# Understanding Land Use, Land Cover and Woodland-Based Ecosystem Services Change, Mabalane, Mozambique

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## Abstract

Charcoal production constitutes a key ecosystem service in Mozambique, with an estimated market value of US$400 million a year. Due to the central role the charcoal industry plays in local livelihoods, availability of suitable wood for charcoal production has decreased because of changes in land use and land cover (LULC). This paper applied a probabilistic modelling approach combining Bayesian Belief Networks (BBNs), Geographic Information Systems, Remote Sensing data, field data, and expertise from different stakeholders to understand how changes in LULC affect woodland-based ecosystem services (ES) in the Mabalane landscape, southern Mozambique. Three scenarios of policy interventions were tested: Large private; Small holder and Balanced. A BBNs was used to explore the influence of these scenarios from 2014 to 2035 on the resulting LULC. This research facilitated stakeholder engagement and improved the understanding of the interaction between LULC changes and woodland-based ES. The results highlighted the importance and spatial distribution of woodland-based ES to the local communities and that availability of suitable wood for ES will decrease under the first scenario.

Keywords: Modelling, scenarios, spatial analysis, woodland-based ecosystem services

## 1. Introduction

Humanity benefits from the services that ecosystems provide, but human use of land impacts the services that the land can deliver. Land use is characterised by human activities such as cropping, grazing, logging, mining and processes such as urbanisation, whereas land cover is the expression of land use in a set of discrete classes such as forest, grassland and wetlands (Watson, Pham, & Maeder, 2000). Changes in land use and land cover (LULC) play a considerable role in influencing supply of the woodland-based ecosystem services (ES) that rural inhabitants rely on heavily (Egoh et al., 2008). Changes in the supply of woodland-based ES are difficult to predict but can be explored through scenarios that represent alternative pathways of future development (Carpenter, Bennett & Peterson, 2006). The main aim of the scenario approach is to use multiple perspectives in order to explore a specific problem.

Bayesian Belief Networks (BBNs) are probabilistic graphical models that quantify the relationship between variables and explicitly accommodate uncertainty and variability in model predictions (Uusitalo, 2007; Aalders, Hough & Towers, 2011). BBNs provide quantitative outputs in the form of probabilities (Marcot, Steventon, Sutherland & McCann, 2006). They are increasingly being used in environmental management, in decision support systems and to evaluate the impact of interventions (Uusitalo, 2007). Previous work in this direction has dealt mostly with BBNs structure and has included limited spatial information (Pearl, 1988; Clark et al., 2001).

Linking BBNs and Geographic Information Systems (GIS) allows users to perform probabilistic mapping and has already been used in other studies (see Stassopoulou, Petrou & Kittler , 1998; Taylor, 2003; Walker, Pham & Maeder, 2004; Pullar & Phan, 2007; Stelzenmuller, Lee, Gamacho & Rogers, 2010; Morgan, Hutchins, Fox, & Rogers. 2012; Verweij, Winograd, Perez-Soba, Knapen & Randen, 2012; Gonzalez-Redin, Luque, Poggio, Smith & Gimona, 2016).

In this study, the QUICKScan approach (Verweij, Simoes Penello, Alves, Ferraz & Comont, 2014) is used to integrate stakeholder knowledge, field data, BBNs and GIS. QUICKScan is a tool to facilitate the decision process in participatory settings. By including stakeholder knowledge and the ability to calculate impacts in-situ, QUICKScan supports the discussion and the convergence of perceived values. QUICKScan enables the creation of alternative storylines for questions defined by stakeholders and translates these in-situ into a model by combining tacit expert knowledge with available spatially-explicit monitoring and statistical data. It builds on concepts from Participatory Modelling (Voinov & Brown Gaddis, 2008) and Participatory GIS (McCall, 2003) and uses visualisation and interpretation tools to support the exploration of options, allowing and facilitating discussion of alternatives, analysing their consequences, and determining trade-offs and synergies (Verweij et al., 2010).

QUICKScan currently provides access to spatially distributed phenomena, overlaying, temporal comparisons and various visualisation options. Verweij et al. (2012) pointed out that QUICKscan is both a framework and a software tool that can be applied in group processes with decision makers, experts and stakeholders, to develop and explore potential policy options and assess likely impacts of various options. The framework applied here addresses five questions: 1) What aspects in policy are appropriate to improve the supply of woodland-based ES? 2) What is the LULC picture of the future when compared to the present? 3) What elements and interactions are relevant in understanding the evolution of the LULC pattern? 4) What strategies and options can be devised to improve the existing situation? and 5) Which hotspot areas and services could be identified as targets for intervention?

With this approach, we obtained maps representing each scenario that can be used to identify which communities are most susceptible to changes in woodland-based ES. Such an approach is a useful tool in discussions of how best to support rural communities. This paper presents a method to evaluate possible interventions on LULC and its consequence for woodland-based ES. It is based on a holistic and systematic integral framework that represents consequences of policy intervention for LULC and woodland-based ES.

## 2. Methods

A method to evaluate possible interventions on LULC and their uncertain spatial consequences on woodland-based ES for a case study in Mabalane District, Gaza Province in Southern Mozambique was required. To address this, we have used and combined scenario planning (Lindgren & Hans, 2009), BBNs, stakeholders knowledge, remote sensing, field data and geospatial data together with translation of the results into maps using GIS (Gonzalez-Redin et al., 2016). Smucker, Campbell, Olson and Wangui (2007) argued that the integration of information derived from multiple methods is necessary because of the complex interactions among local and regional driving forces that underlie changes.

### 2.1 Study Area

Mabalane District (Southern Mozambique, see Fig. 2.1) covers 9,000 km², has more than 32,000 inhabitants with a density of 3.6 inhabitants per km² (Instituto National de Estatística [INE], 2008). The study area receives low and variable rainfall, averaging 623 mm annually between November and March. It also, experiences high evapo-transpiration (1413 mm per year) and frequent floods, leading to high agricultural risk (Ng'ang'a, Maute, Notenbaert, Herrero & Moyo 2012).
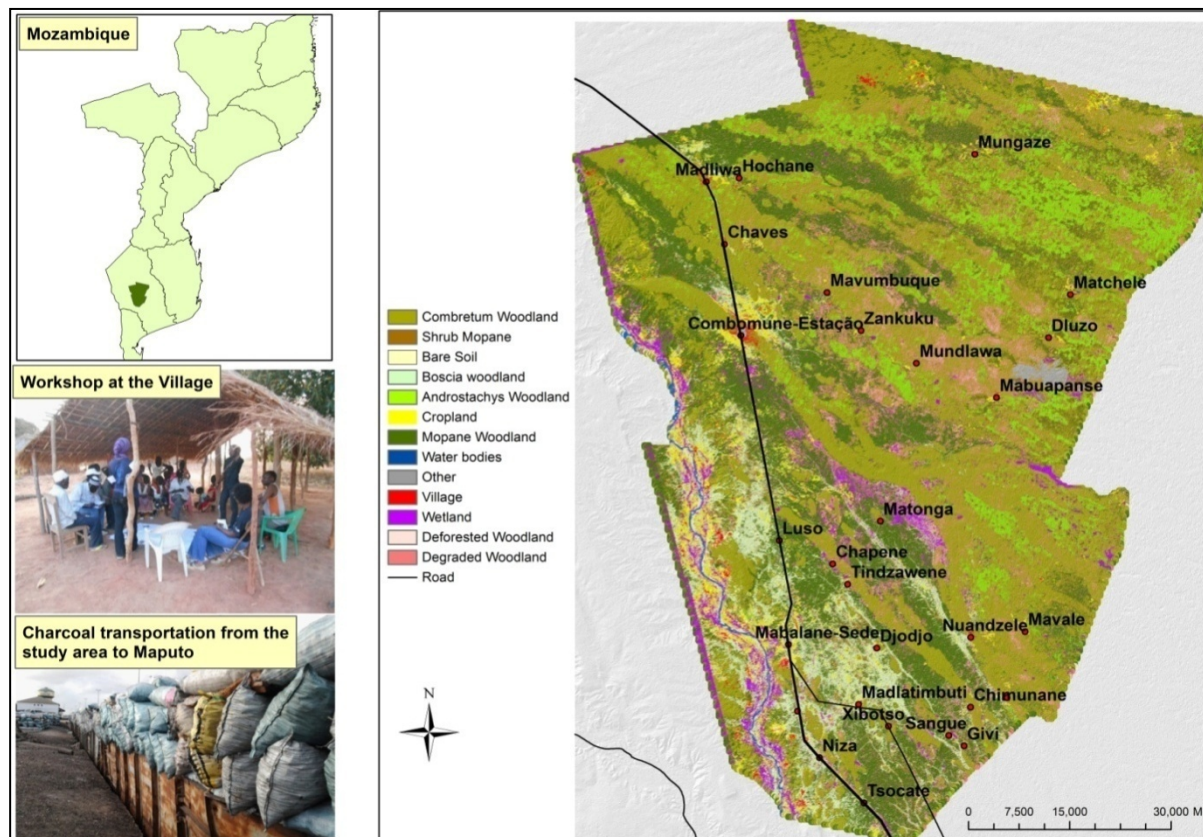
Figure 2.1 The study area (Mabalane District) with the intersection between current LULC and biomass loss from 2007 to 2014 shown as deforested and degraded woodland and LULC elements. The location of Mabalane District in Mozambique is shown in the upper left image

