# Environmental conservation and social benefits of charcoal production in Mozambique

**Citation for published version:**
Zorrilla Miras, P, Mahamane, M, Metzger, M, Baumert, S, Vollmer, F, Luz, AC, Woollen, E, Sitoe, A, Patenaude, G, Nhantumbo, I, Ryan, C, Paterson, J, Matediane, MJ, Ribeiro, N & Grundy, I 2018, 'Environmental conservation and social benefits of charcoal production in Mozambique', *Ecological Economics*, vol. 144, pp. 100-111. https://doi.org/10.1016/j.ecolecon.2017.07.028

**Digital Object Identifier (DOI):**
10.1016/j.ecolecon.2017.07.028

**Link:**
Link to publication record in Edinburgh Research Explorer

**Document Version:**
Publisher's PDF, also known as Version of record

**Published In:**
Ecological Economics

Ecological Economics 144 (2018) 100–111

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

# Environmental Conservation and Social Benefits of Charcoal Production in Mozambique

Pedro Zorrilla-Miras[a,*], Mansour Mahamane[b], Marc J. Metzger[a], Sophia Baumert[b], Frank Vollmer[a], Ana Catarina Luz[d], Emily Woollen[a], Almeida A. Sitoe[b], Genevieve Patenaude[a], Isilda Nhantumbo[c], Casey M. Ryan[a], James Paterson[a], Maria Julieta Matediane[c], Natasha Sofia Ribeiro[b], Isla M. Grundy[e]

[a] The University of Edinburgh, School of GeoSciences, Edinburgh, UK
[b] Universidade Eduardo Mondlane, Faculty of Agronomy and Forest Engineering, Mozambique
[c] International Institute for Environment and Development, UK
[d] cE3c – Centre for Ecology, Evolution and Environmental Changes, Facudade de Ciências da Universidade de Lisboa, Portugal
[e] Department of Biological Sciences, University of Zimbabwe, Harare, Zimbabwe

ARTICLE INFO

*Keywords:*
Bayesian Belief Networks
Land use Land Cover Change
Poverty Alleviation
Well-being
Ecosystem Services
Social-Ecological Systems

ABSTRACT

Charcoal is an important source of energy and income for millions of people in Africa. Its production often drives forest degradation and deforestation which have impacts on the local people that remain poorly understood. We present a novel methodology for analysing the contribution of woodland ecosystem services (ES) to rural well-being and poverty alleviation, which takes into account access mechanisms to ES, trade-offs between ES, and human response options. Using a participatory approach, a set of land use change scenarios were translated into a probabilistic model that integrates biophysical and social data. Our findings suggest that in highly forested areas woodland degradation does not have a critical impact on the local use of the three ES studied: charcoal, firewood and grass. Social factors show the largest impact on the quantity of charcoal produced, e.g. female-headed households experience the greatest barriers to access charcoal production. Participating in forest associations and diversifying income activities lead to greater charcoal production. Results show that charcoal production increases some aspects of well-being (e.g. household assets), but does not decrease acute multi-dimensional poverty. Great efforts are required to reach a charcoal production system that alleviates poverty, improves environmental sustainability, and provides a reliable charcoal supply.

## 1. Introduction

Charcoal production and trade provides work for millions of people in Africa (IEA, 2014; Openshaw, 2010; Ryan et al., 2016), is the main cooking fuel in many African urban centres (IEA, 2014) and its demand is increasing because of population growth and migration from rural to urban areas (IEA, 2014, Peter and Sander, 2009, Openshaw, 2010, Tomaselli, 2007). In rural areas of Sub-Saharan African countries (where 80% of residential energy demand is for cooking) more than 90% of the population uses firewood for cooking and less than 5% use charcoal; in urban areas the figures change to 25% relying on firewood and nearly 50% on charcoal (IEA, 2014). Charcoal is a provisioning ecosystem service, and increasing evidence suggests ecosystem services (ES), i.e. the benefits people obtain from ecosystems (MEA, 2005a), contribute to the well-being of the rural population in Africa, e.g. provisioning services (firewood, charcoal, grass, fruits, water), regulating services (erosion control, water purification) and cultural services (sacred places, recreation) (Cavendish, 2000; Dewees et al., 2010; Fisher, 2004; Kamanga et al., 2009; Shackleton et al., 2007). As such, charcoal can be an important woodland based provisioning ES for African rural populations, but at the same time can be a driver of deforestation and forest degradation through intensive and selective wood extraction (Chidumayo and Gumbo, 2013; Hosonuma et al., 2012; Luoga et al., 2002; Ryan et al., 2014). Therefore, the land use and land cover change (LULCC) produced by charcoal production is a major driver affecting future provisioning of ES and consequently can have important consequences for human well-being. Despite growing socio-ecological systems understanding (Fischer et al., 2015), the resulting complexities of charcoal production and trade for sustainable land management and local livelihoods remain poorly understood. For

* Corresponding author at: Drummond Street, Geography Building, School of GeoSciences, University of Edinburgh, Edinburgh EH8 9XP, UK.
*E-mail address:* pedro.zorrilla-miras@ed.ac.uk (P. Zorrilla-Miras).

http://dx.doi.org/10.1016/j.ecolecon.2017.07.028
Received 17 October 2016; Received in revised form 19 July 2017; Accepted 19 July 2017

example, not only ecosystem services (ES) supply is key for the well-being of local populations, but also the way the services are used and distributed (Daw et al., 2011; Fisher et al., 2014; Kalaba, 2014; Suich et al., 2015).

In Mozambique, 15% of the population participates in the charcoal market (Cuvilas et al., 2010), which is estimated to have an annual value of 250 million USD (EUEI/GIZ, 2012). Around 70–80% of the urban population uses charcoal as primary energy source and demand is rising with rapid urban population growth (Brouwer and Falcão, 2004; IEA, 2014; Peter and Sander, 2009). Consequent woodland depletion results in a shifting charcoal production frontier that rapidly extends into more remote areas (Luz et al., 2015; SEI, 2002). Charcoal production in Mozambique is affected by a range of factors that apply to most sub-Saharan countries. Policy effectiveness suffers from limited institutional cooperation, integration and coordination between related sectors (Kwaschik, 2008; Zulu and Richardson, 2013). At the same time, the government lacks capacity for effective legislation implementation and enforcement (Kwaschik, 2008, Zulu and Richardson, 2013). Concerning the distribution of benefits from the charcoal value chain, large part of charcoal derived income goes to non-local individuals (Baumert et al., 2016; Kwaschik, 2008) due to communities' lack of technical, institutional, and financial capacity, limiting the success of community-managed projects in Mozambique (Kasparek, 2008; Puná, 2008; Sitoe et al., 2014).

In this paper we analyse the consequences of charcoal production on local well-being in Mabalane District (Southern Mozambique). Specifically, we analyse and evaluate the influence of LULCC on how the villagers use three woodland based provisioning ES (charcoal, firewood and grass) and on local well-being, and identify and evaluate policy interventions that could contribute towards a charcoal production system that alleviates poverty, improves environmental sustainability, and provides a reliable charcoal supply. We also evaluate social factors that can act as access mechanisms to ES (barriers like gender or opportunities like education) (Daw et al., 2011; Fisher et al., 2014). We chose Mozambique as a case study because despite high degradation (0.2–1.7%/yr, Marzoli, 2007) and deforestation rates (2–3%/yr, Ryan et al., 2014), there is still abundant woodland (70% of the land cover; 55 M ha, Marzoli, 2007), and a progressive land use policy, so Mozambique can still make a choice about its future before it is too late (before it is very highly deforested). The method presented allows the use of a social-ecological perspective to develop an integrated analysis of both biophysical and social consequences of charcoal production and its associated LULCC. It allows at the same time the evaluation of potential interventions aimed to improve the studied situation.

## 2. Study Area

Mabalane District, in Gaza Province, covers 8922 $km^2$ (Fig. 1). Its semi-arid climate, erratic rainfalls and poor soils lead to low agricultural yields, and land cover is dominated by woodlands (90% of the study area) with minor extension of other land cover classes (4% cropland, 4% wetlands and water bodies, and 2% villages, bare soil and other classes) (Mahamane et al., 2017).

In Mabalane District, 300 km from Maputo, charcoal production started to increase in early 2000 (Baumert et al., 2016), and has now become the main charcoal supply area of Maputo (Luz et al., 2015). Since 2007, large-scale commercial charcoal production has been evident in the Mopane woodlands (*Colophospermum mopane* (J. Kirk ex Benth. J. Léonard)) of Mabalane (Chavana, 2014; Luz et al., 2015). Mopane is the preferred tree species used for charcoal production in the study area, followed by *Combretum* sp., because it produces the highest quality charcoal: it burns slowly and produces low smoke and little sparks (Chavana, 2014 and own data). There are two main charcoal value chains in Mabalane: one run by local producers and one by large-scale operators. The latter is responsible for the largest amount of wood extraction for charcoal production, with only 8% of its monetary benefits remaining in the local communities (Baumert et al., 2016). Vollmer et al. (forthcoming) found unequal charcoal production patterns at the community (village) level and they could not find a direct relation between charcoal production and alleviation of acute multidimensional poverty. Both findings suggest that most benefits are not reaching the rural poor in Mabalane, yet the direct consequences of forest degradation are felt locally.

