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# Interactive Spatial Decision Support for Sustainable Agroforestry Management: A case Study in East Kalimantan, Indonesia

Dissertação para obtenção do Grau de Mestre em Engenharia do Ambiente, Perfil de Engenharia de Sistemas Ambientais

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*Essentially, all models are wrong, but some are useful.*

*(Box, 1979)*

## Preface and Acknowledgements

This research is based on a project of the companies Geodan S&R (Netherlands) and ITCI (Indonesia), proposing a "Triple P" approach, Profit (economic), People (social) and Planet (environment) for sustainable alternative forest and requested the development of a web decision support system to aid investment decisions. The research was made during my stay in Amsterdam, at Geodan S&R and the *Vrije Universiteit* (VU) Amsterdam in the Spatial Information Laboratory (SPINlab).

This topic was taken as a challenge in an internship at Geodan, which started in June, 2013. The internship was followed by a presentation at the Geodesign Summit Europe 2013 in September, where I was invited to present the system developments, as a speaker with Dr. Willie Smits, ITCI research director. A short field trip to East Kalimantan, Indonesia was done, in October, to help focus in the main initial needs for an agroforestry support decision tool, in that particular area. An initial report about this research was done and presented in January at FCT. In February 2014, the research continued at Geodan S&R and SPINlab, where I further developed my thesis, which is presented here.

I would like to thank Eduardo Dias, my supervisor in Amsterdam, who was always available to discuss and came up with solutions to my problems. António Câmara, my main supervisor for his freedom and that even in distance was always reachable and available.

Thanks to Dr. Willie Smits for his inspiration in this project and the amazing experience of the field trip in Indonesia. I would also like to thank all colleagues at Geodan and VU who helped me out whenever I needed. Vasco, which was always available to give me some input and discuss ideas. Mujgan, for the help and input in a biophysical suitability module that would suit my topic (section 2.3 and 3.1.2). And last, but not least to thank Henk Scholten for the opportunity to be a part of "the group" and that made possible the whole experience at Geodan.

Previous to this thesis presentation, a paper (Freitas et al., 2014)[1] containing information studied and presented was published by Springer, entitled "Interactive Spatial Decision Support for Agroforestry Management" as a chapter of the book "Geodesign by Integrating Design and Geospatial Sciences".

Finally, my family and friends who always supported me in this challenge.

[1] Freitas, A., Dias, E., Diogo, V., Smits, W. (2014) Interactive Spatial Decision Support for Agroforestry Management, Geodesign by Integrating Design and Geospatial Sciences, Part 2: Resilience and Sustainability. ISBN 978-3-319-08298-1, Springer.

## Abstract

Forest managers, stakeholders and investors want to be able to evaluate economic, environmental and social benefits in order to improve the outcomes of their decisions and enhance sustainable forest management.

This research developed a spatial decision support system that provides: (1) an approach to identify the most beneficial locations for agroforestry projects based on the biophysical properties and evaluate its economic, social and environmental impact; (2) a tool to inform prospective investors and stakeholders of the potential and opportunities for integrated agroforestry management; (3) a simulation environment that enables evaluation via a dashboard with the opportunity to perform interactive sensitivity analysis for key parameters of the project; (4) a 3D interactive geographic visualization of the economic, environmental and social outcomes, which facilitate understanding and eases planning.

Although the tool and methodology presented are generic, a case study was performed in East Kalimantan, Indonesia. For the whole study area, it was simulated the most suitable location for three different plantation schemes: monoculture of timber, a specific recipe (cassava, banana and sugar palm) and different recipes per geographic unit. The results indicate that a mixed cropping plantation scheme, with different recipes applied to the most suitable location returns higher economic, environmental and social benefits.



**Keywords:** spatial modelling; agroforestry; sustainable forest management; decision support systems.

## Resumo

Gestores florestais, *stakeholders* e investidores querem avaliar os benefícios económicos, ambientais e sociais, a fim de melhorar os resultados das suas decisões e atingir uma gestão florestal sustentável.

Nesta tese foi desenvolvido um sistema de apoio à decisão espacial que fornece: (1) uma abordagem para identificar os locais mais adequados e benéficos para projetos agroflorestais com base em propriedades biofísicas e avaliar o seu impacto económico, ambiental e social; (2) uma ferramenta para informar potenciais investidores e *stakeholders* do potencial e oportunidades inerentes a uma gestão integrada de sistemas agroflorestais; (3) um ambiente de simulação que permite a avaliação através de um *dashboard* com a possibilidade de realizar análises de sensibilidade interativas para os parâmetros-chave do projeto; (4) uma visualização geográfica interativa em 3D dos resultados económicos, sociais e ambientais, que facilitam a compreensão e facilita o planeamento.

Embora a ferramenta e metodologia apresentada seja genérica, um caso de estudo foi realizado em *East Kalimantan*, na Indonésia. Em toda a área de estudo, foi simulado o local mais adequado para três esquemas de plantação diferentes: monocultura de madeira, uma receita multicultura (mandioca, banana e *sugar palm*) e quatro receitas diferentes por unidade geográfica. Os resultados indicam que um esquema de plantação de culturas mistas, com diferentes receitas aplicadas para o local mais adequado retorna benefícios económicos, ambientais e sociais mais elevados.



Palavras-chave: modelação espacial; sistemas agroflorestais; gestão florestal sustentável; sistemas de apoio à decisão.

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# 1 Introduction

## 1.1 Background and Problem Definition

Forests are important ecosystems that are able to support productive (e.g. supply of wood products) and protective functions such as climate regulation, air pollution filtering, regulation of water resources, conservation of biodiversity and protection from wind erosion, coastal erosion and avalanches (FAO, 2005). Forests, specifically the tropical ones, hold the largest terrestrial carbon store and are active carbon sinks, Figure 1.1. On average, tropical moist forest are estimated to store around 200 tonnes per hectare, 160 tonnes in the above-ground vegetation and around 40 tonnes in the roots. The carbon uptake of tropical forests is equivalent to approximately 15% of the total global anthropogenic carbon emissions, which make their contribution to climate change mitigation significant (Trumper et al., 2009).

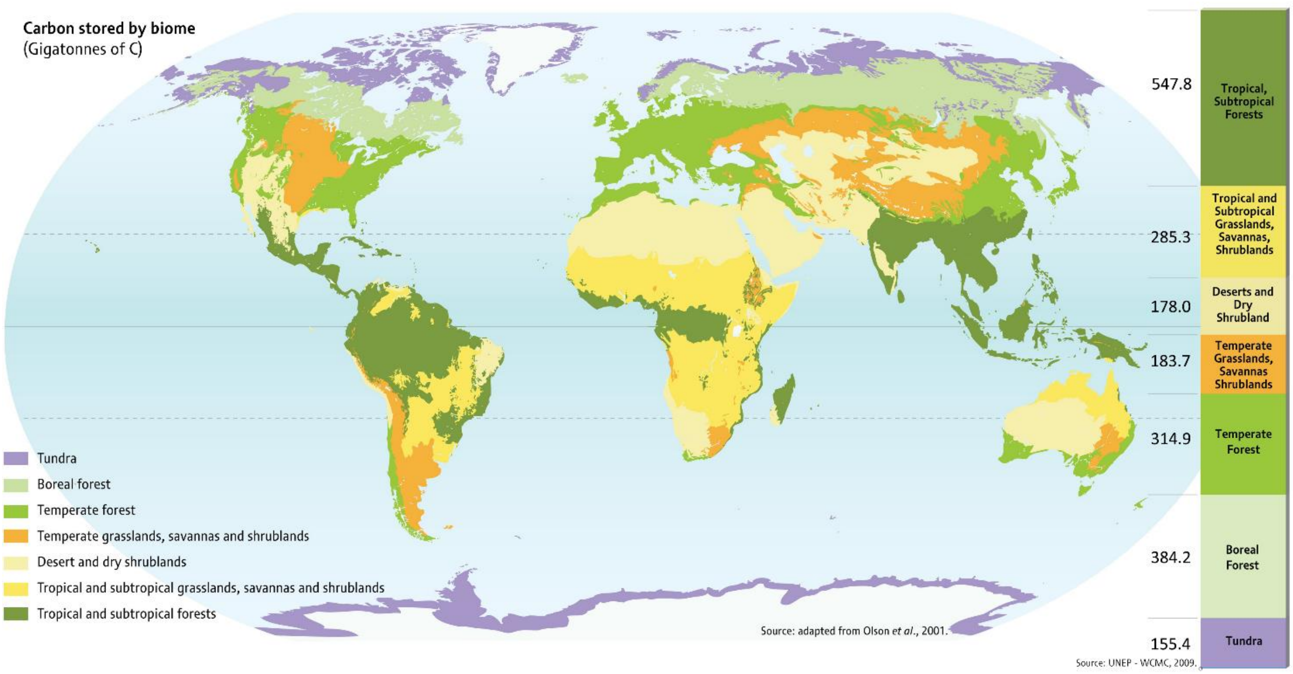



*Figure 1.1 – Carbon stored by biome.*
*Adapted from Trumper et al. (2009)*

In the last decade, around 13 million hectares of forest have been ruined or converted to other uses, such as industrial and agricultural (food and biofuel production) land uses, each year, compared to 16 million hectares per year in the 1990s (FAO, 2010; Geist and Lambin, 2001). Despite this decrease, deforestation rates are still alarmingly high.

In the past, natural and plantation forests were managed with a focus on timber, which yield reasonable economic benefits. Although a focus on timber production, does not produce adequate social or environmental benefits, as neither food for the communities is produced, nor regular jobs are created (Sabarnurdin et al., 2011). Regarding the logging of tropical moist forests, it is estimated that only one to twenty trees per hectare are harvested, whereas the remaining vegetation around is damaged or killed during harvesting, resulting in large carbon losses, biodiversity and ecosystems degradation (Trumper et al., 2009). Reducing emissions from deforestation and degradation is a vital component of tackling dangerous climate change. In addition, tackling illegal and ill-managed logging will be an important part of reducing emissions from forestry. Deforestation causes are complex, ranging from underlying issues of international pressure and poor governance to local resource needs (Geist and Lambin, 2001).

Therefore, there is a need to globally improve the management of forest resources, and particularly to take into account additional forest values (such as biodiversity and social functions) towards long-term sustainable management (Varma et al., 2000). Paletto et al. (2013) define Sustainable Forest Management (SFM) as a dynamic concept with the main purpose of maintaining and enhancing the economic, social and environmental value of forests, for the benefit of present and future generations.

Agroforestry is regarded as a promising approach for sustainable forest management (Schoeneberger and Ruark, 2003). Agroforestry systems are mainly practiced in tropical and temperate regions and include traditional and modern land-use systems in which trees are managed together with crops for multiple benefits. These systems allow communities to produce food, contributing to nutritional security, and to achieve productive and resilient cropping and grassland environments. Moreover, they can provide a range of forest products, including fuel-wood and non-timber products, increase biodiversity, protect water resources and reduce soil erosion. On a large scale, agroforestry systems can also prevent the occurrence of extreme weather events, such as floods and drought (FAO, 2013).

Agroforestry has been on the development agenda for several decades and it was advocated as a solution to a wide range of complex problems resulting from unsustainable forest and farms, especially in tropical areas. Among others, the problems range from nutrient loss, soil degradation and erosion to unstable and inefficient food production and income generation. Therefore a system to inform, educate and simulate the impacts of a new agroforestry project can empower people, which will decrease environmental degradation, loss of natural habitats, as well as the loss of cultural values (Weidner and Fiege, 2011).

Stakeholders are generally uninformed of the benefits of agroforestry and the factors that determine the adoption of agroforestry practices (FAO, 2013). Vacik and Lexer (2013), researched that due to the often conflicting interests in land-use planning, there is a need to involve stakeholders and show them the potential outcome. The lack of awareness of the consequences and benefits of agroforestry projects may lead to unsustainable forest management. Additionally, uncertainty is a dominant feature of decision making in forestry and agroforestry resources management, which might result in the loss of economic opportunities or forest degradation (Morgan et al., 2008). Therefore a tool focused on the benefits of the implementation of a multi cropping scheme can provide the needed awareness of the outcomes for different innovative agroforestry solutions.

Despite the recent progress by other authors, a SDSS for agroforestry management that is able to combine spatially explicit information with non-spatial factors and perform integrative assessments of the economic, social and environmental aspects has not been developed so far. In this study, a system which can address this problem will be researched and a methodology of application will be presented and applied.

## 1.2 Research Questions and Objectives

The main objective of the present study is to explore the capabilities of an interactive spatial decision system for agroforestry systems, developing a tool that integrate economic, environmental and social factors in decision-making. The tool aims to aid and support decision-makers, stakeholders and investors for better planning and management. The study is focused on an agroforestry multi-cropping culture in East Kalimantan, Indonesia.

To achieve such goal the following questions must be addressed:

*a) How to integrate and evaluate economic, environmental and social parameters on a SDSS?*

*b) How can a multi-cropping agroforestry scheme be integrated in a SDSS?*

*c) How to estimate crops yield in a SDSS?*

*d) Which indicators are relevant for a sustainable agroforestry project?*

*e) How can these indicators be quantified and what are its data requirements in a SDSS?*

*f) How can the indicators be depicted for visualization in a SDSS?*

*g) What user experience rules should be followed in a SDDS?*

# 2 Literature Review

A literature review of agroforestry systems (section 2.1) was initially made, in order to identify its main characteristics. This was followed by a literature review on Spatial Decision Support Systems (SDSS) for agroforestry projects (section 2.2), analyzing previous agroforestry systems (section 2.2.1.), as well as sustainability indicators to be applied (section 2.2.2.). A literature review in user experience design (UX) and user interaction with DSS was also done (section 2.2.3). Finally, a literature review in land evaluation methods was also covered (section 2.3).

## 2.1 Agroforestry Systems

> "*Agroforestry is a collective name for land-use systems and technologies in which woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately combined on the same management unit with herbaceous crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economic interactions among the different components*" (Lundgren and Raintree, 1982).

Agroforestry systems are practiced in tropical and temperate regions and include traditional and modern land-use systems in which trees are managed together with crops for multiple benefits. It's based on the premise that systems that have a more complex structure and functionality than either a crop or tree monocultures result in greater resources (such as water, light and nutrients) capture and utilization efficiency, improving the nutrient cycle's diversity (Nair et al., 2008).

These systems allow communities to produce food, contributing to food and nutritional security, and to achieve productive and resilient cropping and grassland environments. Moreover, they can provide a range of forest products, including fuel wood and non-timber products, increase biodiversity, protect water resources and reduce soil erosion. On a large scale, agroforestry systems can also prevent the occurrence of extreme weather events, such as floods and drought (FAO, 2013).

In the present days, agroforestry is recognized as an integrated applied science that has the potential for addressing land-use management problems, as well as environmental problems found in both developing and industrialized nations (Nair et al., 2008; Nair et al., 2009). An important consideration in design of agroforestry systems, however, is the interplay and importance of ecological, economic, and social attributes and objectives of agroforestry systems.

From an environmental perspective, agroforestry systems tend to have a greater carbon sequestration potential than agricultural systems, biodiversity benefits may also be realized, although it can increase water demand, Figure 2.1. (Nair et al., 2009; Trumper et al., 2009).

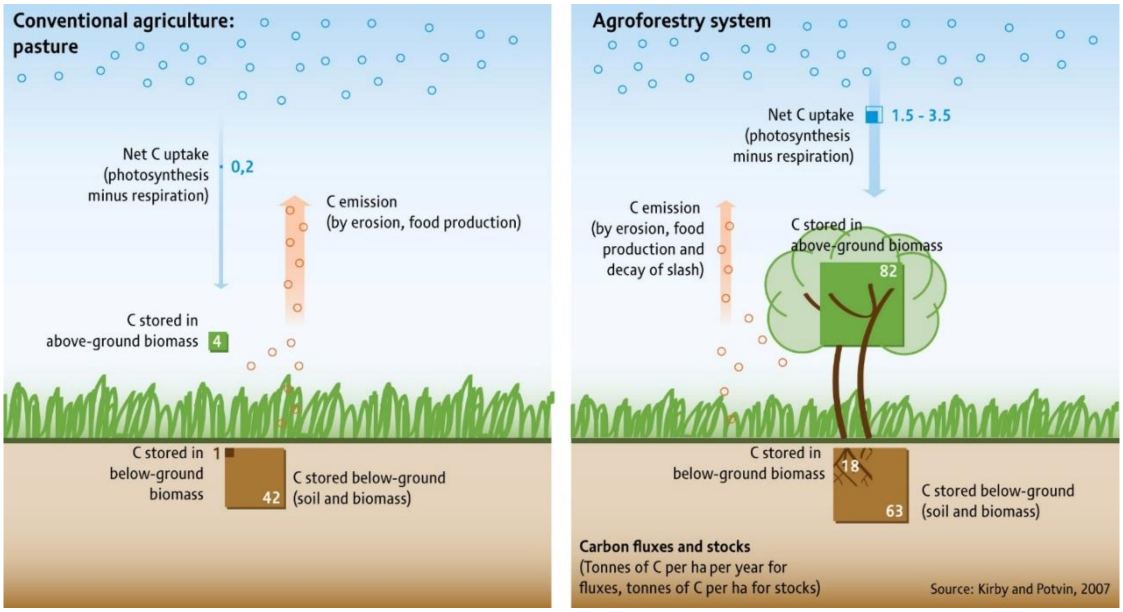



*Figure 2.1 - Conventional agricultural vs Agroforestry System.*
*Source: Adapted from Trumper et al., 2009 and Kirby and Potvin, 2007.*

As presented in the Figure 2.1, an agroforestry system not only has a greater net (photosynthesis minus respiration) carbon uptake, but also the carbon stored within above and below-ground biomass is much higher. Particularly, the average carbon storage by agroforestry practices are estimated at around 10 tonnes per hectare in semi-arid regions, 20 tonnes per hectare in sub-humid and 50 tonnes per hectare in humid regions, whereas sequestration rates of smallholder agroforestry systems in the tropics are around 1.5–3.5 tonnes of carbon per hectare per year (Montagnini and Nair 2004; FAO, 2013).

Besides carbon storage and other advantages, such as soil erosion and biodiversity conservation, agroforestry is also regarded as a promising approach for sustainable forest management (Schoeneberger and Ruark, 2003). The diagram developed by Nair et al., 2008, Figure 2.2, summarizes the mechanisms and processes involved in sustainable agroforestry systems.

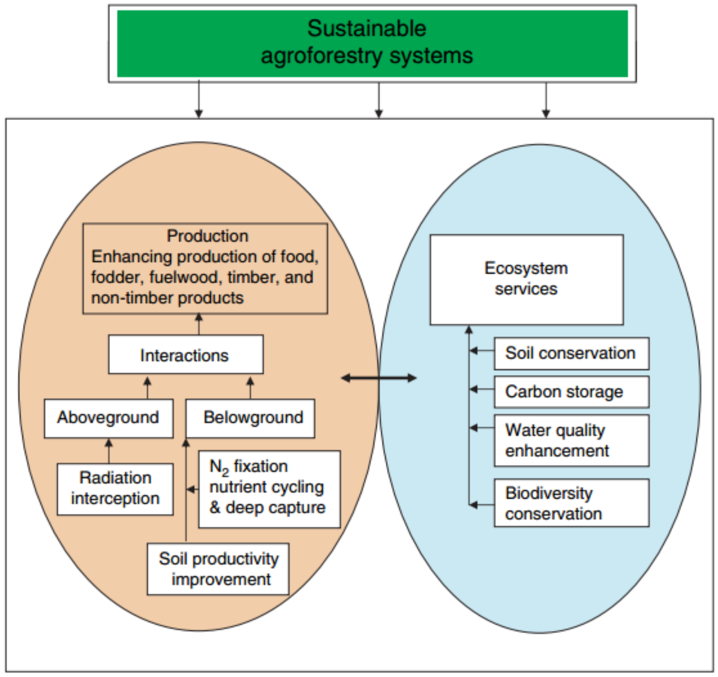



Figure 2.2 – *Mechanisms and processes of sustainable agroforestry systems.*
*Source: Nair et al., 2008.*

In the Figure 2.2, it is clear that a sustainable agroforestry takes special account between the connection of the ecosystem services and the production of the crops, timber or food, trying to enhance it in a sustainable way. As ecosystem services, it is presented soil conservation, carbon storage, water quality enhancement and biodiversity conservation. As interactions there are the aboveground and belowground interactions, which are really important for an efficient system.

Regarding Indonesia, in 1978, the involvement of communities in forest management was taken up as a major issue at the World Forestry Congress in Jakarta. Since then, the term agroforestry has been widely disseminated to the public (Rohadi et al., 2013).

Studies by Fernández (2004) and Fernández et al. (2003) have shown that agroforestry systems in North Sumatra also contribute to biodiversity conservation and maintain the surrounding natural forest resources for orangutan habitat. Sabarnurdin et al. (2011) confidently predict that agroforestry systems can provide solutions for various social and environmental problems such as global poverty issues, global warming, and environmental degradation. Agroforestry systems offer a solution to the challenge of scarcity of the four basic human needs: food, shelter, energy, and water. Agroforestry is an appropriate option and an important strategy for improving productivity of forest lands as it provides a bridging function of fulfilling the need for agricultural land and expanding the local economy, while preserving forest resources.

## 2.2 Decision Support Systems (DSS) and Spatial Decision Support Systems (SDSS)

DSS are "*computer based systems that represent and process knowledge in ways that allow the user to take decisions that are more productive, agile, innovative and reputable"* (Holsapple, 2008)

"*tools providing support to solve ill-structured decision problems by integrating a user interface, simulation tools, expert rules, stakeholder preferences, database management and optimization algorithms*" (Muys et al., 2010).

Decision support systems are a computer-based application that helps business or organizations with management, operations and decision-making. Those systems are usually interactive, aggregating high amounts of complex data in an easy way of access and reasoning, providing a platform that aid users in problem solving (Druzdzel and Flynn, 2010).

A DSS have four major component categories, a user interface (discussed on section 2.2.3), a database, a model and analytical tools, and the DSS architecture and network (Sprague and Carlson, 1982). All of those components are important for an efficient decision system process.

According to Power (2006) the main advantage or benefit of a DSS is time saving on the decision process, enhancing the effectiveness of the decision outcome. Additionally it can improve interpersonal communication about the problem, as well as increasing organizational control.

Spatial context plays a decisive role in some decisions processes and in that case spatial decision support systems (SDSS) is needed. SDSS has been defined by Densham (1991) as "*explicitly designed to provide the user with a decision-making environment that enables the analysis of geographical information to be carried out in a flexible manner*". Brown (2000) noted the importance of the temporal and spatial scales, as well as the need to understand the objectives of a model.

DSS have been an important tool in forest management since the early 1980s, as it helps to take into account many environmental, economic, administrative, legal and social aspects (Reynolds, 2005; Segura et al., 2014). Nevertheless, the first crop simulation models were developed to estimate light interception and photosynthesis already in the 1960s (Loomis and Williams, 1962; Bouman et al., 1996).

Agroforestry projects present very complex and interdependent economic, technical, political and social challenges, with its sustainability ultimately depending on the extent to which a well-coordinated land management strategy is designed and implemented (Sampson, 1998). An approach of land-use planning is considered very important to assess the long-term effects of the present management decisions (Mönkkönen et al., 2014 and Varma et al., 2000). Therefore it is clear a need for a system that takes into account these issues mentioned above.

### 2.2.1 Forestry and Agroforestry Models

Forestry and agroforestry systems are complex, involving complex mechanisms, depending on its specific land characteristics and forest requirements. Several models were developed in the past to understand and simulate the performance of forestry and agroforestry succession and productivity.

The first models of agroforestry economics were focused mainly on silvopastoral systems and simulated monetary returns from trees based on forestry models (Arthur-Worsop 1984; Cox et al. 1988). In the 1980s, the first biophysical simulations of agroforestry systems were made, including the potential of agroforestry in New Zealand (Arthur-Worsop, 1984), as well as intercropping of crops with pine (*Pinus taeda*) in United States (McNeel and Stuart, 1984).

Kosonen et al. (1997) studied the financial, economic and environmental profitability of reforestation of *Imperata* grasslands in Indonesia, a monoculture in a similar area to the case study of the present research. Furthermore, soil erosion and biodiversity indices were also developed for different vegetation covers, where the slope and the richness of bird and tree species were the principal components considered.

From a financial perspective, Hinssen and Rukmantara (1996) built a cost comparison model for budgeting of reforestation projects. While Chertov et al. (2005) used geo-visualization of forest simulation modelling on a case study of carbon sequestration and biodiversity. Wang et al. (2010) presents an integrated assessment framework and a spatial decision support system as a tool to support forestry development with consideration of carbon sequestration. Vierikko et al. (2008) studied the interrelationships between ecological, social and economic sustainability at the regional scale, analyzing their trade-offs. Segura et al. (2014) compared different decision support systems (DSS) for forest management and concluded that the majority of DSS do not include environmental and social values, focusing mainly on market economic values.

Several computer-based systems for agroforestry economics and management were analyzed, based on the framework of Graves et al. (2005), Table 2.1**Erro! A origem da referência não foi encontrada.**. Their framework was adapted to the scope of the thesis and seven systems were characterized on its key characteristics such as the background, systems modelled, objective of the economic analysis, spatial and temporal scales, generation and use of bio-physical data, model platform and interface, and input requirements and outputs.

The models examined were the Agroforestry Production Development Tool (UBC, 2014), the Agroforestry Calculator (Agriculture Western Australia and Campbell White and Associates Pty Ltd, 2000), the Water Nutrients and Light Capture in Agroforestry Systems model (WaNuLCAS) (Van Noordwijk and Lusiana, 2003), the Agroforestry Estate Model (Knowles and Middlemiss, 1999), ARBUSTRA (Liagre, 1997) and POPMOD (Thomas, 1991). Besides that one, the last model to be considered on the comparison, Table 2.1, is the proposed system of this study, an interactive spatial decision support system, supporting multi-cropping culture implementation on an area and considering environmental, social and economic as indicators.

Regarding spatially explicit systems, forest management systems have been developed in the past, but mainly based on ecologic predictions, such as individual tree growth (Phillips, 2003) or forest succession (He and Mladenoff, 1999; Gustafson et al., 2000), not taking into account economic parameters. Van der Hilst et al. (2010) studied the potential, spatial distribution and economic performance of regional biomass chains, using attainable yields for biophysical suitability. Van der Hilst et al. (2014) described an integrated spatiotemporal model of bioenergy production potentials, focused in agricultural land use. Diogo et al. (2014) combined empirical and theory land-use modelling approaches to evaluate the economic potential of biofuel production. Van der Hilst et al. (2012a) studied a spatiotemporal cost supply for bioenergy production in Mozambique, which can be adapted to an agroforestry project with the production of ethanol. Additionally, Van der Hilst et al. (2012b) quantitatively assessed the spatial variation of environmental impacts on bioenergy crops.

Suitability is very important to assess the agroforestry system success and several authors studied it in different regions, focusing on its spatial analysis. Bydekerke et al. (1998) studied the Agroforestry System Suitability in in Southern Ecuador, focusing on its spatial analysis to determine suitable areas of *Annona cherimola*. Bentrup and Leininger (2002), studied the spatial suitability assessment, focusing on willow and forest farming agroforestry systems in a watershed environment. Bernard and Depommier (1997) studied the spatial analysis of dynamics of agroforestry parklands. Unruh and Lefebvre (1995) studied the spatial analysis of regions in Africa, using climate, soil land use and plant species data to determine its suitability.

Although none of the spatial decision support system revised for agroforestry take into account a multi-cropping culture approach. Besides that are too technical to aid decision for a non-expert and the incorporation of environmental and social parameters are too weak. Segura et al. (2014) suggest that the future development of DSS for forest management should place stronger emphasis on economic models integrating the value of environmental services and collaborative decision making of multiple decision makers and stakeholders. In addition, decision support and management should be augmented with spatially explicit analysis as the costs and opportunities for different solutions have intrinsic geographic variability.