Ninety percent of the economically active population in Mabalane is dedicated to small-scale agricultural production, with an average land area of 1.5 to 3 ha per family (Levy & Kaufmann, 2014). Agriculture is the main activity in the area, being the main production system composed of staple crops such as maize, millet, and sorghum, and intercropped with beans and other vegetable crops (Ng'ang'a et al., 2012). Livestock rearing (goats, sheep, chickens, pigs and cattle) is an important agricultural activity due to the presence of suitable grazing areas. Following the end of the civil war (1992), the number of livestock in the area has been increasing (United Nation World Program [UNWP], 2006).

Other main activities in the study area include timber sales and harvesting of non-timber forest products such as bush meat and wild fruits. A notable feature of the economy is the presence of migrant workers (mainly coming from Inhambane province) involved in charcoal production, the majority of whom work in large-scale charcoal production camps (Baumert et al., 2016).

In the study area, the most important tree species used for charcoal production are Colophospermum mopane and Combretum sp. The annual charcoal production almost doubled in the study area between 2008 and 2009, from 23.87m³ to 43.16m³, due to an increase in demand for energy from urban centres such as Maputo (Mabalane, 2009). The study area currently has the highest number of licences for charcoal production in Gaza province and it is the most important supply area of charcoal to Maputo (Falcão, 2013; Luz et al., 2015). Puna (2008) attributed this increase in energy needs to have been the primary cause of deforestation, supporting earlier research by Moyo, O'Keefe & Sill (1993) who found that deforestation and the need for wood energy are among the major environmental problems in Mozambique.

*2.2 From BBNs and Scenarios to Maps*

2.2.1 Data and Knowledge Input

Xiang (2002) argued that a discrete Bayesian network consists of a directed acyclic graph and a corresponding

set of Conditional Probability Tables (CPTs). BBNs therefore qualifies the direct relationship between variables with arcs in the directed acyclic graph and quantifying these relationships with CPTs. In this study, the data used to build the CPTs came from qualitative information from social and economic surveys, biophysical surveys, grey literature data and expert opinion.

LULC classes were defined using data from forest plots and other ground observations, where woodland cover types were defined based on unique species compositions (Woollen et al., 2016). Current LULC maps were created using remote sensing data (Landsat 8 from May and October, sentinel 1 from November and Advanced Land Observing Satellite 2 acquired in November 2014), and image fusion techniques; the classification was done using Support Vector Machine classifier (SVMC) using ENVI version 5.2. SVMC is a non-parametric classifier, which includes a set of related learning algorithms that are used for classification and regression (Han, Chan, & Zhu , 2007) (see appendix C). The goal of image fusion techniques is to improve the spatial resolution, geometric precision and classification accuracy. An overall accuracy of 94% was achieved. The LULC map was modified to include areas of biomass loss from 2007 to 2014 (as deforested and degraded woodland), (Fig 2.1) derived from Advanced Land Observation Satellite (ALOS-2) Phased Array L-Band Synthetic Aperture Radar (PALSAR-2) (Luz et al. Forthcoming).

From the LULC map, we obtained the proportion of land occupied by each LULC category. These proportions were introduced into the BBNs below as a variable called "current land cover". Each state of the CPT represents one land cover class, and the probabilities represent its current extension (proportion of the study area occupied). The BBNs contained another variable called Future LULC, with the same structure. The probabilities of Future LULC are influenced by the current LULC and a combination of interventions. Expert knowledge was used to create CPTs for the future LULC.

Biophysical data and social surveys in the studied villages from Baumert et al. (2016), Vollmert et al. (Forthcoming) and Woollen et al. (2016) were used to obtain data about ES availability from each land cover class in the study area. From the forest data collected in the field, the proportion of total biomass within a plot belonging to any of the tree species used for different woodland-based ES was computed. For each LULC category, the mean proportion of total biomass was calculated from several plots, which was used to estimate the potential supply of each ecosystem service. The provision od woodland-based ES from each LULC category in comparison with other LULC categories was calculated (Table 3 and Appendix A). For more information about the process and data, see Woollen et al., (2016) and Zorrilla-Miras et al. (Forthcoming). These data were used to build the ES nodes in the BBN.

Table 1. Distribution of land cover in Mabalane (2014), derived from data fusion classification.

| Categories | ha | Area % |
|---|---|---|
| Degraded woodland | 162 149 | 3.4 |
| Shrub Mopane | 77 041 | 1.6 |
| Bare soil | 15 187 | 0.3 |
| Boscia woodland | 198 686 | 4.1 |
| Androstachys woodland | 434 576 | 9.0 |
| Combretum woodland | 2 166 335 | 44.8 |
| Cropland | 214 039 | 4.4 |
| Mopane woodland | 1 299 763 | 26.9 |
| Water bodies | 10 393 | 0.2 |
| Other | 33 237 | 0.7 |
| Villages | 27 299 | 0.6 |
| Wetlands | 191 775 | 4.0 |

## 2.2.2 BBN Construction

BBNs was selected because it is useful in situations where it is necessary to integrate qualitative and quantitative data (Smith, Howes, Price & McAlpine, 2007). In order to create the BBNs structure, consultation was undertaken with stakeholders via workshops (a national workshop in Maputo; a provincial workshop in Xai Xai, the capital of Gaza Province; and three workshops at the village level in Mabalane District) (more information about the workshops methodology in Zorrilla-Miras et al. (Forthcoming)). The aim of these workshops was to

stimulate local input and feedback about the Mabalane landscape and to obtain a local perspective of issues surrounding land use, ES provisioning and also how these are influenced by policy intervention and other factors.

During participatory workshops different interventions were proposed and discussed. Consultations with experts were carried out in order to select the most relevant interventions (see appendix B) proposed by the workshop participants. The participants identified the most important woodland-based ES in the Mabalane landscape. Only five important woodland-based ES that were identified by the participants were selected due to data availability and are supported by our empirical data. There were: charcoal, wild foods, grass, construction material and firewood. To model the selected woodland-based ES and future LULC, a BBN model with five output nodes was developed. Input nodes of the network are all connected to LULC changes, land management and topography. The model was created using Netica software (Norsys Software Corporation, https://www.norsys.com).

The BBNs has three types of variables: interventions, LULC and woodland-based ES supply variables (Fig. 2.2). The interventions were grouped into two different categories (see appendix B):

- Technical interventions with two elements such as improving technical capacity of communities and a forest management plan.
- Institutional interventions with four elements such as improve institutional capacities of communities; improve forest control; improve non-charcoal income activities; and adapting harvesting licences to community exploitation.