Our research was carried in seven villages, each with fewer than 70 households (HH), distributed along a forest degradation gradient, from high (after charcoal peak) to low degradation (pre-charcoal peak) as described in Baumert et al. (2016). Approximately 85% of the investigated sample of HH (n = 261, from a total number of 308 HH) are farmers and up to 70% also produce charcoal. A HH was defined as a unit based on members who “eat from the same pot” (Tvedten et al., 2012). Subsistence agriculture is the most predominant farming system, practiced on a small scale (mean cropland size = 1.70 ha $HH^{-1}$ (S.D. 2.11)). Main crops are maize, cow peas, peanuts and sesame. Sixty percent of the HH keep livestock (cattle, goats, chickens, pigs) as insurance and production gains are not targeted.

## 3. Methods

The objective of the paper is articulated through a series of specific research questions designed to query a newly developed Bayesian Belief Network (BBN) of the charcoal production system in Mabalane (Research questions included in the Analysis section). We used a BBN to conceptualize the charcoal production in Mabalane as an integrated system to compare the consequences of policy interventions on woodland based provisioning ES supply and on the well-being of the local population. The BBN and three alternative future scenarios were developed in a participatory process involving a broad range of stakeholders and experts to increase the saliency and relevance of research. The process followed eight main steps (Fig. 2) that are described in the next paragraphs.

### 3.1. Stakeholder Consultation Process

BBNs have been used in participatory approaches in the environmental sector (Cain et al., 2003; Castelletti and Soncini-Sessa, 2007; Düspohl et al., 2012; Zorrilla et al., 2010) and several different guidelines have been produced (Bromley, 2005; Cain, 2001; Pollino and Henderson, 2010). We assimilated the most pertinent aspects of those guidelines for a participatory BBN construction in Mabalane, using stakeholders to help design the BBN structure.

Participatory workshops are often structured around a topic, which typically emphasises a specific theme or subject that can be explored in depth (Bryman, 2004). In our case, the focus was on the construction of a causal diagram by the participants. We asked them to link aspects of rural wellbeing, ecosystem services, land use change and possible interventions so that well-being of rural habitants and natural conservation could be improved at the same time (Table 1). We conducted five workshops at different levels: 1) one with stakeholders working in institutions at national level held in Maputo (18 participants); 2) one with stakeholders working at provincial and district levels held in Xai Xai (14 participants); and 3) three with local communities of the study area (24 participants, with a diversity in gender, age and main income activity). The objectives of the workshops were: a) to ensure that all important aspects were considered during the process of construction of the BBN structure; b) to get a local perspective of issues related to land use, ES and rural well-being; and c) to learn how these are influenced by interventions and other factors. We were also interested in the new variables that were generated from the discussion among participants, as these workshops provide an excellent means for knowledge exchange and discussion (Bromley, 2005).

The method used in the village workshops followed a similar pattern as Maputo and Xai-Xai workshops (Table 1), adapted to the local

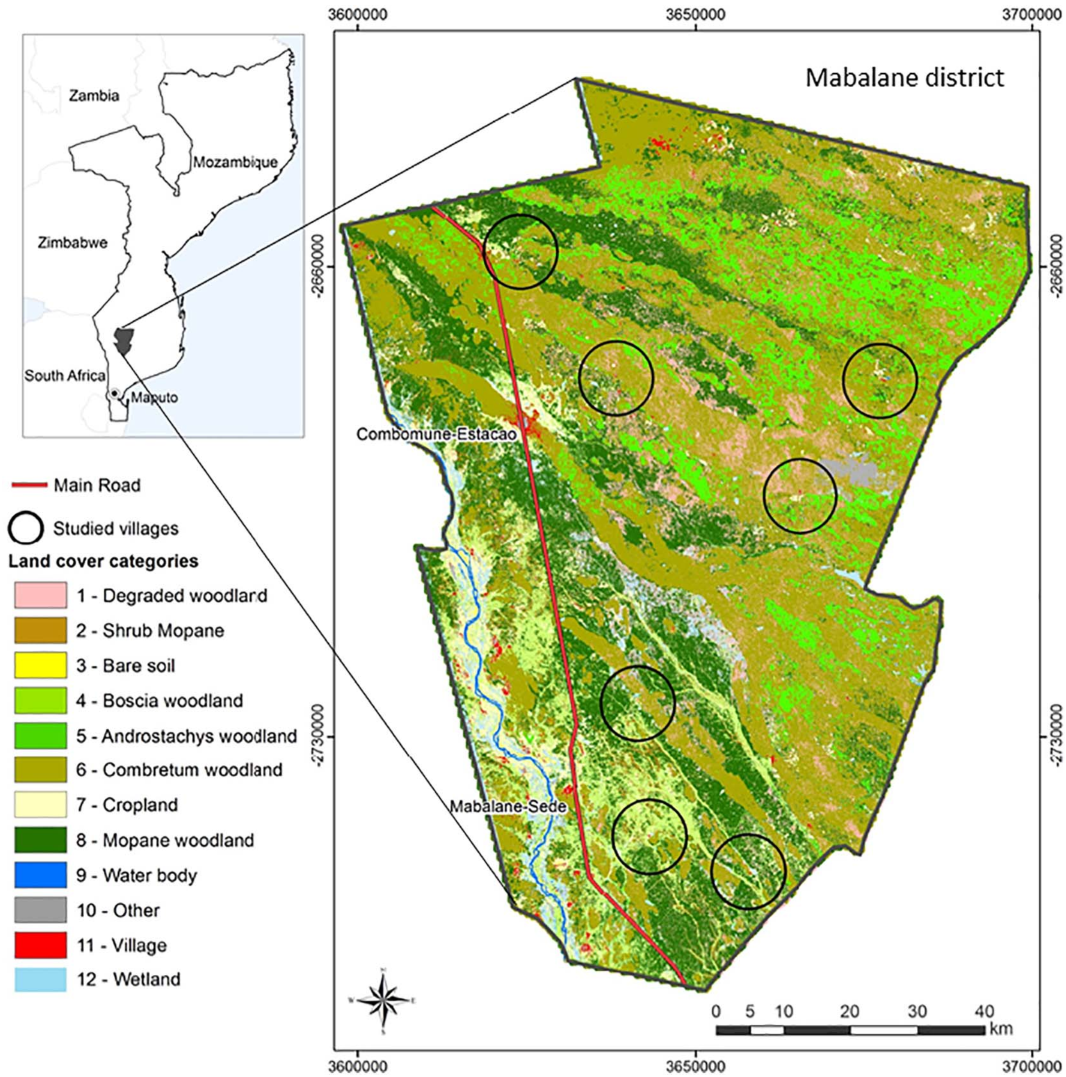


**Fig. 1.** Studied villages marked with a 5 km radius circles used to characterize the land cover of each village, located in Mabalane District, Gaza Province.

circumstances; e.g., as some of the participants cannot read and write, photos and pictures were used to represent the variables. In each village one group built one causal diagram (Steps 1–5; Table 1). Details of the methods followed can be found in Appendix A.

### 3.2. BBN Structure Construction

A BBN is a statistical multivariate model defined as a directed acyclic graph where the nodes represent the variables of the model and the links indicate a statistical dependence between them, defined through a conditional distribution based on Bayesian probability or conditional probability (Jensen, 2001). BBNs have been burgeoning in environmental sciences in recent years (Aguilera et al., 2011). BBNs can explicitly accommodate uncertainty and variability in the model predictions (Aalders et al., 2011; Uusitalo, 2007); are useful in situations where it is necessary to integrate qualitative and quantitative data (Smith et al., 2007); are a useful tool for dealing with complex systems (Aguilera et al., 2011; Kelly et al., 2013); for integrating multiple knowledge domains and combining different sources of knowledge (Henriksen and Barlebo, 2008; Uusitalo, 2007); and for analysing trade-offs (Barton et al., 2012; Cain et al., 2003; Farmani et al., 2009; Peterson et al., 2008).

The resulting nine causal diagrams from the workshops (3 diagrams from the national and provincial workshops and one from each of the village workshops) were digitised using the software yEd Graph Editor (Version 3.14.3). From them we obtained three lists with a) the most repeated variables, b) the betweenness centrality[1] of each variable and c) their number of links. After this analysis, a common diagram was designed including the variables more repeated, connected and central, and the more repeated links between them. The result was set as our reference BBN for Mabalane District. Finally, this BBN was adapted: a) to focus the BBN on the production of charcoal, considered the most important driver of LULCC in Mabalane; b) to introduce the most meaningful interventions from a set of 74 proposed by the stakeholders, based on qualitative information gained through participatory rural appraisals activities (semi-structured interviews, participatory mapping and focus groups on charcoal, poverty and wealth rankings (Baumert et al., 2016)); c) to introduce the most relevant variables involved in the access mechanisms to ES (selected using statistical tests of HH survey data collected in the villages (Vollmer et al., forthcoming) using non-parametric Mann-Whitney and Kruskal-Wallis tests and Poisson linear regression models (for continuous variables) (details in Appendix B); and d) to adapt the BBN to data availability. The BBN was constructed using Netica software (Netica "5.15" 64 Bit).