*Table 2.1 - Characteristics of the different agroforestry economic systems. Adapted from Graves et al., 2005.*

| | POPMOD | ARBUSTRA | Agroforestry Estate model | WaNuLCAS | Agroforestry calculator | Agroforestry Production Development Tool (APD) | Proposed Model |
|---|---|---|---|---|---|---|---|
| ***Background*** | | | | | | | |
| **First reference** | 1989 | 1995 | 1996 | 1996 | 1999 | 2013 | 2013 |
| **Country of origin** | UK | France | New Zealand | Indonesia | Australia | Canada | Netherlands |
| **Language** | English | French | English | English, Indonesian,Portuguese | English | English | English |
| **Initial primary use** | Research | Research | Decision-support | Research | Decision-support | Decision-support, Planning | Decision-support, Planning |
| **Systems modelled** | Arable and agroforestry | Forestry, arable and agroforestry | Forestry, arable, livestock,agroforestry and silvopastoral | Forestry, arable and agroforestry | Arable and agroforestry | Arable and agroforestry | Forestry, Agroforestry |
| **Objective of economic analysis** | Comparison | Comparison and feasibility | Comparison and feasibility | Comparison | Comparison | Comparison and feasibility | Comparison and feasibility |
| ***Spatial scale*** | | | | | | | |
| **Scale** | One-hectare | One-hectare, field and farm | One-hectare and farm | One-hectare | One-hectare | One-hectare or acre | One-hectare or acre |
| **Multiple planting** | No | Yes | Yes | No | No | Yes | Yes |
| **Temporal scale** | Annual | Annual | Annual | User-defined | Annual | Annual | Annual |
| **Time period** | 30 years | 120 years | User-defined | User-defined | 50 years | 15 years | 20 years (default), User-defined |
| **Generation and use of biophysical data** | Empirical model | No biophysical model, direct yield data for trees | Empirical model | Mechanistic model | No biophysical model,direct yield data for trees | No biophysical model,direct yield data for crops | Biophysical model |
| **Use of Spatial Data** | No | No | No | No | No | No | Yes |
| ***Platform/interface*** | | | | | | | |
| **Platform** | Spreadsheet | Spreadsheet | Visual Basic | Graphical development environment, Spreadsheet | Spreadsheet | Spreadsheet | Graphical development environment, Spreadsheet |
| **Model interface** | Input into cells | Graphical user interface | Graphical user interface | Graphical user interface (Stella modelling software needed) | Semi-graphical user interface | Semi-graphical user interface | Designed graphical user interface |
| ***Inputs and outputs*** | | | | | | | |
| **Input requirements** | Moderate | High | Moderate | Very high | Low | Moderate | Moderate |
| **Databases** | Tree data | None | Tree data | Various | Tree data | Online Biophysical Data | Crop Yields and Requirements, |
| **Outputs** | Mostly economic | Mostly economic | Biophysical and economic | Mostly biophysical | Mostly economic | Economic, Environmental and Social | Economic, Environmental and Social |
| **Model available online** | N/A | N/A | N/A | Yes, free.http://www.worldagroforestrycentre.org/sea/Products/AFModels/WaNulCAS | N/A | Yes, Free. http://agroforestry.ubcfarm.ubc.ca/agroforestry-production-development-tool | N/A |
| **Source** | (Thomas, 1991) | (Liagre 1997) | (Knowles and Middlemiss, 1999) | (Van Noordwijk and Lusiana, 2003), | (Agriculture Western Australia and Campbell White and Associates Pty Ltd, 2000) | (UBC, 2014) | (Freitas et al., 2014) |

### 2.2.2 Sustainability Indicators

The concept of sustainability or sustainable development has been defined as "*meeting the needs of the present without compromising the ability of the future generations to meet their needs*" (World Commission on Environment and Development, 1987). In other words, it is based on the interdependence between human societies and the natural environment.

Sustainability is commonly defined by its three pillars concept, environmental, social and economic pillar, Figure 2.3. A sustainability indicator can be defined as a measurable aspect of environmental, economic, or social systems that is useful for monitoring changes in system characteristics relevant to the human and environmental needs.

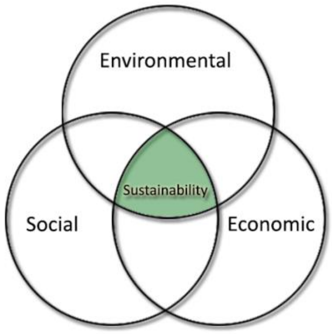



*Figure 2.3 -The three dimensions (pillars) of sustainability.*

An indicator intends to simplify, quantify, standardize, and communicate information. For any issue or case study, an indicator will measure, weight or aggregate valuable information with the goal of understanding it and raising awareness among policymakers and civil society (UN, 2007).

In that way, the use of sustainability indicators is essential for an integrated systems assessment. The selection of each indicator from each domain for the desired decision-making process, will affect the type of analysis and focus of the exercise, therefore it is important to discuss each indicator importance between decision makers. For each situation, evaluating different possible indicators, it is important to select the most relevant. The overall analysis of the system helps to determine which indicators capture aspects that significantly contribute to sustainability (Fiksel et al., 2013). Despite that, when selecting indicators the gross value or benefit from monitoring them has to surpass their overall costs (Pannell and Glenn, 2000).

Related with the sustainability meaning, the phrase "*the triple bottom line*" was introduced in 1994 by John Elkington (founder of a British consultancy called "*SustainAbility*"). The Triple Bottom Line (TBL) evaluates the same pillars and it is also referred as "*Triple P*" thus consists of three Ps: profit (economic performance), people (social performance) and planet (environmental performance). The goal is to measure the economic, social and environmental performance of an enterprise or corporation over a period of time (Willard, 2002).

Forestry can play a big role in sustainable development, such as reducing poverty and deforestation, halting the loss of forest biodiversity, reducing land and resource degradation, and contribute to climate change mitigation. The Intergovernmental Panel on Climate Change (IPCC), states that considering forestry mitigation options, important environmental, social, and economic benefits can be gained, involving local people and stakeholders and developing adequate policy frameworks. Thus, forestry and agroforestry projects have to be seen in the framework of sustainable development (IPCC, 2007).

Most of DSSs and SDDs don't account the sustainability approach, being mainly based on economic indicators and outputs. Weidner and Fiege (2011) developed the Model for Assessing the Sustainability of Agroforestry Systems (MASAS), examining the land-use potential for environmental, economic and social benefits, in the Philippines uplands. The different sustainability dimensions are evaluated by a set of indicators that are measured using quantitative data (e.g., material input required or gross margin) and qualitative information (e.g., complexity to manage). The model is based on a scoring mechanism, where which indicator is scaled from 1 (lowest score – least desirable to 5 (highest score – most desirable).The MASAS model also took into account a weighting factor, as some indicators can contribute to the model with a different weight, depending on its importance. The model combined different indicators and weights on an overall score of the agroforestry system sustainability. The goal of their study was to examine how agroforestry can contribute to income generation, environmental protection and social welfare of upland farmers in the Philippines.

Sipos (2005) also took into account the sustainability pillars when researching the complexity of agroforestry accounting, in order to build the "BC Sustainable Agroforestry Calculator". A generic methodology is presented for this tool, intended to calculate the potential of agroforestry systems, integrating economic, ecological and socials considerations in northwestern North America. The ranking mechanism of the tool, evaluating the current practices, ranges from -2 to 2, whereby a mark of 0 is assigned as a starting point, 1 as improved, 2 is greatly improved, -1 is degraded, -2 is greatly degraded. The goal of this scale is to evaluate changes to the system, depending on the agroforestry practices done, through a ranking process of those variables considered.

Capacity to generate sustainable socioeconomic and environmental benefits also depends on the financial viability of the implemented plantation model. Godsey (2008) described economic budgeting for agroforestry practices, explaining the steps for developing an enterprise budget, suggesting Net Present Value (NPV), Internal Rate of Return (IRR), and Annual Equivalent Value (AEV) as common economic indicators.

Generalized indicators of sustainable development are described by the United Nations, as well as its contribution for the agenda 21 and millennium development goals, present in appendix 2 (UN, 2007). As the scope of the study is based on agroforestry systems, a literature review of indicators that can assess environmental, social and economic dimensions was made and aggregated into a list, Table 2.2.

*Table 2.2 - Potential Indicators to use in agroforestry assessment.*
*Adapted from Sipos (2005), based on work by Gomez-Sal (2003), Pannell and Glenn (2000), Sanchez (1995), Weidner and Fiege (2011), UBC (2014) and Godsey (2008).*

| Dimension | Indicator |
|---|---|
| **Environmental** | Air pollution |
| | Biodiversity |
| | Carbon storage potential |
| | Competition between trees & crops |
| | Crop root depth |
| | Diversity of production |
| | Forest management |
| | Greenhouse gas |
| | Habitat diversity and connectivity |
| | Invasive plants |
| | Land productivity |
| | Microclimate |
| | Native plants |
| | Organic matter in soils |
| | Pesticide usage |
| | Pollinator habitat |
| | Renewable resources |
| | Resilience of ecosystem |
| | Share of nitrogen-fixing crops |
| | Soil erosion and Soil pH and nutrients |
| | Soil water storage capacity of crops |
| | Sustained productivity |
| | Water availability |
| | Water quality |
| **Social** | Aesthetics |
| | Agroforestry tourism |
| | Community gatherings |
| | Complexity to manage |
| | Contentment |
| | Contribution of the agroforestry system to meet nutritional needs |
| | Cultivation of culturally significant material |
| | Cultural preferences |
| | Greater confidence in future |
| | Perceived social benefits of increasing environmental stewardship |

*Table 2.2 (Continuation) – Potential Indicators to use in agroforestry assessment.*

| | |
|---|---|
| **Economic** | Agroforestry tourism |
| | Agroforestry Branding |
| | Annual Equivalent Value (AEV) |
| | Available family income/capita |
| | Consistency of income |
| | Dependency of production on a single crop |
| | GPM/ total subsidy/ working person/ agricultural area/capita |
| | Gross profit margin (GPM) |
| | Internal Rate of Return (IRR) |
| | Material input required |
| | Net present value (NPV) |
| | New product/innovation |
| | Number of jobs |
| | Provisioning services |
| | Return to labor |
| | Risk of pest and disease problems |
| | Subsidy of crops/ha |
| | Sustained productivity |
| | Tax incentive |
| | Use of marginal land |

### 2.2.3 User Experience (UX)

*"All the aspects of how people use an interactive product: the way it feels in their hands, how well they understand how it works, how they feel about it while they're using it, how well it serves their purposes, and how well it fits into the entire context in which they are using it."* (Alben, 1996)

User Experience (UX) design is a multidisciplinary approach which draws from other fields such as interface design, information architecture, or psychology. UPA (2006) defines user experience as *"Every aspect of the user's interaction with a product, service, or company that make up the user's perceptions of the whole".* Therefore, the interface design and user experience of a software, such as a DSS, determines whether it will be used, as well as if it will be used effectively.

Druzdzel and Flynn (2010) define that "*DSSs do not replace humans but rather augment their limited capacity to deal with complex problems*", therefore its user interface experience and friendliness is crucial. Even if the model has a really good scientific theory behind, providing an approximation of reality and its recommendations are technically correct, they will not be embraced and accepted if they are not easily understood. If a system is not quickly understandable, users may accept or reject a system's advice for the wrong reasons and the purpose of the system to aid a better decision is not met (Lehner et al., 1990; Druzdzel and Flynn, 2010).

Despite its quality and reliability, there are many DSS that are just used once and some authors studied the many reasons of this lack of success (Uran and Janssen, 2003; Adelman, 1992). The difficulty of its use, taking a lot of time and its user interface complexity, is one of the main reasons (Ubbels and Verhallen, 2000). Other than that, the uncertainty by the user of the model output and how useful it is to solve the decision question (Jones et al., 1998).

Upon several years of research in how DSS works and how people interact with those systems, Power (2007), defines rules for DSS user interface design, being one of the most important the system consistency, as the terminology and commands used must be consistent, from menus to help screens. An aesthetic and minimalist interface design with only the strictly necessary information load for user understanding. The type and amount of information displayed should be considered as it will impact the human memory processing and therefore the ease and speed of the system's use. Additionally, information should appear in a natural and logical order. Interactive commands and user feedback through the usage of the system is also important, so the user gets informed on the impact of its actions and selections. The system should also permit easy reversal of user actions to encourage the DSS or SDSS exploration. Providing "help" capabilities and appropriate system documentation is desirable, so it can easily answer at least the main questions about the system.

Understanding the user needs is important, as it gives information on how to adapt the system and therefore improve the user experience for the final user. Additionally, it is proven that a system with a user friendly environment improves learning. This might allow the user to learn how different parameters are linked and their importance.

## 2.3 Land evaluation methods

*"The assessment of land performance when used for a specified purpose, involving the execution and interpretation of surveys and studies of land forms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation."(*FAO, 1976)

Land evaluation is defined as the implementation and interpretation of climate, soil and other aspects of land in terms of its requirements for different land-use forms. The evaluation of land characteristics is a key step in land suitability assessment for a specified land-use, as it aids predicting yield (FAO 1976).Despite that, it is also important for land allocation and land preparation for a specific land-use type or the reclamation of land (FAO, 1976). The main role of land evaluation in the present study is to determine the biophysical suitability of a desired area for different land-use types.

A methodical way of land evaluation is set out in "*A Framework for Land Evaluation"* (FAO, 1976) and "*Land Evaluation Part I"* (Sys et al., 1991) and the procedure consists of four main steps:

a. Describing land-use types;
b. Determining the requirements, e.g. water, nutrients for each land-use type;
c. Mapping land units and describing their properties, e.g. climate, slope, soils;
d. Comparing the land-use type's requirements with the land unit's properties, in order to achieve a land suitability classification or index.

The land evaluation concept described in *FAO 1976* addresses the goods and services of the land related to its numerous functions and the sustainability of its used as well current concerns related to climate change, biodiversity and desertification. The first principle described was to assess the biophysical suitability of land for a specified land use (FAO, 2007). Other principles were:

a. An evaluation should be the comparison of the gained benefits and profits and the required inputs on different land types;
b. The process of land evaluation have to be a multi-disciplinary approach;
c. It should include the biophysical, economic, social and political environment of the area of interest;
d. Suitability should incorporate productivity, social equity and environmental concerns;
e. Land evaluation includes comparison between more than one land use form.

Many concepts and definition of the framework remain effective and the aim of the FAO Revised Framework is to link the environmental concerns and issues of sustainable livelihood to the basic concepts of the FAO Framework of 1976.

According to FAO (1976) and Sys et al. (1991), three approaches exist to evaluate biophysical suitability of land: land characteristics, land qualities or a combination of land characteristics and land qualities approach. Land characteristics are measurable biophysical properties of the environment and consist of two main categories, the climate factor groups and soil and terrain factor groups (Gaiser and Graef, 2001; Sys et al., 1991; FAO, 1976).

**Climate factors group:**

a. Rainfall (annual precipitation, length of dry season);
b. Temperature (mean maximum temperature , mean annual temperature and mean minimum temperature) ;
c. Humidity (air humidity during crop cycle) ;
d. Radiation (fraction of sunshine hours during crop cycle).

**Soil and terrain factor groups:**

a. Topography (terrain slope gradient) ;
b. Wetness (drainage class) ;
c. Soil physical characteristics (soil depth, texture/structure class, gravel, carbonate and gypsum content) ;
d. Soil chemical characteristics ( clay fraction, base saturation, sum of basic cations, total organic carbon and pH) ;
e. Degree of salinity-alkalinity (electrical conductivity and exchangeable sodium percentage in the topsoil).

Land qualities are resultant of the interaction of single land qualities and they can be measured, calculated or estimated and represents the requirements of the land-use type. Sys et al. (1991) suggests three broad land qualities:

- Gross productivity;
- Required recurrent (management) inputs;
- Non-recurrent (improvement) inputs.

These broad land qualities are the result of single land qualities interaction. The land qualities related to crop biophysical productivity are described below (Sys et al., 1991; FAO, 1976):

- Moisture availability;
- Nutrient availability;
- Oxygen availability in the root zone;
- Adequacy of foothold for roots;
- Conditions of germination;
- Salinity or alkalinity;
- Soil toxicity;
- Resistance to soil erosion;
- Pests and diseases related to the land;
- Flooding hazard ;
- Temperature regime;
- Radiation energy and photoperiod;
- Climatic hazards affecting crop growth (including wind, hail, frost);
- Drying periods for ripening of crops;
- Air humidity as affecting crop growth;

Compared to the land quality approach, the land characteristic approach has the disadvantage that the interaction between land characteristics cannot be taken into account. However, it has the advantage that characteristics can be rated easily. Since each land-use type has special requirements, land suitability must be defined for a specific land-use type.

Land-use requirement is the necessary condition for a productive implementation of a specific land-use type. A land-use type can be described by a set of land-use requirements which expresses the demand of the land-use area matching procedure (Rossiter, 1996).

Figure 2.4, shows the land evaluation approach of BIOSAFOR for plantation of tree species, on a case study for saline soils (Vashev et al., 2010).

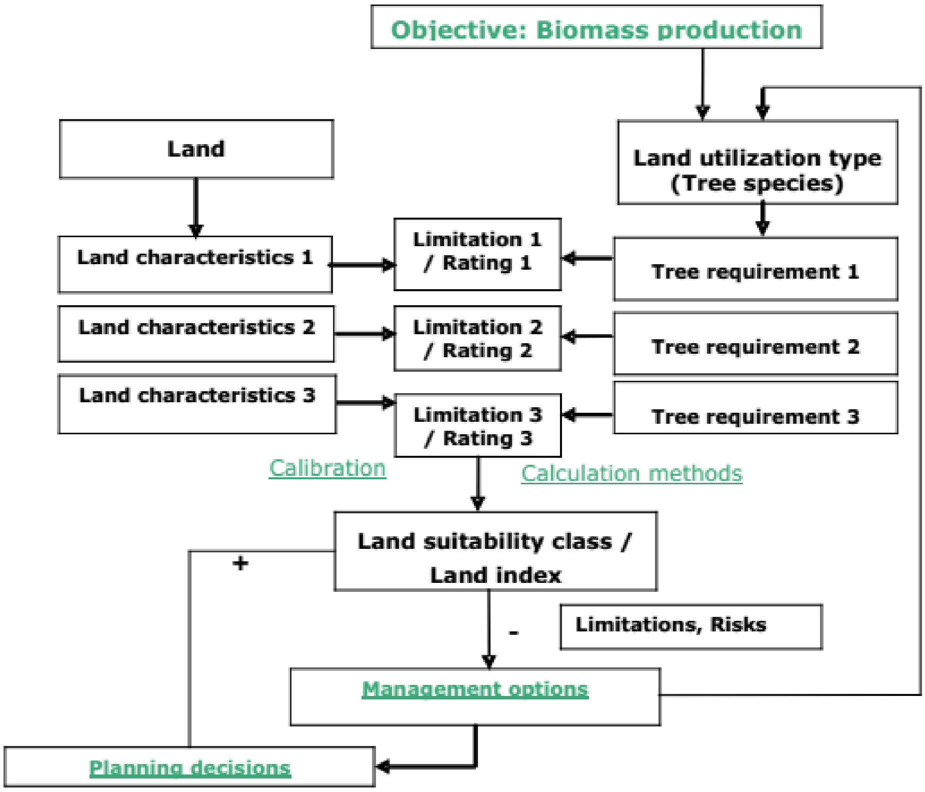



*Figure 2.4 - Land Evaluation Approach by BIOSAFOR.*
*Source: Vashev et al., 2010*

In the diagram, Figure 2.4, the authors present that the land characteristics can be either evaluated by a limitation or a parametric approach (represented as rating in the figure above), whereas a limitation is a deviation from the optimal condition which affects the land-use type “negatively”. Therefore if a land characteristic is optimal for the crop to grow, it has no limitation.

Regarding the limitation approach, FAO (1976) suggest five degrees of limitations to evaluate land qualities or characteristics: no limitation, slight limitation, moderate limitation, severe limitation and very severe limitation. The limitation levels can be expressed as land classes and each land characteristic or quality can be defined as:

- S1 (very suitable);
- S2 (moderately suitable);
- S3 (marginally suitable);
- N1 (not suitable, can be improved);
- N2 (not suitable, cannot be improved).

On the other hand, the parametric approach is a numerical approach, depending on the crop-specific requirements ratings. Those ratings are defined between 25 (unsuitable) and 100 (very suitable), indicating the level of limitation for the growth of the tree species under the given land characteristics (Verdoodt and Van Ranst, 2003; Sys et al., 1991; FAO, 1976).

When the parametric approach is applied the following rules should be respected:

- The number of land characteristics should be restricted to a minimum. The qualities expressed by one characteristic should be rated together.
- Important characteristics should be rated in a wide scale (e.g. 25-100), while less important ones should be rated in a narrower scale (e.g. 60-100).
- If a characteristic is better than the optimal condition the maximum rating can be higher than 100.

Although parametric and limitation approaches are used separately, it is possible to combine characteristics of both approaches and use it for land evaluation. In Table 2.3, the ratings for different levels of limitation are depicted and can be used for evaluation, when the characteristics of both approaches are combined. Therefore, if the crop requirements are only available for limitation method, Table 2.3 can be used to convert it into ratings.

*Table 2.3 - Number of limitation and the associated suitability classes and ratings.*

| **Limitations** | **Suitability classes** | **Intensity of limitation** | **Rating** |
|---|---|---|---|
| 0 | S1 | No | 100-95 |
| 1 | S1 | Slight | 95-85 |
| 2 | S2 | Moderate | 85-60 |
| 3 | S3 | Severe | 60-40 |
| 4 | N | Very severe | 40-25 |

*Source: Sys et al., 1991.*

The first column shows the number of limitations and the second, the associated suitability class. A land characteristic with 0 or 1 limitation is considered very suitable (S1). Columns 3 and 4 show the intensity of limitation and the associated rating respectively.

The Storie index is a method of rating land's potential utilization and productive capacity, based on soil and climate characteristics of the area. This method is independent of other physical or economic factors that might determine the decision of a certain crop in a given location (Storie, 1948 and 1950).

Therefore, based in the theory that the scarcest resource is the limiting factor for tree growth, the Storie Method calculates a climate index, and a soil and terrain index. Thus within each group of soil and terrain, and climate characteristics the rating of the most limiting factor is used (Sys et al., 1991; Rabia and Terribile, 2013). The climate index is converted to climate rating and subsequently with soil and terrain index, a land index is calculated, equations and explanation further on the methodology section 3.1.2 (Sys et al., 1991; UC, 2008; Wicke et al., 2011).

# 3 Methodology

This section elaborates on the methodology that is implemented to achieve the research goals. A system to aid support decision in agroforestry will be determined. Based on literature review, the most suitable approaches were chosen, leading to the design of the modelling framework and its parameters, section 3.1. The modelling framework inputs parameters, such as the field operations. A biophysical suitability module was developed, based in land evaluation methods, to estimate the production yield in each recipe and location, is presented in section 3.1.2. The sustainability indicators to assess the system performance in terms of economic, environmental and social aspects are presented in the section 3.2. Based on data collection, both from literature review and the Indonesia field trip, the system was build and adjusted to local data. Due to data confidentiality of the Indonesian company and lack of data in some modelling factors, the proposed methodology has been implemented on adjusted data sets. Although these data sets were created so as to be as close as possible to real conditions in the study area. Taking into account the proposed modelling framework, a desired model structure, optimization and implementation are covered in section 3.3 and 3.4, respectively. The model prototype was developed in Excel environment and ArcGIS® geographic analysis capabilities. This prototype was tested and improved, through several iterations based on the outputs given in each one of the iterations. The main methodological steps, explained above and work developed are summarized below in Figure 3.1.

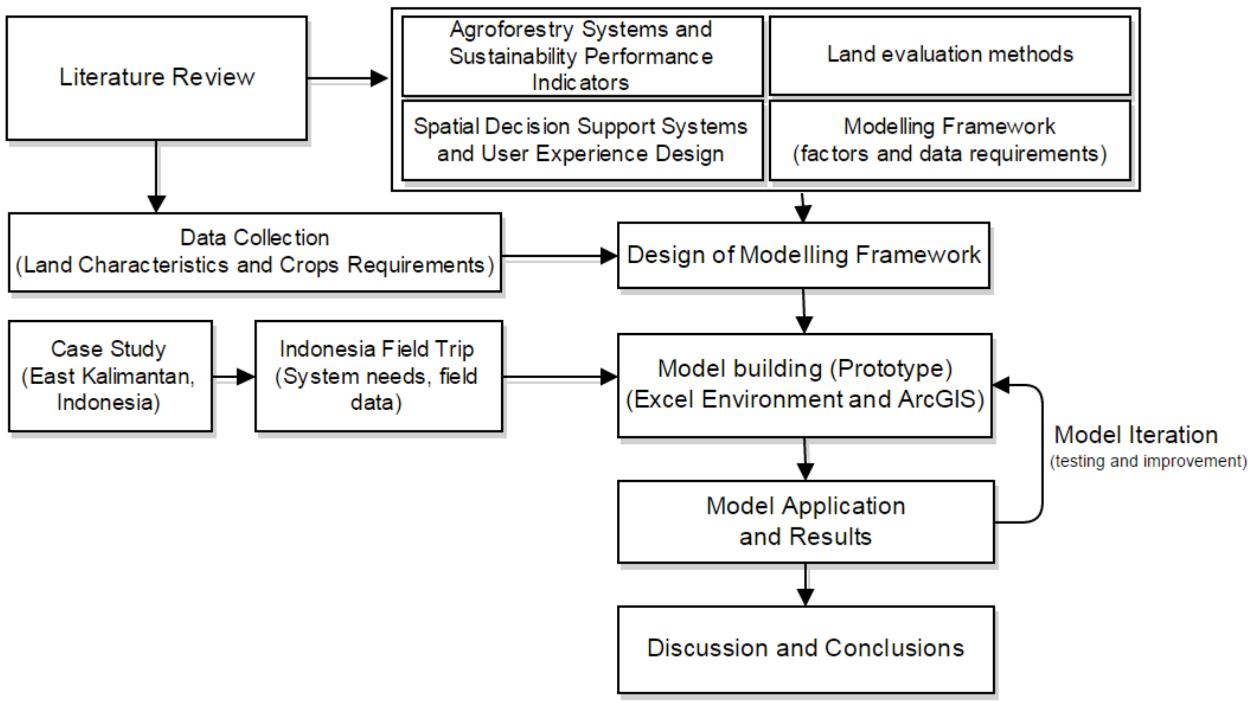



*Figure 3.1 - Main methodological steps*

## 3.1 Modelling framework

The system is intended to be a spatially explicit integrative assessment tool for agroforestry projects. It allows the comparison of the economic, social and environmental performance of different management options, by combining spatial data on biophysical features, population, infrastructure and transportation networks with data on economic and technical factors. It also functions as an exploratory tool, being deployed in an interactive environment that enables sensitivity analyses of system performance for the main key factors (e.g. cost of production factors, market prices of commodities) and different spatial options (designs) in forest plantations. Inspired on the developments of the cost comparison model developed by Hinssen and Rukmantara (1996) and additional related literature reviewed, a conceptual model was developed for a spatially explicit system analysis in agroforestry projects, taking into account an assessment of a sustainability performance.

The model presented, see next page Figure 3.2, aims to determine the local performance of agroforestry recipes, defined as a mix of crops that are sequentially cultivated in a certain area. The considered recipes are defined according to the opportunities and constraints set by the biophysical features of specific regions, depending mainly on its land characteristics (e.g. slope, soil) and crops requirements. As biophysical suitability differs on each area and it is one of the most crucial factors of productivity of the crops, it is important to take into account its location and plan the best location to be applied each one of the crops and recipes (mix of crops). The biophysical suitability module is extensively explained in section 3.1.2.

