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ABSTRACT

A Bayesian belief network (BBN) was developed to assess preferred combinations of trees in live fences and on pastures in silvopastoral systems. The BBN was created with information from Rivas, Nicaragua, using local farmer knowledge on tree species, trees' costs and benefits, farmers' expressed needs and aspirations, and scientific knowledge regarding tree functional traits and their contribution to ecosystem services and benefits. The model identifies combinations of trees, which provide multiple ecosystem services from pastures, improving their productivity and contribution to farmer livelihoods. We demonstrate how the identification of portfolios of multifunctional trees can satisfy a profile of desired ecosystem services prioritized by the farmer. Diagnostics using Bayesian inference starts with an identification of farmer needs and 'works backwards' to identify a silvopastoral system structure. We conclude that Bayesian belief networks are a promising modeling technique for multi-criteria decisions in farm adaptation processes, where interventions must be adapted to specific contexts and farmer preferences.

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1. Introduction

Pasture is a major land use in Central America, occupying more than 60% of the agricultural land area. Silvopastoral systems, in which trees are maintained from the original forest vegetation or re-introduced in pastures as sparse trees or live fences, have been promoted as an alternative production system with many potential economic and environmental benefits. These are based on higher total production of fodder (Pérez Almario et al., 2013) and other products including wood for construction and firewood, and fruit for human consumption (Sánchez et al., 2004). They also provide an alternative for the management of soil nutrients and carbon stocks of tropical pastures (Casals et al., 2013), improve water-balance (Espeleta et al., 2004) and can enhance animal well-being and productivity from the shelter and shade provided by trees (Souza de Abreu, 2002). Several of these functions are related to specific tree characteristics and functional traits (Casals et al., 2013; Pérez Almario et al., 2013; Rusch et al., 2014). In addition, silvopastoral systems in Central America can contribute significantly to conserving native biodiversity (Harvey et al., 2008), and can provide both climate mitigation (Ibrahim et al., 2010) and adaptation benefits (Harvey et al., 2014). Hence, silvopastoral systems can be viewed as eco-intensified agroecosystems with the capacity to provide high levels of ecosystem services. There are also some disservices associated with the trees in pastures; trees can negatively affect pasture growth directly through competition for resources and indirectly by shading. The magnitude of these effects can be reduced by selecting species with low or positive impacts on pasture primary productivity (Rusch et al., 2014) and through the spatial arrangement of the trees. For instance, trees

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along live fences minimize pasture shading (Sauceda, 2010), and also overcome problems of reduced tree regeneration pastures due to animal trampling, browsing, and weed control (Esquivel et al., 2008). Good planning, and improved management of silvopastoral systems, in addition to an integration of climate mitigation and adaptation efforts (Harvey et al., 2014) are therefore prerequisites for successful adoption and maximum provision of ecosystem services.

Despite the clear benefits and multifunctionality of silvopastoral systems (SPS), improvement and transformation of these systems in Central America continues to be limited (Alonso et al., 2001; Mercer, 2004). A number of studies provide explanations of the limited adoption of improved SPS. A driving force is the livestock farmer perception that shade from large trees reduces pasture productivity (Marie, 2010). In Costa Rica and Nicaragua, tree cover in pastures typically lies between 2% and 12% on average (Villanueva et al., 2004; Ruiz et al., 2005; Villacís, 2003). Esquivel et al. (2007) found that pasture biomass productivity declined when tree cover reached 30% or higher. Broadly speaking there seems to be substantial potential for increasing tree cover – an additional 18% on average in these studies – with low risk to decreasing farm productivity in the region. For SPS technology to be adopted by farmers however, we need clear identification of the qualitative and quantitative benefits, acceptable levels of risk, and increased SPS compatibility with available farm resources focusing on the use of familiar native tree species (Rogers, 2003).

Technology adoption studies have largely focused on evaluating the likelihood of adoption of single technologies, given multiple farm(er) characteristics using binary logit/probit approaches (Scherr, 1995; Lapar and Pandey, 1999; Adesina et al., 2000; Cramb, 2005; Levasseur et al., 2009). Complementary approaches are called for when extension services must consider the likelihoods that multiple practices have been co-adapted to the specific conditions of a farm, based on farmers' expressed needs. Adapting silvopastoral practices to meet these specific farmer needs is a multi-dimensional problem in which farmer knowledge and preferences must be combined with scientific and technical knowledge of agricultural extension services.