[1] Betweenness centrality is an indicator of a node's centrality in a network. It is equal to the number of shortest paths from all vertices to all others that pass through that node. A node with high betweenness centrality has a large influence on the network (Freeman, 1977).

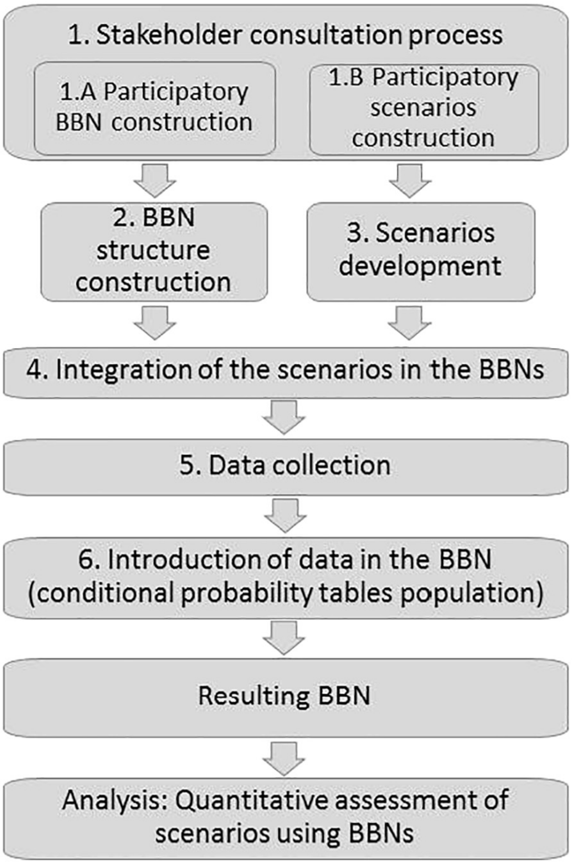


**Fig. 2.** Main steps followed in the study.

**Table 1**
Steps followed in Maputo and Xai-Xai workshops.

1. Introduction to ES, well-being and causal diagrams.
2. Selection of four well-being components considered as most important for rural habitants and as most dependent on ecosystem services.
3. Linking the four well-being components with the ecosystem services on which they depend.
4. Inclusion and linking of factors (drivers of change) affecting the forest and the provision of ecosystem services.
5. Inclusion and linking the proposed interventions to improve well-being and to diminish the consequences on LULCC change.
6. Each group explained their resulting causal diagram to the other participants, and a discussion was held between them.

### 3.3. Scenarios Development

Scenarios are plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships (MEA, 2005b). Scenarios are used to assist in the understanding of possible future developments in complex systems that typically have high levels of scientific uncertainty (Rounsevell and Metzger, 2010). Scenarios of future LULCC in Mozambique were constructed for the year 2035 using input from stakeholders collected at the national and provincial workshops mentioned above. In a first round of workshops, stakeholders provided information about the most important drivers of LULCC in Mozambique; in a second round, stakeholders evaluated and corrected three sets of previously prepared narratives. Three scenarios were constructed: a) *Large private investments* characterised by low socio-economic development of small farmers and as a consequence high rural-to-urban migration; b) *Small holder promotion* with successful improvement of small farmers' situation (education, health care, infrastructures, capacity building) and, as a consequence, lower rural-to-urban migration; and c) *Balanced situation* with intermediate circumstances (Table 2).

### 3.4. Integration of Scenarios in the BBN

The qualitative scenario narratives were incorporated into the BBN by defining different combinations of interventions and different levels of urban charcoal demand (Table 3). This last variable is not an intervention, but a driver of change in charcoal production that has great uncertainty and cannot be directly controlled by the government.

In *Large private investments* scenario, none of the interventions introduced in the BBN are applied and we consider urban charcoal demand increases greatly as a result of the great migration to urban centres. The government attempts to trigger development by promoting large investments, resulting in limited change in the participation of the rural population in charcoal production.

In *Small holder promotion* all proposed interventions are applied successfully, as the government seeks to improve local rural capacities and nature protection. Urban charcoal demand remains constant, a result of low migration from rural areas to urban centres and of an increase in the use of other types of energies.

In *Balanced* scenario, charcoal demand suffers an increase but not as high as in the first scenario, and three interventions are applied: facilitated access to licences; development of a forest management plan by the communities; and improved forest control.

### 3.5. Data Collection

The data used to build the conditional probability tables (CPTs), which are tables where statistical relationships between different nodes are defined, were collected from various sources:

- Data for the ES/well-being relationships, influenced by the access mechanisms, were derived from a HH survey in the studied villages and from an Acute Multidimensional Poverty Index (AMPI) constructed using this data. An extensive HH survey was done on 261 HH, with questions about poverty indicators and use of woodland based provisioning ES. Details of the HH survey method can be consulted in Vollmer et al. (forthcoming). Poverty is a complex notion and there is not an international consensus on its definition

**Table 2**
Summary of the main drivers of change that determine the three scenarios of LULCC in Mozambique to 2035.

| Drivers | | Scenarios | | |
|---|---|---|---|---|
| LULCC driver | Most important drivers | *Large private investments* | *Small holder promotion* | *Balanced* |
| Economic | Government promotion of companies | Large international companies | Small local companies and cooperatives | Large and small companies |
| Technology | Access to technology (Internet and mobile phones) by small scale farmers | Same as current | Large increase | Slow increase |
| Societal | Political involvement from society | Same as current | Large increase | Slow increase |
| Policy | Social and environmental policies | Same as current implementation | Greatly improved implementation | Some improved |

**Table 3**
Different combinations of the interventions and of urban charcoal demand are used to represent the scenarios.

| Interventions | Scenarios | | |
|---|---|---|---|
| | *Large private investments* | *Small holder promotion* | *Balanced* |
| Facilitate communities access to licensing | Current licence system<br>7% of charcoal sacks through licences obtained by associations[a] | Facilitated access to licences<br>50% of charcoal sacks through licences obtained by associations | Facilitated access to licences<br>50% of charcoal sacks through licences obtained by associations |
| Improve communities' technical capacity | Current<br>Traditional kilns | Improved<br>Improved kilns (e.g. Casamance Kilns): Average efficiency improvement in charcoal conversion of kilns 14%[b] | Current<br>Traditional kilns |
| Improve institutional capacities of the communities | Current<br>36% of the potential beneficiaries are receiving 20% of taxes revenue.[c] | Active<br>90% of potential beneficiaries are receiving 20% of taxes revenue | Current<br>36% of potential beneficiaries are receiving 20% of taxes revenue (Mozambique).[c] |
| Develop forest management plan | No Forest Plan | Existing F. Plan | Existing F. Plan |
| Improve forest control | Current<br>75 Forest wardens[d] (1 Forest warden for 670 $km^2$)[e] | Improved<br>300 forest wardens (1 Forest warden for 166 $km^2$) | Improved<br>300 forest wardens (1 Forest warden for 166 $km^2$) |
| Promote of non-charcoal income activities | Low<br>271 agricultural extension technicians in Gaza Province (2014)[f] | High<br>1000 agricultural extension technicians in Gaza Province | Low<br>271 agricultural extension technicians in Gaza Province |
| External driver of change | | | |
| Urban charcoal demand | Very higher demand than currently | Current demand | Higher demand than currently |

[a] Baumert et al., 2016.
[b] SEI, 2002, Chidumayo and Gumbo, 2013, Kwaschik, 2008, Peter and Sander, 2009, Kammen and Lew, 2005.
[c] DNTF, 2015. Data for the whole Mozambique.
[d] DNTF, 2014. Data for Gaza province.
[e] Forest areas and other woody vegetation estimated for 2002 in Gaza: 50,270 $km^2$ (5,027,000 ha). Total area of Gaza province: 75,334 $km^2$. Sitoe et al., 2012.
[f] DNEA, 2014.

or measurement. It is widely measured in income or consumption expenditure deficiencies, but due to the complexity of the phenomenon, multidimensional measurements of poverty are increasingly being used (Alkire et al., 2015). To assess poverty at HH level we use a multidimensional poverty index (AMPI) based on three domains (human, social and economic capital) and nine dimensions (sanitation, water, health, formal education, food security, access to services, associations and credit, assets owned and housing) (Vollmer et al., forthcoming).

- Data for land cover/ES relationships came from a model of potential ES supply assessment that uses field data of a) type of ES used from each tree species, b) tree species biomass present in each land cover category, c) production functions that set the proportion of the biomass in each land cover class that delivers each ES (Woollen et al., 2016; Appendix C).
- Data for the current land cover map was obtained from satellite images and field data (Mahamane et al., 2017).
- LULCC related to each intervention is based on government reports, stakeholder opinions (the participants of the above mentioned workshops), research team knowledge, and results from the literature, specifically Del Gatto (2003), Kasparek (2008), and SEI (2002).

### 3.6. Introduction of Data in the BBN (Conditional Probability Tables Population)

We prepared a table with data for each HH about well-being, social factors and use of ES, and data about ES supply for each village. Then, the data were introduced in the BBN with the "Incorporate case file" command in Netica software (Netica "5.15" 64 Bit). The software calculates the conditional relationships between the variables of the BBN (CPTs) based on the data incorporated in this way. The land cover map was introduced as a variable, where each state represented a land cover category and the probabilities represented the proportion of the area occupied by each.