Each recipe has its own timing and economic values in terms of field operations, field inputs, commodities and costs, which is also taken into account in the model. All the revenues, costs and investments are aggregated to calculate economic performance indicators, such as net present value, return on investment, internal rate of return and the annual equivalent value. Storage and transportation locations and costs are calculated through a network analysis, depicted on section 5.1.2. The labor force availability and settlements location are also analyzed by the same network approach. For the desired study area, a grid approach is used, dividing all area in smaller units that can be analyzed individually. Therefore a location based decision will be possible having information, per unit of area (e.g. per hectare) of all the field operations needed, as well as costs and revenues.

Carbon sequestration potential is part of the environmental performance, but also revenue, as carbon emission permits can be traded on the market. On the other hand the social performance is assessed by the labor needed for the project. Examples of recipes are given on the case study description (section 4.1).

The analysis is initially done per unit of area, as it has different suitability, costs and revenues and therefore a different NPV. After the analysis per unit of area, all are summed up (e.g. Sum of the NPVs) or weighted averaged (e.g. ROI of the project). Finally, the system has data requirements, in order to simulate the costs and benefits, such as technological (e.g. material needed), biophysical and economic (e.g. field operations prices) factors requirements, as well as spatial data (e.g. location of roads), presented on Table 3.1, see page 26.

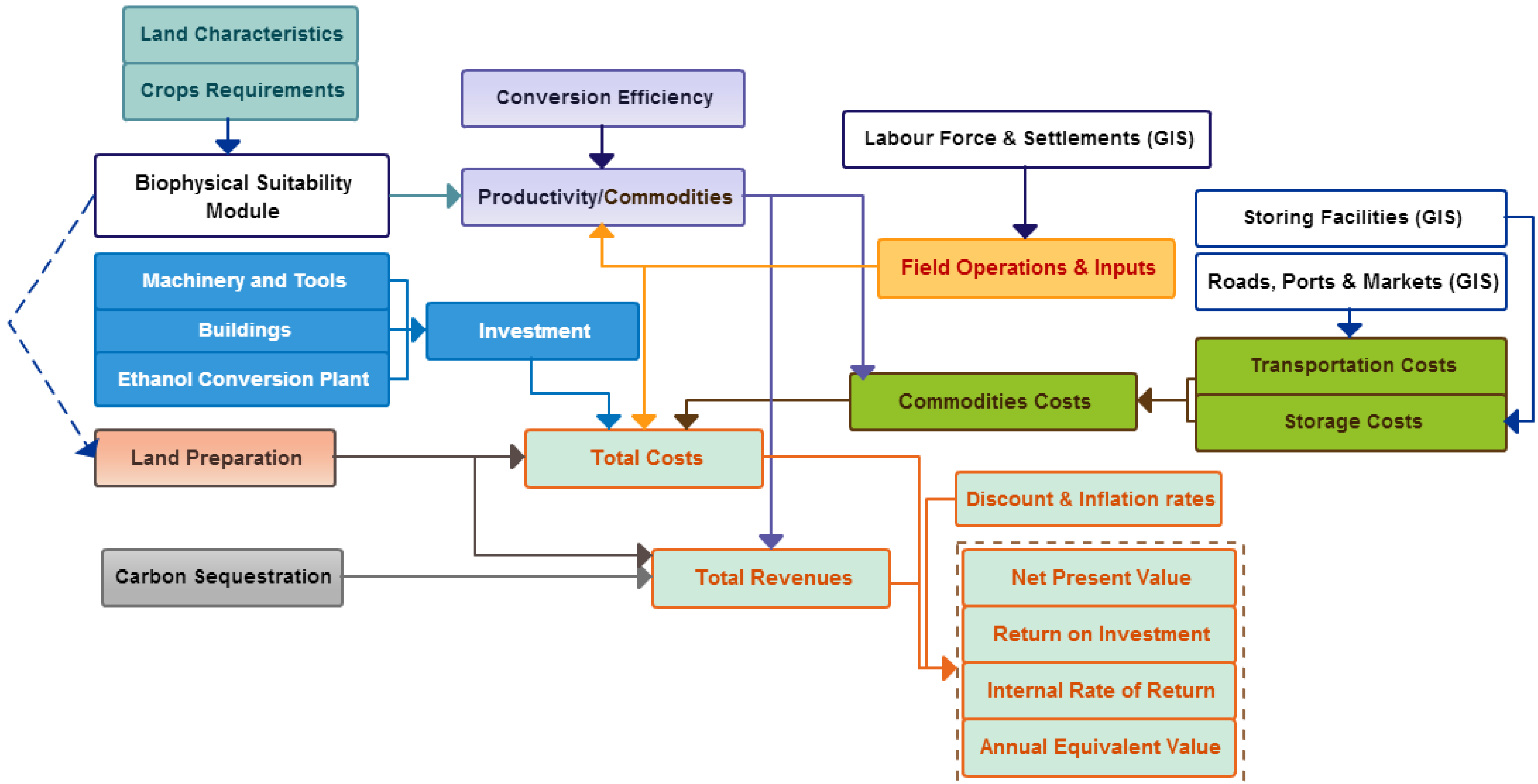



*Figure 3.2 – Conceptual model of the spatially explicit sustainability analysis of an agroforestry project per recipe.*

*Table 3.1 - Data requirements per recipe and year*

| Data Requirement | Unit |
|---|---|
| **Recipe content** | |
| Crop density | (crop and density/ha) |
| Time of crop plantation (if applicable) | |
| **Material Needed (Investment)** | |
| Material usage quantity | (hours/number needed) |
| Price | ($/unit) |
| Capacity of the material unit | (hours) |
| **Biophysical Suitability** | |
| **Land characteristics** | |
| Climate characteristics | (n/a) |
| Soil and terrain characteristics | (n/a) |
| **Crop requirements** | |
| Climate requirements | (n/a) |
| Soil and terrain requirements | (n/a) |
| **Field operations** | |
| Number of field operations per year | (nr/ha) |
| Labor hours per field operation | (h/ha) |
| Cost per field operation | ($/ha) |
| Revenues per field operation | ($/ha) |
| **Field operation input factors** | |
| Wages per expertise type | ($/h) |
| Fuel prices | ($/L) |
| Additional inputs needed and prices (e.g. fertilizer) | ($/ha) |
| **Commodities** | |
| Production(Yield) per commodity(e.g. crop) and year | (t/ha/y) |
| Costs (Transportation, Storage) per commodity | ($/ha) |
| Market price of commodities | ($/ha) |
| **Environmental** | |
| Carbon sequestration potential per perennial | ($tCO_2$/ha) |
| Carbon credits price | ($/ha) |
| Biodiversity (Diversity of species) | (nr/ha) |
| **Economics** | |
| Discount rate | (%) |
| Inflation rate | (%) |
| Depreciation rate | (%) |
| **Spatial data layers** | |
| Transportation network (e.g. roads, rivers) | location and length |
| Biophysical data (e.g. slope, soil) | data per unit of area |
| Settlements/villages | location |
| Location of markets/facilities | location |

### 3.1.1 Modelling Input

#### 3.1.1.1 Field Operations and Inputs

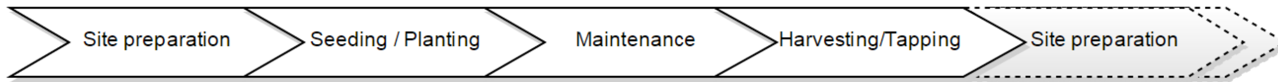



*Figure 3.3 - Agroforestry field operation stages*

Field operations are defined in terms of the number of each operation per year, per recipe and per unit area. This amount of number of each operation needed per year will be associated a number of hours (labor input hours), which will determine the exact need of each operation, in the project.

The field operations taken into account in the system, Figure 3.3, are:

- **Site Preparation and Land clearing**;

Site preparation and land clearing operations involves the suppression and removal of existing trees and weeds. Depending on the biophysical suitability of the area and the recipe to apply, a land clearance might also be required in order to reforest it. This land clearance is translated into a cost and revenue, as some materials can be sold.

- **Seeding and planting;**

Depending on the crop/tree, the operation can be seeded or transplanted from a nursery, where they previously grow to a later stage.

- **Maintenance;**

As maintenance is understood activities, such as pruning, weeding and fertilizing.

- **Harvesting** (e.g. cutting timber, harvesting crops, tapping)

Different field operations have different duration and technical expertise, depending on each recipe. Therefore for each field operation is associated a specific work (labor h/ha) and technical expertise (low, medium, high), which reflect different costs.

The field inputs are the inputs needed for each field operation, such as labor force, fuel consumption, number of seeds and fertilizer per hectare and recipe. These were the initial inputs considered, but the system can support more complexity as needed during the project. Additional field inputs or operations can be added for different progress or scenarios.

All field inputs are combined to give a final value per unit of area ($/ha) for each field operation described, Figure 3.4. The total cost of field operations per recipe is calculated by the multiplication of each field operation input with the according number of field operations.

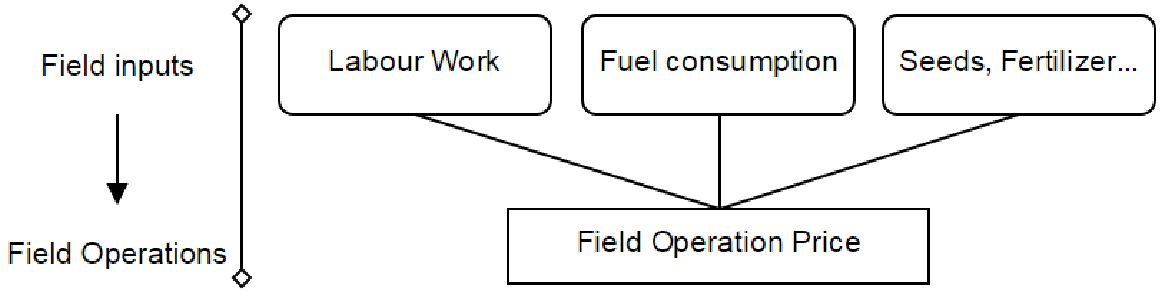



*Figure 3.4 - Final value ($/ha) for each field operation combination*

#### 3.1.1.2 Commodities

The produced commodities entail spatially explicit field operations costs and inputs including labor force, planting, maintenance, harvesting and tapping, which are integrated in the total costs of the system. Commodities are dependent on the area suitability and yields per year, hectare and recipe.

Commodities include timber and crops (such as cassava and pineapple), as well as by-products (such as broom, roof covers and furniture). Conversion efficiency factors are used to determine the final products, depending on the type of mechanism applied for the transformation. The user is able to introduce and change the commodities produced as needed.

Besides the revenues derived from selling the commodities in the markets and the production costs, there are also highly variable costs that have to be considered, such as transportation and storage. Transportation is one of the economic factors with more expression as access to the production sites is often difficult.

#### 3.1.1.3 Labor Force

Since labor force is required for the realization of the project, it is important to take into account the location of the settlements to choose the most suitable location (analyzed on section 5.1.2). The labor force will be determined by the hours of work needed for certain recipe and unit area.

Depending on the number of labor hours needed, the labor will be categorized in different intensity levels. Low, normal and high intensity levels. Therefore when selecting a recipe, the labor intensity needs will be taken into account, making the recipe suitable or not for a determined unit of area.

Labor has two important perspectives, as a financial cost for the system but also as a social output via the increase of employment rate and welfare improvement. The employment of rural labor is one of the greatest benefits accredited to agroforestry systems. Research on Guatemala, found that adoption of agroforestry systems increased up to 44% the amount of labor used per hectare, in some areas (Current et al., 1995).

#### 3.1.1.4 Discount rate

A discount rate accounts for the "time-value of money" by discounting future costs and returns to a present value equivalent. The further into the future that costs and returns occur the less they are worth in terms of today's monetary value.

In literature discount rates for agroforestry range from 0 to 20%, depending mainly on the market and social perception (Current et al., 1995; Kapp, 1998). In the discount rate, inflation and depreciation factors can also be included.

### 3.1.2 Biophysical Suitability Approach – Land Index

The biophysical suitability of an area is the first step to simulate the output of the agroforestry system to be implemented. In order to evaluate the biophysical suitability, the land characteristic approach described in FAO 1976 and Sys et al. 1991 can been applied, calculating the crop yields and the recipe suitability. The land characteristic approach has the advantage that characteristics can be rated directly, therefore, that approach is used, see Figure 3.5.

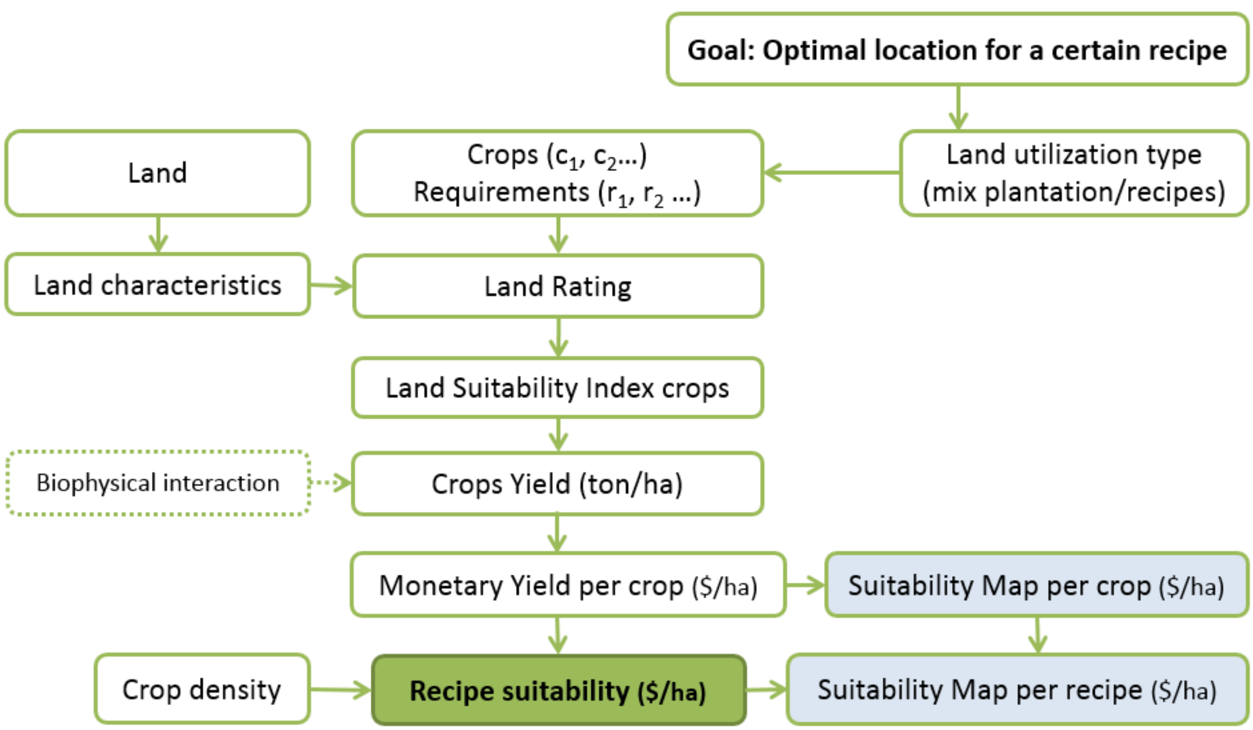



*Figure 3.5 – Optimal location and suitability for a recipe methodology*
*Source: Adapted from Vashev et al. 2010.*

Figure 3.5, shows that to achieve the goal of the optimal location for a recipe, an evaluation of the crops, its requirements, as well as the land characteristics of the location are needed. A land rating is done based on those characteristics and a land suitability index is calculated. A more extensive explanation of the biophysical land-use suitability is presented on Figure 3.6. Based on the land suitability index, a crop yield is determined, which enables the calculation of the recipe suitability and therefore a suitability map. There are biophysical interactions between the crops in a mixed plantation, which have an impact on yield of the crops. However, taking the impact of biophysical interactions is beyond the scope of this study and it is assumed that there is no interaction (neither negative nor positive) between the crops.

The land characteristics are evaluated by parametric approach, as it was proved to be the most suitable approach to quantify and correlate the crop yields with climate, soil and terrain factors, as it considers the synergy between limitations (Gaiser et al., 2001; Sys, 1993). The parametric approach is a numerical approach and depending on the tree-specific requirements the characteristics are rated between 25 (unsuitable) and 100 (very suitable), as stated in the literature review, section 2.3.

The Storie Index is a method based on the theory that the scarcest resource within each group of soil and terrain, and climate characteristics is the limiting factor for plant growth. As explained in section 2.3, a climate index($I_c$) and a soil and terrain index ($I_{St}$) are calculated based on this method:

$$I_{st}(\text{Soil and terrain index}) = (\frac{A_{st}}{100} \times \frac{B_{st}}{100} \times \frac{C_{st}}{100} \times (\dots) \times \frac{n}{100} \quad (1)$$

(Wicke et al., 2011)

Where,

$A_{st}$, $B_{st}$, $C_{st}$ are the rating of the most limiting factors within each group of soil and terrain characteristics (topography, wetness, soil physical characteristics, soil chemical characteristics, and salinity and alkalinity);

n the number of ratings.

$$I_c(\text{Climate index}) = (\frac{A_c}{100} \times \frac{B_c}{100} \times \frac{C_c}{100} \times (\dots) \times \frac{n}{100} \quad (2)$$

(Wicke et al., 2011)

Where,

$A_c$, $B_c$, $C_c$ are the rating of the most limiting factors within each group of climate characteristics (rainfall, temperature and radiation).

Hence, within each group of land characteristics, the rating of the most limiting factor is used for index calculations.

In order to calculate the total land evaluation the climate index is transformed into a climatic rating ($R_c$), by the follow equations:

$$R_C = \begin{cases} I_C \times 1.60 & \text{when } I_C \leq 25 \\ I_C \times 0.94 + 16.67 & \text{when } 25 < I_C \leq 92.5 \\ I_C & \text{when } 92.5 < I_C \leq 100 \end{cases} \quad (3)$$

(Wicke et al., 2011)

The climate rating ($R_c$) is then multiplied by the soil and terrain index ($I_{st}$) to determine a land index (LI), which represents the suitability of the land for the given crop species and is relative to the constraint-free yield:

$$LI = R_C \left(\frac{I_{st}}{100}\right) \quad (4)$$

(Wicke et al., 2011)

The land index values range between 0 (not suitable) and 100 (very suitable) and to estimate the yield (Y), the LI is multiplied with the constraint-free yield/ maximum attainable yield ($Y_{max}$):

$$\mathrm{Y\ (t/ha/y)} = \mathrm{Ymax} * \left(\frac{\mathrm{LI}}{100}\right) \quad (5)$$

(Wicke et al., 2011)

Where, Ymax is the constraint-free yield/ maximum attainable yield (t/ha/y).

The maximum attainable yield is the theoretical yield the can be achieved if a specific crop grows under optimal environmental conditions, without any losses from pests. Crop yield is only limited by the crops genetic and physiological potential (Wicke et al., 2011).

The process of land evaluation and the requirements are schematically presented in Figure 3.6.

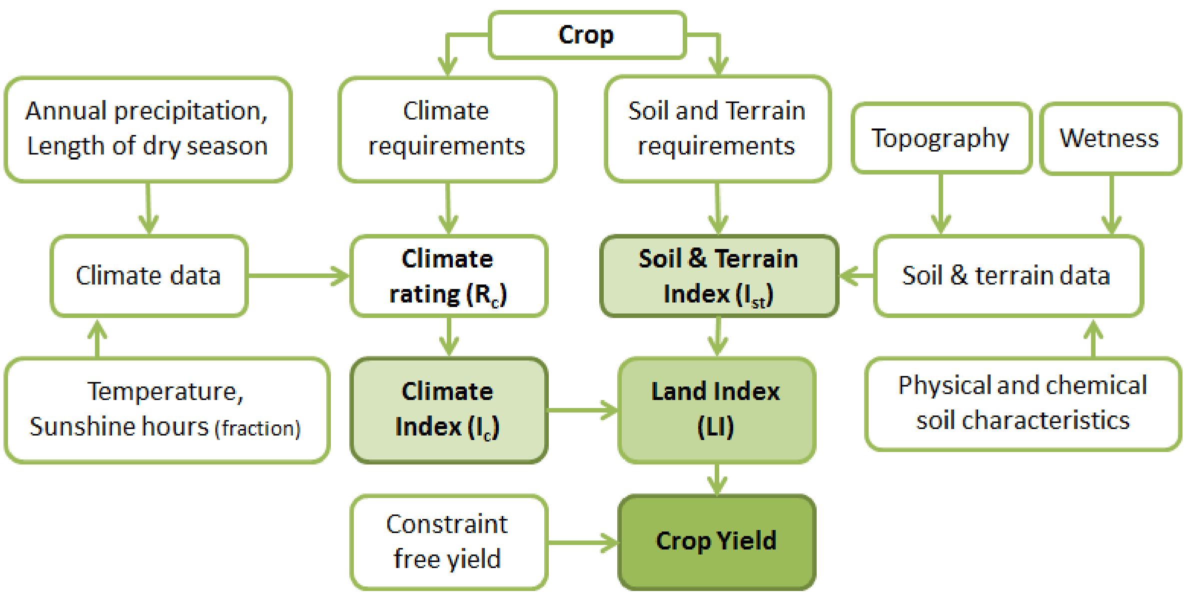



*Figure 3.6 – Biophysical land use suitability*

Figure 3.6, shows that in order to determine the suitability of an area for a specified land-use type, data on climate, soil and terrain requirements are needed. Further it also shows for which groups of land characteristics within climate, and soil and terrain data is needed to calculate a climate index and soil and terrain index.

Generic table for climate and soil and terrain are produced with land characteristics described in *FAO framework (1976)* and *Sys et al. (1991)*, are presented in Table 3.2 and Table 3.3.

*Table 3.2 – Climate characteristics*

| | S1 | S2 | S3 | N |
|---|---|---|---|---|
| | 95 | 75 | 50 | 32,5 |
| ***Rainfall*** | | | | |
| *Annual precipitation* | - | - | - | - |
| *length of dry season/months* | - | - | - | - |
| ***Temperature*** | | | | |
| *Mean maximum temperature* | - | - | - | - |
| *Mean annual temperature* | - | - | - | - |
| *Mean minimum temperature* | - | - | - | - |
| ***Radiation*** | | | | |
| *Fraction of sunshine hours* | - | - | - | - |

*Source: Adapted from* FAO framework (1976) *and* Sys et al. (1991)

Within the climate characteristics, Table 3.2, there are six characteristics that should be considered for land evaluation, such as annual precipitation, length of dry season/months, mean max/min/annual temperature and fraction of sunshine hours.

*Table 3.3 - Soil and terrain characteristics*

| | S1 | S2 | S3 | N |
|---|---|---|---|---|
| | 95 | 75 | 50 | 32.5 |
| **Topography** | | | | |
| *Slope gradient %* | - | - | - | - |
| **Wetness** | | | | |
| *Drainage class*[a] | - | - | - | - |
| **Physical Soil Characteristics** | | | | |
| *Gravel content (volume %)* | - | - | - | - |
| *$CaCO_3$ (%)* | - | - | - | - |
| *Gypsum (%)* | - | - | - | - |
| *Texture class*[b] | - | - | - | - |
| **Chemical Soil Characteristics** | | | | |
| *CEC (cmol/kg clay)* | - | - | - | - |
| *Base saturation (%)* | - | - | - | - |
| *TEB (cmol/kg soil)* | - | - | - | - |
| *Organic carbon (%)* | - | - | - | - |
| *pH* | - | - | - | - |
| **Degree of salinity-alkalinity** | | | | |
| *ECe /$dsm^{-1}$* | - | - | - | - |
| *ESP (%)*[c] | - | - | - | - |
| [a] Drainage classes: E-excessively drained, S-somewhat drained, W-well drained, M-moderately drained, I-Imperfectly drained, P-poorly drained, V-very poorly drained | | | | |
| [b] Texture classes: 1-clay (heavy), 2-silty clay, 3-clay, 4-silty clay loam, 5-clay loam, 6-silt, 7-silt loam, 8-sandy clay, 9-loam, 10-sandy clay loam, 11-sandy loam, 12-loamy sand, 13 sand | | | | |

*Source:* Sys et al.*, 1991.*

Regarding soil and terrain characteristics, Table 3.3, it is considered the topography, wetness, physical and chemical soil characteristics, as well as the degree of salinity-alkalinity.

Although parametric approach is being used, the data from literature on crop requirement might be only available for limitation approach. In that case, the requirements meant for limitation approach will be adapted to the parametric approach. Therefore, the Table 3.4 presented below, is being used to rate the land characteristics if the available data is based on limitation approach rather than parametric approach.

*Table 3.4 – Adaption from limitation to parametric approach*

| Suitability classes | Intensity of limitation | Rating | Land classes | Rating |
|---|---|---|---|---|
| S1 | No | 100-95 | S1 | 95 |
| S1 | Slight | 95-85 | S2 | 75 |
| S2 | Moderate | 85-60 | S3 | 50 |
| S3 | Severe | 60-40 | N | 32.5 |
| N | Very severe | 40-25 | - | - |

*Source: Adapted from* Sys et al., 1991

The first, second and third column shows the suitability classes and the associated intensity of limitation and rating described by Sys et al. (1991). The fourth and fifth column shows slightly modified land classes and the associated rating used in this study. This has been done to make the model more structured and simple in order to rate different crops for the area under study. Land class S1 is rated 95 with the assumption that the possibility for land characteristics of the area to be 100% suitable is small. If a crop requirement table only shows the classification or rating for the characteristics that have an impact on the yield of the crop, only those characteristics are rated.

In order to ease calculation and further integration on the overall proposed SDSS system, an excel model of the biophysical land suitability is created to rate the soil and terrain and climate characteristics for any crop, section 5.2. The biophysical land characteristics of the desired study area are added to the model and the requirements of each crop can be added and matched, in order to estimate the yield of the crops and recipes. The formulas, based on the methodology described in this study, are applied to make the model functional for suitability evaluation of any crop for the study area and to estimate its yield.

#### 3.1.2.1 Land evaluation per recipe

A recipe consist of more than one crop, therefore the suitability of the study area should be evaluated per crop. In a mixed-culture plantation one crop can have an impact on the yield of other crops, although we assume that there is no interaction between the crops within a recipe, as it is beyond the scope.

In the present study, the yield per hectare is calculated by multiplying the crop mass for its density per hectare, equation 6:

$$\text{Yield (t/ha)} = \text{crop mass (t/unit)} \times \text{cropping density (unit/ha)} \ (6)$$

In order to estimate the performance of a recipe per hectare, the yield of each crop within a recipe should be converted into a unit that can be combined, so a monetary unit is the chosen one, $ per hectare. This can be done by multiplying the yield of each crop by its price, equation 7:

$$\text{Monetary Yield(\$/ha)} = \mathrm{Y}_m = \text{Yield(t/ha)} \times \text{Price(\$/t)} \ (7)$$

Subsequently the recipe monetary yield, can be estimated by summing the yield of all crops within a recipe:

$$\text{Recipe Yield (\$/ha)} = \mathrm{Y}_{m,1} + \mathrm{Y}_{m,2} + (\dots) + \mathrm{Y}_{m,c} (8)$$

Where, *c* is the number of crops in the recipe.

### 3.1.2.2 Suitability maps

For spatial planning, localization of the different yields is needed, therefore suitability maps are created. Having the yields values and its location, it is possible to create suitability maps of the yield per crop and also aggregate this yields on a suitability map of the recipe (with the different crops), presented in Figure 3.7.