In order to translate the effect of the intervention into LULC, four intermediate variables were identified:

- Introduce bullet point reducing external charcoal production with two parameter values (same production and reduced production by external producers) (Baumert et al., 2016)
- Improved value chain with two parameter values (current access and improved access)
- Illegal charcoal production with two parameter values (low and high illegal production) Introduce new bullet point: "Reducing villagers production"
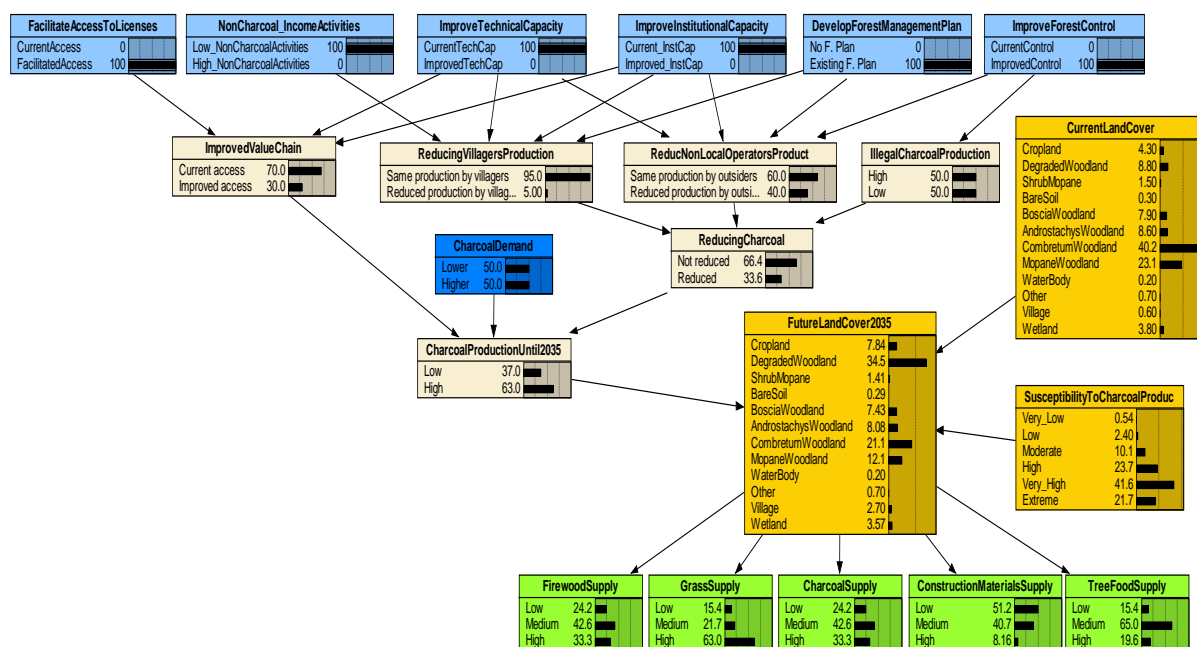


Figure 2.2 General BBNs for LULC and woodland-based ES scenarios in Mabalane District. Each variable represents a specific factor that is part of a system of interaction factors that influences the LULC change and woodland-based ES of rural in habitants. The links represent the direction of the relationship between specific variables. The probabilities of the interventions are set to represent Scenario Balanced

As soon as the BBNs model was poputated with data and knowledge, the model was inspected for its capability to compute future LULC and its consequences on woodland-based ES supply.

2.2.3 Scenarios

Using the BBNs, we quantitatively evaluated the consequences of the scenarios for land use change as well as for specific woodland-based ES (charcoal, firewood, grass, construction material and wild food). In developing the scenarios several workshops with stakeholders were carried out (more information about the workshops methodology in Zorrilla-Miras et al. (Forthcoming)). In these workshops, the definitions, themes and drivers of three scenarios were iteratively adapted (Table 2). The three scenarios of interventions in relation to charcoal demand are:

- Large private (Private): Very high charcoal demand than currrently and current interventions (current licence system, current technical capacity of communities, current institutional capacities of communities, no forest management plan, weak forest control and low non-charcoal income activities) due to the presence of large-scale charcoal production camps and low local power supplemented with low implementation of environmental and social policy provision;

- Small holder promotion (Small holder): Current charcoal demand and high interventions (facilitated access to licensing by the communities, improved technical capacity of communities, improved institutional capacities of communities, developed forest management plan, improved forest control and promote non-charcoal income activities) with increased local power and public policies (sustainable development); and

- Balanced: Higher charcoal demand than currently and mixed interventions with improved interventions (developed forest management plan, facilitated access to licensing by the communities and improved forest control) and current intervention (current technical capacity of communities, current institutional capacities of communities and low non-charcoal income activities) (Table 2).

The BBNs was used to explore the influence of different possible interventions from 2014 to 2035 on woodland-based ES and LULC (Fig 2.2).

Table 2. Themes and drivers of the three scenarios. Private (business as usual) is stronger public policies promoting large scale private sector and reduced local voice, accompanied with low implementation of social and environmental policy. Small holder (sustainable development) is the increase of local power. Balanced (a combination of both) lies somewhere between private and small holder

| Themes | Drivers | Large private investment | Small holder promotion | Balanced |
|---|---|---|---|---|
| Economic | Government promotion | Large international companies | Small local companies and cooperatives | Large and small companies |
| Technology | Increasing access to technologies (Internet and mobile phones) | Same as current/little change | High increase/fast increasing access | Slow increase/slow increasing access |
| Societal | Political involvement from the society | Same as current/little involvement | High increase/high involvement | Slow increase/medium involvement |
| Policy | Social and environmental policy implementation | Same as current/very weak implementation | Much improvement/strong implementation | Some improvement/ little implementation |
| Environment | Climate change | Medium impact | Medium impact | Low impact |

2.2.4 Susceptibility to LULC Change Index

To explore the spatial distribution of LULC change, a susceptibility index was derived by combining different spatial data relevant to LULC. The spatial information selected is Geographic Accessibility and Topographic Wetness Index (TWI) developed by Beven & Kirkby (1979). Research in other parts of the world has shown that there is a positive correlation between LULC changes and distance to roads (Liu, Iverson & Brown, 1993; Mertens & Lambin, 1997, Sprague & Oyama, 1999; Jansen, Bagnoli & Focacci 2008; Freitas, Hawbaker & Metzger; 2009). Geographic accessibility refers to the ease of reaching goods and services (distances and time that influence access to resources). It is one of the major determining factors that influences LULC change, and charcoal production in particular. In the Mabalane landscape, the most important factor that influences charcoal

production is accessibility to the markets (Freitas et al., 2009). Accessibility to markets in Mozambique is generally influenced by road availability and conditions, so distance from the main roads was used as an indicator of access to markets. Consideration was also paid to the distance from the town as market centres. Production of charcoal was found to be favourable around the villages. Therefore, distance from the village centres was also introduced as a way to incorporate the ease of access of charcoal production of the villages. Therefore, three distance maps were created: distance from paved roads, from the town centres and from the village centres. Euclidean distance equation was selected in computing the following parameter:

$$P\left(\frac{x}{d_{cr}}, d_{rt}\right) = [1 + exp. (\propto +\beta.d_{cr} + \varphi.d_{rt} \tag{1}$$

where:

$d_{cr}$: is Euclidean distance between the road and the rest of the pixels of the study area.

$d_{rt}$: is distance between the selling point on the road to the town and

$\propto, \beta\ and\ \varphi$ $\propto$, βandφare coefficients.

Water is a limiting factor for woodland ecosystem services and an important element for charcoal making, which is a highly demanding physical activity in an arid and warm environment. For this reason TWI was selected assuming that higher soil moisture can maintain a larger woodland ES supply. The TWI has been computed to quantify spatial scale effects on hydrological processes (Siviapalan et al., 1990; Famiglietti & Wood, 1991), to detect hydrological flow paths (Robson, Beven and Neal, 1992), and to identify biological processes (White & Running, 1994) as well as to characterise vegetation patterns (Zinko, Seibert, Dynesius & Nilsson, 2005). Soil moisture is regularly articulated as an index. For this paper, TWI was used which has been shown to present reasonable estimators of surface soil moisture (Quinn, Beven & Culf, 1995; Fei, Schibig & Vance, 2007). The TWI was derived from the digital elevation model (DEM-30m) with two classes. This index showed areas of potential soil moisture (with value 1) and dry area (with value 2).

After calculating the TWI, distance from road, villages and towns data were converted into percentages and combined as follows:

$$S = Dr + Dt + Dv + 1/TWI \tag{2}$$

where the susceptibility to LULC change index of a particular pixel to LULC (S) was determined as the addition of the distance from roads (Dr), distance from town (Dt), distance from villages (Dv) and the inverse topographic wetness index (TWI).

The output was divided into classes. Division into classes considers the highest and lowest value of the susceptibility to LULC change index according to the four indicators. A score ranging from 1 to 6 was assigned to each class, with a score of 1 attributed to the extreme susceptibility to LULC change (range between 0 to 10%, meaning short distances and high TWI), 2 to very high (range between 10 to 20 %), 3 to high (range between 20 to 40 %), 4 to moderate (range between 40 to 60 %), 5 to low (range between 60 to 80%) and 6 to very low susceptibility (range between 80 to 100%) (Fig. 2.3).The filling sink technique was used in order to fill any remaining sinks (Planchon & Darboux, 2002).