## 4. Description of the BBN

The BBN uses as spatial and social boundaries the seven villages studied in Mabalane District. The BBN assumes the proposed interventions will be applied during the next 20 years, and the outputs represent the results of those interventions for the year 2035. For the well-being indicators, the data used come from the household survey, so the units are HH. The results are more easily interpreted if we understand the probabilities as proportion of the HH in the studied area.

The BBN has six main types of variables: interventions, land cover, ES supply, ES use, access mechanisms and human well-being. Fig. 3 shows the final BBN, which is described in full detail in Appendix D. The land cover map was introduced as a variable, where each state represents a land cover category and the probabilities represent the proportion of the area occupied by each (Fig. 1). We focused on the following provisioning ES: charcoal supply, firewood supply and grass supply because they were closely related with local well-being and because were the woodland based provisioning ES most repeated in the causal diagrams constructed during the village workshops.

To assess poverty at HH level we use the AMPI based on nine indicators (see Section 3.5). Three of the indicators have also been included disaggregated from the index as well-being indicators: Food security, Housing and Assets owned. The variables selection was based on the stakeholder classification (Appendix E).

The objectives of the interventions included in the BBN are to increase poverty alleviation based on charcoal production, to achieve environmentally sustainable charcoal production and to address a reliable charcoal supply. Descriptions of the interventions are shown in Table 4. Interventions related to decreasing charcoal demand have not been included, due to the focus on the production side of the value chain. Cautions concerning the interventions can be found in Appendix F.

Fig. 3 refers to the Balanced scenario and will be used to describe the BBN rational: Some but not all interventions have been applied from 2015 up until 2030: improved facilitated access to charcoal licences, development of a forest management plan and an improvement of forest control. These interventions reduce the rate of charcoal production by large non-

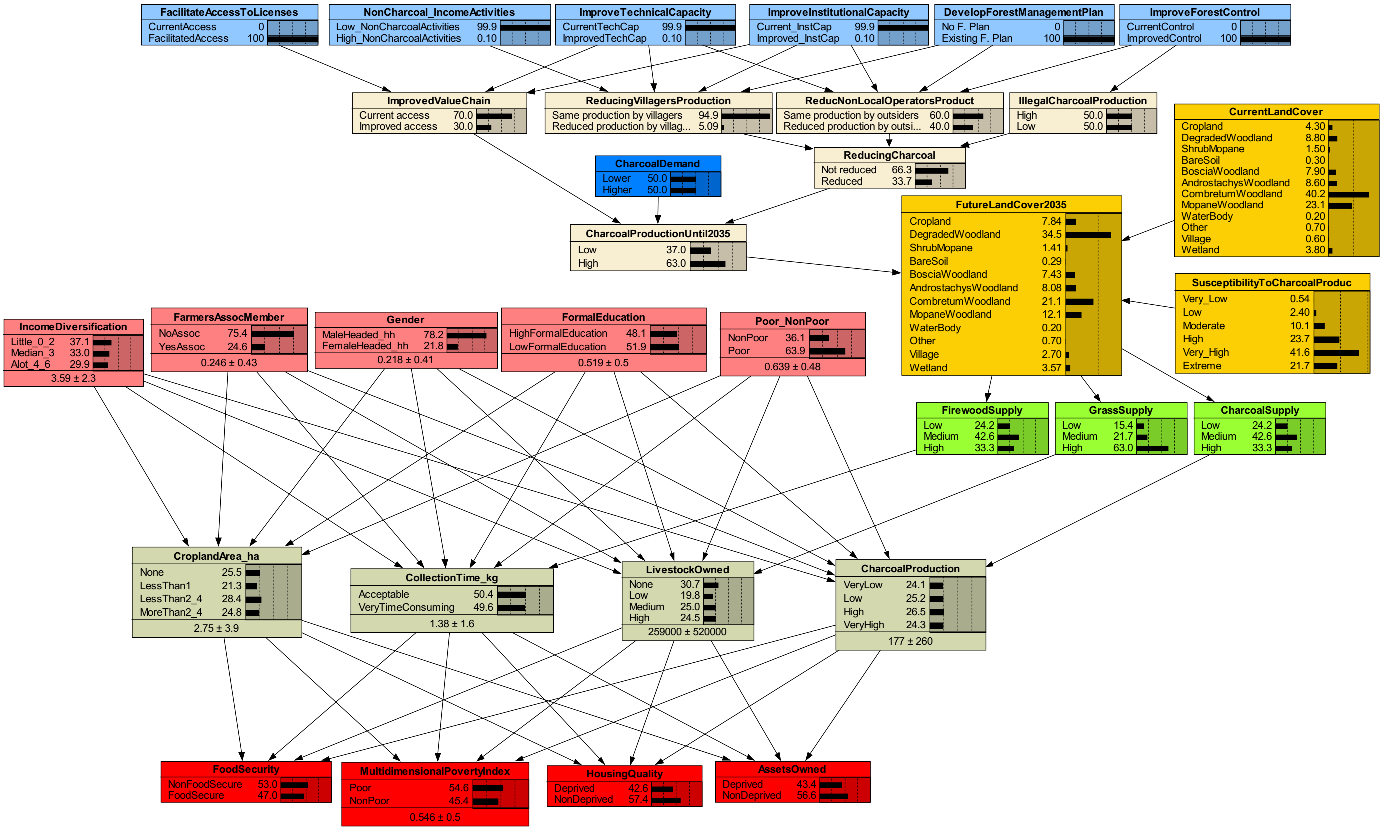


**Fig. 3.** BBN showing interactions between LULCC, ES and well-being in Mabalane. Each variable represents an interaction factor and each link represents a relationship between variables. The colour of the variables represent different type of variables: LULCC variables are yellow, ES supply green, ES use grey, and well-being of rural habitants red. Blue variables are the policy interventions, and pink are access mechanisms variables.

local operators and there is a 63% chance that the total charcoal production remains high along the time period. The effect has been an increase of degraded woodland from 9% to 35%, a decrease of high charcoal supply areas down to 33%, and an increase of HH producing very high quantities of charcoal up to 24%. The consequences for the locals are that 55% of the villagers remain in multidimensional poverty.

**Table 4**
Description of the interventions included in the BBN.

| Intervention | Description | Refs.[b] |
|---|---|---|
| Improve forest technical capacity of communities | • Provide knowledge of the ecological characteristics of trees such as growth rate or time necessary for regeneration after different interventions.<br>• Improve silviculture or forestry technics (pruning, thinning, seeding, etc.).<br>• Improve charcoal process knowledge (e.g. improved kilns).<br>• Capacitate people regarding ES and conservation, i.e., inform about the risks of natural resources depletion. | 1,3,6,7,9 |
| Develop forest management plan at community level | • Capacitate on designing and management of forest management plans.<br>• Design sustainable strategies of forest exploitation (e.g., define areas size, rotation plan). | 6 |
| Improve institutional capacities of communities | • Provide support for improving community organisation and running associations.<br>• Support and foster forest committees or associations.<br>• Guide, help and control the application of the forest management plans.<br>• Coordinate with communities the control of external or illegal charcoal production being done by the forest authorities.<br>• Promote fair and sustainable charcoal commercialisation channels. | 1,2,3,6,9 |
| Improving forest control/enforce forest legislation | • Improve capacity of the government to implement charcoal policy: increase budget, tools, training, etc.<br>• Improve the involvement of local communities to stop illegal charcoal production. | 1,2,7,9 |
| Facilitate access of communities to licensing process[a] | • Allow community associations to produce more charcoal than currently: the licence volume of 1000 steres[a] per year is very low for communities where charcoal is a widespread activity. A bigger allowance for community associations would increase the revenues from taxes both for the community and the government.<br>• Improve the process of negotiation and signing of the licences for external producers and the community. | 1,5,8,9 |
| Promotion of non-charcoal income generating activities | • Promote improved agriculture techniques and increase the support to livestock rearing.<br>• Promote new activities like game reserve, fowl rearing, bee keeping and honey production, indigenous fruit juice processing, harvesting medicinal plants and herbal teas, carpentry, etc.<br>• Train on investment opportunities, business development, and increased access to information.<br>• The provision of technical and institutional training is needed over several years. | 2,3,4,6,7 |

[a] One stere permits the production of one sack of charcoal which in the study area is traded with a weight of 70–90 kg.
[b] References that propose the interventions: 1-Baumert et al., 2016, 2-Dewees et al., 2010, 3-Fisher, 2004, 4-Jones et al., 2016, 5-Kamanga et al., 2009, 6-Kasparek, 2008, 7-Kwaschik, 2008, 8-Schure et al., 2013, 9-Zulu and Richardson, 2013.