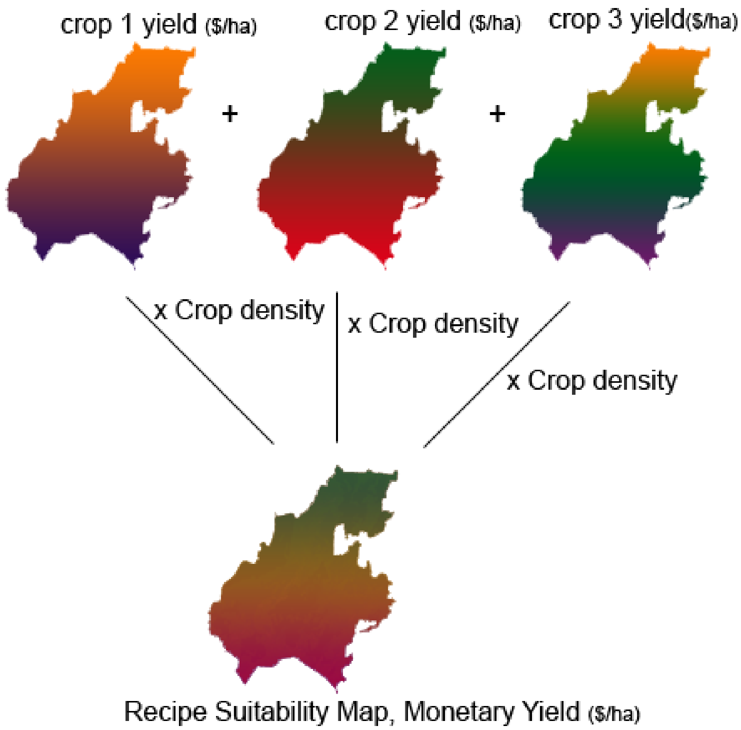



*Figure 3.7- Recipe Suitability Map methodology*

In Figure 3.7, a suitability map of the revenue per hectare ($/ha) is initially created per crop separately. A density will be applied to each crop to determine its area proportion in the recipe. Each crop map with its density proportion is then combined (intersected) together, creating a suitability map with the suitable locations for the desired recipe and its aggregated revenue per hectare.

## 3.2 Sustainability Performance Indicators

The system is intended as an easy tool to use and understand, allowing an explorative analysis on the potential performance of the system. Therefore instead of complex indices or a multi-criteria analysis, simpler indices were chosen to provide transparency and clear information. Based on the list of potential indicators that might be used in agroforestry assessment, Table 2.2, the sustainability indicators can be divided in economic, environmental and social assessment. To assess the overall sustainability performance, there indicators chosen in the different categories were:

**Economic Performance**

- Net Present Value (NPV);
- Internal Rate of Return (IRR) ;
- Annual Equivalent Value (AEV) ;
- Return on investment (ROI).

**Environment Performance**

- Carbon Storage Potential;
- Diversity of biodiversity.

**Social Performance**

- Number of jobs;
- Return on Labor.

The indicators selected are in line with one of the millennium development goals, mainly those which intends to ensure environmental sustainability (environmental indicators) and eradicate extreme poverty (creation of employment through number of jobs).

### 3.2.1 Economic Performance

Economic performance is one of the most important factors in investors decision, analyzing the overall model, Figure 3.2, there are several economic parameters, to assess such as costs and revenues, based on the investment needed.

The total costs ($T_{costs}$) related to the recipes implementation include different categories of expenses: field operation and input costs, commodities costs (commercialization and storage) and transportations costs. Thus, the specific yearly costs per hectare for a certain recipe are calculated as:

$$T_{costs} = FO_{costs} + I_{costs} + C_{costs} + T_{costs} \text{ (\$/ha)} \quad (9)$$

Where,

$FO_{costs}$ - field operation costs ($/ha);
$I_{costs}$ – input costs ($/ha);
$C_{costs}$ – commodities costs ($/ha);
$T_{costs}$ - transportations costs ($/ha);

Transportation costs are calculated on a combination of geographic data of the roads, ports and markets, simulating the price depending on the distance to transport the commodities via advanced network analysis (analyzed section 5.1.1). Accordingly to its distance, from source to market, fuel price can be taken into account, simulating its cost.

The total revenues represent the sum of the cash inflow of the entire project, such as cash inflow from commodities, land clearance, as well as carbon emission permits. Thus, the specific yearly revenues per hectare for a certain recipe are calculated as:

$$T_{revenues} = C_{revenues} + Lc_{revenues} + CS_{revenues} \text{ (\$/ha)} \quad (10)$$

$C_{revenues}$ – commodities revenues (\$/ha);
$Lc_{revenues}$ – land clearance revenues (\$/ha);
$CS_{revenues}$ - carbon sequestration revenues (\$/ha).

Both total cost and total revenues are calculated per year, as management decisions are made yearly in the specific case study.

#### 3.2.1.1 Capital assets

For each recipe there is a different materials needed, as well as its quantity of usage, that has to be combined for the total calculation of the material needed on the project. Therefore, the capital assets investment needed in the project, is algebraically represented as:

$$\sum_{i=1}^{n}\sum_{j=1}^{l}\left\lceil\frac{max\ c_{j,i}}{k_{j,i}} \times p_j\right\rceil \text{ (\$/ha)} \quad (11)$$

Where, $c_j$ is the usage quantity of the capital asset j;

$k_j$ is the usage capacity of the capital asset j;

$p_j$ is the price of the capital asset j;

$l$ is the number of different capital assets used on the recipe;

$n$ is the number of selected recipes on the project.

To individually assess the need of conversion plants or storage buildings on the project, a similar approach can be done:

$$\textbf{Nr. ethanol conversion plants needed} = \left\lceil\frac{\max e_i}{k}\right\rceil \quad (12)$$

Where $e_i$ is the ethanol produced per recipe i;

$k$ is the conversion capacity of the ethanol conversion plant;

$n$ is the number of selected recipes on the project.

### 3.2.1.2 Economic Performance Indicators

The economic performance, based on Godsey (2008) and other literature review recommendations for economic budgeting for agroforestry practices, is assessed by the Net Present Value (NPV), Internal Rate of Return (IRR), Annual Equivalent Value (AEV) and Return on Investment (ROI), calculated based on the investment, total costs and revenues, explained in the previous section. Those are essential economic key factors for investors' decision. Specification of the investment needed for the project is also considered, being determined by the required number of units and costs of machinery, tools, buildings and conversion plants units (e.g. sawmill).

*Net Present Value*

The Net Present Value, assesses the long-term benefits of different recipes and therefore different land use practices (different recipes implementation), we calculate the NPV per hectare using the following equation:

$$\mathrm{NPV} = \sum_{\mathrm{t}=0}^{N} \frac{(B_t - C_t)}{(1+\mathrm{i})^{\mathrm{t}}} \quad (\$/\mathrm{ha}) \ (13)$$

Where, NPV is the net present value cumulated to year n;

i = discount rate, or the opportunity cost of investing (%);

NPV = Net Present Value of recipe per hectare ($/ha);

$B_t$ – Benefits/ Cash Inflow per year t ($/y);

$C_t$- Costs per year t ($/y), being $C_0$the initial investments;

t = annuity period (y);

*N* = lifetime of the project t (y).

The value of carbon sequestration from the agroforestry project (see Section 3.2.2) is integrated in the NPV as an additional benefit.

The discount rate, is mutual to the different indicators selected, and will be will be possible to be changed by the user, through a slider, for the desired scenario of simulation. The annuity time period to be assumed is 20 years, which is in line with the usual timeframe for an agroforestry project. When comparing investments, the one with the highest NPV, assuming the same discount rate, is considered the most desirable on the economic perspective.

*IRR*

Another economic indicator is the internal rate of return (IRR) that represents the rate at which the net present value (NPV) of a project's cashflow, measured over the project's life, equals zero. Therefore it uses the same equation as net present value, but instead of solving for the NPV, an arbitrary NPV of $0 is assumed:

$$\mathrm{IRR} = \sum_{\mathrm{t}=1}^{N} \frac{(B_t - C_t)}{(1+\mathrm{i})^{\mathrm{t}}} = 0 \quad (\$/\mathrm{ha}) \ (14)$$

The discount rate becomes the unknown variable in the equation and represents the rate at which all discounted cashflow will equal zero. The final value of the equation is the rate at which future incomes will return the initial investment (Godsey, 2008).

*AEV*

The Annual Equivalent Value (AEV), calculates an annuity that would give the equivalent net present value at the same discount rate. NPV equation assumes that cashflow varies for each year of the project. On the contrary, the AEV equation assumes that the cashflow is the same each year and it can be represented as:

$$AEV = \frac{NPV}{\sum_{t=0}^{N} \frac{1}{(1+i)^t}} \quad (15)$$

*ROI*

ROI is the internal annual rate of return of an investment. It is the compound interest rate that equates the present value of future incomes with the present value of future costs.

$$\mathrm{ROI} = \frac{\mathrm{T_{revenues}} - \mathrm{T_{costs}}}{\mathrm{T_{costs}}} (\%) \quad (16)$$

### 3.2.2 Environmental Performance

The environmental performance is assessed by the amount of carbon sequestration potential ($CO_2$ tons) and biodiversity index, per recipe.

Agroforestry systems and reforestation has an important carbon storage potential in its multiple crop species, through their ability to sequester and store carbon over long periods.  It relies on the premise of the fundamental biological and ecological processes of photosynthesis, respiration, and decomposition. The perennial components of the trees and crops absorb carbon dioxide ($CO_2$) on the photosynthesis process, resulting in carbon stored in their biomass. When vegetation is decomposed, burned or through the process of respiration $CO_2$ release takes place. This is especially important because can contribute to climate change mitigation (Montagnini and Nair, 2004; Weidner and Fiege, 2011).

The indicator carbon sequestration potential, estimates how much tonnes of carbon each agroforestry recipe, potentially sequesters on the tree/crop lifetime:

$$\mathrm{CS_{recipe}} = \sum_{j=1}^{t} n_{T_j} \times \mathrm{Sequestration}_{T_j} (CO_2 \text{ tonnes}) \quad (17)$$

Where, $n_{T_j}$ - number of trees of a specific tree species in the recipe;

$T_j$- specific tree species;

$\mathrm{Sequestration}_{T_j}$ – $CO_2$ stored of a specific tree species on its lifetime (t) (CO2e tonnes);

t – number of different tree species of the recipe;

Afforestation and reforestation are included in trading schemes for carbon sequestration offsets, and therefore through credits generates revenue (eq. 3) (Saundry, 2009).

$$\mathrm{CS_{revenues}} = \sum_{\mathrm{i=1}}^{\mathrm{x}} \mathrm{CS_{recipe}} \times \mathrm{Ccredits_{price}} \text{ (\$) (18)}$$

Where, $\mathrm{Ccredits_{price}}$- $CO_2$ emission permits market prices;

x – number of recipes on the agroforestry project;

Regarding the biodiversity indicator, many authors have tried to develop biodiversity indexes, but the amount of data necessary and uncertainty is still high. Kosonen et al. (1997), developed biodiversity indices for the different vegetation covers, in a case study in South Kalimantan, on the basis of the method of Kangas and Kuusipalo (1993). The indices developed are based in the richness of bird and tree species. Birds reflects the diversity of insects and plant life, as birds are specialized feeders and nesters. Tree species richness describes the habitat diversity well enough in this case (Kosonen et al., 1997). Due to this uncertainty and lack of local data, an economic value for biodiversity won't be calculated and the biodiversity index indicator will be based on the diversity of tree/crop species.

$$\mathrm{Diversity} = \sum_{\mathrm{j=1}}^{\mathrm{t}} \mathrm{T_j} \text{ (19)}$$

Where, $T_j$- specific tree/crop species;

t – number of different tree/crop species of the recipe;

If future projects demand, it is possible to enhance this indicator or change with field data on species sightings, depending on the future need for this evaluation framework.

### 3.2.3 Social Performance

The social performance is assessed by the number of jobs created, as well as return on labor. These indicators are in line with the millennium development goals, such as the one eradicate extreme poverty, whereas the jobs provide an income which might lower the poverty in the area.

As each field operation has its own hours of work, as well as its own expertise, is it possible to calculate the work days per recipe and year and the type of expertise needed:

$$\text{Work days per recipe} = \sum_{j=1}^{x} \frac{\mathrm{n_{O_j}} \times \mathrm{h_{O_j}}}{h} \ (days/ha) \ (20)$$

Where, $\mathrm{n_{O_j}}$ - number of times a specific field operation is executed per year;

$\mathrm{h_{O_j}}$ - number of hours needed of a specific field operation;

$h$ - number of hours of work per day;

x – number of different field operations;

Therefore, aggregating the work days per recipe, we obtain the:

$$\text{Work days of the project } = \sum_{i=1}^{x} \text{Work days per recipe } (days/ha) \ (21)$$

x – number of recipes on the agroforestry project;

Considering the work days in a year and the work days needed, per recipe, a rough approach of the jobs created is calculated:

$$\text{Number of jobs} = \frac{\text{Work days needed per recipe}}{\text{Work days on a year}} \ (22)$$

By the same methodology, it is possible to calculate the works days and number of jobs per expertise type.

**Return on labor**

Return on labor is the average discounted financial benefit per unit of labor put into a project. The labor input, as well as costs and benefits vary per year. Therefore, return on labor, is merely an “economic construction” and allows comparison between different agroforestry systems or projects and is not a real wage obtained from each day of work. It is calculated by the follow equation:

$$\mathrm{RL} = \frac{\sum_{\mathrm{t}=0}^{N} \frac{(B_t - C_t)}{(1+\mathrm{i})^{\mathrm{t}}}}{\sum_{\mathrm{t}=1}^{N} \frac{L_{input}}{(1+\mathrm{i})^{\mathrm{t}}}} \ (\$/\mathrm{h}) \ (23)$$

(Wicke et al., 2011)

where, RL – return on labor ($/h)

i – Discount rate, or the opportunity cost of investing (%)

$B_t$ – Benefits/ Cash Inflow in year t (€/ha)

$C_t$– Costs in year t ($/h)

t – annuity period (years)

*N* – lifetime of the project (years)

$L_{input}$ – labor input in year i (h/ ha)

## 3.3 Model Structure

Regarding the model structure, the Microsoft Excel™ was chosen as implementation environment for a first prototype system, due to its flexibility to add and edit different parameters or values, integrating all the system parameters in different spreadsheets. Each parameter has a sheet, in order to ease comprehension and changes for the final user. A dashboard was created to gather the essential controls for the end-user where different parameter values can be simulated.

Reforestation and agroforestry investments can be complex due to the uncertain future conditions. Therefore investors are often skeptical about investing on agroforestry projects. To address this problem an interactive tool with a sensitivity analysis was built so that different parameters could be simulated. For example, price fluctuations can be analyzed and simulated in order to evaluate its impact.

The simulation of different parameters through interactive sliders can be instantly visualized spatially in an interactive 2D geographic visualization interface, with a 3D visualization option. In this interface, combining geographic location (latitude, longitude) and outcomes data, the user can navigate on the map, helping the comprehension of the different locations benefits.

This way it is possible to simulate spatial and non-spatial variations in a framework that can help better informed decisions, while exploring different possible scenarios. Besides that, this implementation provides an easy and flexible environment to become aware of the sensitivity to different parameters, allowing a combination of different alternatives and scenarios that wouldn't be possible in a hard copy consulting report.

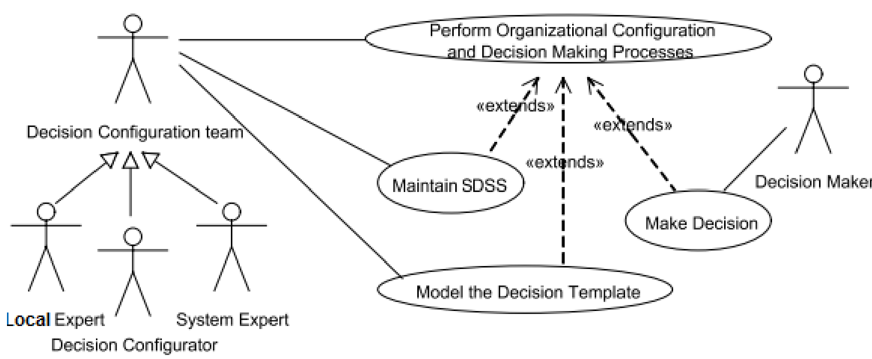



*Figure 3.8 - General use case of the SDSS system. Adapted from Nurminen et al. (2008)*

A spatial decision support system is comprised by the decision configuration team and the decision maker, which have to work together for better decision making, see Figure 3.8 (Nurminen et al., 2008).

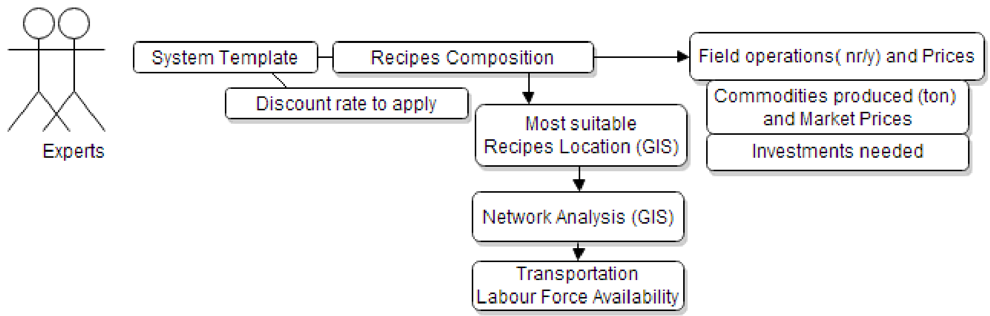



*Figure 3.9 – Experts use case*

The experts, Figure 3.9, are characterized by the GIS technicians, system configurator and local expert(s). A GIS technician is responsible for the GIS data preparation, such as the combination of different parameters layers to determine the biophysical suitability of the recipe and its most suitable location, based on local expert knowledge.

Local experts are responsible to provide the recipes composition and its biophysical and operation needs, such as the number and price of the field operations necessary, the commodities produced and the labor force available in the area.

The potential final users for the presented system are top managers and investors. Although, the administrative level and stakeholders will be supported by the SDSS in indirect way, they might not be working with the system, but their consensus could change the output of the DSS and moreover on how transparent and understandable these outputs are.

Therefore based on UX rules and literature review, a use case of the model and mockups of a possible software user interface, as well as system recommendations, were made and presented in the results, section 5.2.

### 3.3.1 Optimization Methodology

In order to associate automatically the most suitable areas (location) for the desired goals based on the system indicators (e.g. higher NPV), an optimization algorithm was developed. The optimization algorithm, works as a maximization, identifying the maximum value of the desired parameter, as well as the recipe that provides it.

For each grid cell *x, y* there is a set of NPV function that contains the NPV of each recipe, S such as:

$$S_{x,y} = \{NPV\ (i)_{\ x,y}, \dots\ , NPV\ (n)_{\ x,y}\}$$

Where, n is the number of considered recipes.

This set of NPV function, will be composed by the recipes chose by the user for the calculation. NPV in each grid cell is to be maximized, therefore for each grid cell *x,y*, α is determined such as the maximum element of the set $S_{x,y}$ algebraically represented as:

$$\alpha = \max_{i \in S}[NPV\ (i)_{\ x,y}]$$

It is then identified the recipe to be chosen in each grid cell *x,y* by determining β as the argument associated with the maximum value:

$$\beta = arg\ \alpha = arg \max_{i \in S}[NPV\ (i)_{\ x,y}]$$

$\alpha$ provides the maximum value of the NPV of every x,y spatial location on the selected area, β gives the recipe where the maximum value is. Therefore, by the same approach, the selection of the most suitable areas for different indicators, such as carbon sequestration or number of jobs, can be done.

## 3.4 Model Implementation

The model implementation was designed based on literature review and the model structure methodology. Therefore a system use case was made, Figure 3.10, explaining the overall mechanism of the system.

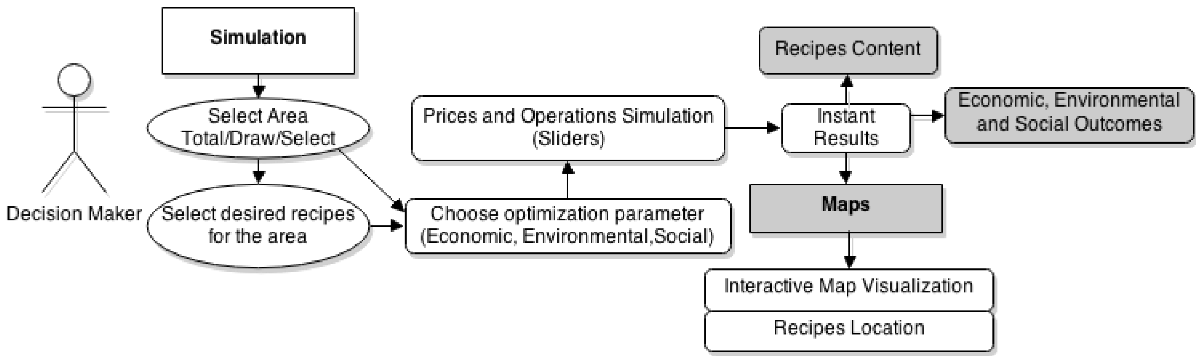



*Figure 3.10 - System use case (decision maker approach)*

The decision maker, intended as the final user of the system, uses the interface where he can chose the area to assess, as well as the recipes to apply. Additionally an optimization parameter can be selected for the calculation of the best location and recipe for that parameter maximization. A simulation of the field operations and commodities prices is possible through interactive sliders. The system aims to be programmed in a way that the selection of those parameters (area and recipes) will instantly produce results of the simulations, whether the user change a price of a commodities or choose a different recipe to be applied on that area. In Figure 3.11, the main menu mockup is presented, where the user has the option to choose simulation of the project or maps, presenting the different characteristics of the area on an interactive map.

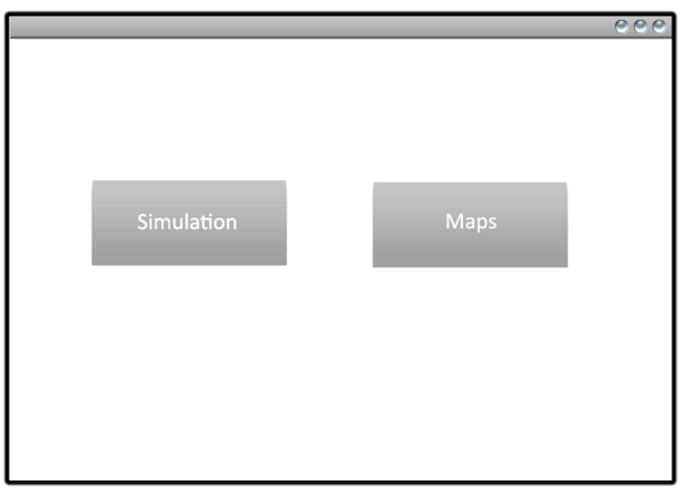



*Figure 3.11- System mockup of the main menu*

Regarding the selection of the area, (Figure 3.12) the user can select the areas in different ways: a) the whole study area, b) to draw the desired area or c) to select the area based on homogenous polygons (same biophysical characteristics, such as soil and slope).

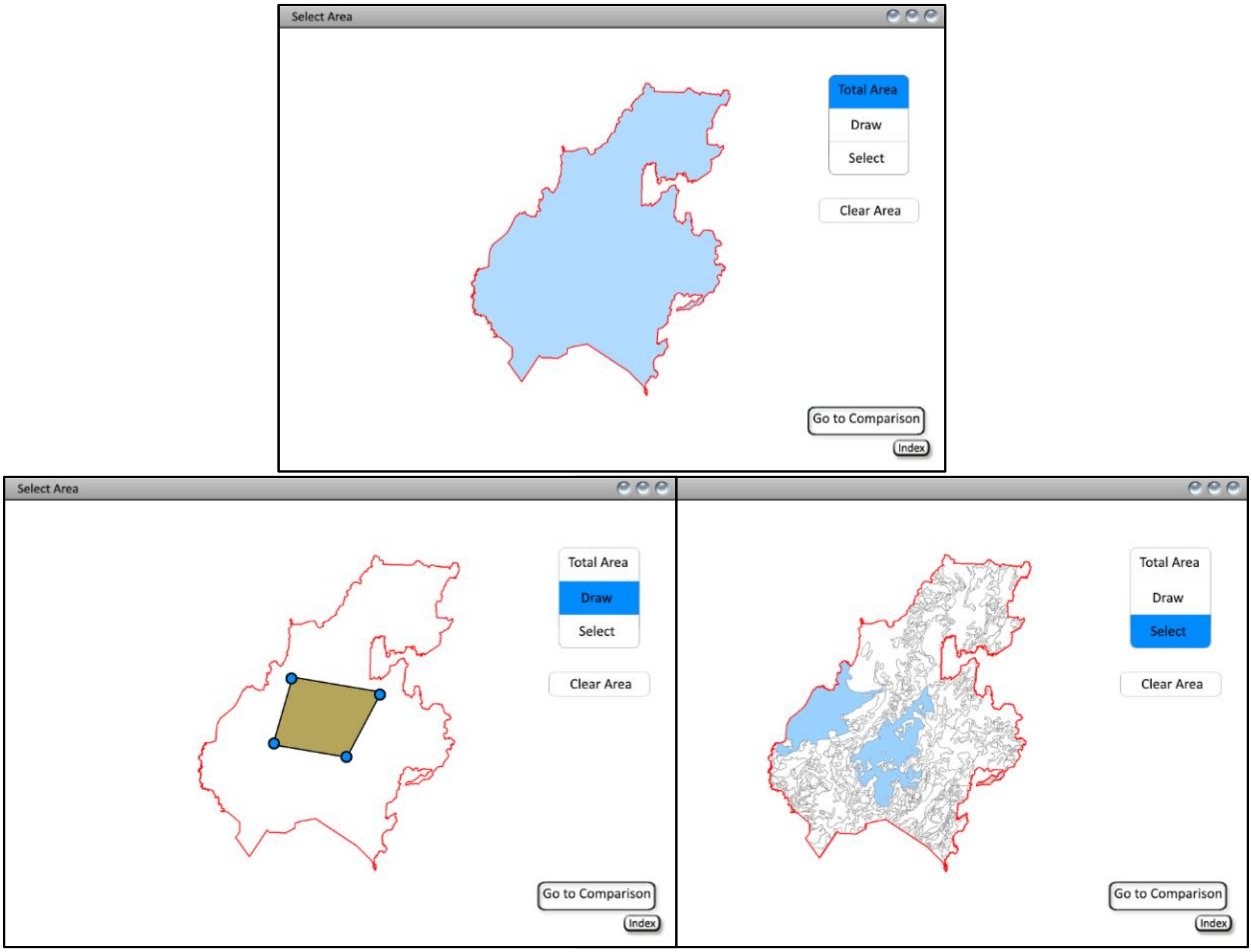



*Figure 3.12- System mockup of the area selection menu*

Once the area is selected, the user can simulate different recipes and choose its optimization goal (economic, environmental or social), as well as simulate different parameters values through interactive sliders, Figure 3.13.