Bayesian belief networks (BBNs) are increasingly being used in ecological modeling, decision support in the provision and demand of ecosystem services, and environmental and resource management (Varis, 1997; Kuikka et al., 1999; McCann et al., 2006; Uusitalo, 2007; Aguilera et al., 2011; Haines-Young, 2011; Barton et al., 2012; Landuyt et al., 2013). BBNs have seen limited use in modeling of silvopastoral systems. Joshi et al. (2001) use a BBN to describe socio-economic variables that influence farmers' decisions regarding plot level management of tropical agroforestry systems in Indonesia. They use participatory rural appraisal and conventional socio-economic methods to generate data and collapse them into conditional probability tables of a BBN. López and colleagues (2007) used BBNs to model factors affecting adoption of trees in pasture lands in Nicaragua and Costa Rica (Villanueva et al., 2003; López et al., 2007).

They find that the most important decisions that influence on-farm tree cover in Costa Rica are weed control, tree harvesting, live fence pruning and planting of new live fences (Villanueva et al., 2003). In Nicaragua, manual versus chemical weed control in pastures, pruning of trees in live fences, harvesting branches and trees for firewood, posts and timber, and land use change were the main factors determining the degree of tree cover retained in pastures and live fences.

Both studies use Netica BBN software (www.norsys.com) to model a number of underlying farm practices, ecological and socio-economic factors that in turn determined these main effects.

Sadoddin et al. (2005) use BBNs to evaluate biophysical, social, ecological and economic factors determining the dryland salinity effects of different management scenarios on terrestrial and riparian ecosystems in the Darling Basin, Australia. They argue that BBNs are particularly useful for communicating risk and uncertainty and providing a framework for analysing cause and effect relationships in natural systems. The advantage of BBN's over neural networks is their functionality for also analysing decision processes. Baynes et al. (2011) use a BBN to model how farmers respond to offers of extension assistance in Leyte, Philippines. They argue that BBNs are particularly useful in identifying critical success factors and stumbling blocks in scaling up of extension programmes. Poppenborg and Koellner (2014) use BBNs to calculate the probability of crop choice in a multi-criteria analysis using the analytical hierarchy process. BBNs have also been used to model ecosystem service delivery of farm and forest management options, see for example (Barton et al., 2008; Gret-Regamey et al., 2013; McVittie et al., 2015).

In most BBN applications of farm management, farmer choices are modelled as outcome nodes conditional on farmer preferences, which in turn may be conditional on farm and landscape characteristics. The probabilities of farmer choices are deduced from farm and farmer characteristics using the same causal logic as in regression analysis. Often data to populate BBNs is collected in a single survey or round of group based interviews.

In this paper we use a BBN to demonstrate both deductive and inductive reasoning regarding the likelihood of farmers' adoption of trees in pastures. We structure the BBN with the desired ecosystem services as the outcome node, and the specific context and characteristics of the farm and farmer as the conditioning variables. This inverts the causal logic seen in previously published BBN papers on farmer choice of practices and bears resemblance to the causal logic of the ecosystem services cascade from ecosystem structures through ecological functions to ecosystem services, benefits and values (Haines-Young, 2011). It allows demonstrating how to use Bayesian inference from desired ecosystem service outcomes to choice of ecosystem structure – in this case, trees in pastures. The paper also demonstrates how a BBN can be used to join together all available data with new evidence to inform decision-making. We use BBNs to link mapping of current tree species composition in pastures, farm characteristics, farmer and scientific knowledge of species functional traits and ecosystem services and disservices of trees, farmer preferences for ideal pasture composition, and farmer beliefs about opportunities and constraints regarding adoption of tree species. We demonstrate how the BBN can be deployed online, making the knowledge more widely available to e.g. extension services.