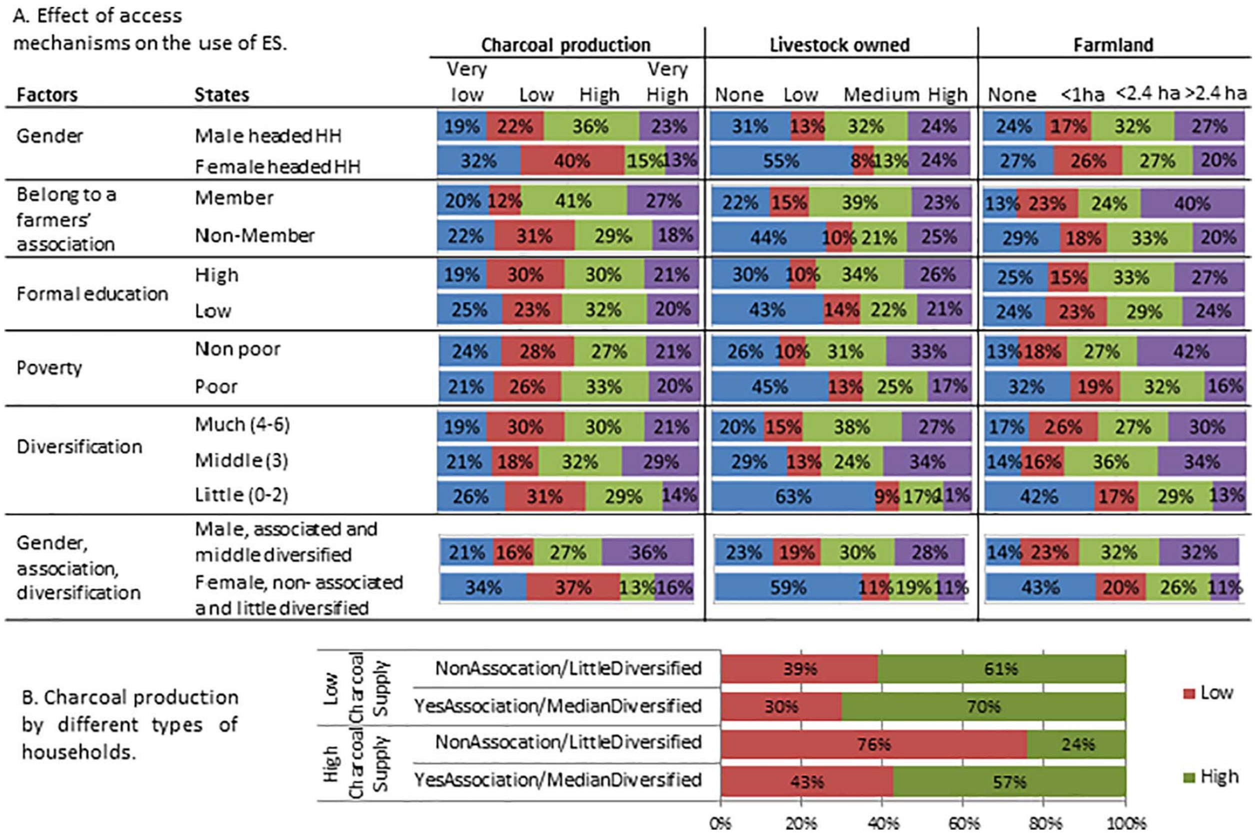


**Fig. 4.** Results from the analysis of the BBN constructed to simulate charcoal production in Mabalane District. A. Effect of the "access mechanisms" variables on the use of charcoal production, livestock owned, and farmland size. The probabilities have been calculated with the combination of interventions and future land represented by *Balanced* situation. There was no effect on time spent collecting firewood. B. Charcoal production by different types of households, under High or Low charcoal supply situation.

## 5. Analysis

The BBN was used to investigate six pertinent questions about the charcoal production in Mozambique by evaluating the effects of alternative combinations of the states of the variables on the probability distributions of woodland based provisioning ES and livelihood indicators.

### *5.1. How Important is the Influence of Charcoal Production, Livestock and the Time Spent Collecting Firewood on Local Well-being?*

We set 100% probabilities for each of the different states of the ES use variables (e.g., very high charcoal production, high charcoal production), and checked the resulting changes in the probabilities of the well-being indicator variables. Charcoal production has a low influence on housing and multidimensional poverty and a positive effect on assets owned and food security (Appendix G, Table G.1). This is in accordance with the qualitative data from the BBN workshops: HH primarily use income from charcoal to buy food and some small assets (e.g., soap, clothes). The quartile of HH producing the least charcoal have higher rates of food security than those producing Low and High. This can occur since some of the better-off HH are not producing charcoal (or very little) because they do not need it to achieve a successful livelihood.

Livestock owned shows a stronger influence than charcoal production on the four well-being indicators analysed: the more livestock owned, the lower rates of multidimensional poverty HH, the higher assets owned and the higher food security. Farmland area has a positive influence on multidimensional poverty, assets owned and food security, but not on housing. The time spent on the collection of firewood has little influence on the four well-being indicators (more details in Table G1., Appendix G).

### *5.2. How Do Changes in ES Supply Affect the Use of ES and Local Well-being?*

We wanted to know if a decrease of ES supply would have a big effect on how the villagers use those ES. To find it out, we classified the villages as having low, medium or large ES supply and compared the mean quantity used per HH in each type of village. In the case of charcoal, low supply of charcoal leads to higher charcoal production (Appendix G, Fig. G.1). To understand the results, it is important to know that the "Low charcoal supply" situation was fed with data from the villages with the longest charcoal production period and thus with fewer trees suitable for charcoal (Mopane and *Combretum*). In those villages, large-scale operators have driven the biggest part of woodland degradation (Baumert et al., 2016), and the long prevalence of charcoal production (Luz et al., 2015) led to a high number of HH producing charcoal (because they have learnt how to do it and are used to produce it) and having means to obtain assets. Meanwhile in the "High charcoal supply" villages, the big operators have not yet arrived, charcoal has been produced for a shorter period of time and only some of the villagers produce charcoal.

In this highly forested study area, changes in firewood and grass supply produce little changes on the variables that represent its ES use: Time spent collecting firewood and Livestock owned (Appendix G, Fig. G.1). These results suggest that the supply of these two ES is not a limiting factor in the study area.

The effects of ES supply on well-being act through the "ES use" variables (see Fig. 3), and knowing the small effects explained in the previous paragraph, it is normal to obtain no differences in HH well-being under different ES supply situations owned (Appendix G).


**Fig. 5.** Evaluation of the three scenarios imposed, compared with the current situation, on LULCC, ES supply, ES use by the local inhabitants and well-being.

### 5.3. What Are the Most Important Access Mechanisms Influencing Woodland ES Use and Local Well-being?

Gender is the strongest barrier to ES use: HH headed by a woman produce smaller quantities of charcoal, own fewer livestock, spend more time collecting firewood and work smaller farmlands than male headed HH (Fig. 4A). On the contrary the strategies for producing more ES seems to be participating in a farming or forest association, having highest level of formal education and having more than two income streams (e.g. income from agriculture, livestock, own business, wage, forest products, non-forest environment): those HH produce more charcoal, own more livestock and work bigger farmlands (Fig. 4A). Finally, poverty (measured with the AMPI) affects differently the quantity of ES used by the villagers: poor HH have smaller farms and less livestock but produce slightly more charcoal than non-poor HH.

The "access mechanisms" variables ordered from high to low influence on charcoal production are: Gender > Being member of association > Income diversification > Multidimensional poverty > Formal education. In the case of livestock and farmland, the influence is different: Income diversification > Multidimensional Poverty > Being member of association > Gender > Formal Education. The effects of the "access mechanisms" variables on Time collecting firewood are small.

The influence of individual “access mechanism” variables on the well-being components is limited. However, the combination of different factors has greater effects than a single factor: female headed, non-associated and little diversified HH are associated with food insecurity, few assets owned and high rates of multidimensional poverty. Taking out the gender factor, the influence of Association and Diversification follows a similar pattern although not so sharp. Looking deeper into the HH data, only 5% of the female headed HH are members of an association, compared to 25% of the male headed HH.

### *5.4. Do Access Mechanisms to ES Use Have a Different Influence Under Different Supply of ES?*

We analysed the effects of the access mechanisms to ES use (poverty, formal education, gender, associations and income diversification) under different situations of ES supply (e.g. Very high, High, Low and Very low charcoal supply). The most important interaction was detected between charcoal supply and diversification and association: in the high charcoal supply villages (where the charcoal production has not yet peaked) associated and diversified HH produce much more charcoal than non-associated and little diversified HH (57% vs 24%), the effect being greater than in the low charcoal supply villages (70% vs 61%) (where the charcoal peak has already passed) (Fig. 4B). Belonging to a farmer or forest association has a bigger influence than diversification. However, there are not such clear differences with education, gender or poverty. A similar effect is observed with livestock, what reveals some kind of interaction that should be further analysed.

### *5.5. What Interventions Have the Greatest Potential to Reduce Woodland Degradation?*

The effect on LULCC of individually applied intervention is small (2%–5% decrease in woodland degradation) and increases when more than one intervention is applied (6%–9%). Improve Forest Control is estimated to produce the highest effect (12% when applied alone and up to 16% when applied in combination) because it could reduce both small-scale community and large-scale non-local charcoal production, while the other interventions would only directly affect local small-scale production.