2.2.5 Linking BBNs and GIS

Linking BBNs and GIS allows users to perform probabilistic mapping (see Stassopoulou et al., 1998; Taylor 2003; Walker et al., 2004; Pullar & Phan 2007; Stelzenmuller et al., 2010; Morgan 2012; Verweij et al., 2012; Gonzalez-Redin et al., 2016). The QUICKscan tool allows application of BBNs models on spatial data. Verweij et al. (2012)'s methods were used in order to develop the model by integrating probabilistic and deterministic variables in analysing land use changes and woodland-based ES in a spatial perspective. The main advantages are that it allows the linkage of BBNs and GIS software. The data used have different resolutions and accuracies, so data preparation was required for the system (data input as raw measured from the field, qualitative data from workshops, vector and raster data from GIS). This approach supports an interactive workflow, where the scenario is defined by a BBNs, a value layer is created from grid layers created by the valuation tool and an overlay calculation is made to produce maps of scenarios and woodland-based ES. ESRI Arc Map version 10 was used to prepare the maps.

GIS data (current LULC and susceptibility to LULC change index) were added to the QUICKscan library. The relationship between LULC and woodland-based ES was developed, based on the biophysical data collected from the field (Table 3; more information in Appendix A). From these relationships, knowledge rules were established,

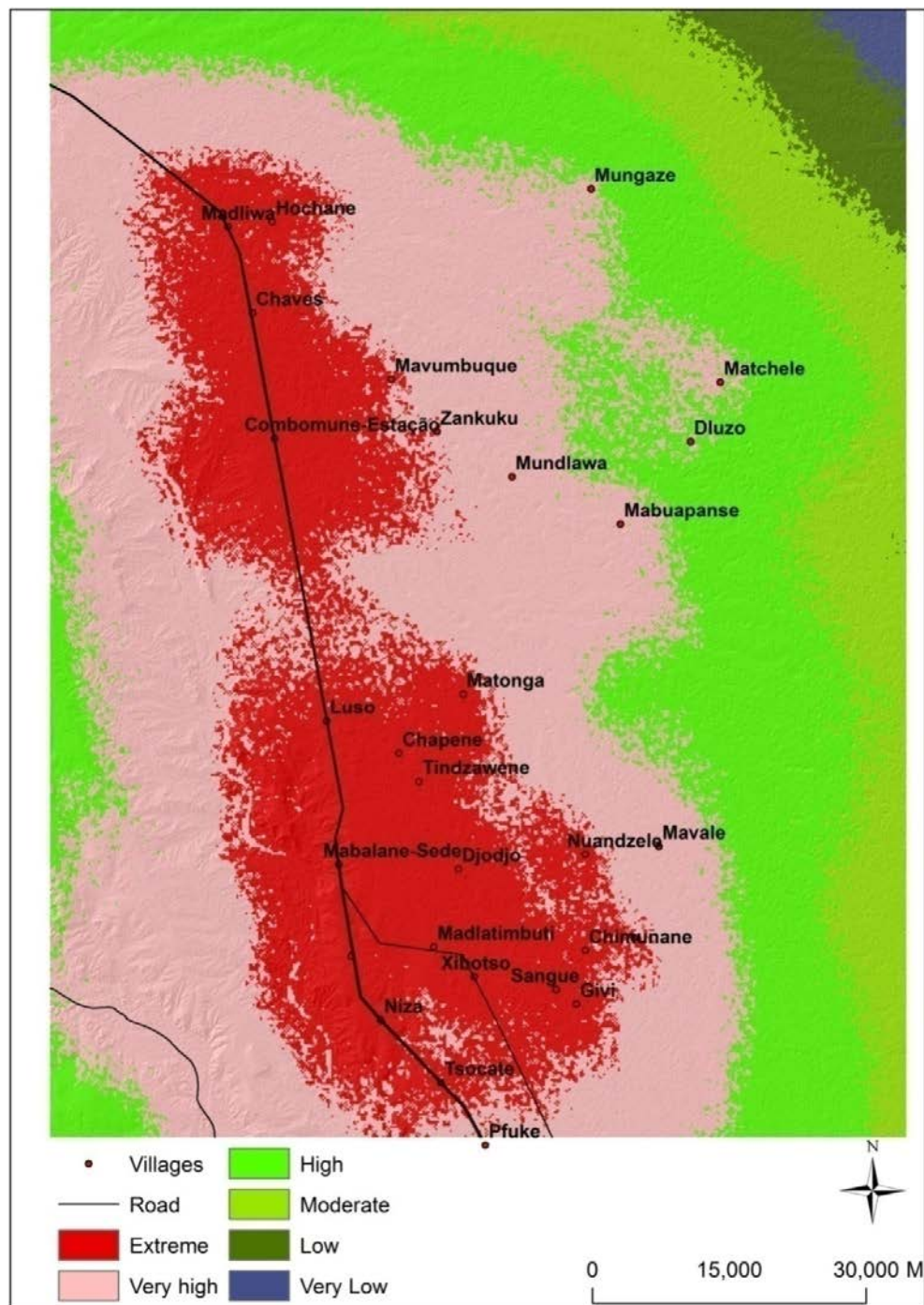allowing ecosystem service modelling.



Figure 2.3 Susceptibility to LULC change Index which provides a concise summary of the study area and shows potentially vulnerable areas in red

Verweij et al. (2012) argued that the rules use quantitative classifications or qualitative typologies to help formulate the objective. Rules were used to capture different options (scenarios) and the results from alternatives were aggregated and displayed in charts for visualisation in order to compare different scenarios at a single glance and facilitate investigation. Rules, BBNs, LULC map and susceptibility of LULC change index are enveloped with the generic Open MI interface.

Table 3. Relationship between land cover and woodland-based ES, based on field data from Mabalane.

| Woody cover | Charcoal | | | Firewood | | | Construction | | | Wild Food | | | Grass | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mg C/ha | Percentage | Class | Mg C/ha | Percentage | Class | Mg C/ha | Percentage | Class | Stems/ha | Percentage | Class | Mg/ha | Percentage | Class |
| *Androstachys* | 1.8 | 43 | M | 1.3 | 20 | M | 25.7 | 100 | H | 44.8 | 8 | M | 0.1 | 5 | M |
| Mopane | 4.0 | 95 | H | 6.8 | 100 | H | 6.6 | 26 | M | 552.1 | 100 | H | 0.7 | 62 | M |
| *Combretum* | 4.2 | 100 | H | 6.2 | 91 | H | 1.3 | 5 | M | 101.0 | 18 | M | 1.1 | 100 | H |
| *Boscia* | 0.0 | 0.0 | L | 0.1 | 0 | L | 3.3 | 13 | M | 518.5 | 94 | H | 0.8 | 75 | H |
| Shrub Mopane | 0.0 | 0.0 | L | 0.1 | 1 | L | 0.2 | 1 | L | 76.9 | 14 | M | 0.3 | 32 | M |

Mg/ha = mega grams dry weight per hectare; the highest value for each ecosystem service was considered as 100%, H = high (>67%), M = medium (5-67%), L = low (< 5%) and other land cover categories very low.

Two alternative approaches were tested in order to develop future LULC and woodland-based ES models: modelling a 'maintain probability distribution' (in cell counts) and modelling the 'highest probable state'. In this study, modelling a 'maintain probability distribution' was selected to make the results more policy oriented. This method maintains the overall probability distribution in modelling woodland-based ES in comparison to the original BBNs probability distribution (Stewart 2011).

At a supplementary workshop with Mozambican experts at district level, the first draft of LULC maps were presented and examined and the knowledge rules were reviewed in light of the outputs. The modelling approach, the quality and scale of the inputs were investigated.

## 3. Results

### 3.1 Estimated Land Use and Land Cover Change Under Different Scenarios

The results from the key LULC investigation give a clear and robust message up to the year 2035 (Table 4 and Fig. 3.1). The significant shifts in LULC from forested areas towards agricultural land and degraded woodland is due to the overall demand for agricultural and charcoal products. Table 4 shows under the three scenarios that degraded woodland and agricultural fields increased, having gained especially from Mopane and Combretum woodland. Under the Small holder promotion scenario there is little change in LULC elements such as: Mopane and Combretum woodland. The Balanced scenario also shows an overall increase in degraded woodland throughout the study area.

