 217, while the highest index value for allocation 200 Ha was 216 respectively. This meant that there were two optimal replanting rates for Stage 3, 100 Ha and 200 Ha. From this calculation, there were only 0 Ha and 100 Ha allocations left for the Stage 2. The backtracking process for Stage 2 indicated that the highest index values for 0 Ha and 100 Ha total allocations were 148 and 149 respectively. This meant that there were two optimal replanting rates for Stage 2, 0 Ha and 100 Ha. From this calculation, there was 0 Ha allocation left for Stage 1. The three optimal combinations of allocations produced are shown by the arrows in Figure 6.

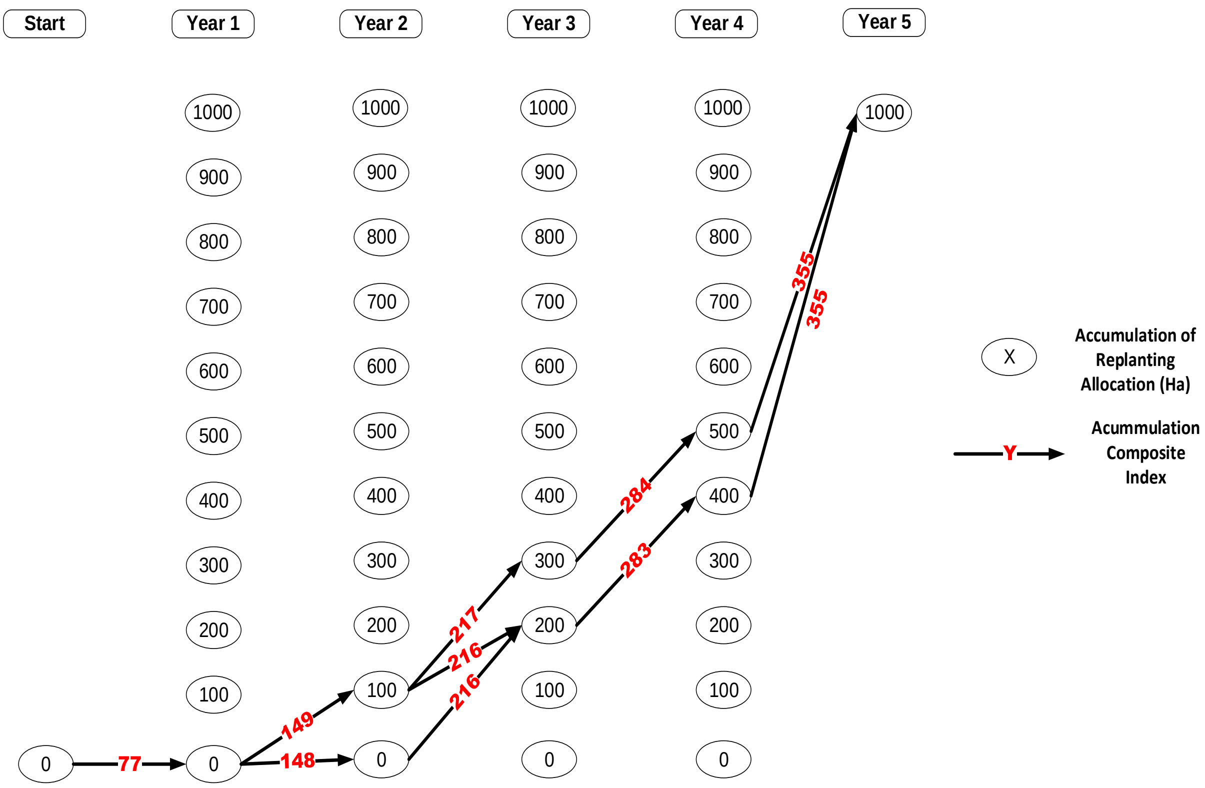

Fig 6. Dynamic Programming Results.