The simulations show that under successful application of all the proposed interventions, the land affected by forest degradation could be reduced by approximate 20%–30%, and that the interventions have a higher impact with lower urban charcoal demand than with a high charcoal demand. Higher urban charcoal demand situation increases forest degradation by 13% while lower demand decreases it by 14% if taking “current charcoal demand” as baseline.

### *5.6. What Are the Consequences of the Three LULCC Scenarios on ES Provision?*

We tested the consequences of the scenarios introducing different combinations of interventions and urban charcoal demand (Table 3). *Large private investments* scenario produces the biggest change, with the reduction of Mopane woodland land cover from 23% (land cover of Mopane woodland in 2015) to 8% of the study area, and *Small holder promotion* the smallest, with a decrease of Mopane woodland to 18% (Fig. 5). *Balanced* scenario produces an intermediate LULCC. These LULCC under the three scenarios have different consequences for the supply of ES, occurring some trade-offs. Under *Large private investments*, areas with high charcoal and firewood supply would diminished while areas with high grass supply would increase (after charcoal production, the resulting degraded woodlands have a more open structure that facilitates the growth of grass).

The consequences of the LULCC scenarios on the quantity of ES used by villagers are different for each ES. The largest changes occur in the production of charcoal: compared to the current situation, under *Large private investments* the proportion of HH producing high amounts of charcoal would increase. Quantity of livestock owned and time spent collecting firewood would not change significantly, showing that the supply of those ES is not a limiting factor for its use in Mabalane.

Finally, and in accordance with the results explained previously, the LULCC scenarios have little influence on the well-being variables (Fig. 5).

## 6. Discussion

### *6.1. Discussion of Results*

Deforestation and woodland degradation reduced woodland based provisioning ES supply, but surprisingly, there is little change in its use. For example, under *Large private investment* Scenario (with the greatest rates of forest degradation) more HH produce very high and high quantities of charcoal than currently. There seem to be two reasons for this. Firstly, the data show that villages with degraded forests and low charcoal supply have higher charcoal production, because these villages have become specialised and accustomed to producing charcoal. Second, most of the Mopane woodlands in the study area are degraded more than deforested (as in other cases of charcoal production in Africa (Chidumayo and Gumbo, 2013)) and villagers can still keep producing charcoal from smaller trees and other types of woodlands (Chavana, 2014, own data). Furthermore, enough woodland remains and therefore the degradation does not seem to be greatly affecting livelihoods, the quantity of charcoal produced and livestock owned, or the time spent in firewood collection (in line with Barany et al., 2005). Nevertheless, continued charcoal production at current rates will ultimately deplete Mopane and other woodland types (e.g., *Combretum* woodlands) and affect other ES (firewood, grass, food or medicines) (Woollen et al., 2016). Therefore, the question about the future of Mabalane woodlands is not how much land will be degraded, but what will be the intensity of degradation.

The analysis revealed only a weak effect of charcoal production on multidimensional poverty alleviation. The majority of HH only produce a small amount of charcoal, with a value of less than 1 USD per day. While this can improve food security and the assets owned by the HH, it has a limited effect on other aspects of the AMPI including sanitation, education, health, social relationships or housing. In some of these last components of well-being, public policies have a greater impact. These results are consistent with various studies showing that forest resources have a small role to play in poverty alleviation (Arnold and Ruiz-Pérez, 2001; Barany et al., 2005; Fisher, 2004; Puná, 2008; Shackleton et al., 2007), although are in opposition to some studies that use a poverty indicator based on income (like Khundi et al. (2008) in Uganda). Our data and methodology is unable to test whether the most prosperous HH are able to use charcoal as a pathway out of poverty (Kamanga et al., 2009). Nevertheless, they do show that forest resources (charcoal production in particular) are important for the cover of basic needs, and therefore can work as safety nets (Angelsen et al., 2014; Arnold et al., 2006; Fisher, 2004; Openshaw, 2010; Shackleton et al., 2007; Zulu and Richardson, 2013), specially for the poorest HH (Shackleton et al., 2008).

As suggested by previous studies (Daw et al., 2011; Fisher et al., 2014; Kalaba, 2014; Suich et al., 2015), we have found that there are access mechanisms to ES use and that their effects seem to be driving the ES use more importantly than ES supply. The most important being:

- Gender: female headed HH produce less quantities than male headed HH, like Khundi et al., 2008 in Uganda but unlike Smith et al. (2017) in Malawi.
- Diversification: HH with a high number of income streams produce higher quantities of charcoal, also noticed by Smith et al. (2017) in Malawi and by Jones et al. (2016) in a different part of Mozambique.

- Association: a higher proportion of HH being part of forest or farmers associations produce charcoal.

Vollmer et al. (forthcoming) showed that individual factors have a small effect on AMPI, and that only a combination of different factors results in clear differences between HH. We found similar results: the combination of several access mechanisms produces bigger differences than individual mechanisms in food security, assets owned and multidimensional poverty. Ethnicity and religion seem to have some relationship with livestock and agriculture, but not with charcoal production. This therefore, could be analysed in more detail in future studies. Other clear access barriers to charcoal production are the difficulty of locals to sell directly charcoal in Maputo and to obtain charcoal licences, as previously highlighted by Schure et al., 2013 in other African countries and similarly to the financial barriers found by Khundi et al. (2008).

Fig. 4B shows that associated and diversified HH have a greater capacity to adopt new production activities such as charcoal production than other HH. This is in line with previous findings of how technology, skills and capital may be required to initiate and capture benefits from forest products (Amusa et al., 2017; Arnold and Ruiz-Pérez, 2001; Shackleton et al., 2007). During wealth-ranking focus groups, the villagers explained that wealth and poverty are related with (in order of importance) work ethic, social networks (alone or with partner), farm size, gender, livestock and housing. Work ethic could be related with diversifying income streams and social networks with being part of associations, so the quantitative results from the HH survey are aligned with the qualitative results obtained with the focus groups.

The high woodland cover in the study area (90%) meant that, although we selected villages with different woodland degradation stages, woodland based provisioning ES supply is currently not a critical factor restricting ES use by local communities. Therefore, with the data available, the different scenarios of LULCC simulated only small consequences in local well-being. The biggest influence observed is due to social factors more than to ecological limitations, e.g., in the villages where large-scale charcoal production started earlier, the proportion of villagers producing charcoal is higher, and it is produced in largest quantities. Even when the woodlands are degraded, villagers continue producing charcoal from lower quality natural resources (smaller trees and non-preferred tree species). Gender of the HH head is the most social influential factor for a lower use of ES (production of charcoal, quantity of livestock owned and the area farmed), while diversification of income activities and participating in associations are associated with increases in the use of those ES by villagers. Nevertheless, higher production of charcoal does not directly result in a decrease of multidimensional poverty. The results show that charcoal production is working more as a safety net that helps villagers to prevent their situation from worsening. Improving social services like education, health care, drinking water and infrastructure (roads, markets), are clear actions to decrease multidimensional poverty in Mabalane.

### 6.2. Discussion of Methods

The analysis of social-ecological systems often lack important data and stakeholder involvement has been proposed as needed and appropriate (Carpenter et al., 2006; Olsson et al., 2004). The involvement of stakeholders and local people in the construction process of the presented BBN has proven to be key because it provided information that could not be obtained by consulting the literature or by collecting field data. Stakeholder involvement reduces the time necessary to understand the situation from only publications and legitimizes that the critical facts for the people involved in the issue have been included (Bromley, 2005).

Together with the difficulty of analysing land use change in this type of ecosystem (Grainger, 1999), the weak policy implementation in the study area (Dewees et al., 2010) prevented us to use local data to construct the relationships between land use change and policy interventions. To overcome this lack of data we used the scarce data found in similar case studies and under similar type of interventions plus expert opinion and stakeholder involvement. Other important data lacking are related to the long term data on extension, type and intensity of woodland degradation and recovery rate, what has been overcome with short term data (2007–2014) from a biomass change study (Luz et al., forthcoming). Therefore, the presented BBN illustrates how BBNs can deal with uncertainties and data scarcity in social ecological systems.

Our results do not show dramatic changes in woodland based provisioning ES resulting from the policy interventions. We argue that is due to the high woodland cover in the study area, which ensures that ES supply is not a limiting factor for its use, and due to the small differences in land cover across the studied villages. For future studies we propose to use the HH and not the village as the reference unit to study the relation of well-being with woodland based ES. In that way, differences in the distance from individual houses to forest can show clearer effects of land use change on the use of ES and clearer effects of woodland scarcity on local well-being.

The process done to build the BBN provided a holistic understanding of the case study in a systematic way, and therefore facilitates the detection of the most crucial variables involved and of data gaps. This is useful when complex systems make difficult to distill the key management strategies that can deal with tradeoffs and benefit a wider type of actors (e.g. ES supply, forest cover, local and regional well-being).

This paper is of the first that analysed with field data impacts of different management options at the same time on ES supply and on well-being using a multidimensional approach to poverty (Suich et al., 2015).

## 7. Conclusions

The novelty of using BBNs to explore quantitatively scenarios of the future has proved to be a very appropriate approach to analyse complex systems. Local data and direct input from stakeholders and locals has been used to describe the multiple relationships between charcoal production, LULCC, woodland provisioning ES and well-being in social-ecological systems. The method allowed us to deal with the complexity of the case studied and with the uncertainties and lack of data that these kind of cases confront.