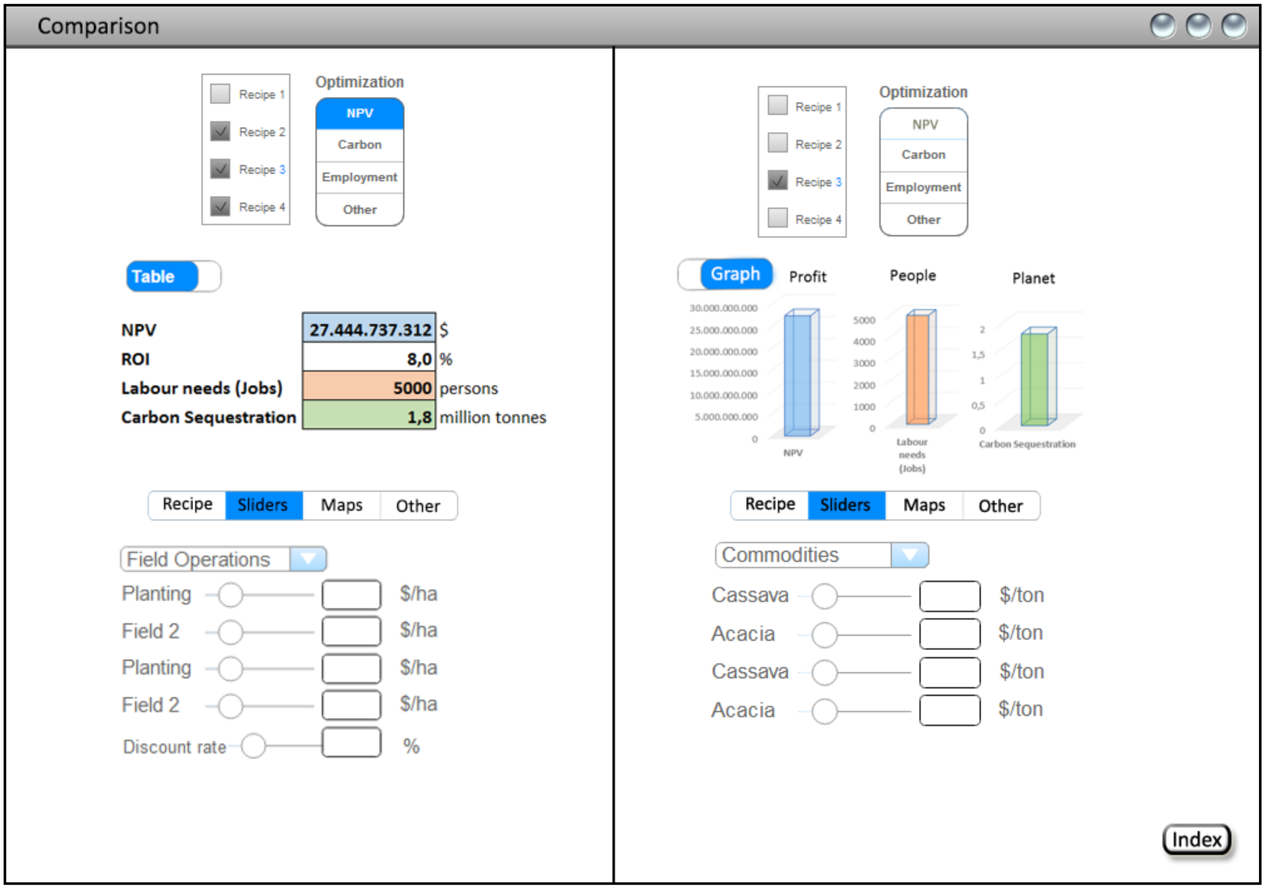



*Figure 3.13 - System mockup of the comparison menu.*

The user can choose the recipes and an optimization parameter or just the optimization parameter and the system will find the most suitable recipes combination for this selection. If the user chooses the recipes on its own, the optimization parameter has to be selected in order to combine the best recipes for the chosen parameter, otherwise the system can't calculate. I.e., if the user choose 3 recipes to be simulated and NPV as optimization parameter, the system will give the most profitable (higher NPV) recipe for each unit of area selected. Different units of area have different suitability, therefore different recipes might be applied.

With the area, recipes and optimization selected, it is possible to analyze the results of the simulation, such as the indicators outcomes (economic, environmental and social), the recipes content and its location on the chosen area. Additionally, a sensitivity analysis tool to simulate different operations prices (e.g. field operations, commodities) through interactive sliders is also available.

Thus, the user can see have instants results of the recipes content, location on the maps and the economic, environmental and social outcomes. The interface is made in a way that the user can compare side by side different combinations, without leaving the same interface menu, easing the decision process.

The configurator or "admin", intended as the system expert, has exclusive access to where GIS data and information of the all the parameters of the system can be changed. Admin use case presented in Figure 3.14.

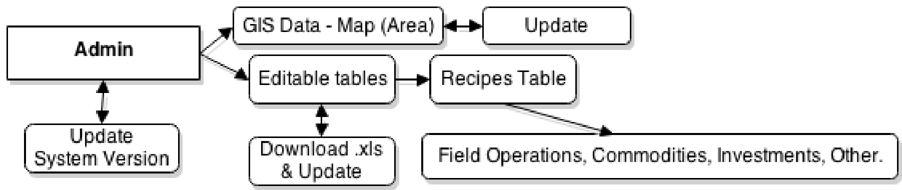



*Figure 3.14 - System use case (Admin approach)*

The Figure 3.15, shows the admin menu, which will be hidden for the final user.

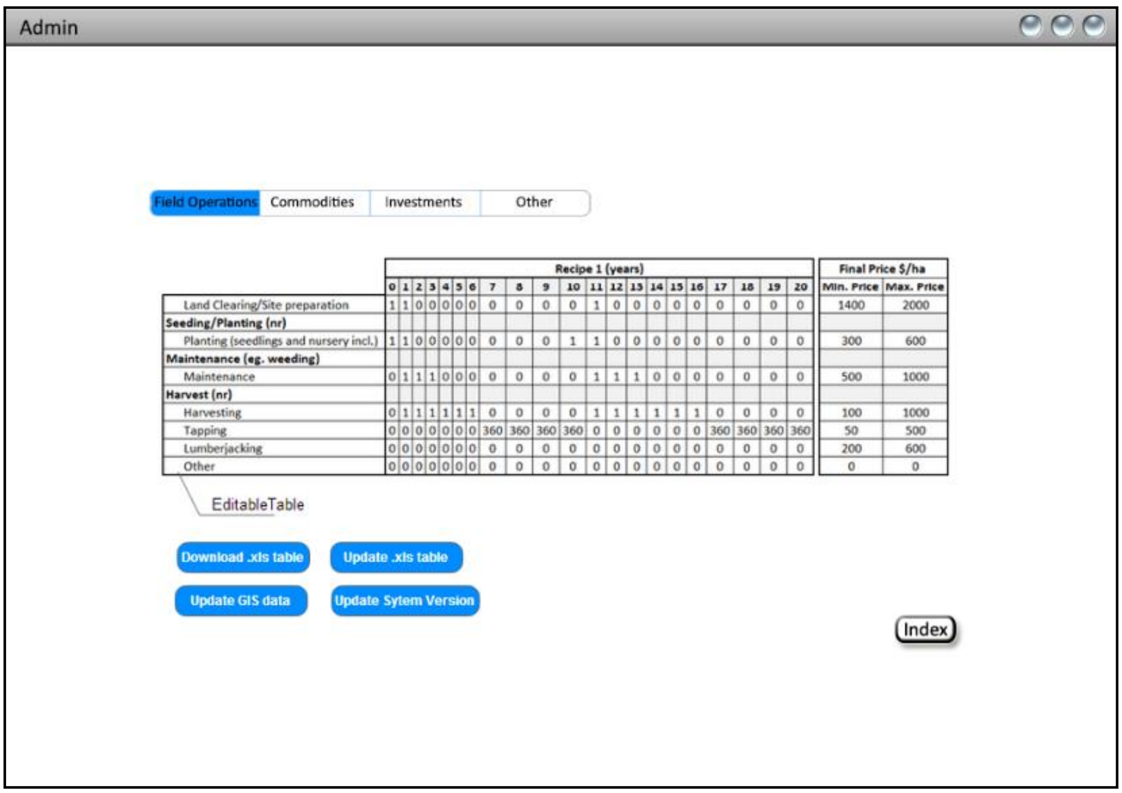



*Figure 3.15- System mockup of the admin menu*

The information of the recipes, such as field operations, commodities and investments are implemented in a excel file, which can be easily downloaded and uploaded through a template. The system version can also be updated, to fix bugs or ease technical problems.

The mockups for an implementation in a stand-alone application previous presented in Figure 3.11 to Figure 3.15, were made based on modelling framework, literature review and especially on the use case of the system explained above.

# 4 Case Study Area

Indonesia has the third largest area of tropical forest in the world, 68% of its landmass, storing valuable biodiversity is contained in those forests. Wood manufacturing paper and printing industry is also an economically significant sector, 3-4 % of the country GDP (Leitmann et al., 2009). According to 1998 data, almost 24% of 69.4 million hectares under logging concessions were degraded (Kartodihardjo and Supriono, 2000).

The study area is located in East Kalimantan, Indonesia, Figure 4.1, where a local company manages a forest concession of around 200 thousand hectares. According to Padoch and Peluso (1996), Kalimantan Island has the biggest estimated standing stock of important timber among the five largest islands in Indonesia. The concession aims to implement a sustainable forestry management strategy, profitable but also fostering development in local communities and promoting the conservation of the surrounding environment. This way, economic, human development and environmental goals can be jointly pursued. Biophysical characteristics of study area are analyzed in the case study results, section 5.1.

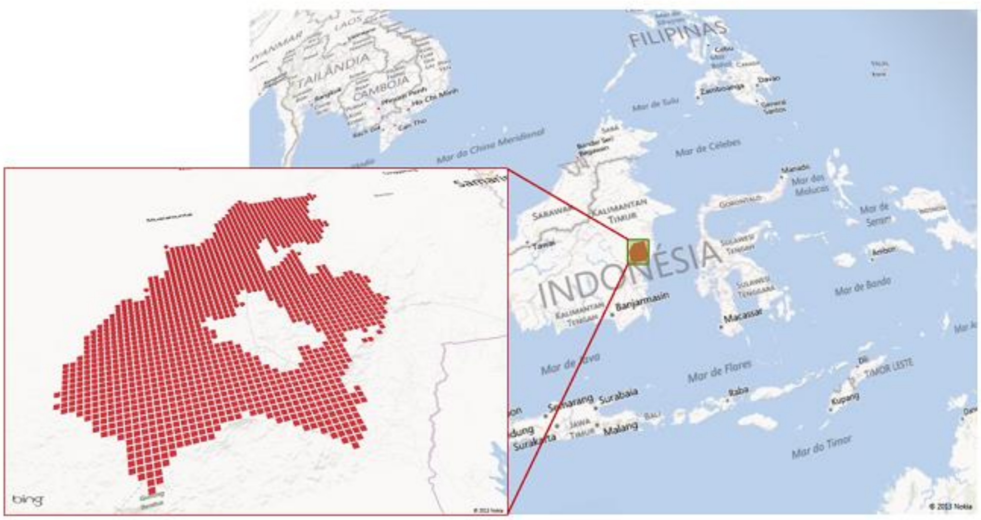



*Figure 4.1 - Location and area of the field project - East Kalimantan, Indonesia.*
*Source: Adapted from BingMaps®.*

Sustainable use of the forest relies upon a multi-cropping reforestation scheme, in which different trees species and crops benefit together from mutual synergies, being therefore more efficient than monoculture schemes for environmental goals (Gamfeldt et al., 2013). Species vary in their nutrients, sunlight and soil moisture requirements to establish and grow successfully (Stringer, 2001). Integrating many different species in one unit of land with different spacing, with optimal sunlight utilization through a succession of species will also reduce losses of nutrients. It relies on an integration of growing cycles with different lengths in one total longer rotation of the system. The total success of an ecosystem depends on how the complex processes are adapted to local conditions, and the evaluation of the recipes by a local expert. Everything depends upon competition driven utilization of light and nutrients, as well as strategies in the process of succession during development of a locally stable ecosystem. Matching site-species is a necessity to promote growth and maintain long-term sustainability (Chokkalingam et al., 2006). Additionally, planting of mixed tree species in different land categories, promotes biodiversity and carbon sequestration.

## 4.1 Recipe example

The crops considered for the recipe example are Cassava, Sugar Palm (*Arenga Pinnata)* and Banana. In order to assess the suitability of land per crop, requirement tables have to be produced and evaluated for each land utilization type.

The Ecocrop database of FAO provides basic environmental requirements for the crops, such as information on optimum and marginal conditions. However for a more accurate yield estimation, a requirement table with further characteristics and the suitability classes per characteristic should be used such as "Land Evaluation Part II: Crops requirement" (Sys et al.1993). The study area is assessed by the parametric approach for the production of three crops mentioned above.

In order to maximize the productivity, a recipe has specific timing and biophysical conditions. The following recipe is an example for a wet tropical climate condition on terrain with less than 30% slopes, well-drained soil, reasonable good access from roads, and with enough local labor and local needs for food and energy (Freitas et al., 2014).

- Start (Year 0): Land preparation, Planting, Fertilizing
    - Clearing planting spots, digging planting holes, mobilizing compost;
    - Transporting plants to field, planting trees (nitrogen fixer, woody crop and sugar palms) and cassava mixed;
- Year 1: Harvest and Maintenance, new Planting
    - Harvest of the cassava for food, animal feed and production of ethanol;
    - Maintenance of the planted trees;
    - Planting of banana in between the trees;
- Year 2: Harvest and Maintenance
    - Harvest of the bananas;
    - Maintenance of the trees;
- Year 3: Harvesting and Maintenance
    - Fuel wood from thinning;
    - Harvest of palm fibers;
    - Last maintenance of trees;
- Year 4-6: Harvest of palm fibers and Fuel Wood removal
    - Harvesting of palm fibers;

- Removal of the remaining fuel wood (year 6);
- Year 7-9: Start tapping of sugar palms
- Year 10: Harvesting of sugar palms
    - Last tapping of sugar palms;
    - Harvest of sugar palm fruits and sugar palm wood;
- Restarting the Recipe.

In the next subparagraph, the requirements of the three crops of the recipe example are discussed.

*Figure 4.2 - Recipe implementation example with different crops.*
*Courtesy of Willie Smits.*

### 4.1.1 Banana

The banana plant, often referred as a "tree", is a large herb, with succulent stem, which is a cylinder of leaf-petiole sheaths, reaching a height up to 7.5 m (Morton, 1987). The important factors for a banana tree that should be taken into account are the depth and drainage of soil because banana has a restricted root zone. The soil should be fertile with a depth of 0.5 - 1m and should contain sufficient amount of organic matter. The optimal pH range is between 6.5 and 7.5 and it requires warm and humid climate, however, it can also grow at sea level and up to an altitude of 1200metres. The plant can be cultivated in a temperature range of 10°C and 40°C, but the growth is slow at temperatures of 20°C or below and more than 35°C. Banana yields are higher for temperature above 24°C and requires around 1700 mm rainfall per year for its satisfactory growth. The best soil properties for Banana is a soil with 40% clay, 75% silt and/or 85% loam (UNIDO, 2008).

As an example of application for the case study, the requirements for banana were researched, although a methodology of its implementation and adaption to another crop is explained on section 3.1.2. Table 4.1 and Table 4.2 presents the suitability classes and its requirements for Banana from a case study on Thailand and Indonesia, respectively.

*Table 4.1 - Suitability Classes and Requirements for Banana, case study in Thailand*

| | Climate | | Slope (%) | Drainage | Soil characteristics | | | | | Saline (dS/m) Alkaline (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ann Rain (mm) | Mean T (º C) | | | Texture | Fertility | | | | |
| | | | | | | CEC | BS | pH H2O | OC | |
| S1 | >1500 | 18-22 | 0-2 | Mod-good | SiCL, CL, SiL, SC, L | 16-24 | 35->50 | 5.8-7.5 | >2.4 | 0-2<br>0-4 |
| S2 | 1250-1500 | 16-18 | 2-4 | Imperfect | SCL | <16 | 20-35 | 4.2-5.6<br>7.5-8 | 2.4-<br>1.5 | 2-4<br>4-8 |
| S3 | 1000-1250 | 14-16 | 4-6 | Poor | SL, LS | 16 (+) | <20 | 5.2-4.5<br>8.0-8.2 | 1.5-<br>0.8 | 4-6<br>8-12 |
| N | <1000 | <14 | >6 | Poor | fS, S, cS | - | - | | <0.8 | >6<br>>16 |
| S1=Suitable, S2=Moderately suitable, S3=Marginally suitable, N=Not suitable(N1=Not suitable (improvable), N2=Not suitable (permanent) | | | | | | | | | | |
| SiCL=Silt clay loam, CL= Clay loam, SiL=Silt loam, SC=Sandy clay, SL= Sandy loam, L=Loam, fS=Find Sand cS=Coarse sand, S=Sand | | | | | | | | | | |

*Source: (Kuneepong and Apauthaipong, 2010)*

*Table 4.2 - Suitability Classes and Requirements for Banana, case study in Indonesia*

| Land-use requirements/land characteristics | Land suitability class | | | |
|---|---|---|---|---|
| | S1 | S2 | S3 | N |
| Annual average temp | 20-23 | 23-30<br>18-20 | 30-40<br>15-18 | >40<br><15 |
| Water availability<br>Average annual rainfall (mm) | 1250-1750 | 1750-2000<br>1000-1250 | 2000-2500<br>750-1000 | >2500<br><750 |
| Drainage | good | Mod, poor | Poor, mod rapid | Very poor, rapid |
| Soil texture | Fine, slightly fine, medium | - | Slightly coarse | coarse |
| Soil depth | >100 | 75-100 | 50-75 | <50 |
| CEC-clay (cmol/kg) | >16 | <16 | | |
| Base saturation (%) | >35 | 20-35 | <20 | |
| pH H2O | 5.0-6.0 | 4.5-5.0 | <4.5 | |
| C-organic (%) | >1.2 | 0.8-1.2 | <0.8 | |
| Salinity (ds/m) | <4 | 4-6 | 6-8 | >8 |
| Alkalinity/ESP % | <15 | 15-20 | 20-25 | >25 |
| Slope (%) | <8 | 8-16 | 16-30 | >30 |
| Surface stoniness (%) | <5 | 5-15 | 15-40 | >40 |

*Source: (Ritung et al. 2007)*

Both Table 4.1 and Table 4.2 show four suitability classes (S1, S2, S3, N) for the same banana species, although as can be seen the criteria for temperature, rainfall and pH are not the same. The reason is that both studies used different sources for the crop requirement, we can conclude that expert knowledge is very important to aid the decision on the crop productivity. The selection of a different suitability class have a crucial impact on the yield estimations of the crop.

### 4.1.2 Arenga Pinnata

One of the species in the case study is the sugar palm (*Arenga pinnata*), Figure 4.3. Besides yielding sugar, this palm also provides a great number of other products and benefits to its users, such as bioethanol from the sugar palm juice, after fermentation and distillation (Smits et al., 1991). It has a positive contribution to small households (e.g. opportunities for additional sources of income, clean fuel for cooking, transport, electricity, etc.) and requires little maintenance (Mogea et al. 1991, van de Staaij et al. 2011). The bioethanol produced from the sugar palm can then be used to replace gasoline in motorcycles, small vehicles, small machines and generators, and can also be used as cooking fuel in special burners (Smits, 2010). A mixed production system can therefore provide food security, energy, regulate water, support biodiversity, sequester more carbon, as well as create jobs year-round, because each culture has its harvesting period.

*Figure 4.3 – Local extracting the sugar palm juice from Arenga pinnata, Indonesia.*

Sugar palm tree grows best in warm tropical climate where the rainfall is high and where the sunshine is abundant. The tree prefers fertile soils however, it grows on all types of soil from heavy clay to loamy sands. According to Ecocrop (2014), the minimum optimum temperature is around 22°C and the maximum optimum temperature is around 28°C.

### 4.1.3 Cassava

Cassava is considered a perennial woody shrub, which grows mainly tropical and subtropical areas. It requires warm humid climate, grows on all soil types, but grows best on light sandy loam or on loamy sands. It tolerates a wide range of pH (pH 4-8) and grows well on poor soils. The growth is optimal in areas with an altitude below 150m, the average temperature is 25-27°C. It is also suitable on poor soils and produces best when the rainfall is below 500mm or as high as 5000mm (USDA, 2003).

*Figure 4.4 - Cassava Plantation, 70days, Kalimantan.*
*Courtesy of Willie Smits.*

# 5 Results

In this section, the results are presented, divided in case study results, section 5.1, biophysical module, section 5.2 and system application, section 5.3. Due to data confidentiality of the Indonesian company and lack of data in some modelling factors, the proposed methodology has been implemented on adjusted data sets. These data sets were created so as to be as close as possible to real conditions in the study area.

## 5.1 Case study results

The case study analyses are presented in this section. The biophysical characteristics were analyzed, such as the soil, terrain and climate. Besides that a network analysis of the labor needs and transportation to the nearest port is also presented, section 5.1.2.

### 5.1.1 Soil, Terrain and Climate

The soil characteristics of the study area were extracted from the *Harmonized World Soil Database* (HWSD). The database contains a list of Soil Typological Units (STU), which characterize different soil types. The STUs are described by characteristics specifying the soils nature and properties, such as soil texture, moisture regime and gravel content. The STUs are grouped into Soil Mapping Units (SMU) to form soil associations, whereas a SMU can have up to nine sub-soil units (FAO et al., 2012). The study area has four SMUs: 3749, 4446, 4459 and 4563, see Figure 5.1.

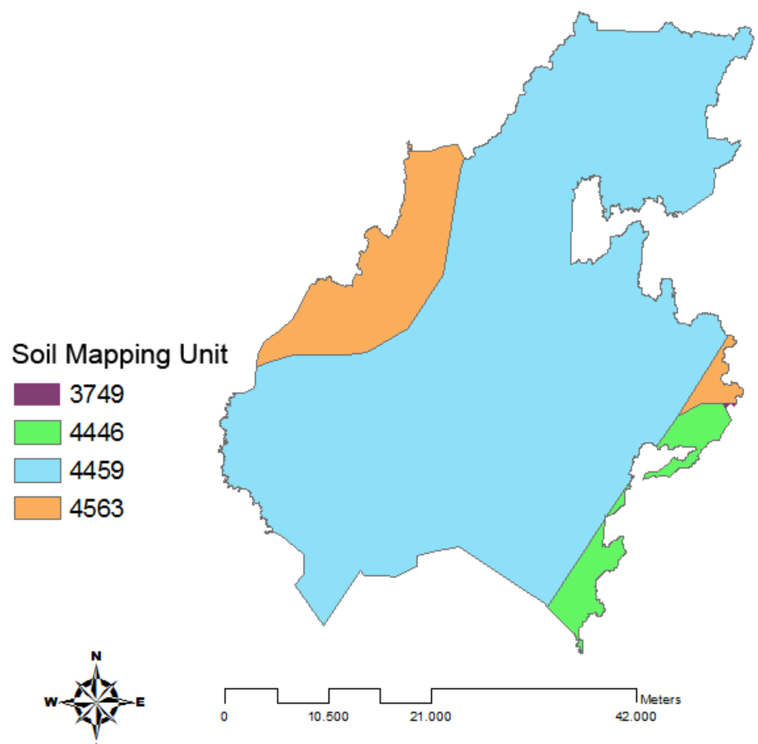



*Figure 5.1 - Soil map of the study area.*
*Source: Adapted from data in FAO et al., 2012.*

The study area mainly consists of SMU 4459 and SMU 4563 has the second largest area followed by SMU 4446. Compared to other SMUs, the area of SMU 3749 is very small and would not make a significant difference if it is not taken it into account in the overall land evaluation. Therefore, it is assumed that the study area has only three soil mapping units. The soil characteristics of each soil mapping unit are depicted below in Table 5.1 to Table 5.3.

*Table 5.1 -Topsoil characteristics of Soil Mapping Unit 4446*

| Dominant Soil Group | **AC - Acrisols** | | | |
|---|---|---|---|---|
| Sequence | 1 | 2 | 3 | 4 |
| Share in Soil Mapping Unit (%) | 40 | 40 | 10 | 10 |
| Drainage class (0-0.5% slope) | Moderately Well | Moderately Well | Poor | Well |
| Gravel Content (%) | 23 | 13 | 4 | 2 |
| Calcium Carbonate (% weight) | 0 | 0 | 0 | 0 |
| Gypsum (% weight) | 0 | 0 | 0 | 0 |
| USDA Texture Classification | sandy clay loam | clay (light) | loam | sandy loam |
| CEC (clay) (cmol/kg) | 14 | 11 | 24 | 9 |
| Base Saturation (%) | 49 | 29 | 36 | 29 |
| TEB (cmol/kg) | 2.7 | 3.7 | 2.9 | 0.9 |
| Organic Carbon (% weight) | 0.98 | 1.23 | 1.1 | 0.7 |
| pH (H2O) | 5.1 | 4.9 | 5 | 4.8 |
| Sodicity (ESP) (%) | 2 | 1 | 2 | 3 |
| Salinity (ECe) (dS/m) | 0.1 | 0.1 | 0.1 | 0.1 |

*Source: FAO et al., 2012.*

The dominant soil of the SMU 4446 is Acrisols and that it has 4 sub-soil units. The organic carbon ranges from 0.7 to 1.23, the soil is poorly to well drained and is moderately acidic.

*Table 5.2 - Topsoil characteristics of Soil Mapping Unit 4459*

| Dominant Soil Group | **AC - Acrisols** | | | |
|---|---|---|---|---|
| Sequence | 1 | 2 | 3 | 4 |
| Share in Soil Mapping Unit (%) | 30 | 30 | 30 | 10 |
| Drainage class (0-0.5% slope) | Imperfectly | Imperfectly | Imperfectly | Moderately Well |
| Gravel Content (%) | 5 | 8 | 26 | 11 |
| Calcium Carbonate (% weight) | 0 | 0 | 3.9 | 0 |
| Gypsum (% weight) | 0 | 0 | 0 | 0 |
| USDA Texture Classification | loam | clay (light) | loam | loam |
| CEC (clay) (cmol/kg) | 19 | 10 | 42 | 20 |
| Base Saturation (%) | 27 | 35 | 100 | 51 |
| TEB (cmol/kg) | 2.5 | 4.7 | 15.6 | 3.1 |
| Organic Carbon (% weight) | 1.73 | 2.73 | 1.4 | 0.99 |
| pH (H2O) | 5 | 4.9 | 7.6 | 4.9 |
| Sodicity (ESP) (%) | 1 | 1 | 4 | 1 |
| Salinity (ECe) (dS/m) | 0.1 | 0.1 | 0.1 | 0.1 |

*Source: FAO et al., 2012*

The dominant soil group of SMU 4459 is also Acrisols, around 90% of the soil is imperfectly drained and 10% is moderately well drained. Around 70% of the soil texture is classified as loam and is also moderately acidic.

*Table 5.3 - Topsoil characteristics of Soil Mapping Unit 4563*

| Dominant Soil Group | **AR - Arenosols** | | | |
|---|---|---|---|---|
| Sequence | 1 | 2 | 3 | 4 |
| Share in Soil Mapping Unit (%) | 50 | 30 | 10 | 10 |
| Drainage class (0-0.5% slope) | Somewhat Excessive | Moderately Well | Poor | Moderately Well |
| Gravel Content (%) | 4 | 10 | 4 | 5 |
| Calcium Carbonate (% weight) | 0 | 0 | 0 | 0 |
| Gypsum (% weight) | 0 | 0 | 0 | 0 |
| USDA Texture Classification | sand | loam | loam | loam |
| CEC (clay) (cmol/kg) | 39 | 30 | 24 | 19 |
| Base Saturation (%) | 100 | 37 | 36 | 27 |
| TEB (cmol/kg) | 3 | 4.1 | 2.9 | 2.5 |
| Organic Carbon (% weight) | 0.4 | 1.45 | 1.1 | 1.73 |
| pH (H2O) | 6.4 | 5.1 | 5 | 5 |
| Sodicity (ESP) (%) | 3 | 1 | 2 | 1 |
| Salinity (ECe) (dS/m) | 0.1 | 0.1 | 0.1 | 0.1 |

*Source: FAO et al., 2012.*

The SMU 4563 has 50% sand texture and 50% loam, and the pH of the soil ranges from 5 to 6.4. The soils of this mapping unit are poorly to somewhat excessively drained. The soil organic carbon is between 0.4-1.73%, which is low to moderately high for humid tropics (Sys et al., 1991; FAO et al., 2012).

Regarding the slope of the study area, it ranges from a gradient of 0% to above 40%, see Figure 5.2. Most of the study area is flat or with a low or moderate low slope gradient, ranging from 0 to 15 %.

The annual rainfall of the study area ranges between 1870-2680mm per year, Figure 5.3 . The mean temperature is around 27C° and the mean minimum and mean maximum temperature range between 23C° and 29C°. The monthly rainfall is between 150mm and 223mm, while the average monthly potential evapotranspiration is around 117mm. When the monthly precipitation is less than of potential evapotranspiration, the month is considered dry. Since this is not the case for the study area, it can be concluded that the study area has no dry seasons.