6.3. Discussion

In this application, the composite indicators method was used to translate data generated from a simulation model into composite indices, which supported the analysis of trade-offs between the various sustainability impacts of replanting. Stakeholders played a significant role in determining the reference values and weights for each indicator. Based on the results given in Table 4, increasing the replanting allocation for priority districts would not always produce an increased index value of replanting impact. For example, in Langkat district, while the allocation of replanting scenarios increased to more than 600 Ha for Years 1, 2 and 3, the index value of replanting scenario was found to remain constant. This could have been because the total of less productive areas in Langkat district for the next 3 years was less than 600 Ha. A similar condition occurred in Deli Serdang, Simalungun and Asahan districts. In contrast, in South Tapanuli district, replanting scenarios with rates over 600 Ha produced a higher index.

The indices, derived from composite indicators that captured sustainability impacts, became the main input for the dynamic programming model. The dynamic programming results show that Langkat district required different allocations of replanting quota in the next five years to maintain its production levels of latex in that it was likely to require a low replanting rate from Years 1 to 3, while needing a higher replanting rate in Year 5. In contrast, Deli Serdang and Simalungun districts were likely to need more than 300 Ha replanting quotas in the first three years.

Furthermore, in South Tapanuli district, the highest index value was gained by implementing higher replanting quota scenarios (more than 500 Ha) at Years 4 and 5. These results confirmed that the capacity of supply in targeted districts were different. To manage the capacity of supply from these districts, different replanting quota allocations for each district are therefore required.

The application of the proposed tool to the case study demonstrated the incorporation of sustainability issues in the formulation of replanting policies for several districts in North Sumatera Province, Indonesia. The stakeholders involved in the application of this approach were initially sceptical that such a tool could be valuable in supporting decisions related to sustaining natural rubber supply from North Sumatera. A key challenge lay in finding consensus between related stakeholders on the selection of indicators and weights of those indicators to be included in the formulation of replanting policy. Each stakeholder had different priorities with respect to the indicators that related to their concerns. For example, rubber primary processors tended to be more concerned with current and future supply while local governments were more concerned about social impacts such as the number of rubber smallholders with immature lands and the number of tappers works in rubber plantations.

7. Conclusion

The allocation of replanting quotas is an important strategic decision in planning sustainable supplies in agricultural industries such as natural rubber because the availability of the raw material (latex) depends on the availability of mature trees and people to harvest the latex. This paper contributes a novel hybrid approach for using sustainability aspects to inform decisions related to the formulation of replanting policies. An integration of the composite indicators and dynamic programming methods was developed as the hybrid approach. In contrast to similar approaches that support replanting decisions, the approach introduced in this paper brings together three aspects of sustainability: social, economic and environmental. For example, Manisri and Pichitlamken (2017) considered economic aspects such as pricing and oversupply during the formulation natural rubber replanting decisions while Bouchard et al (2016) used economic impacts in forest value chains, such as profit, harvested volume and transportation cost, in determining allocation of replanting in forests.

This paper reports the application of the approach and associated software tool to a case study from the Indonesian rubber industry. The research involved key stakeholders who provided necessary data and contributed to the weighting and prioritisation of sustainability dimensions and associated indicators. The population of the tool with real world data demonstrated the feasibility of using the composite indicators and dynamic programming methods in determining optimal replanting quotas, by assessing a trade-offs between the three sustainability goals. For the Indonesian rubber industry case study, although the approach was applied in five distinct districts, further work is needed to evaluate the accuracy of the composite indicator values and sensitivity tests are needed to identify those that have the biggest impact on outcomes. Further, the approach could be used in a number of decision contexts, e.g., for strategic decisions in specific districts or in the formulation of longer term plans that inform policy, and it may be that available data and the necessary indicators and their importance to the final outcomes differ for different decision contexts.

There are also opportunities for wider deployment of the approach. To apply it in other tree-based industry sectors, such as rubber production in other countries or the production of other tree-based products such as palm oil, further work would include, as in this research, engagement with target users in the new application domains, the acquisition of necessary data and comparable validation and verification of results, especially where the end user goals may be different. More widely, the approach could be used in other problem domains where there is a need to make trade-offs between multiple performance indicators, where the decision making process includes sequential decisions and where multiple simulation methods are needed to build models of whole system behaviours. Such approaches are becoming increasingly important in addressing global challenges, such as those identified through the United Nations Sustainable Development Goals, where whole system performance is governed by interplays between individual human behaviours, and overarching (e.g., societal, industrial and governmental) systems and processes.

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