Table 4. Comparison between LULC elements in the current situation and 2035 under the three scenarios.

| LULC types | Present | | Large private | | Small holder | | Balanced | |
|---|---|---|---|---|---|---|---|---|
| | ha | % | ha | % | ha | % | ha | % |
| Degraded woodland | 23414 | 3.23 | 367076 | 50.54 | 107342 | 14.77 | 231573 | 31.88 |
| Shrub Mopane | 11124 | 1.53 | 10470 | 1.44 | 10459 | 1.44 | 10460 | 1.44 |
| Bare soil | 2193 | 0.30 | 2153 | 0.30 | 2148 | 0.30 | 2149 | 0.30 |
| *Boscia alb.* woodland | 57570 | 7.93 | 54071 | 7.44 | 54099 | 7.45 | 54110. | 7.45 |
| *Androstachys* woodland | 62752 | 8.64 | 59011 | 8.12 | 58957 | 8.12 | 58981 | 8.11 |
| Combretum woodland | 312818 | 43.06 | 97194 | 13.38 | 247217 | 34.03 | 175411 | 24.15 |
| Cropland | 30907 | 4.25 | 56684 | 7.80 | 56685 | 7.80 | 56728 | 7.81 |
| Mopane woodland | 187685 | 25.84 | 28193 | 3.88 | 137864 | 18.98 | 85491 | 11.77 |
| Water bodies | 1500 | 0.21 | 1500 | 0.21 | 1500 | 0.21 | 1500 | 0.21 |
| Other | 4799 | 0.66 | 4799 | 0.66 | 4799 | 0.66 | 4799 | 0.66 |
| Village | 3941 | 0.54 | 19216 | 2.65 | 19300 | 2.66 | 19175 | 2.64 |
| Wetland | 27692 | 3.81 | 726401 | 3.58 | 26025 | 3.58 | 26020 | 3.58 |

Large private investments show much more dramatic changes, with the Mopane and Combretum woodland being largely degraded. Change from "natural" land cover elements (Albizia versicolor, Boscia albitrunca, Androstachys johnsonnii woodland as well as wetlands) to cropland have been set constant under the three scenarios because in

this arid and poor soil region agriculture is not usually done in the degraded woodlands from charcoal production. The growth in human settlements was also shown constant under the three scenarios as charcoal production does not have a great direct impact in population change.

The scenario maps showed that changes from the current LULC map are dominated by changes occurring in the central and southern zones of the study area. The development of agricultural and degraded lands along accessible routes and close to the towns (Mabalane-Estação and Combomune) and roads is a common feature of the scenario maps. Villages were gradually increasing in size in the three scenarios as a result of an ever-growing population. Under Small holder promotion scenario there is little change in the distribution and cover of woodlands, as all are assumed to be well protected and governed due to the improved interventions. Agricultural land expansion is limited to the areas close to the cities and roads. Large private investments scenario shows a dramatic change in Mopane and Combretum woodlands, reflecting ongoing woodland degradation for charcoal. Under the Balanced scenario there is a moderate change in the spatial distribution and woodland cover, but the greatest change is in woodland degradation in the central part of the study area.
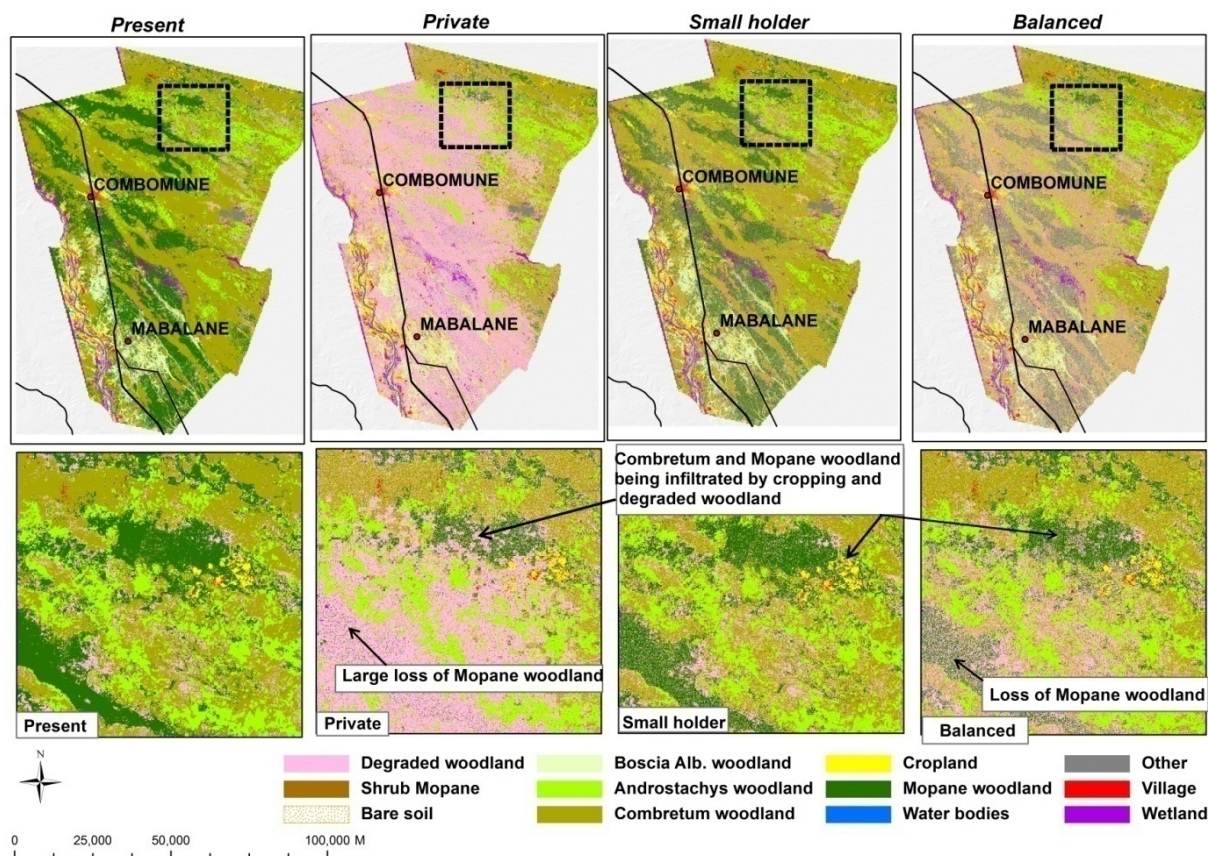


Figure 3.1 Spatial distribution of LULC for 2014 and 2035 in Mabalane, southern Mozambique, under *present situation*, *large private investments* (Private), *small holder promotion* (Small holder) and *Balanced* scenarios

### 3.2 Impact of Changing Land Use and Land Cover on Woodland-Based ES Supply

The woodland-based ES supply was derived for each of the current LULC elements in the study area. The percentage of the district area with high potential for charcoal supply shows changes from 2014 to 2035 (69% in present situation, 17% in Large private investment, 53% in Small holder promotion and 36% in Balanced) (Fig. 3.2). Figs. 3.3 and 3.4 summarise the status of the woodland-based ES from 2014 to 2035 under those scenarios. The colour indicates the assumed condition of each ecosystem for each of the given services, with red indicating very low supply, yellow indicating low supply, pale green indicating medium supply and green indicating high supply. Under the three scenarios the results also show an overall decrease in high supplies of firewood, charcoal, construction material and wild food from the present situation to 2035, but an increase in grass supply. Changes are greater under Large private investments and Smaller under the small holder promotion scenario. During supplementary workshops at district at national level, the results were presented to with Mozambican experts.