The existence of two main value chains, one run by local producers and one by large operators, result in a greater part of the forest degradation being caused by the large operators, with the villagers obtaining lower revenues and dealing with the consequences of deforestation. Woodland degradation means a decrease in the supply of some provisioning woodland based ES (charcoal and firewood). Nevertheless, due to the selective tree harvesting for charcoal production and to the remaining high forest cover, current woodland degradation in the case study has limited impact on human well-being. Due to the government's lack of capacity and to the rising charcoal demand in the next decades, increasing local capacities will be an important alternative to improving charcoal production with the objectives of alleviating poverty, improving environmental sustainability, and providing reliable charcoal supply. Support for increasing local capacities (technical and institutional) and facilitating the access of locals to the licence scheme have been proposed as important actions in this paper, acknowledging the important difficulties that community based natural resource management faces to success. Improving the control of the illegal charcoal production has proved to be efficient in reducing charcoal production, as that measure affects the two existing value chains. Other interventions proposed, but not analysed with the BBN are: improving land ownership (so that the villagers can have security over their woodlands, and therefore can put effort into improving its recovery) and promoting a more transparent relationship between the large operators and the locals.

## Acknowledgments and Funding

This work (ACES project, NE/K010395/1) was funded with support from the Ecosystem Services for Poverty Alleviation (ESPA) programme (funded by the Department for International Development (DFID), the Economic and Social Research Council (ESRC) and the Natural Environment Research Council (NERC)).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2017.07.028.

## References

Aalders, I., Hough, R.L., Towers, W., 2011. Risk of erosion in peak soils - an investigation using Bayesian belief networks. Soil Use Manag. 27, 538–549.
Aguilera, P.A., Fernández, A., Fernández, R., et al., 2011. Bayesian networks in environmental modelling. Environ. Model. Softw. 26 (12), 1376–1388. http://www.sciencedirect.com/science/article/pii/S1364815211001472.
Alkire, S., Foster, J., Seth, S., et al., 2015. Multidimensional Poverty Measurement and Analysis. Oxford University Press.
Amusa, T.O., Jimoh, S.O., Azeez, I.O., 2017. Socio-economic factors influencing marketing of non-timber forest products in tropical lowland rainforests of south-western Nigeria. South. For. J. For. Sci. 1–8. http://dx.doi.org/10.2989/20702620.2016.1255411.
Angelsen, A., Jagger, P., Babigumira, R., et al., 2014. Environmental income and rural livelihoods: a global-comparative analysis. World Dev. 64 (S1), S12–S28.
Arnold, J.E.M., Ruiz-Pérez, M., 2001. Can non-timber forest products match tropical forest conservation and development objectives? Ecol. Econ. 39, 437–447.
Arnold, J.E.M., Köhlin, G., Persson, R., 2006. Woodfuels, livelihoods, and policy interventions: changing perspectives. World Dev. 34 (3), 596–611.
Barany, M., Holding-Anyonge, C., Kayambazinthu, D., Sitoe, A., 2005. Firewood, food and medicine: interactions between forests, vulnerability and rural responses to HIV/AIDS. In: Proceedings From the IFPRI Conference: HIV/AIDS and Food and Nutrition Security, (Durban, South Africa).
Barton, D.N., Kuikka, S., Varis, O., et al., 2012. Bayesian networks in environmental and resource management. Integr. Environ. Assess. Manag. 8 (3), 418–429. http://www.ncbi.nlm.nih.gov/pubmed/22707420.
Baumert, S., Luz, A.C., Fisher, J., et al., 2016. Charcoal supply chains from Mabalane to Maputo: who benefits? Energy Sustain. Dev. 33, 129–138.
Bromley, J., 2005. Guidelines for the Use of Bayesian Networks as a Participatory Tool for Water Resource Management. Based on Results of the MERIT Project. CEH, Wallingford.
Brouwer, R., Falcão, M.P., 2004. Wood fuel consumption in Maputo, Mozambique. Biomass Bioenergy 27 (3), 233–245.
Bryman, A., 2004. Social Research Methods. Oxford University Press, Oxford.
Cain, J., 2001. Planning Improvements in Natural Resources Management: Guidelines for Using Bayesian Networks to Support the Planning and Management of Development Programmes in the Water Sector and Beyond. Centre for Ecology and Hydrology, Wallingford, UK.
Cain, J., Jinapala, K., Makin, I.W., et al., 2003. Participatory decision support for agricultural management. A case study from Sri Lanka. Agric. Syst. 76 (2), 457–482. http://linkinghub.elsevier.com/retrieve/pii/S0308521X02000069.
Carpenter, S.R., DeFries, R., Dietz, T., et al., 2006. Millennium ecosystem assessment: research needs. Science 314, 257–258.
Castelletti, A., Soncini-Sessa, R., 2007. Bayesian networks and participatory modelling in water resource management. Environ. Model. Softw. 22, 1075–1088.
Cavendish, W., 2000. Empirical regularities in the poverty-environment relationship of rural households: evidence from Zimbabwe. World Dev. 28 (11), 1979–2003.
Chavana, R., 2014. Estudo da cadeia de valor de carvão vegetal no sul de Moçambique. IIAM Instituto de Investigação Agrária de Moçambique, Maputo, Mozambique.
Chidumayo, E.N., Gumbo, D.J., 2013. The environmental impacts of charcoal production in tropical ecosystems of the world: a synthesis. Energy Sustain. Dev. 17 (2), 86–94.
Cuvilas, C.A., Jirjis, R., Lucas, C., 2010. Energy situation in Mozambique: a review. Renew. Sust. Energ. Rev. 14 (7), 2139–2146.
Daw, T., Brown, K., Rosendo, S., et al., 2011. Applying the ecosystem services concept to poverty alleviation: the need to disaggregate human well-being. Environ. Conserv. 38 (04), 370–379.
Del Gatto, F., 2003. Forest Law Enforcement in Mozambique: An Overview. Ministry of Agriculture, National Directorate of Forestry and Wildlife, Maputo, Mozambique.
Dewees, P.A., Campbell, B.M., Katerere, Y., et al., 2010. Managing the Miombo woodlands of Southern Africa: policies, incentives and options for the rural poor. J. Nat. Resour. Policy Res. 2 (1), 57–73.
DNEA (National Directorate for Agricultural Extension), 2014. Anual Report - 2014. (Maputo, Mozambique).
DNTF (Direcção Nacional De Terras e Florestas), 2014. Melhoramento da Fiscalização Florestal e Faunística em Moçambique – Pano de Acção. Ministério Da Agricultura, República De Moçambique, Maputo, Mozambique.
DNTF (Direcção Nacional De Terras e Florestas), 2015. Relatório de Balanço Anual de Actividades e 2014. Ministério Da Agricultura, República De Moçambique, Maputo, Mozambique.
Düspohl, M., Frank, S., Döll, P., 2012. A review of Bayesian networks as a participatory modeling approach in support of sustainable environmental management. J. Sustain. Dev. 5, 12.
EUEI/GIZ, 2012. Biomass Energy Strategy (BEST)-Mozambique. (Maputo, Mozambique).
Farmani, R., Henriksen, H.J., Savic, D., 2009. An evolutionary Bayesian belief network methodology for optimum management of groundwater contamination. Environ. Model. Softw. 24 (3), 303–310. http://www.sciencedirect.com/science/article/pii/S1364815208001527.
Fischer, J., Gardner, T.A., Bennett, E.M., et al., 2015. Advancing sustainability through mainstreaming a social-ecological systems perspective. Curr. Opin. Environ. Sustain. 14, 144–149.
Fisher, M., 2004. Household welfare and forest dependence in Southern Malawi. Environ. Dev. Econ. 9, 123–130.
Fisher, J.A., Patenaude, G., Giri, K., et al., 2014. Understanding the relationships between ecosystem services and poverty alleviation: a conceptual framework. Ecosyst. Serv. 7, 34–45.
Freeman, L., 1977. A set of measures of centrality based on betweenness. Sociometry 40, 35–41.
Grainger, A., 1999. Constraints on modelling the deforestation and degradation of tropical open woodlands. Glob. Ecol. Biogeogr. 8, 179–190.
Henriksen, H.J., Barlebo, H.C., 2008. Reflections on the use of Bayesian belief networks for adaptive management. J. Environ. Manag. 88 (4), 1025–1036. http://www.sciencedirect.com/science/article/pii/S0301479707001922.
Hosonuma, N., Herold, M., De Sy, V., et al., 2012. An assessment of deforestation and forest degradation drivers in developing countries. Environ. Res. Lett. 7, 4.
IEA (International Energy Agency), 2014. Africa Energy Outlook - World Energy Outlook Special Report - WEO2014_AfricaEnergyOutlook.pdf. OECD/IEA, Paris, France.
Jensen, F., 2001. Bayesian Networks and Decision Graphs. Springer-Verlag, New York, USA.
Jones, D., Ryan, C.M., Fisher, J., 2016. Charcoal as a diversification strategy: the flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. Energy Sustain. Dev. 32, 14–21.
Kalaba, F.K., 2014. A conceptual framework for understanding forest socio-ecological systems. Biodivers. Conserv. 23 (14), 3391–3403.
Kamanga, P., Vedeld, P., Sjaastad, E., 2009. Forest incomes and rural livelihoods in Chiradzulu District, Malawi. Ecol. Econ. 68 (3), 613–624.
Kammen, D.M., Lew, D.J., 2005. Review of Technologies for the Production and Use of Charcoal. Renewable and Appropriate Energy Laboratory Report. Energy and Resources Group & Goldman School of Public Policy, University of California, Berkeley, CA, USA, pp. 1–19.
Kasparek, M., 2008. Sustainable Forest Management and Conservation Project. Evaluation of Pilot Measures in Botswana, Malawi, Mozambique and Namibia. FANR/SADC-GTZ.
Kelly, R.A.L., Jakeman, A.J., Barreteau, O., et al., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environ. Model. Softw. 47, 159–181. http://www.sciencedirect.com/science/article/pii/S1364815213001151.
Khundi, F., Jagger, P., Shively, G., Sserunkuuma, D., 2008. Income, poverty and charcoal production in Uganda. Forest Policy Econ. 13 (3), 199–205.
Kwaschik, R., 2008. Proc. “Conf. on Charcoal and Communities in Africa”. Global Non-timber Forest Products (NTFP) Partnership and International Network for Bamboo and Rattan (INBAR), Maputo, Mozambique.
Luoga, E.J., Witkowski, E.T.F., Balkwill, K., 2002. Harvested and standing wood stocks in protected and communal miombo woodlands of eastern Tanzania. For. Ecol. Manag. 164, 15–30.
Luz, C.A., Baumert, S., Fisher, J., Grundy, I., Matediane, M., Patenaude, G., Ribeiro, N., Ryan, C., Vollmer, F., Woollen, E., Zorrilla-Miras, P., 2015. Charcoal Production and Trade in Southern Mozambique: Historical Trends and Present Scenarios. Conference Paper. XIV World Forestry Congress, South Africa.
Luz, C.A., Ryan, C., Baumert, P., Zorrilla-Miras, F., Vollmer, E., Woollen, Mahamane, M., 2017. The contribution of charcoal to deforestation and degradation: a case study from Southern Mozambique. Land Degrad. Dev (forthcoming).
Mahamane, M., Zorilla-Mirras, P., Verweij, P., Sitoe, A., Ryan, C., Patenaude, G., Grundy, I., Metzger, M., Ribeiro, N., Baumert, S., Vollmer, F., 2017. Understanding land use, land cover and woodland-based ecosystem services change, Mabalane, Mozambique. Energy Environ. Res. 7 (1).
Marzoli, A., 2007. Inventário florestal nacional: avaliação integrada da floresta em Moçambique (AIFM). Direção Nacional de Terras e Florestas, Maputo, Mozambique.
MEA (Millennium Ecosystem Assessment), 2005a. Millennium Ecosystem Assessment: Ecosystems and Human Wellbeing: Synthesis. Island Press, Washington DC, USA.
MEA (Millennium Ecosystem Assessment), 2005b. Ecosystems and Human Well-being: Findings of the Scenarios Working Group of the Millennium Ecosystem Assessment. Island Press, Washington DC, USA.
Olsson, P., Folke, C., Berkes, F., 2004. Adaptive co-management for building resilience in social-ecological systems. Environ. Manag. 34, 75–90.
Openshaw, K., 2010. Biomass energy: employment generation and its contribution to poverty alleviation. Biomass Bioenergy 34 (3), 365–378.
Peter, C., Sander, K., 2009. Environmental Crisis or Sustainable Development Opportunity? Transforming the Charcoal Sector in Tanzania: A Policy Note. World Bank, Washington DC, USA.
Peterson, D.P., Rieman, B.E., Dunham, J.B., et al., 2008. Analysis of trade-offs between threats of invasion by nonnative brook trout (*Salvelinus fontinalis*) and intentional isolation for native westslope cutthroat trout (*Oncorhynchus clarkii lewisi*). Can. J. Fish. Aquat. Sci. 65 (4), 557–573. http://www.nrcresearchpress.com/doi/abs/10.1139/f07-184#.VpzA8UatIXg.