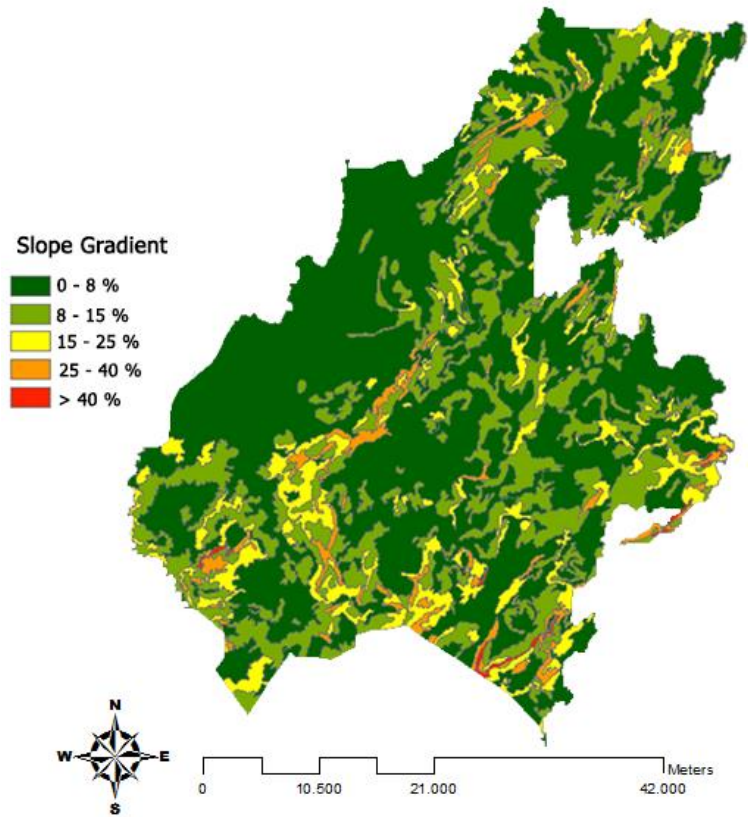



*Figure 5.2 - Slope map of the study area*

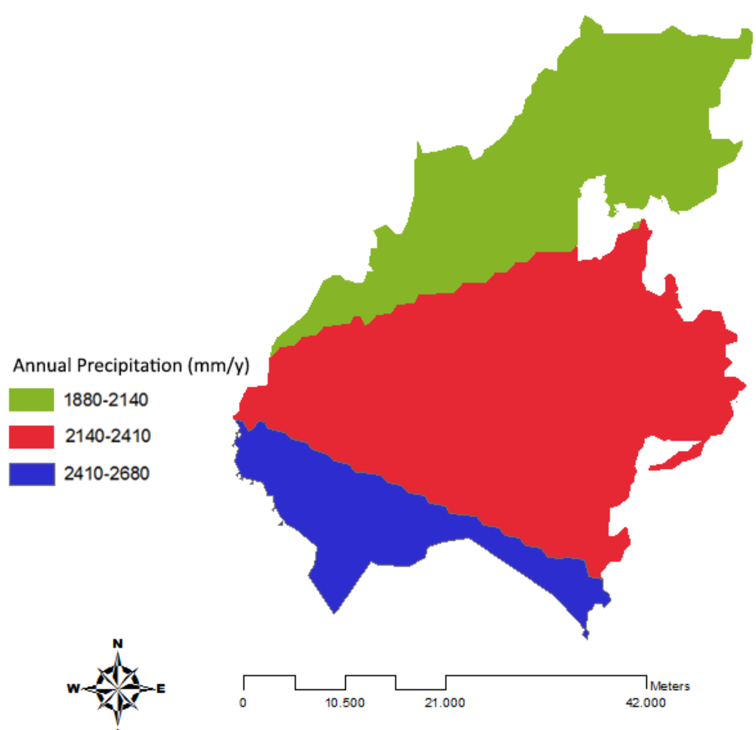



*Figure 5.3 - Annual Precipitation (mm/y)*

### 5.1.2 Network analysis

Datasets on water bodies, transportation network and settlements had to be further processed with ArcGIS software package in order to represent some of the factors assumed to drive the decision support system, namely distance to ports and distance to villages.

Regarding distance to settlements, the road networks were firstly selected. According to the available roads, the distance to the settlements was calculated using the cost distance function of Spatial Analyst toolset, which calculates the least cumulative cost distance for each cell to the nearest destination (i.e. one of the settlements) over a cost surface (in this case, road network).

However, this only takes into account the distance to the settlements of the cells that make part of the road network, while it is required to assign every cell in the study area with a distance value. Therefore, the remaining cells where assigned with the distance value of the closest road cell using the Euclidean allocation function. At the same time, the distance of each cell to the nearest road cell was determined using the Euclidean distance function (Figure 5.4).

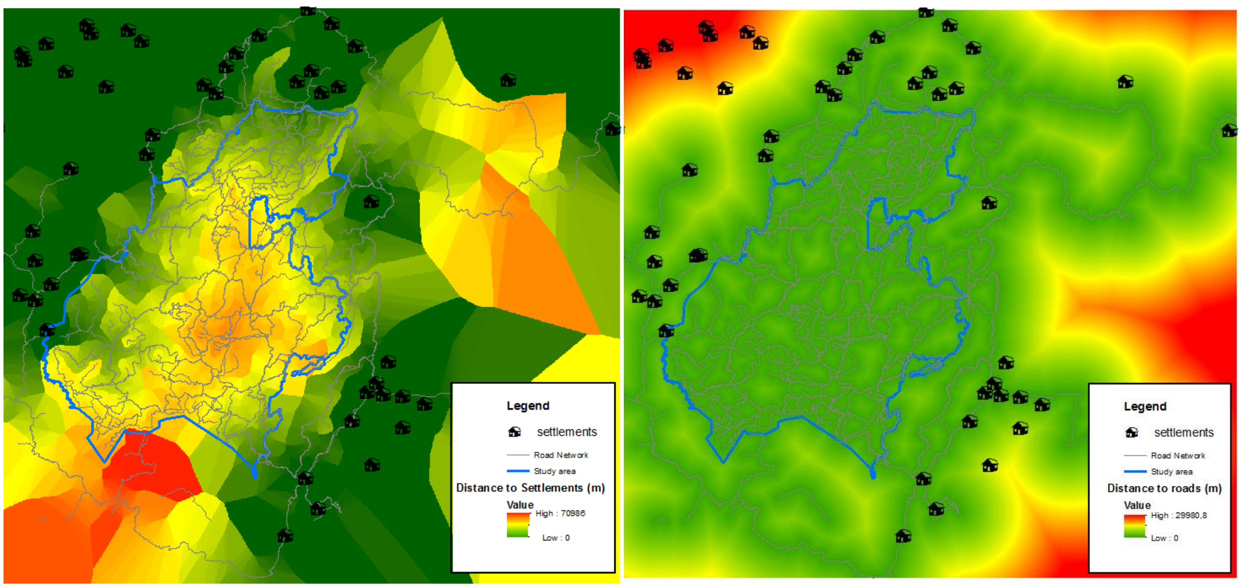



*Figure 5.4 – Distance to settlements and Distance to nearest roads respectively.*

The previous two maps were overlapped and for every cell their values were summed, allowing to obtain a map depicting the least cumulative distance to the settlements according to the existing road network. Therefore the total distance is presented on Figure 5.5, where it is possible to see the most suitable locations, in terms of labor force availability, depending on the roads and settlements available.

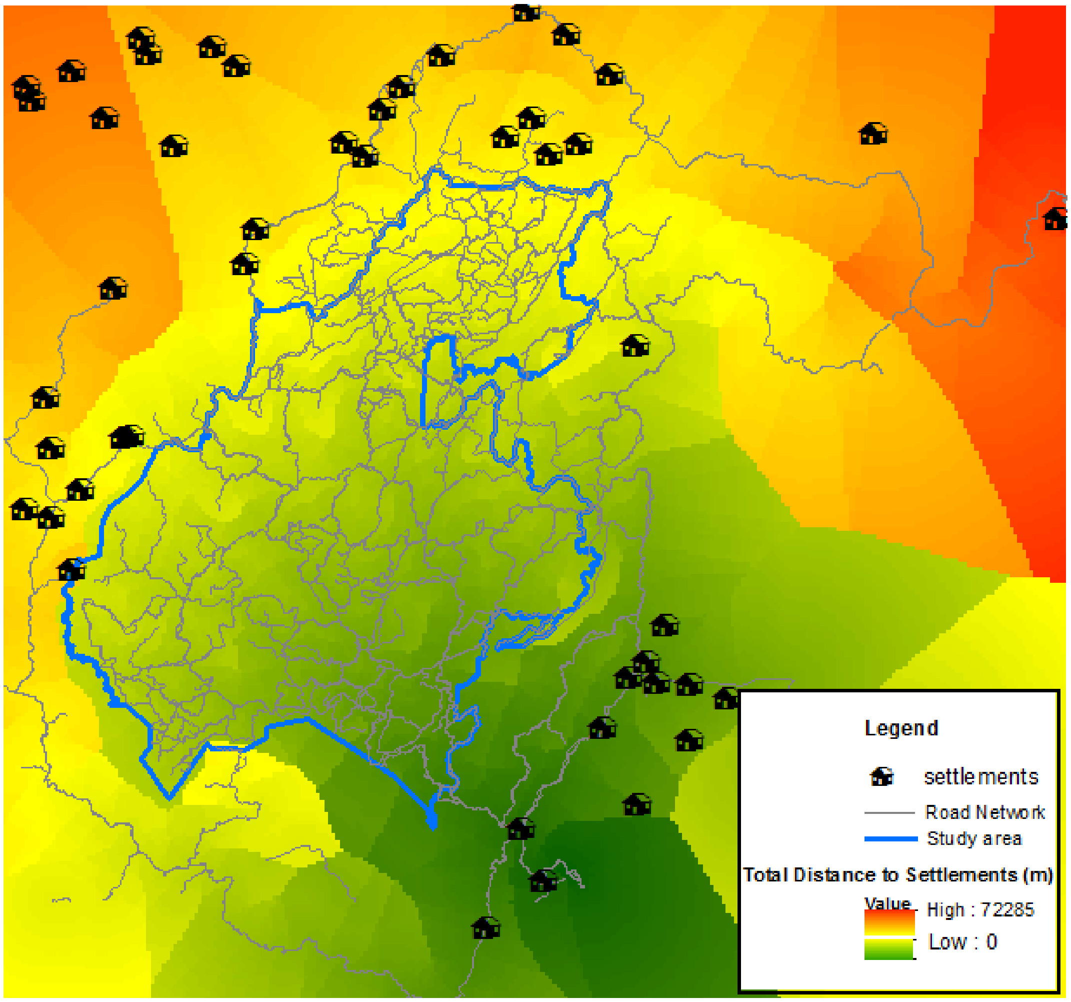



*Figure 5.5* - Distance to every point based on villages and roads available, study area border in blue.

Green surfaces are the closest areas to the villages, whereas orange and red are the most distant and inaccessible. This is an important analysis for labor intensive recipes that have higher labor needs, and it is more suitable for those recipes to be implemented closer to the location of the labor force.

Regarding distance to the port and markets, the same type of network analysis, overlap of Euclidean distance and Euclidean allocation maps, can also be applied to determine the best cost-effective way to transport the commodities to the port and markets. In the Figure 5.6 is illustrated the total distance to the port. In this example, we assumed that all the transport is done to the port, although it is possible to use the same method to estimate transportation distance and costs for a storage unit or ethanol plant processor, in any other location.

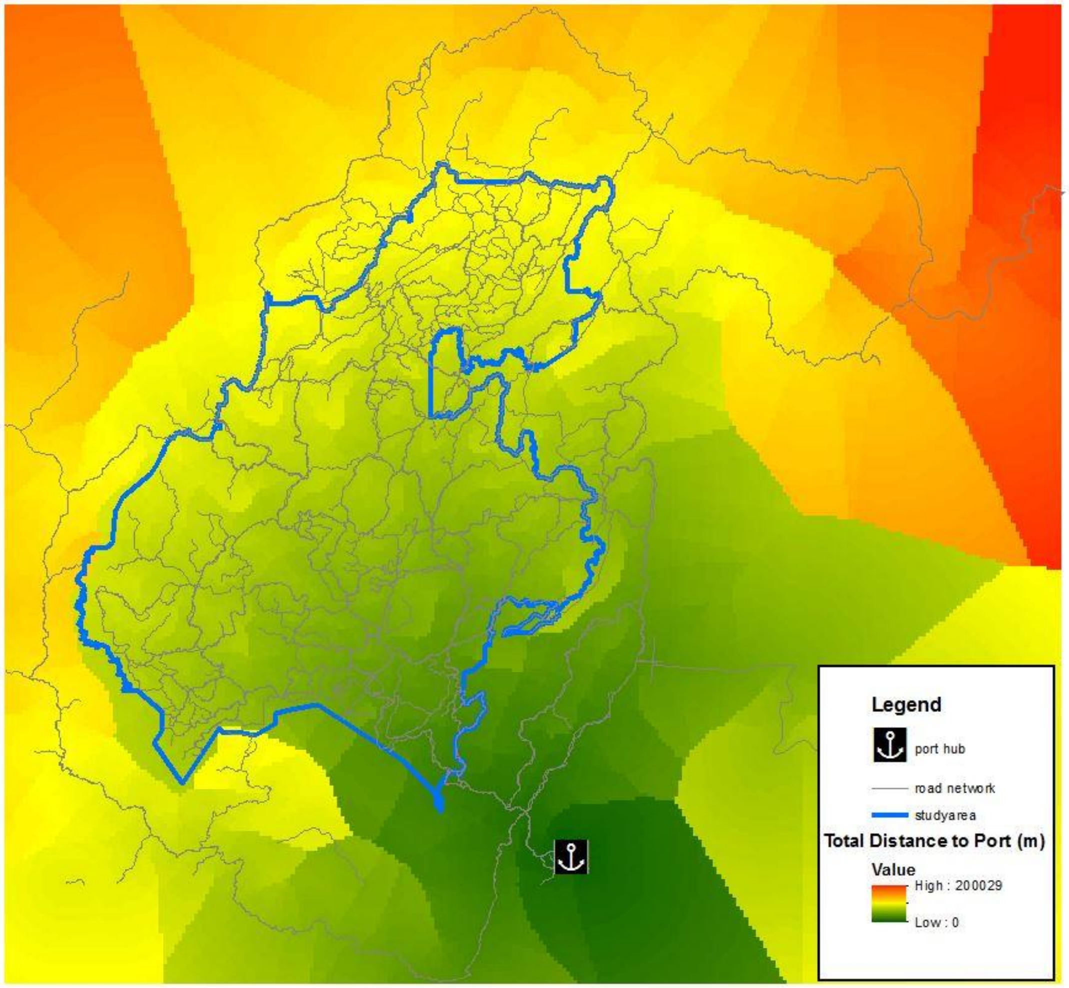



*Figure 5.6 - Total distance to port, from any location in the study area (m)*

The total distance needed from any point in the study area to the port gives valuable information to estimate the transportation costs of the commodities and therefore on the overall costs for the project. Based on the distance from a study area location to the port, a price of the transportation can be applied, $ per distance ($/m or $/km), providing an estimation of costs of transportation for the recipe.

It can be concluded that the network analysis maps provide important information on labor availability in different areas of the study area, as well as a possible estimation of transportation costs involved.

## 5.2 Biophysical Module

The biophysical module calculates the land indices and yields for the different crops of the project. As an example of the work done with the biophysical module, it will be presented the results of the ratings for banana, Table 5.4.

*Table 5.4 – Banana ratings for different land characteristics*

| Banana | | | | |
|---|---|---|---|---|
| Rating / Requirement | S1 | S2 | S3 | N |
| | 95 | 75 | 50 | 32,5 |
| Slope | 0-8 | 8-16 | 16-30 | > 30 |
| Annual precipitation | 1250-1750 | 1000-1250; 1750-2000 | 750-1000 ; 2000-2500 | < 750; > 2500 |
| length of dry season/months | - | - | - | - |
| Mean max temp | - | - | - | - |
| Mean annual temp | 20-23 | 18-20; 23-30 | 15-18; 30-40 | < 15; > 40 |
| Mean min temp | - | - | - | - |
| Fraction of sunshine hours | - | - | - | - |
| Drainage class (0-0.5% slope) | W | M,P | - | VP |
| Topsoil Gravel Content (%) | < 5 | 5-15 | 15-40 | > 40 |
| Topsoil Calcium Carbonate (% weight) | 0-2 | - | - | 10-15 |
| Topsoil Gypsum (% weight) | - | - | - | - |
| Topsoil USDA Texture Classification | 4, 5, 7, 8, 9 | 10 | 3, 11, 12 | 13 |
| Topsoil CEC (clay) (cmol/kg) | >16 | <16 | - | - |
| Topsoil Base Saturation (%) | >35 | 20-35 | <20 | - |
| Topsoil TEB (cmol/kg) | - | - | - | - |
| Topsoil Organic Carbon (% weight) | >1,2 | 0,8-1,2 | <0,8 | - |
| Topsoil pH (H2O) | 5-6 | 4,5-5 | <4 | 0 |
| Topsoil Sodicity (ESP) (%) | <15 | 15-20 | 20-25 | >25 |
| Topsoil Salinity (ECe) (dS/m) | <4 | 4-6 | 6-8 | >8 |
| S1=Suitable, S2=Moderately suitable, S3=Marginally suitable, N=Not suitable | | | | |
| Drainage classes: E-excessively drained, S-somewhat drained, W-well drained, M-moderately drained, I-Imperfectly drained, P-poorly drained, V-very poorly drained | | | | |

*Source: Adapted from Kuneepong et al. 2009.*

Table 5.4 estimates the rating according to the different land characteristics for banana, which provides information on the best characteristics to apply the crop. In this case, the best conditions, rating S1 is land with low slope gradient (0-8%) and moderate annual precipitation and temperature.

Based on the banana ratings for different land characteristics, a matching is done in order to generate the crop suitability in a determined location. Considering as example a location with low slope gradient and a soil mapping unit 4446, a matching was performed for banana to estimate the ratings and land indices, presented in Table 5.5.

*Table 5.5 – Ratings for Banana in SMU 4446 and estimated indices and yield*

| **Soil mapping unit** | **4446** | | | |
|---|---|---|---|---|
| | 40% | 40% | 10% | 10% |
| **Soil and terrain** | | | | |
| ***Topography*** | | | | |
| Slope gradient % | 95 | 95 | 95 | 95 |
| ***Wetness*** | | | | |
| Drainage class | 75 | 75 | 75 | 95 |
| ***Physical soil characteristics*** | | | | |
| Gravel content (volume %) | 50 | 75 | 95 | 95 |
| $CaCO_3$ (%) | 95 | 95 | 95 | 95 |
| Gypsum (%) | 95 | 95 | 95 | 95 |
| Texture class | 75 | 50 | 95 | 50 |
| ***Chemical soil characteristics*** | | | | |
| Cation exchange capacity of clay fraction(cmol/kg clay) | 75 | 75 | 95 | 75 |
| Base saturation (%) | 95 | 75 | 95 | 75 |
| Total exchangeable bases (cmol/kg soil) | 95 | 95 | 95 | 95 |
| Organic carbon (%) | 75 | 75 | 75 | 50 |
| pH H2O | 95 | 75 | 75 | 75 |
| ***Degree of salinity-alkalinity*** | | | | |
| ECe /$dsm^{-1}$ | 95 | 95 | 95 | 95 |
| ESP (%) | 95 | 95 | 95 | 95 |
| **Climate** | | | | |
| ***Rainfall*** | | | | |
| Annual perception | 95 | 95 | 95 | 95 |
| Length of dry season/months | 95 | 95 | 95 | 95 |
| ***Temperature*** | | | | |
| Mean max temp | 95 | 95 | 95 | 95 |
| Mean annual temp | 95 | 95 | 95 | 95 |
| Mean min temp | 95 | 95 | 95 | 95 |
| ***Radiation*** | | | | |
| *Fraction of sunshine hours* | 95 | 95 | 95 | 95 |
| Soil and terrain Index $\mathbf{I_{ST}}$ | 26,7 | 26,7 | 50,8 | 22,6 |
| Climate Index $\mathbf{I_C}$ | 90,3 | 90,3 | 90,3 | 90,3 |
| Climate Rating $\mathbf{R_C}$ | 101,5 | 101,5 | 101,5 | 101,5 |
| Land Index **LI** | 27,1 | 27,1 | 51,5 | 22,9 |
| Yield **Y (t/ha)** | 2,6 | 2,6 | 5,0 | 2,2 |

The suitability indices, such as Soil and terrain Index, Climate Index and Land Index were calculated for the characteristics mentioned above. As explained in methodology, multiplying the land index for the maximum attainable yield, we estimate the productivity yield of banana per hectare, see last row of Table 5.5. Each sub-soil unit of the soil mapping unit is rated / matched separately, giving the range of the suitability indices and yield values.

The same method was applied to the different SMUs of the study area, SMU 4459 and SMU 4563, generating the indices and yields in those units, and therefore yield information for the whole study area. Although it is not available the precise location of the sub-soil units, the range of those values are applied with Spatial Analyst tools of ArcGIS® to create the banana yield map, Figure 5.7.

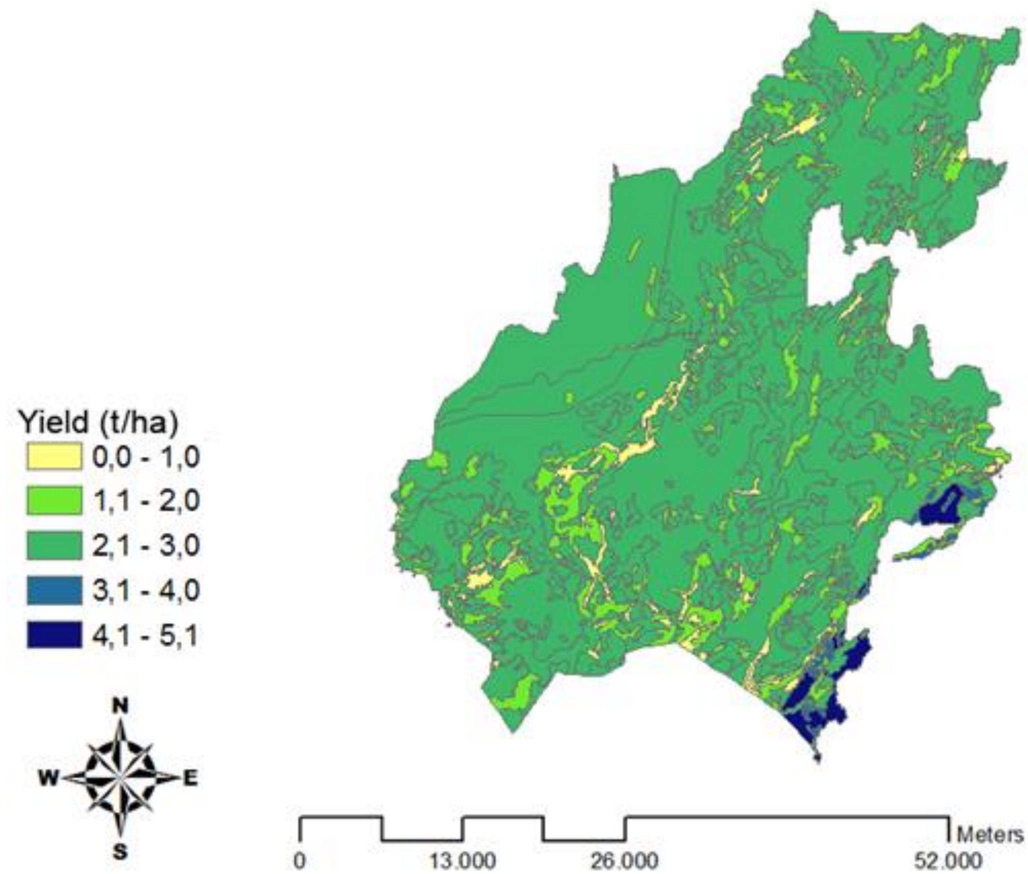



*Figure 5.7 – Yield of banana per hectare.*

The yield map, Figure 5.7, provides information of the estimated tonnes of banana that can produced per hectare in the whole area, considering a maximum attainable yield of 9.7 tonnes per hectare (Fischer et al., 2001). The maximum production occurs in the SMU 4446, within the range of 4.1 to 5.1 tonnes per hectare. Multiplying the market price of banana for its productivity yield, it is possible to calculate the monetary yield, in other words, the $ per hectare expected for banana, Figure 5.8.

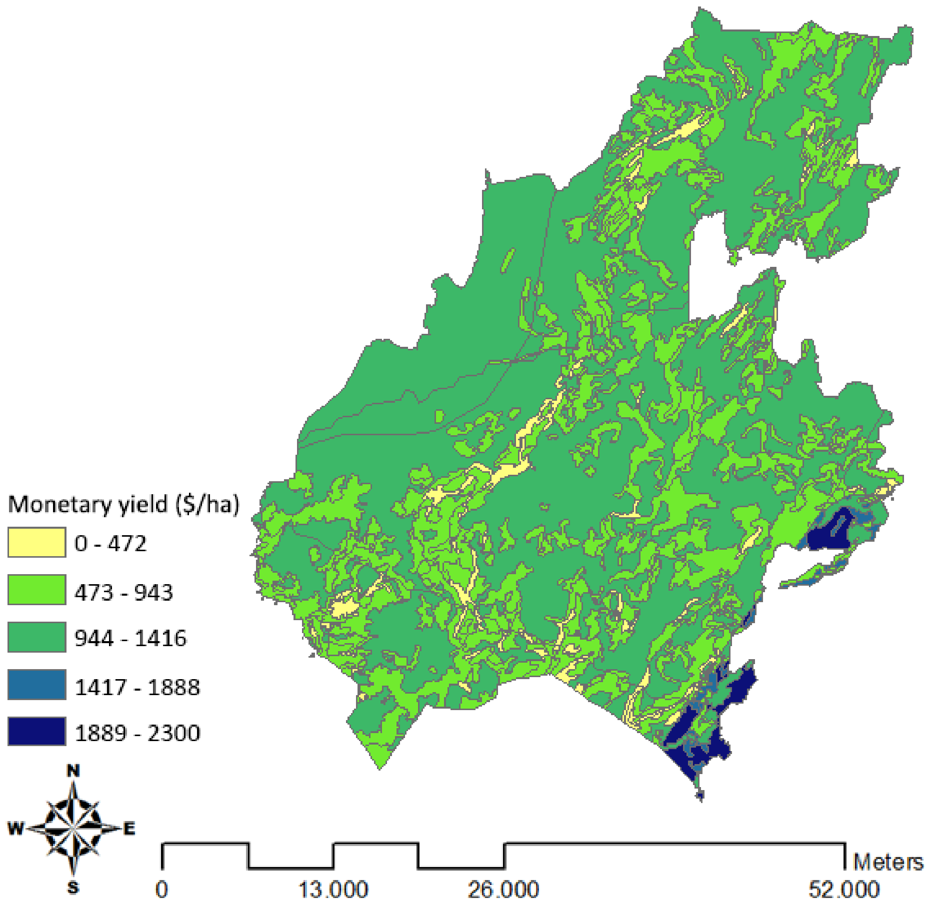



*Figure 5.8 -Monetary yield for banana.*

As expected, in Figure 5.8, the same areas of higher yield (Figure 5.7) match the areas that will generate higher monetary yield. In other words, we can see the locations which will generate more revenue for banana.

The same method of generating ratings, indices and yields was performed for the remaining crops of the recipe, creating similar yield maps that can be matched together to create a suitability map of the recipe. A density of 1/3 for each crop was applied. In the Figure 5.9, banana, cassava and sugar palm monetary yield maps were combined in a final monetary yield map of the recipe.