They did not translated major comments, what we have considered as a positive validation of the results obtained.
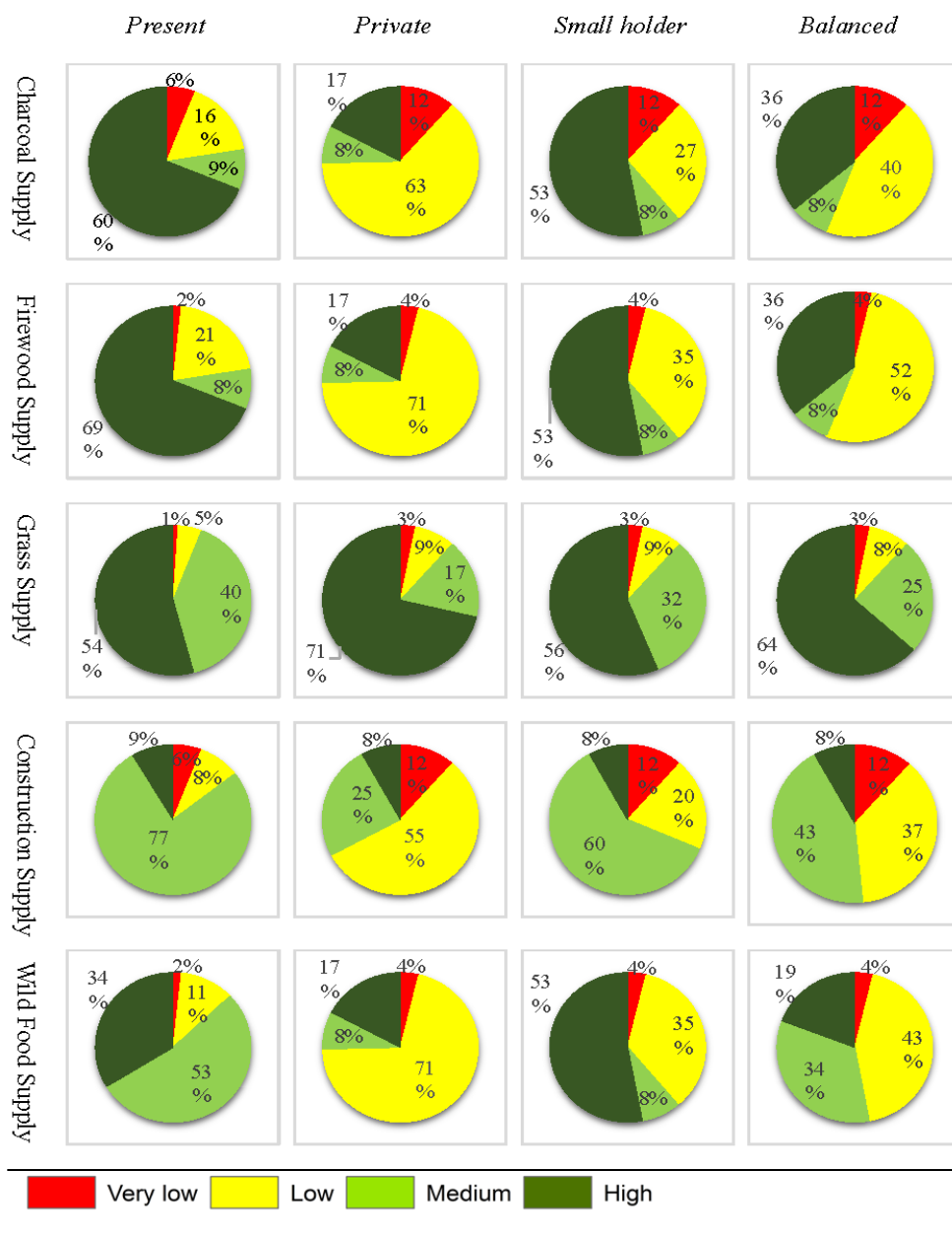


Figure 3.2 Conditional probabilities for present situation and future woodland-based ES supply in Mabalane, southern Mozambique, under *Large private investment* (Private), *Small holder promotion* (Small holder) and *Balanced* scenarios

Figs. 3.3 and 3.4 show the spatial distribution of the woodland-based ES from the current situation to 2035 under the three scenarios in the study area. The green patches represent a departure from a high ecosystem service supply and the red represents a low ecosystem service supply. From visual interpretation of woodland-based ES supply, it is clear that high supplies of charcoal, firewood and wild food supplies are dominant under both the present situation and Small holder promotion, but low supplies are dominant under Private and Balanced.
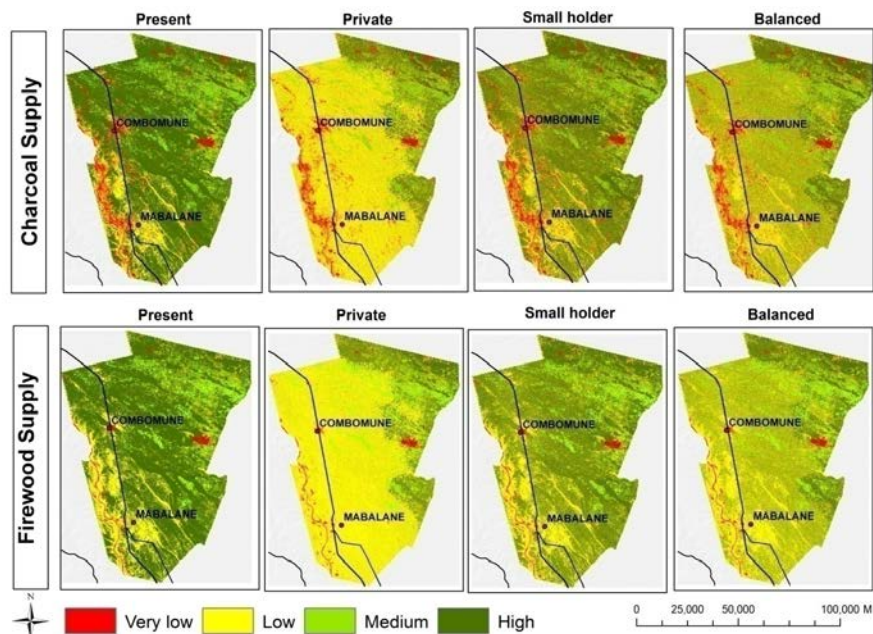
Figure 3.3 Spatial distribution of current and future fire wood and charcoal supplies in Mabalane, southern Mozambique, under *Large private investment* (Private), *Small holder promotion* (Small holder) and Balanced scenarios
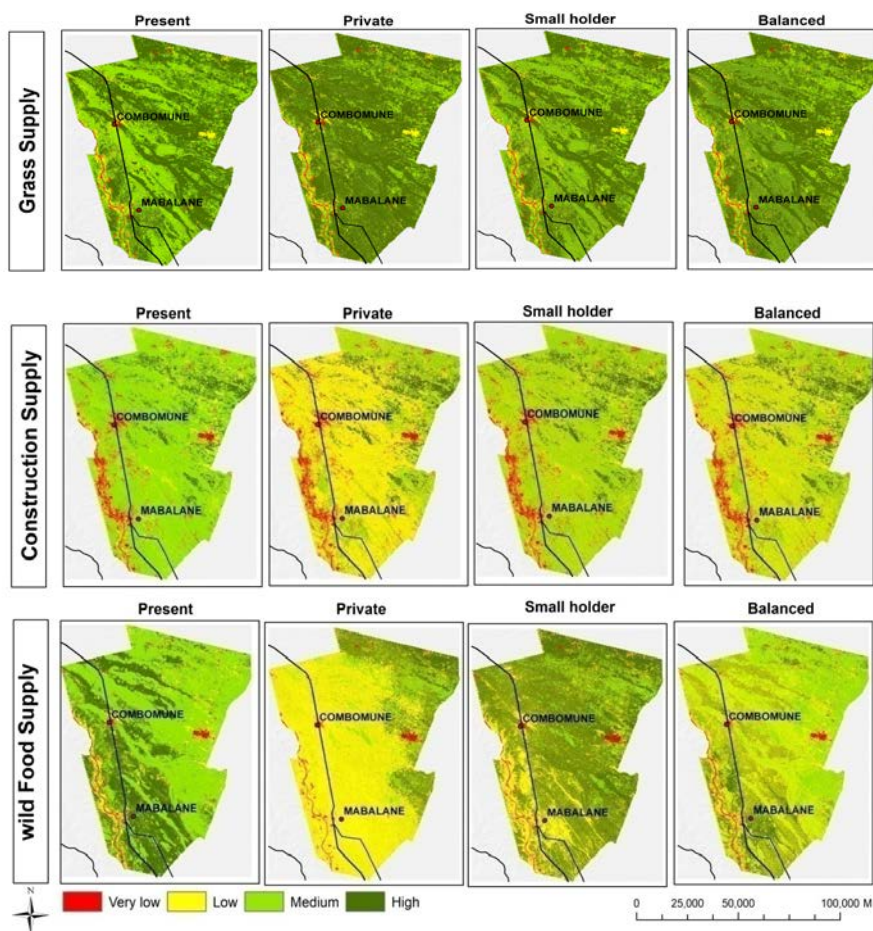


Figure 3.4 Spatial distribution of current and future grass, construction material and wild food supplies in Mabalane, southern Mozambique, under *Large private investment* (Private), *Small holder promotion* (Small holder) and *Balanced* scenarios

## 4. Discussion

The paper describes a method to translate qualitative scenarios into quantitative future LULC maps that can be used in developing woodland-based ES models based on the combination of different approaches. The first approach provides a qualitative output from the participatory workshops. The second approach uses BBNs and provides more quantitative outputs in the form of probabilities. Nakicenovic & Swart (2000) maintain that scenarios are used to assist in the understanding of possible future developments of the complex systems that typically have high levels of scientific uncertainty. This is particularly true of the Mabalane landscape, where little is known about the effects of dynamic changes in woodland-based ES. The third approach uses QUICKscan software, in order to bring together different relevant perspectives and knowledge. This approach holds great potential. Ames & Anselmo (2008) argued that the use of BBNs in this kind of probabilistic map algebra is currently delayed only by the lack of dedicated tools to support the analysis. However, the QUICKScan software does give the ability to integrate BBNs with spatial data and geovisualisation. With these approaches, we obtained maps representing each scenario that can be used to identify which communities are most susceptible to change in their woodland-based ES. This provides useful discussion material when attempting to improve local inhabitants understanding the consequences of their actions, or inaction.