Pollino, C.A., Henderson, C., 2010. Bayesian networks: a guide for the application in natural resource management and policy. In: Landscape Logic Technical Report No. 14. Australian Government, Department of the Environment, Water, Heritage and the Arts.
Puná, N., 2008. Charcoal supply chain study in Mozambique. In: Kwaschik, R. (Ed.), Proceedings of the "Conference on Charcoal and Communities in Africa". Global Non-timber Forest Products (NTFP) Partnership and International Network for Bamboo and Rattan (INBAR), Maputo, Mozambique.
Rounsevell, M.D.A., Metzger, M.J., 2010. Developing qualitative scenario storylines for environmental change assessment. Wiley Interdiscip. Rev. Clim. Chang. 1, 606–619.
Ryan, C.M., Berry, N.J., Joshi, N., 2014. Quantifying the causes of deforestation and degradation and creating transparent REDD + baselines: a method and case study from central Mozambique. Appl. Geogr. 53, 45–54.
Ryan, C.M., Pritchard, R., McNicol, I., Owen, M., Fisher, J.A., Lehmann, C., 2016. Ecosystem services from southern African woodlands and their future under global change. Philos. Trans. R. Soc. B 371, 20150312.
Schure, J., Ingram, V., Sakho-Jimbira, M.S., et al., 2013. Formalisation of charcoal value chains and livelihood outcomes in Central and West Africa. Energy Sustain. Dev. 17 (2), 95–105.
SEI (Stockholm Environment Institute), 2002. Charcoal Potential in Southern Africa (CHAPOSA). (Stockholm, Sweden).
Shackleton, C.M., Shackleton, S.E., Buiten, E., Bird, N., 2007. The importance of dry woodlands and forests in rural livelihoods and poverty alleviation in South Africa. Forest Policy Econ. 9 (5), 558–577.
Shackleton, S., Campbell, B., Lotz-Sisitka, H., Shackleton, C., 2008. Links between the local trade in natural products, livelihoods and poverty alleviation in a semi-arid region of South Africa. World Dev. 36 (3), 505–526.
Sitoe, A., Salomão, A., Wertz-Kanounnikoff, S., 2012. The context of REDD + in Mozambique: Drivers, agents and institutions. In: Occasional Paper 79. CIFOR, Bogor, Indonesia. http://www.cifor.org/publications/pdf_files/OccPapers/OP-79.pdf.
Sitoe, A., Wertz-Kanounnikoff, S., Ribeiro, N., et al., 2014. Community rights and participation in the face of new global interests in forests and lands: the case of Mozambique. In: Katila (Ed.), Forests Under Pressure: Local Responses to Global Issues. IUFRO World Series, vol. 32. pp. 561 (Vienna).
Smith, C.S., Howes, A.L., Price, B., McAlpine, C.A., 2007. Using a Bayesian belief network to predict suitable habitat of an endangered mammal—the Julia Creek dunnart (*Sminthopsis douglasi*). Biol. Conserv. 139, 333–347.
Smith, H.E., Hudson, M.D., Schreckenberg, K., 2017. Livelihood diversification: the role of charcoal production in southern Malawi. Energy Sustain. Dev. 36, 22–36.
Suich, H., Howe, C., Mace, G., 2015. Ecosystem services and poverty alleviation: a review of the empirical links. Ecosyst. Serv. 12, 137–147.
Tomaselli, I., 2007. Forests and energy in developing countries. In: Forests and Energy Working Paper n°2. FAO, Rome, Italy.
Tvedten, I., Rosário, C., Tuominen, M., 2012. Reality Checks in Mozambique. Building Better Understanding of the Dynamics of Poverty and Well-being. Approach and Methodologies. ORGUT, Chr. Michelsen Institute, AustralCOWI, Maputo, Mozambique. http://www.cmi.no/publications/file/4508-reality-checks-inmozambique.pdf.
Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecol. Model. 203 (3–4), 312–318. http://www.sciencedirect.com/science/article/pii/S0304380006006089.
Vollmer, F., Zorilla-Miras, P., Baumert, S., et al., 2017. Charcoal production as a means to a valuable end: Scope and limitations of charcoal income to alleviate acute multi-dimensional poverty in Mabalane district, southern Mozambique. World Dev. Perspect (forthcoming).
Woollen, E., Ryan, C.M., Baumert, S., et al., 2016. Charcoal production in the Mopane woodlands of Mozambique: what are the tradoffs with other ecosystem services? Philos. Trans. R. Soc. B 371, 20150315.
Zorrilla, P., Carmona, G., De la Hera, A., Varela-Ortega, C., Martínez-Santos, P., Bromley, J., Henriksen, H.J., 2010. Evaluation of Bayesian networks in participatory water resources management, upper Guadiana Basin, Spain. Ecol. Soc. 15, 3.
Zulu, L.C., Richardson, R.B., 2013. Charcoal, livelihoods, and poverty reduction: evidence from sub-Saharan Africa. Energy Sustain. Dev. 17 (2), 127–137.