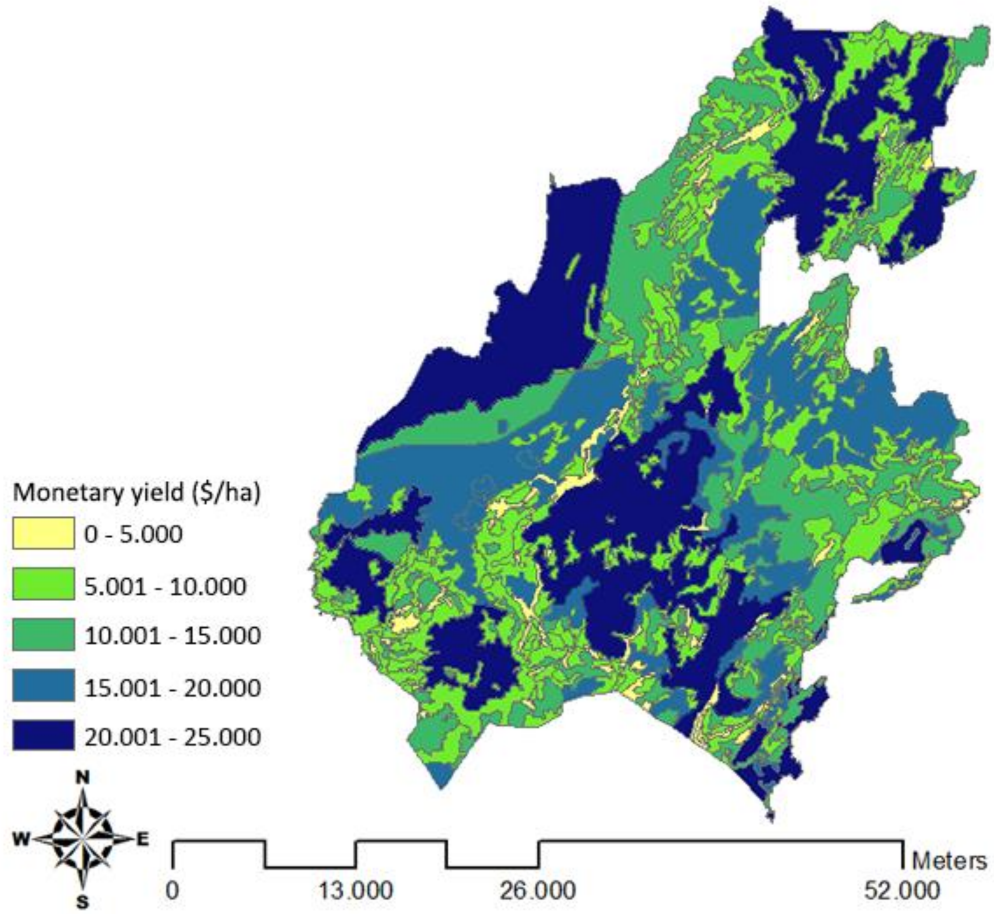



*Figure 5.9 – Recipe monetary yield map, $ generated per hectare.*
*(N.B: Adjusted data due to company confidentially)*

It can be concluded that applying more crops, can result in higher revenue per hectare, as different crops are better in different land characteristics and conditions. The example shows a maximum revenue of $ 25.000 per hectare, which is almost 11 times higher than the maximum revenue of the banana crop only. This maps represents the maximum revenue per hectare expected in the year of maximum production of the crops of the recipe. In this calculation the revenues of ethanol were taken into account. To access the overall 20 years project economic performance, a NPV analysis can be done as presented in the Figure 5.15.

## 5.3 System Developed and Application

The proposed system is hereby implemented using a case study in Indonesia, some of the data was adapted due to company confidentiality while other data is assumed. A system prototype was developed in Microsoft Excel™ environment, Visual Basic programming language and ArcGIS® geographic capabilities, as a preparation for a future development in an online WebGIS system. The prototype was developed in a way to easily analyze or edit each recipe or factor, whereas each column in the sheet represents a year on the 20-year project lifetime considered. A spreadsheet was created for each parameter or factor of the system, example of the field operations sheet can be seen Figure 5.10, which represents the number of each field operations and labor input associated per year and hectare.

**Field operations per year for each crop**

☐ **Recipe A** ☑ **Recipe B**

☐ Recipe C ☐ Recipe D

| **Number of field operations (nr/ha/y)** | **Recipe B (years)** | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| Land Clearing/Site preparation | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| **Seeding/Planting (nr)** | | | | | | | | | | | | | | | | | | | | | |
| Planting (seedlings and nursery incl.) | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| **Maintenance (eg. weeding)** | | | | | | | | | | | | | | | | | | | | | |
| Maintenance | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Harvest (nr)** | | | | | | | | | | | | | | | | | | | | | |
| Harvesting | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Tapping | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 360 | 360 | 360 | 360 | 0 | 0 | 0 | 0 | 0 | 0 | 360 | 360 | 360 | 360 |
| Other | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Labour input per field operation (h/ha/y)** | **Recipe B (years)** | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| Land Clearing/Site preparation | 200 | 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | 200 | 200 | 0 | 0 | 0 | 0 | 200 | 0 | 0 | 0 |
| **Seeding/Planting (nr)** | | | | | | | | | | | | | | | | | | | | | |
| Planting (seedlings and nursery incl.) | 200 | 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | 200 | 200 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| **Maintenance (eg. weeding)** | | | | | | | | | | | | | | | | | | | | | |
| Maintenance | 0 | 200 | 200 | 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Harvest (nr)** | | | | | | | | | | | | | | | | | | | | | |
| Harvesting | 0 | 300 | 300 | 300 | 300 | 300 | 300 | 0 | 0 | 0 | 300 | 0 | 300 | 300 | 300 | 300 | 300 | 300 | 0 | 0 | 0 |
| Tapping | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2880 | 2880 | 2880 | 2880 | 0 | 0 | 0 | 0 | 0 | 0 | 2880 | 2880 | 2880 | 2880 |
| Other | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Figure 5.10 - Number of field operations and Labor input hours needed per year for recipe B, Field Operations tab*

The user can change the number of each field operation per year and observe the impact on economic aspects, as well as the labor input hours needed per field operation. Both values are determined based on field knowledge from local experts.

The commodities are organized in a list where the user can input the quantity (tons or $m^3$) produced per year of the crops and raw materials, final products or by-products, see Figure 5.11.

**List of commodities produced each year per ha**

☐ Recipe A ☑ RecipeB

☐ Recipe C ☐ RecipeD

| | Recipe B (years) | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Crops & Raw materials (ton)** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **Lifetime** |
| Sugar Palm Juice (m3) | 0 | 0 | 0 | 0 | 0 | 0 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | 612 | **8568** |
| Cassava | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **8** |
| Banana | 0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | **190** |
| Agathis | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Pineapple | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Acacia | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| Wood (m3) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | **400** |
| **Final Products** | | | | | | | | | | | | | | | | | | | | | |
| ethanol (m3) | 0 | 0 | 0 | 0 | 0 | 0 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | **685** |
| other (fill if applicable) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| **By-products (units)** | | | | | | | | | | | | | | | | | | | | | |
| roof cover | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| handy craft | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| floorings | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| furniture | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |
| other (fill if applicable) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** |

*Figure 5.11 – Commodities produced in recipe B. (N.B: Adjusted data due to company confidentially)*

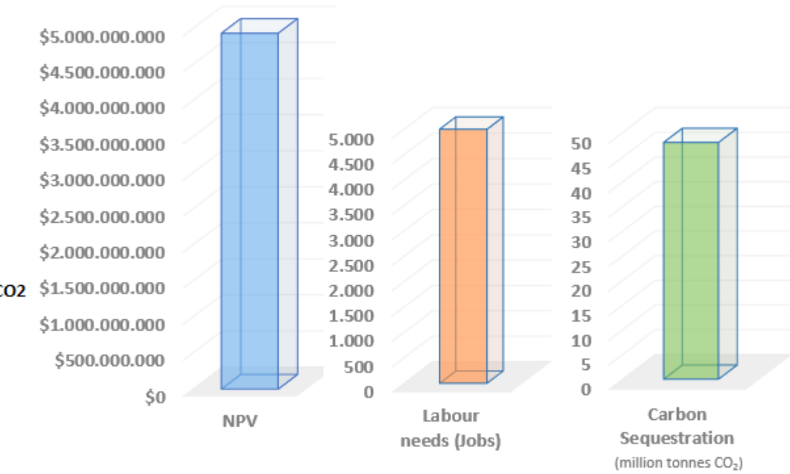
As in the field operations tab, in the commodities tab, the user can also easily edit the production of each crop or final product and simulate its impact in the project. Options to control the market price of each commodity through sensitivity analysis sliders are provided on the dashboard, see Figure 5.12. The production of sugar palm is based on the principle of 17 L/tree/day, considering 100 trees/ha and 365 days in a year of production. In this case, it's considered that all the sugar palm juice is converted in ethanol and the conversion rate of production is 0.08 L of ethanol per 1 L of sugar palm juice (Ecofys and Winrock, 2011).

The SDSS is intended to be an easy to use system and interactive, where the user can easily choose a different value in a certain factor and see instantly its impact. Therefore, the system incorporated with sliders that can control different operational parameters, such as field operations costs. The sliders are used as a sensitivity analysis tool, which is important for a planner, investor or manager, as it can easily see the impact of parameters prices fluctuations on the project. To ease results presentation for the user a dashboard has been developed, see Figure 5.12, where it is possible to control the sliders mentioned and instantly simulate its impact.

## Multi Culture - Recipe Suitability and Economics

| Recipe B | (trees/ha) |
|---|---|
| Cassava | 100 |
| Sugar Palm | 100 |
| Banana | 100 |
| Timber | Remaining |

| | | |
|---|---|---|
| **NPV** | 4.932.514.614,5 | $ |
| **ROI** | 2,9 | % |
| **AEV per hectare** | 2.435,0 | $ |
| **IRR** | 18,1 | % |
| **Return on Labour** | 2,1 | $/h |
| **Labour needs (Jobs)** | 5.000,0 | Jobs |
| **Carbon Sequestration** | 48,0 | M tonnes CO2 |
| **Biodiversity** | 10,0 | Species |




**Area of cultivation**

200000 ha.

**Field Operations**

| | |
|---|---|
| **Land Clearing** | 1200 $/ha |
| **Planting** | 554 $/ha |
| **Maintenance** | 555 $/ha |
| **Tapping** | 30 $/ha |
| **Harvesting** | 1451 $/ha |

**Commodities**

| | |
|---|---|
| **Ethanol (Market)** | 545 $/m3 |
| **Cassava** | 200 $/ton |

*Figure 5.12 – Multi-culture and Economics Dashboard.*
*(N.B: Adjusted data due to company confidentially)*

The present application was developed to assess and compare the economic, environmental and social impact of three different possible agroforestry approaches: a recipe of a monoculture scheme of timber production, a mixed recipe (presented in the dashboard Figure 5.12) and a mixed design approach with four different recipes for all the area, results presented in Table 5.6. As different recipes have different biophysical suitability, it was performed a biophysical suitability to every plantation scheme and therefore to each crop, in order to maximize the overall benefits. In the case of the four mixed recipes, an optimization selection focused on the environmental factor was performed.

As explained in the methodology, all the costs and revenues are initially calculated per unit of area( in this case hectare) and then summed up or averaged so it is possible to assess the overall results of the system, as presented in Figure 5.12. In the dashboard or "cockpit" the user is able to see the content of the recipe and density applied, as well as the possibility to change the field operations and commodities value prices and instantly see the impact in terms of the economic, environmental and social outputs, such as NPV, ROI, AEV per ha, return on labor, labor needs and carbon sequestration. The NPV of $ 4.932.514.614 is the result of the recipe B applied in the 200.000 hectares of the study area. The AEV per hectare of $ 2450 it the weighted average of the whole study area. There are interactive graphs that change accordingly to the prices applied, giving to the user a different visualization on the impact of the different scenarios. Additional commodities can be added to the dashboard, according to the recipe content.

*Table 5.6 - Recipes Performance*[2]

| | **Monoculture** | **Mixed Recipe (B)** | **4 Mixed Recipes** |
|---|---|---|---|
| **Net Present Value** ($) | 412.400.000,00 | 4.932.514.614,50 | 5.817.870.154,87 |
| **Return on Investment** (%) | 2,00 | 2,90 | 3,20 |
| **Annual Equivalent Value per ha** ($) | 203,58 | 2.435,00 | 2.872,02 |
| **Internal Rate of Return** (%) | 24,74 | 18,10 | 18,30 |
| **Return on Labor** ($/h) | 1,40 | 2,10 | 2,49 |
| **Labor needs** (Jobs) | 1.000,00 | 5.000,00 | 6.500,00 |
| **Carbon Sequestration** (Million Tonnes $CO_2$) | 23,0 | 48,0 | 55,0 |
| **Biodiversity** (nr) | 1,00 | 5,00 | 28,00 |

Analyzing the three plantation schemes (Figure 5.13 and Table 5.6), it is possible to evaluate the result of the different implementations and see which is more profitable or which provides more jobs or carbon sequestration. In this particular example, the most beneficial in economic, environmental and social terms is the implementation of 4 different recipes in the same area, resulting in a higher ROI, but also more employment, revenue and carbon sequestration.

[2] Based on fictional data due to commercial confidentiality.

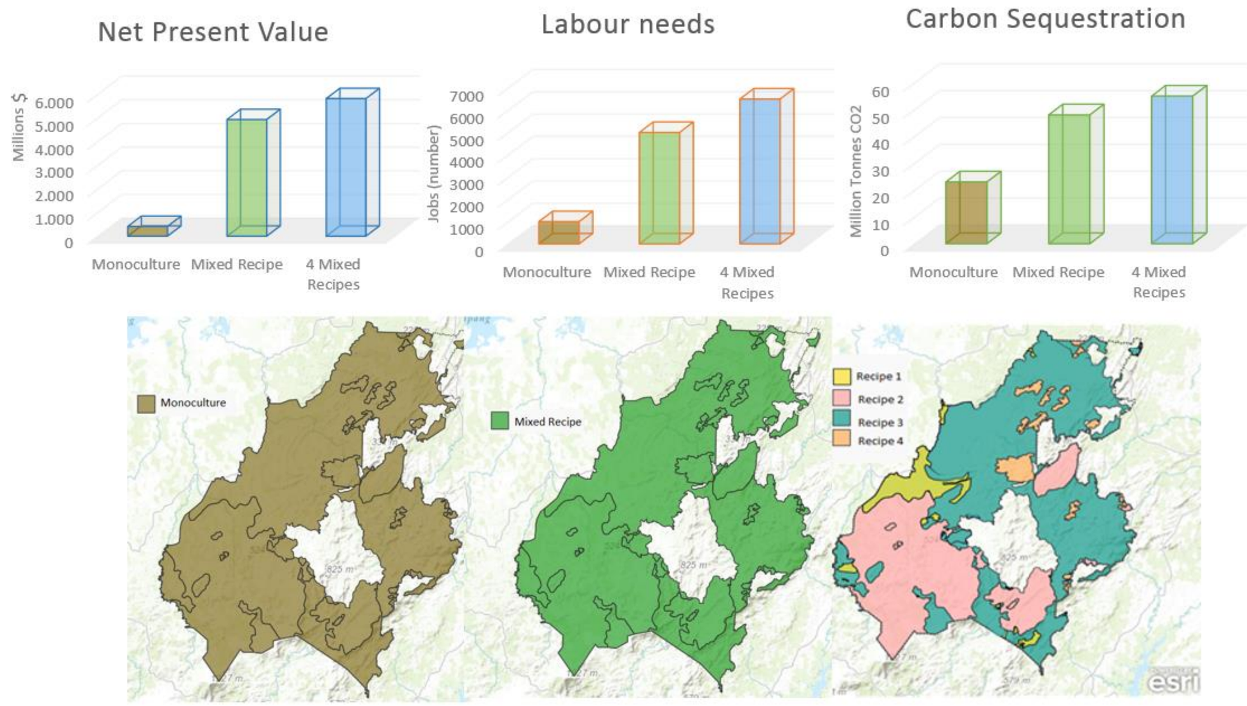



*Figure 5.13 - Recipes Performance*
*(N.B: Adjusted data due to company confidentially)*

In Figure 5.13, the three plantation schemes can be seen in the map, as well as the graphs of the net present value, labor needs and carbon sequestration. Monoculture results in the lowest net present value, as well as labor needs and carbon sequestration. From the results it can be assumed that a mixed plantation scheme has higher net present value, labor needs and carbon sequestration, comparing to the other plantation schemes.

As a different way of presenting the results, a spider-web chart was created, where the performance is measured by the area of the shape in the chart. The bigger the area shape, the better the performance. This chart type was applied to show each plantation scheme performance and it is presented below in Figure 5.14.

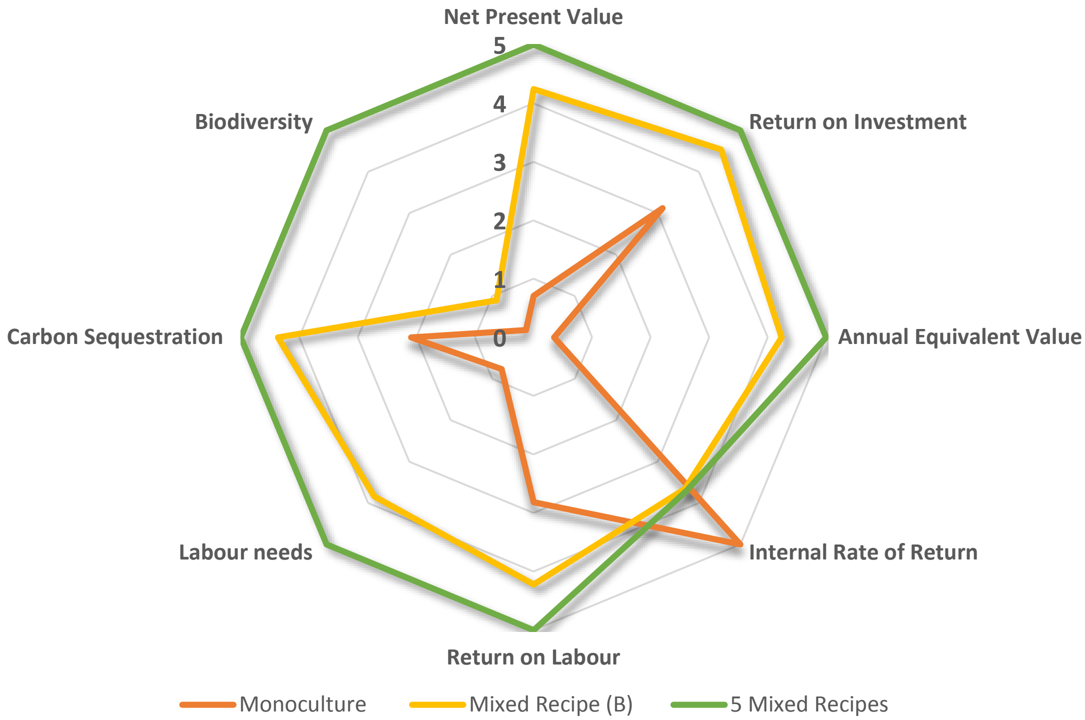



*Figure 5.14 – Spider-web chart rating different plantation schemes*

The spider-web chart shows the same information as Table 5.6, although in this case it is easier to see the performance of the different indicators in each plantation scheme. The values of the different indicators were normalized in a scale between 0 and 5, whereas 0 is the "worst" and 5 is the "best" performance in the comparison. It can be seen that the monoculture scheme has the "worst" performance in almost every indicator, expecting the internal rate of return in each is the best. As IRR is the percentage rate earned on each monetary unit (e.g. dollar) invested for each period it is invested, in the case of the monoculture which only have costs and revenues on the years of plantation and harvesting, this indicator is over valuated. On the other hand, we can clearly see that the four mixed recipes scheme has the "best" overall performance of the indicators, surpassing the recipe B performance.

Additionally, as the project consists of a large geographical area with heterogeneous characteristics, visualization can help to support planning and management. Four recipes examples were applied to all the area, where the user can see which areas and recipes are more profitable (higher NPV) or the ones that have a higher carbon sequestration or higher employment, see Figure 5.15 and Figure 5.16 in next page.

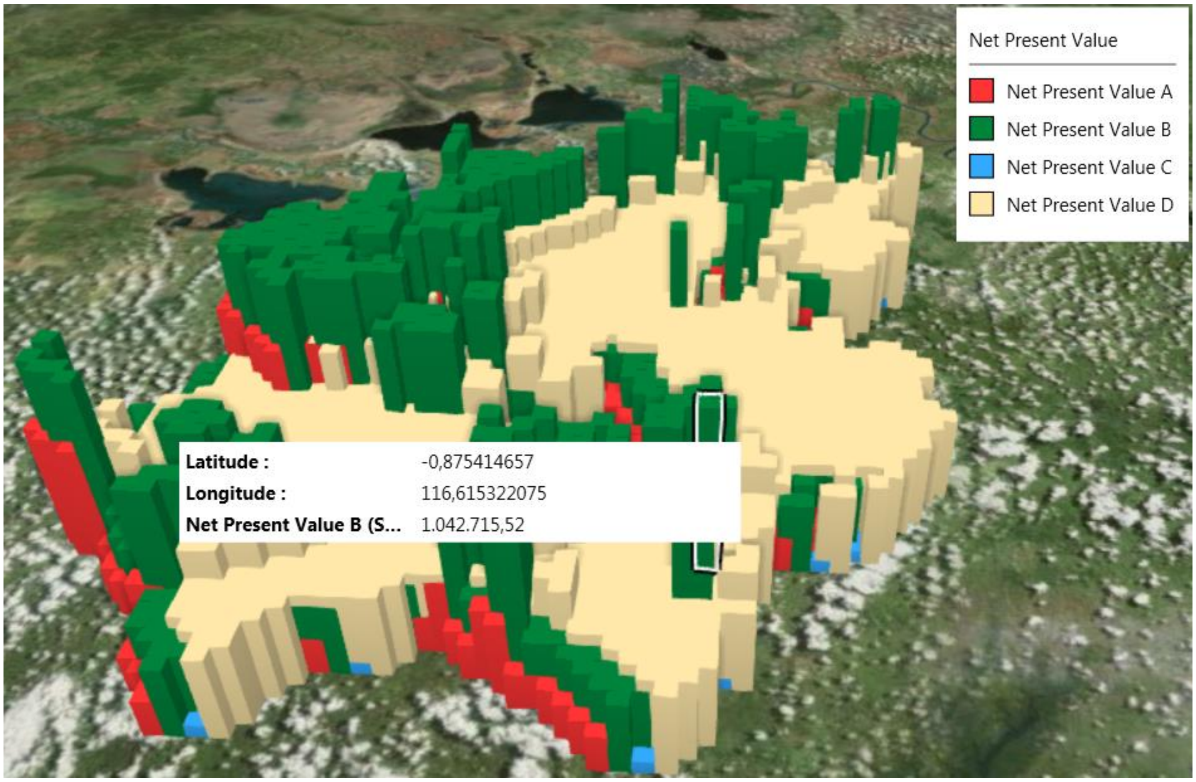



*Figure 5.15 - Interactive geo-visualization of the Net Present Value per recipe.*

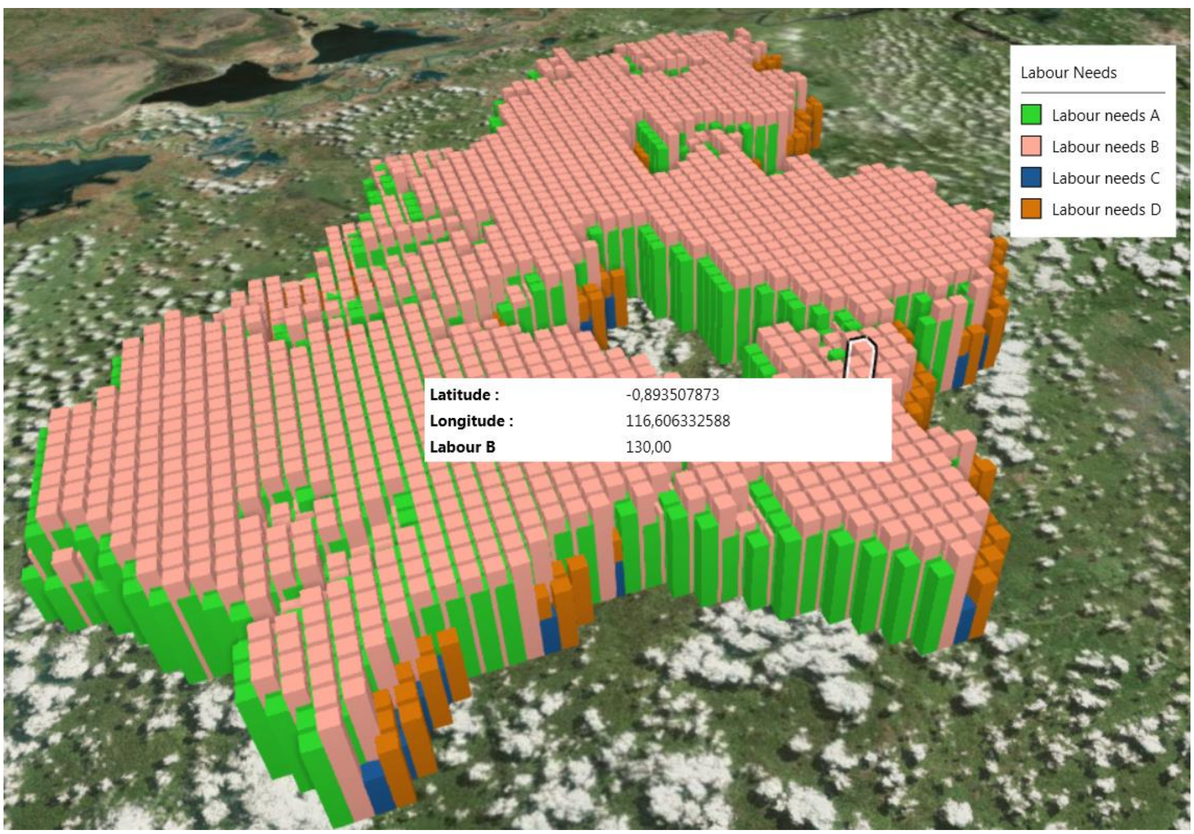



*Figure 5.16 - Interactive geo-visualization of the Labor Needs per recipe.*

The interactive geo-visualization, Figure 5.15, Figure 5.16 and Figure 5.17 was developed using Microsoft™ Power Map Preview. Each column on the 3D graph is geographically positioned via the latitude, longitude and can represent different results of the project, such as net present value, labor needs or carbon sequestration. The user can click on the desirable column and to access additional specific information, such as the exact value in that location for that recipe.

An agroforestry project can have lifetimes from 15 to 30 years usually, which is a long-term investment, therefore to aid visualization of its results through time, it is important to show geographically how the project will develop and when the economic investment pays off. Figure 5.17 shows an example of this type of 3D visualization through time of the revenue in each year of the project.