The three scenarios were articulated and parameterised in order to create alternative LULC futures for Mabalane. The impacts of changes in the spatial distribution of the LULC elements were illustrated. The models of woodland-based ES such as charcoal, firewood, construction material, grass and wild food showed that the high demand for charcoal combined with low interventions (Large private investments scenario) would put the southern and central zone of the study area at risk of losing the majority of their woodland-based ES. According to this scenario, charcoal production will be higher, the tree cover will decrease greatly (especially Mopane and Combretum woodlands) and availability of the woodland-based ES will be highly affected. The visual interpretation within the Large private investments scenario showed that losses were variable and influenced by location. Roads and towns play an important role in the decrease of woodlands and ecosystem service supply.

Smallholder promotion scenario (a more sustainable future) shows that, if the Mabalane landscape experiences low charcoal demand and improved interventions, illegal charcoal production will be low and a slow decrease of woodland and ecosystem service availability will be observed. The Balanced scenario shows that the LULC and the woodland-based ES (firewood, construction material and wild food supplies) changed negatively due to charcoal production. The grass supply increases as a result of charcoal production, suggesting that future grass supply can be an alternative source of income for rural people in the study area.

The three scenarios presented here show how it is possible to move from the narrative into quantitative analysis by developing rules based on participatory workshops combined with knowledge-rules developed from field data (biophysical data). The skeleton patterns are clear, with a high charcoal supply in Mopane and Combretum woodland, high firewood supply in Mopane and Combretum woodland, high construction material supply in Androstachys woodland and a high wild food supply in Mopane and Boscia woodland, strongly suggesting that the conclusions are robust.

The LULC dataset which supports our modelling is known to be acceptable with 87% accuracy assessment (based on validation data collected in the field). The modelling presented here was undertaken with a 30 m grid (pixel size). A large amount of fieldwork would be needed to identify all important woodland-based ES data, but such information is not available for large areas. As additional datasets for woodland-based ES emerge, there is hope to improve these inputs and capture all the most important woodland-based ES.

LULC and woodland-based ES are spatially distributed in nature, consequently the maps produced in well-developed LULC scenarios can help to quickly identify areas with high probability of land use conversion and subsequent losses of both habitat and potential ecosystem reserves (Wilson, Sleeter & Davis, 2014). LULC and ecosystem service scenarios are imperative for land managers to visualise alternative uses of land in order to optimise management practices and improve planning (Alcamo, Kok, Busch & Priess, 2008). LULC change mapping has been widely used when modelling future scenarios using a variety of techniques (Verburg & Overmars, 2009; Rounsevell et al., 2006; Hewitt, van Delden & Escobar, 2014; Van SchrojensteinLantman, Verburg, Bregt & Geertman, 2011), but only recently BBNs have been used for this purpose (Celio, Koellner & Grêt-Regamey, 2014). QUICKScan has proved to be a useful tool for doing so in a direct and straight-forward way. The software also adds the applications that make it easier to communicate results to experts and stakeholders (Verweij et al., 2016). Although the link between the BBNs and the GIS software is done through a pixel basis, we have not conceptualized the commands as individuals acting in the landscape (like agent base models or cellular automata), but as changing general drivers based on spatial information. Production functions have been used to

link LULC elements to ES provision and, using knowledge rules, its linkage through QUICKScan has proved to be transparent and functional.

## 5. Conclusions

In conclusion, this research showed how BBNs and GIS can be used in order to create alternative LULC futures for the Mabalane landscape. The multiple outputs under different LULC scenarios facilitate stakeholder engagements, and improve the understanding of the interaction between LULC changes and woodland-based ES. This helps stakeholders to easily visualise consequences of LULC changes under different conditions and interventions. Spatial distribution of woodland-based ES under the three different scenarios show that the supply of these woodland-based ES, except for grass supply will decrease. This negative change of LULC and woodland-based ES is due to the changing disturbance pattern, driven by lack of policy interventions and   greater demand for charcoal. These negative changes in woodland-based ES will be mainly observed in the central and southern part of Mabalane District. The major benefit of this work is its ability to involve the stakeholders from the input preparation to the output validation, not only to collect the information for development of scenarios and BBNs. The process of selecting the datasets was participatory. The study suggests that the Government and NGOs concerned should improve policies and strategies to achieve a balanced and sustainable development in the Mabalane landscape and its environs.

### Software and Data Availability

ESRI Arc Map version 10 is available at   www.esri.com, Netica version from Norsys Software Corp is available at www.norsys.com and QUICKscan for linking BBNs and GIS is available at www.quickscan.pro (European Environment Agency and Alterra Wageningen UR). Data used in this work were collected as components of the ACES: Livelihoods and Land Use change in Mozambique project. Data can be accessed   by personal request to the lead author. The contact information for the ACES project is available at https://miomboaces.wordpress.com.

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### Conflicts of Interest

The authors declare no conflict of interest.

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**Appendices**

**Supplementary material:** Bayesian networks and Geographic Information Systems as a tool in understanding land use and land cover change, Mabalane woodland -Mozambique

**Appendix A**

Method followed to introduce Land Use and Land Cover (LULC) categories and ES supply relationships in the BBNs and QUICKScan

The supply of woodland-based ecosystem services by each LULC category was calculated based on field data and on production functions that set the proportion of the biomass in each land cover class that deliver each ecosystem service (Woollen et al. 2016) (Table A.1). From that table, we calculated the proportion of ES supplied by each land cover class in relation with the values of the land cover class having the maximum scores (Table A.1). Finally, each land cover class was classified as High (>67%), Medium (67%-5%), and Low (<5%) based on the relative importance of the ES in each village in relation to the maximum supplied village (Table A.1). Other land cover classes (Cropland, Degraded woodland, Bare soil, Water body, Other, Village and Wetland) were classified as having low values in all ES supply, except Degraded woodland (Degraded Combretum and Mopane woodland after charcoal making) that was allocated Medium supply for charcoal, firewood (because the villagers still produce charcoal from previously used areas), and food from trees (because not all fruit trees are cut for charcoal making), and High supply for grass (because the open structure after charcoal production favors an increase of grass) (Table A.1).

Finally we translated those proportions into the Conditional Probability Tables giving 99.8 probabilities of ES supply to the previously fixed relationships. An example can be observed in Table A.3.