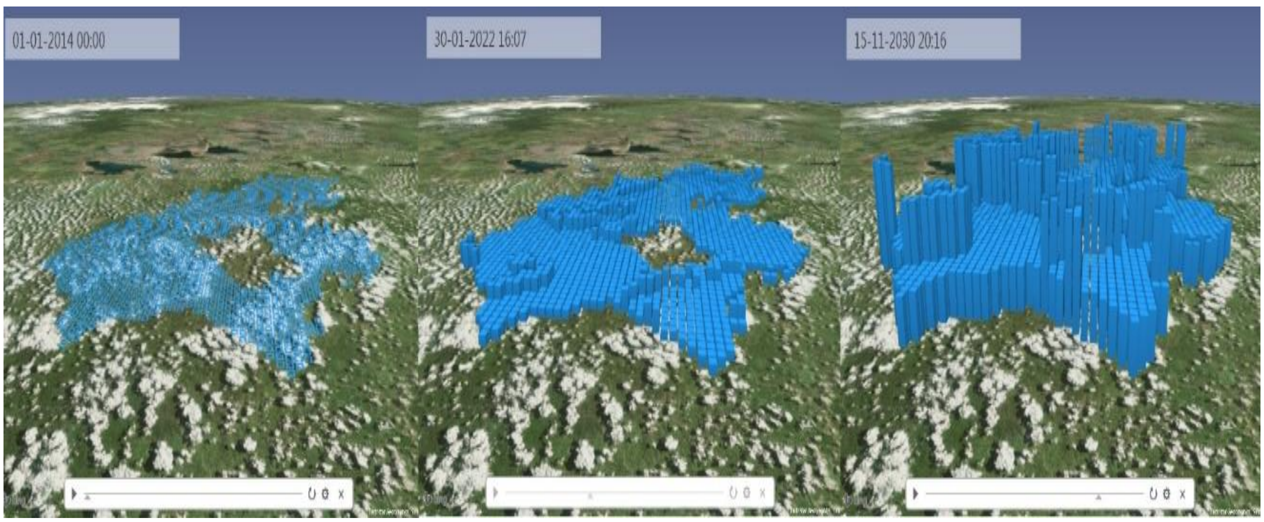



*Figure 5.17 - Interactive Geovisualization of the revenue per recipe, through time.*

In Figure 5.17, it is possible to see that initially in year 0, there is no revenue, as columns have no “height” on the graph. However in the year 8 and year 16 when the commodities are already productive, the revenues occurs.

As explained before, the sliders in the recipe dashboards (Figure 5.12) give the possibility of an interactive sensitivity analysis of each commodity and field operation. A sensitivity analysis on the economic performance was performed in order to assess the sensitivity of the NPV to changes in key factors, such as costs, investment, market prices and discount rate, see Figure 5.18.

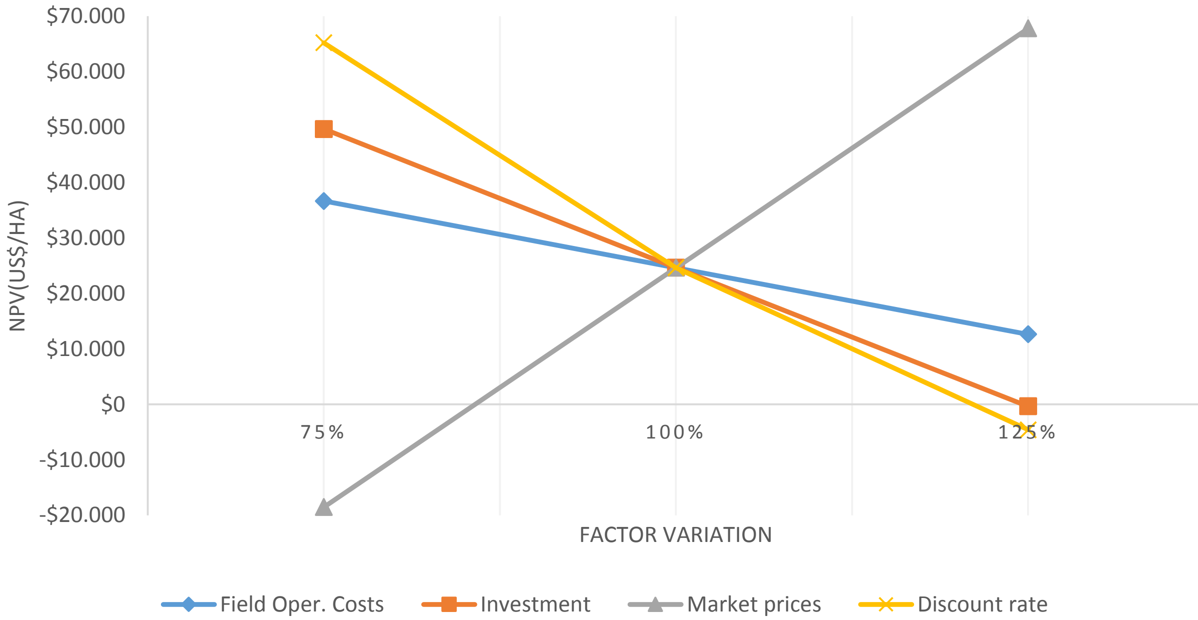



*Figure 5.18 – Sensitivity analysis on the economic performance of the recipe example.*

The objective of the sensitivity analysis sliders is to explore the critical factors of the agroforestry project, from applying different factors in costs, investment, market prices and discount, it can be concluded that the economic performance of the recipe is most sensitive to changes in the market prices, discount rate and investment, achieving negative NPV in some cases. On the other hand, variations on field operation costs appeared to not affect the economic performance.

As market prices is a very sensitive factor, an analysis of the timber price fluctuation in the different recipes was done to assess its economic impact in the overall performance, illustrated in Figure 5.19, see next page.

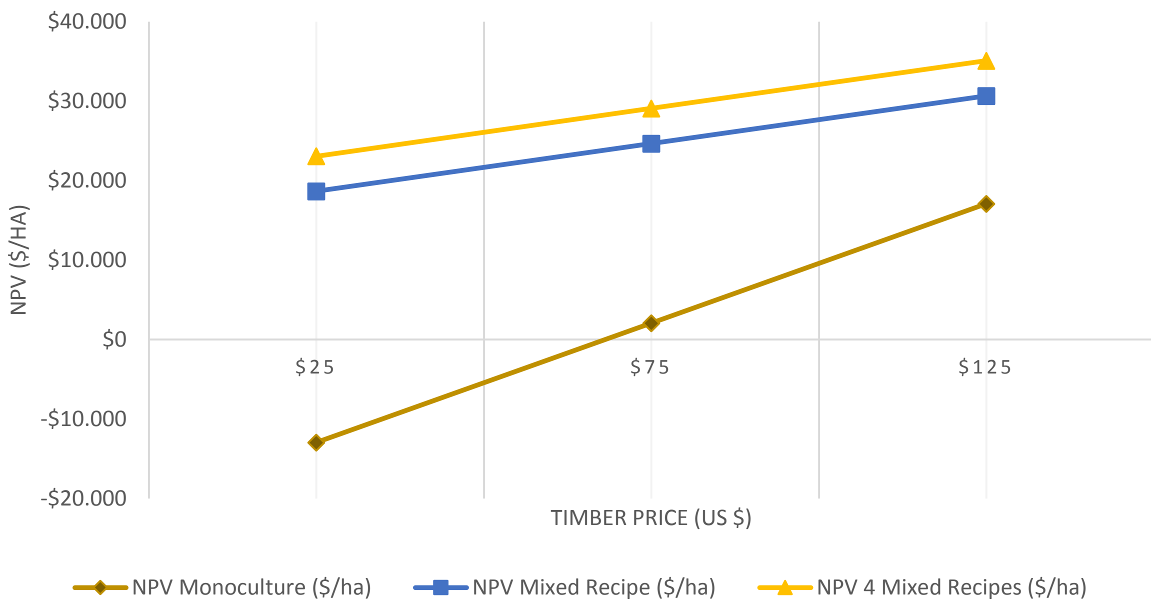



*Figure 5.19 - Sensitivity Analysis of Timber Price.*
*(N.B: Adjusted data due to company confidentially)*

Figure 5.19, provides information on the variation of the overall economic performance of the different recipes due to volatility of the timber market prices. In the present example, it can be seen that the plantation scheme with the 4 mixed recipes is less vulnerable to fluctuation of timber prices. Furthermore, NPV remains positive even if timber market prices are much lower than initially assumed. Therefore, it can be concluded that financial risks are distributed over different crops in this plantation scheme. On the other hand, monoculture schemes appear to be much more vulnerable to sudden changes in commodity prices.

# 6 Discussion

## 6.1 Method and Data

The present study presents a methodology and application of a spatial decision support system for a sustainable agroforestry project. Although the methodology can be applied to any place in the world, in the present thesis it was applied and adapted to a case study in East Kalimantan, Borneo.

To evaluate the suitability of the study area, the land characteristic approach described in *FAO* 1976 has been used. The two suggested approaches are evaluation of land qualities and land characteristics. The evaluation of land qualities is the recommended approach because by evaluating the land characteristics, the interaction between different characteristics are not taken into account. Evaluation of land characteristics by parametric approach is simple. However, evaluation of land qualities is a complex method and requires practice to be accurate and avoid errors.

In this study the impact of groundwater table is not taken into account with the assumption that all the water requirement of the crop is met by precipitation. Groundwater is a more important factor in arid and semi-arid regions where the crops rely on groundwater for their water requirement. Since the climate of the study area is wet tropical with no dry season we assume that all the water requirements are met by the annual precipitation. Further, FAO 1976 states that for a crop with deep rooting zone, the characteristics of subsoil should also be evaluated, but due to lack of data on crop requirements, only the topsoil of the study area is being evaluated. If the study area is flood prone, the possibility and degree of flooding should be defined in order to take its impact on yield estimations into account. However, taking the impact of flooding on yield into account is beyond the scope of this study. The lack of further information on the location of each soil sub-type within a SMU by the HWSD, might have an impact on the crops yield estimation, therefore more accurate soil data might improve the estimation.

Land suitability evaluation is an important process for assessing a project feasibility, aiding its planning and decision-making. Even though the biophysical module approach developed is data intensive and needs judgment of expert knowledge, it is possible to estimate crops' production and therefore produce suitability maps.

The development of suitability maps allowed assessing expected productivity and the economic performance of growing different agro-forestry commodities. An underlying assumption of this approach is that the maps are static and maximum production yields are always attained. Negative impact from short-term events (e.g. heat waves or excess of rainfall) and long-term dynamic processes (changes in climate conditions or soil erosion) are not explicitly incorporated in the current model. Therefore, the tool may over-optimize the real capacity for delivering commodities and, as a result, the determined economic performance can actually be lower than what is being determined by the model. Nevertheless, the present model is able to provide an indication on what could be attained under optimal biophysical circumstances, as well as exploring the sensitivity to changing conditions. In addition, it should be noted that environmental spatial externalities (e.g. resulting from the movement of materials such as water, soil, plants, pests and contaminants) and factors related to economies of scale (e.g. clustering of production systems) were not explicitly taken into account. The system is nevertheless able to inform the main areas where the production of different commodities could become economically attractive and thus provide an indication for decision-makers on the areas where positive externalities and increasing returns to scale are worth being explored.

## 6.2 Sustainability Assessment

The system's performance is evaluated based on sustainability assessment divided in an economic, environmental and social performance. As sustainability has many definitions and its interpretation depends often on the user's background, the system was evaluated by simple indicators, instead of a multi-criteria decision analysis (MCDA). This option was mainly to promote transparency and clearness on the output of the different factors in the system. It is nevertheless prepared to handle further indicators depending on the needs of the different users. MCDA has limitations, such as the methodology of understanding, selecting and modelling weights for each factor/indicator. The main goal is to ensure that the decision makers understand and interpret the meaning of the different indicators easily. On the other hand, in a MCDA the "simple" indicators would be aggregated and the decision maker would have less control and information of which factor/indicator impact. Also, the MCDA techniques rely on statistical analysis and synthesizing data which may present less accurate information for decision-making.

From an economic point of view, the higher NPV is generally desired, however the NPV is an absolute calculation, which does not provide any information about the required annual investment needed or its revenues. In that sense, NPV can misunderstand the manager for the best economic solution. Therefore, it was calculated other indicators to assess the project feasibility such as the ROI, IRR and AEV. Despite that the discount rate applied is a critical factor on the calculation of all this economic indicators, as it was concluded from the sensitivity analysis performed, see Figure 5.18.

Apart from purely economic grounds, an investment decision on an agroforestry project should also take into account non-economic factors, such as carbon sequestration, biodiversity and employment created. Carbon sequestration potential is an important indicator as deforestation is a problem and enterprises start to look for ways of being more environmental friendly and to give their contribution. A method to calculate the $CO_2$ sequestered per tree species was not researched or developed as it is beyond the scope. Therefore the $CO_2$ sequestration per tree or crop is a data requirement in the system. Regarding the biodiversity indicator, an indicator based on the diversity of different species was developed in order to foster a diverse ecosystem with the agroforestry project.

Additionally, as unemployment is a severe problem, return on labor and number of jobs created were analyzed. Unemployment might increase pressure in the forest areas and therefore leading to forest degradation. Apart from that, some projects to be accepted need a minimum number of jobs, which make it a valuable indicator for the system.

All the indicators applied have spatial location and therefore each one can be visualized and analyzed in a 2D or 3D environment, aiding planning and decision-making.

## 6.3 System Development and Results

Some challenges were encountered developing the tool, as all started as an explorative approach, combining all the raw factors in a excel sheet, based on initial needs by Dr. Willie Smits, the research director of the Indonesian company. The development of the prototype tool was made from scratch in an Excel environment, which had several iterations until the last version was presented. The process of adapting the system to a multi cropping scheme was also challenging has different crops and requirements had to be combined together to a land suitability.

The model application was performed for three different plantation schemes, a monoculture scheme of timber production, a mixed recipe and a mixed design approach with different recipes for all the area. As different recipes have different biophysical suitability based on its requirements, a matching of the best location (land characteristics) for those requirements was performed, in order to maximize the overall benefits. Based in the performance results of the different plantation schemes, it was observed that a mixed recipe scheme, with different crops and trees has more benefits in economic, environmental and social terms. In this case, the plantation scheme with four different recipes applied to the whole area was the one with the better performance, whereas the monoculture of timber had the worst overall performance. The optimization algorithm researched and described was not automatically implemented in the prototype presented due to Microsoft Excel environment limitations, although a manual approach of the algorithm was used when selecting the four mixed recipes, focused on the environmental benefits.

The system assumes that the market prices are the same through all the project lifetime, which might not happen due to prices fluctuation every year. Although the sensitivity analysis sliders provides a way to change this prices it in the overall project lifetime and see its impact. Due to data confidentiality of the Indonesian company and lack of data in some modelling factors, the proposed methodology and results presented has been implemented on adjusted data sets. These data sets were created so as to be as close as possible to real conditions in the study area. It should also be kept in mind that although the present study provides an overview of the expected economic, social and environmental benefits, the present findings should nevertheless be further researched, using more accurate and local-specific data.

The interface design and the way the results are presented, determines whether a given system, will be used and whether it will be used effectively. The main innovation presented in the system developed is the straight forward visualization of the outcomes of the project in a dashboard, with the possibility to easily simulate sensitivity analysis through sliders in the market or field operation prices. Additionally the integration of a sustainability performance in the system, where the decision-maker can select which is main objective, whether maximizing economic, environmental or social benefits. Previous works researched are focused mainly on economic parameters, or don’t give the opportunity of selecting the optimization goal. Apart from that, the integration with a 3D geographic visualization of the project results also aims to help planning and decision-making.

# 7 Conclusions

This study describes a methodological framework and presents a spatial decision support system for sustainable forest management, integrating economic, social and environmental performance. Based in research and the contract of the Indonesian company to develop this system, it is clear that there was a need for a tool that would address this challenge of aggregating a multi-cropping plantation scheme in a spatiality explicit system, taking into account the sustainability pillars. This system is ready to use and was developed for decision-makers investors and stakeholders involved in agroforestry projects. Although the system was adjusted to a case study in East Kalimantan, Indonesia, it has the capacity to be adapted to another locations by changing parameters and well as data set inputs.

Adopting agroforestry has enormous advantages as it promotes biodiversity, carbon sequestration and employment for the communities. Additionally it gives more economic security as it is based on a mixed forest approach, whereby trees can still be source of income even if the crops fail due to disease or pests. From the recipes performance results we can conclude that a plantation scheme with more diversity of crops and trees, return in higher economic, environmental and social benefits. It should be noted that this fact is not linear, as this analysis has done based on the combination of each crop and its location suitability.

A field trip was done to Indonesia, where an initial prototype system was presented to stakeholders and investors in Indonesia. The system was appreciated, mainly the option of interactively controlling the different factor prices in a dashboard that aggregates the main outputs and results. Additionally, the fact that provides a spatial visualization of the project lifetime was also appreciated. The field trip was also a nice opportunity to be hands-on in the needs of the project and the different parameters involved that would make a difference in the tool. Based on additional requirements and needs, the system was improved and the final version will be delivered.

The system developed can also be used as a tool to analyze beforehand the performance of agroforestry projects, taking into account regional-specific environmental challenges in terms of climate change and soil and forest degradation. Reforestation projects can benefit and gain efficiency through decision support systems that help to evaluate the feasibility and sensitivity performance of different alternatives to key factors of the project.

The sensitivity analysis is an important analysis as it aid to explore the critical factors of the agroforestry project and therefore estimate how sensitive that factor is and if it is worth to invest. Market prices, discount rate and investment were the factors most sensitive to changes in the economic performance. Additionally, the geographical visualization is also an important decision and communication tool, especially in large area projects with spatial variability of biophysical conditions.

Summarizing the spatial decision support system developed, it provides: (1) a simulation environment to evaluate via a dashboard the outcomes of the project with the opportunity to perform interactive sensitivity analysis for key parameters of the project; (2) a biophysical suitability approach to identify the most beneficial locations for agroforestry projects and evaluate its economic, social and environmental impact; (3) a tool to inform prospective investors and aid stakeholders and decision-makers of the potential and opportunities for integrated agroforestry management; (4) a 3D interactive geographic visualization to facilitate understanding and planning.

## 7.1 Further Developments

During the thesis elaboration, some questions came up that can be answered in further research. Those answers can fulfill some gaps of the presented thesis and improve decision support for agroforestry projects worldwide.

This type of systems, that estimate the outcome of an agroforestry project, in order to be commercially used and trusted needs further work on calibration and adaptations to different scenarios and needs. So the present system is ready to use but for higher credibility there are some further developments needed in terms of calibration of the system based on the field data, such as the commodities produced, costs and revenues made and the labor needs. With this yearly field data, it will be possible to add artificial intelligence algorithms on the system, providing a way for the system to learn and adapt on its own, improving the efficiency and trustfulness of the system. As the biophysical suitability is data-intensive and needs considerable amounts of field data, expert knowledge and calibration, further methods and techniques should be tested and simulated.

In the present study it was not given an economic value for the environmental and social indicators, which should have further research. Regarding the environmental indicators, additional indicators such as taking account the species abundance and its contribution for the environment, should also be researched. Besides that, additional ways to assess the sustainability performance can be researched, such as the application of a multi criteria decision analysis.

Finally, the prototype created was done in an Excel environment with use of Visual Basic programming and ArcGIS® capabilities, taking into account all the UX and system structure research for a stand-alone online WebGIS software. Although the stand-alone software was not developed and it should be done as a further development.

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# Appendixes

## Appendix 1: Indonesia Field Trip

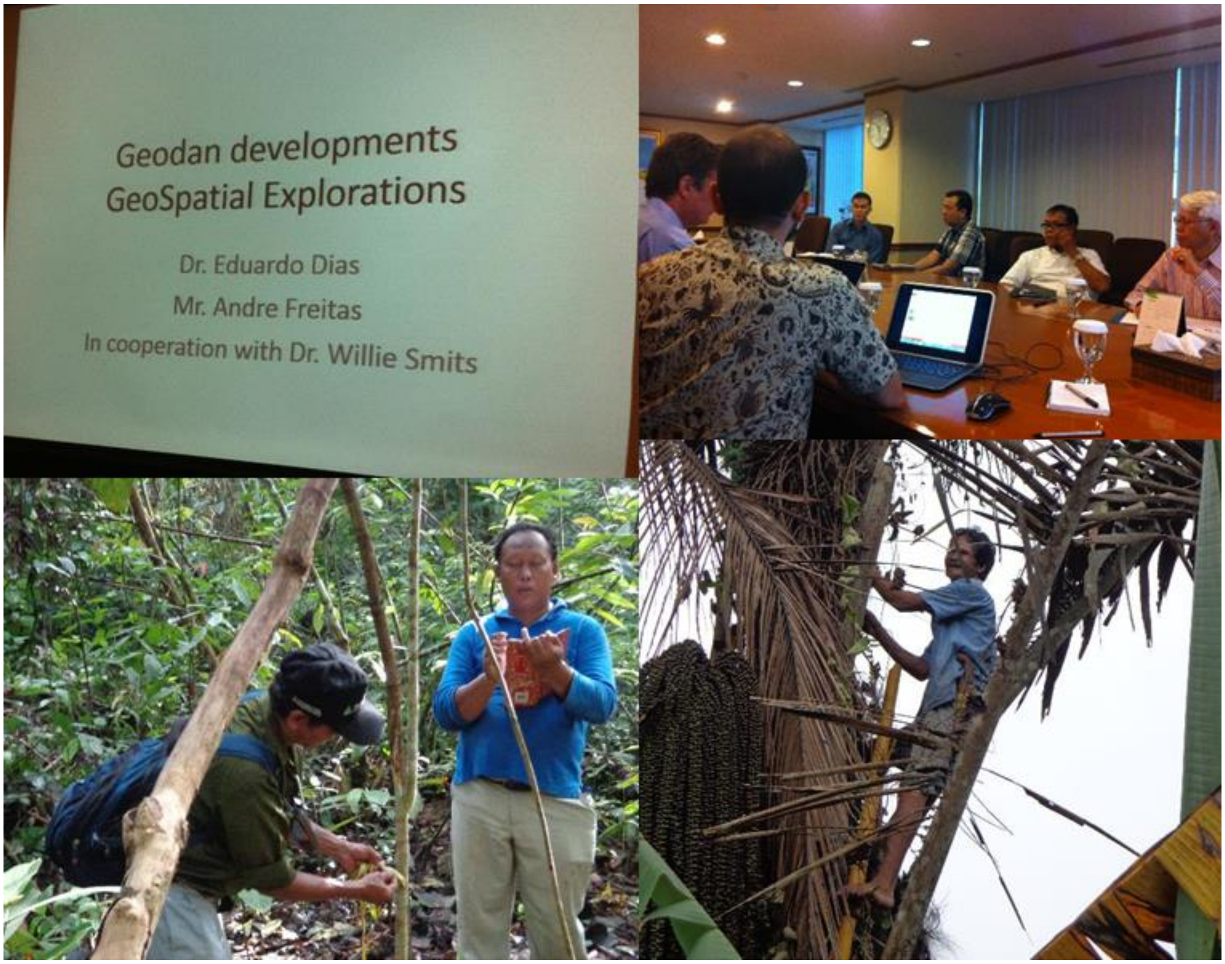


*Figure A.1- Indonesia Field trip and meetings.*

## Appendix 2: CSD Indicators of Sustainable Development

Table A.1 - CSD Indicators of Sustainable Development. Source: UN, 2007

| Theme | Sub-theme | Core indicator | Other indicator |
|---|---|---|---|
| **Poverty** | Income poverty | Proportion of population living below national poverty line | Proportion of population below $ 1 a day |
| | Income inequality | Ratio of share in national income of highest to lowest quintile | |
| | Sanitation | Proportion of population using an improved sanitation facility | |
| | Drinking water | Proportion of population using an improved water source | |
| | Access to energy | Share of households without electricity or other modern energy services | Percentage of population using solid fuels for cooking |
| | Living conditions | Proportion of urban population living in slums | |
| **Governance** | Corruption | Percentage of population having paid bribes | |
| | Crime | Number of intentional homicides per 100,000 population | |
| **Health** | Mortality | Under-five mortality rate | |
| | | Life expectancy at birth | Healthy life expectancy at birth |
| | Health care delivery | Percent of population with access to primary health care facilities | Contraceptive prevalence rate |
| | | Immunization against infectious childhood diseases | |
| | Nutritional status | Nutritional status of children | |
| | Health status and risks | Morbidity of major diseases such as HIV/AIDS, malaria, tuberculosis | Prevalence of tobacco use |
| | | | Suicide rate |
| **Education** | Education level | Gross intake ratio to last grade of primary education | Life long learning |
| | | Net enrolment rate in primary education | |
| | | Adult secondary (tertiary) schooling attainment level | |
| | Literacy | Adult literacy rate | |
| **Demographics** | Population | Population growth rate | Total fertility rate |
| | | Dependency ratio | |

*Table A.1 (continuation) - CSD Indicators of Sustainable Development. Source: UN, 2007*

| Theme | Sub-theme | Core indicator | Other indicator |
|---|---|---|---|
| **Demographics (continued)** | Tourism | | Ratio of local residents to tourists in major tourist regions and destinations |
| **Natural hazards** | Vulnerability to natural hazards | Percentage of population living in hazard prone areas | |
| | Disaster preparedness and response | | Human and economic loss due to natural disasters |
| **Atmosphere** | Climate change | Carbon dioxide emissions | Emissions of greenhouse gases |
| | Ozone layer depletion | Consumption of ozone depleting substances | |
| | Air quality | Ambient concentration of air pollutants in urban areas | |
| **Land** | Land use and status | | Land use change |
| | | | Land degradation |
| | Desertification | | Land affected by desertification |
| | Agriculture | Arable and permanent cropland area | Fertilizer use efficiency |
| | | | Use of agricultural pesticides |
| | | | Area under organic farming |
| | Forests | Proportion of land area covered by forests | Percent of forest trees damaged by defoliation |
| | | | Area of forest under sustainable forest management |
| **Oceans, seas and coasts** | Coastal zone | Percentage of total population living in coastal areas | Bathing water quality |
| | Fisheries | Proportion of fish stocks within safe biological limits | |
| | Marine environment | Proportion of marine area protected | Marine trophic index |
| | | | Area of coral reef ecosystems and percentage live cover |
| **Freshwater** | Water quantity | Proportion of total water resources used | |
| | | Water use intensity by economic activity | |
| | Water quality | Presence of faecal coliforms in freshwater | Biochemical oxygen demand in water bodies |
| | | | Wastewater treatment |

*Table A.1 (continuation) - CSD Indicators of Sustainable Development. Source: UN, 2007*

| Theme | Sub-theme | Core indicator | Other indicator |
|---|---|---|---|
| **Biodiversity** | Ecosystem | Proportion of terrestrial area protected, total and by ecological region | Management effectiveness of protected areas |
| | | | Area of selected key ecosystems |
| | | | Fragmentation of habitats |
| | Species | Change in threat status of species | Abundance of selected key species |
| | | | Abundance of invasive alien species |
| **Economic Development** | Macroeconomic performance | Gross domestic product (GDP) per capita | Gross saving |
| | | Investment share in GDP | Adjusted net savings as percentage of gross national income (GNI) |
| | | | Inflation rate |
| | Sustainable public finance | Debt to GNI ratio | |
| | Employment | Employment-population ratio | Vulnerable employment |
| | | Labor productivity and unit labor costs | |
| | | Share of women in wage employment in the non-agricultural sector | |
| | Information and communication technologies | Internet users per 100 population | Fixed telephone lines per 100 population |
| | | | Mobile cellular telephone subscribers per 100 population |
| | Research and development | | Gross domestic expenditure on R&D as a percent of GDP |
| | Tourism | Tourism contribution to GDP | |
| **Global economic partnership** | Trade | Current account deficit as percentage of GDP | Share of imports from developing countries and from LDCs |
| | | | Average tariff barriers imposed on exports from developing countries and LDCs |

*Table A.1 (continuation) - CSD Indicators of Sustainable Development. Source: UN, 2007*

| Theme | Sub-theme | Core indicator | Other indicator |
|---|---|---|---|
| **Global economic partnership (continued)** | External financing | Net Official Development Assistance (ODA) given or received as a percentage of GNI | Foreign direct investment (FDI) net inflows and net outflows as percentage of GDP |
| | | | Remittances as percentage of GNI |
| **Consumption and production patterns** | Material consumption | Material intensity of the economy | Domestic material consumption |
| | Energy use | Annual energy consumption, total and by main user category | Share of renewable energy sources in total energy use |
| | | Intensity of energy use, total and by economic activity | |
| | Waste generation and management | Generation of hazardous waste | Generation of waste |
| | | Waste treatment and disposal | Management of radioactive waste |
| | Transportation | Modal split of passenger transportation | Modal split of freight transport |
| | | | Energy intensity of transport |