Table A.1 Relation between land cover and woodland-based ES based on the field data. The relationships were examined by Woollen et al. (2016). The land cover elements were evaluated in the term of their area of supply

| Land cover | Charcoal (mgC/ha) | Firewood (mgC/ha) | Construction materials (stems/ha) | Food from trees (stems/ha) | Grass (mgC/ha) |
|---|---|---|---|---|---|
| Androstachys | 1.8 | 1.3 | 25.7 | 44.8 | 0.1 |
| Mopane | 4.0 | 6.8 | 6.6 | 552.1 | 0.7 |
| Combretum | 4.2 | 6.2 | 1.3 | 101.0 | 1.1 |
| Boscia | 0.0 | 0.0 | 3.3 | 518.5 | 0.8 |
| Shrub mopane | 0.0 | 0.1 | 0.2 | 76.9 | 0.3 |
| *Percentage* | | | | | |
| Androstachys | 43% | 20% | 100% | 8% | 5% |
| Mopane | 95% | 100% | 26% | 100% | 62% |
| Combretum | 100% | 91% | 5% | 18% | 100% |
| Boscia | 0% | 0% | 13% | 94% | 75% |
| Shrub mopane | 0% | 1% | 1% | 14% | 32% |
| *Classification* | | | | | |
| Androstachys | Medium | Medium | High | Medium | Medium |
| Mopane | High | High | Medium | High | Medium |
| Combretum | High | High | Medium | Medium | High |
| Boscia | Low | Low | Medium | High | High |
| Shrub mopane | Low | Low | Low | Medium | Medium |

Table A.2 Estimated ES supply for non-woodland land cover categories. For the purpose of display and analyse, each map of woodland-based ecosystem services was grouped into high, medium, low and very low supply classes

| Land cover | Charcoal (mgC/ha) | Firewood (mgC/ha) | Construction materials (stems/ha) | Food from trees (stems/ha) | Grass (mgC/ha) |
|---|---|---|---|---|---|
| Cropland | Low | Low | Low | Low | Low |
| Degraded woodland | Medium | Medium | Low | Medium | High |
| Bare soil | Very low | Very low | Very low | Very low | Very low |
| Water Body | Very low | Very low | Very low | Very low | Very low |
| Other | Low | Low | Low | Low | Low |
| Village | Low | Low | Low | Low | Low |
| Wetland | Low | Low | Low | Low | Low |

Table A.3 Example showing how the probabilities of supplying charcoal were introduced in the CPTs defining the land cover – ES supply relationship

| Land cover categories | Charcoal supply | | |
|---|---|---|---|
| | Low | Medium | High |
| Androstachys | 0.1 | 99.8 | 0.1 |
| Bare soil | 99.8 | 0.1 | 0.1 |
| Boscia | 99.8 | 0.1 | 0.1 |
| Combretum | 0.1 | 0.1 | 99.8 |
| Cropland | 99.8 | 0.1 | 0.1 |
| Degraded woodland | 0.1 | 99.8 | 0.1 |
| Mopane | 0.1 | 0.1 | 99.8 |
| Other | 99.8 | 0.1 | 0.1 |
| Shrub mopane | 99.8 | 0.1 | 0.1 |
| Village | 99.8 | 0.1 | 0.1 |
| Water Body | 99.8 | 0.1 | 0.1 |
| Wetland | 99.8 | 0.1 | 0.1 |

**Appendix B**

Description of the different intervention proposed by the participants during the workshops.

1. Technical intervention with two elements such as improved technical capacity of communities and woodland management planning.

    a. Improve technical capacity of communities: for the improvement of the charcoal production some technical capacities must be increased in at least a minimum number of villagers. This technical capacity must cover: knowledge of the wooded area of the community and the diversity of species included their knowledge of some properties of the most common trees such as growth rate, time necessary for the regeneration of the woodland after different interventions e.g., silviculture or forestry techniques (pruning, thinning, seeding, etc.); knowledge of how to improve the charcoal process (e.g.; improved kilns); knowledge of the benefits the woodland produces and the risks of losing them; improving the capacity to design and manage a simple woodland management plan.

    b. Woodland management plan. Once the villagers have the capacities above, they will be able to design and manage a woodland management plan. A major change in comparison with the current situation would be that a small group is able to read a topographical map, to design a set of different exploitation areas based on the time needed for the regeneration of the areas, and to design a plan of harvesting rotation of those areas.

2. Institutional interventions with three elements such as improved institutional capacities of communities, improving control of the woodland areas and adapting licences to community exploitation.

    a. Improve institutional capacities of communities would imply the difficult task of providing the villagers with the tools to be able to organise themselves and be able to run associations.

        i. This is necessary to realise the proposed woodland management plan. Without a committee or association, i.e. a group of villagers that can guide, help and control the application of the plan, the plan is less likely to be applied. This should include a way to be able to control external or illegal charcoal producers.

        ii. Institutional capacity is also necessary for participation in a charcoal association that commercialise the charcoal produced. It is not necessary to help the community to create an association, but to give them the tools to be able to create and, more important, for maintaining and participating in its decisions over time.

    b. Improving forest control by the formal institutions is also necessary. Presently the control is weak. Supporting and incentivising communities in the control of illegal producers would be the best way of improving the current situation. Local community participation can be key to identify illegal producers. In collaboration with forest officers they could locate and halt illegal activities through the application of official penalties.

    c. Adapting licences to community exploitation: two main changes need to be made in the regulation and implementation of the licenses scheme for charcoal production. The first is to allow the associations created by the villagers to produce a larger amount than currently: the licence volume of 1000 steres per year is very low for communities where charcoal is a widespread activity (Baumert, et al., 2016). A larger allowance for community associations would increase the revenues from taxes both for the community and for the government. The second change would imply a more rigorous control of external producers and their obligations such as to negotiate exploitation within the respective community during a community meeting. This would minimise corruption and would increase the visibility and importance of charcoal production for the community.

        Both categories of intervention are strongly linked, so without institutional intervention, the technical intervention will not be effective in the context of sustainable charcoal production. Previous attempts in this direction in the study area have shown that sustainable use of the woodland can be achieved only if the villagers have an alternative source of income, which can substitute or improve the income they presently receive from charcoal production.

**Appendix C**

**Description of the LULC Method.**

This section describes the method of LULC classification. This study used a combination of:

- The Landsat8/OLI surface reflectance product with 30-m resolution, which was download from the United States Geological Survey.

- The sentinel-1 data product with Level-1 Ground Range Detected (GRID), image mode IW, was acquired in November 2014.

- The Advanced Land Observing Satelite-2 (ALOS-2) was used with the Phased Array type L-band Synthetic Aperture Radar-2 (PALSAR-2) acquired in November 2014.

Pre-processing

The sentinel 1 and ALOS-2 PALSAR-2 data were calibrated, filtered to despeckle using Lee 5000 were used and terrain corrected before application. During terrain correction a Panchromatic from Landsat 8 (Band 8) data with 15 m resolution has been used and the data was resampled to a pixel size of 25 m ground resolution. The digital number values (DN) of both SAR data were converted into backscatering value in decibel (db) scale. Mosaic, clip, and exported the sentinel 1 and ALOS-2 PALSAR-2 data into geotiff were done. using sentinel toolbox was used for the processing the both SAR data.

Landsat8/OLI acquired in May and September 2014 were converted to surface reflectance. Panchromatic and cirrus band were not used in this study. Computing NDVI, TNDVI and NDWI were done and stacked process were carried up using Sentinel 1 ALOS-2 PALSAR-2, Landsat acquired in May and October, NDVI, TNDV and NDWI.

Image Classification

The woodland Land cover classes were defined using data from forest plots and other ground observations (see table C.1), where woodland land cover types were defined based on unique species compositions (Woollen et al., 2016). The new training data from field data and high resolution images of Google Earth for obvious classes (non-woodland classes) such as water bodies and urban areas (see Table C.2). 75% of the data were randomly selected for training and 25% for validation data. Image fusion techniques and the classification based to Support Vector Machine classifier (SVMC) using ENVI version 5.2. SVMC is a non-parametric classifier, which includes a set of related learning algorithms that are used for classification and regression (Han et al., 2007). Kappa statistics and overall accuracy assessment was applied to compare the accuracy of classified data.

Table C.1 Table showing the woodland classes connected with number of polygon using for the classification process

| Classes | No polygons | Area (Mean) in ha |
| --- | --- | --- |
| Androstachys johnsonii woodland | 28 | 0.126 |
| Mopane woodland | 51 | 0.126 |
| Combretum – Guibortia - Strychnos woodland | 68 | 0.126 |
| Boscia albitrunca woodland | 13 | 0.126 |
| Aloe marlothii dominated Mopane shrubland | 3 | 0.126 |
| Albizia versicolor - Sclerocarya birrea - Mixed woodland | 3 | 0.126 |

Table C.2 Table showing the non-woodland classes connected with number of polygon using for the classification process

| Classes | No Polygons | Area (Mean $\pm$ SD) |
| --- | --- | --- |
| Bare soil | 12 | $2.1 \pm 3.6$ |
| Fallows | 7 | $1.8 \pm 1.5$ |
| Fields | 68 | $4.7 \pm 5.1$ |

| | | |
|---|---|---|
| Gaderns | 5 | $0.64 \pm 0.6$ |
| Permanent water bodies | 8 | $3.5 \pm 4.5$ |
| Towns with metallic roofs | 10 | $17.9 \pm 36.1$ |
| Villages with grass roofs | 52 | $8.9 \pm 1.7$ |
| wetlands seasonal water | 51 | $4.3 \pm 8.3$ |

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