2. Materials and methods

2.1. A BBN approach to diagnosing farmer ecosystem service demand

In this paper we model desired ecosystem services and costs of trees in pasture as observable characteristics of the farmer, and use inference in a BBN to calculate the posterior probabilities of functional traits given desired ecosystem services, and next the posterior probability of trees species given a probability distribution of desired functional traits (conditional on ecosystem services). Finally, we model tree species composition in paddocks as conditional on farm(er) socio-economic characteristics.

Bayesian belief networks are a graphical representation of a joint probability distribution decomposed into a set of conditional probability distributions (Kjærulff and Madsen, 2013). As such, they are a generic modeling tool used both for representing a correlation structure in a causal network and for decision analysis under uncertainty. BBNs are a useful tool for integrating knowledge domains across the causal structure of the ecosystem services cascade from biophysical structure to ecosystem benefits and values (Haines-Young, 2011; Landuyt et al., 2013; McVittie et al., 2015). BBNs in the ecosystem services literature have mainly been used for what could be called 'deductive integrated assessment' following a cascade of cause-effects to conduct e.g. scenario or decision analysis under uncertainty. Spatial BBNs using land use and landscape structure to predict the probability of ecosystem services at particular locations is an example of a 'deductive' application of BBNs and a promising research field in ecosystem services (Landuyt et al., 2013; Gonzalez-Redin et al., 2016). To our knowledge the 'inductive' features of BBNs have not been explored in the ecosystem services modeling literature. By inductive we mean 'bottom-up' reasoning from observable outcomes (child nodes) to hidden causes (parent nodes). To use a medical analogy, a symptom is observed (evidence) in a particular patient being diagnosed. The doctor can access patient case histories to calculate the *likelihood* for a given patient of disease or other causes given symptoms; the evidence of symptoms and likelihoods are combined to calculate a posterior probability of disease in the patient given the symptoms. Taking a prior into account is key to Bayesian inference.

From an agricultural extension worker's observation in a paddock of a certain tree species composition (evidence) the BBN is used to infer the probability that the paddock belongs to a certain type of farm(er) (e.g. without knowledge in the field of who's property the paddock is). The causal network structure was designed to simulate the kind of evidence an agricultural extension worker might encounter when entering a new project area for the first time, i.e. field observations of paddock vegetation structure, and farmers' needs and wants expressed through interviews. Throughout the paper we use the terminology Bayesian *belief* network (BBN), whereas 'Bayesian networks' and 'Bayes' nets' are terms often also used in the environmental management literature (Barton et al., 2012). In our case, using 'belief' emphasises that knowledge contained in the network as based on farmer local knowledge, extension worker and researcher knowledge, and subjective judgement used in linking different fields of knowledge in a network for a specific decision-support purpose.

Compared to spreadsheets (e.g. Excel) or simulation-based causal chain models, for example Analytica (www.lumina.com) Bayesian networks are unique in providing inductive analysis capability (Barton et al., 2012). The fact that BBNs allow for non-parametric, qualitative models, should make them ideal as expert systems for extension work with farmers. Fig. 1 illustrates some desirable properties of BBNs in the integration of different knowledge domains in an expert system on silvopastoral systems.

From the lower right hand corner of Fig. 1, social scientists collect information on different uses farmers make of trees in their field and relate this to farm characteristics (location, size, production system), and farmer beliefs and preferences. The probability that tree species are found in pastures is conditional on these farm(er) characteristics, denoted *P* (*species*=*farmer characteristics*). In the upper right hand quadrant, biologists and ecologists conduct fieldwork and ethno-botanical interviews to determine the morphological and functional traits of tree species linked to functions that underpin the provision of ecosystem services such as drought tolerance, water use efficiency, soil formation and fertility, forage provision, conditions for understorey vegetation productivity. The probability of trait classes is conditional on species composition – denoted *P* (*traits*=*species*). In the upper left hand quadrant, field surveys are often carried out to determine the relationship between morphological traits of trees and ecological functions. The probability of ecological function is conditional on morphological traits – denoted *P* (*function*/*traits*). In the lower left hand quadrant, researchers use their expert knowledge across similar cases to associate tree traits with ecological functions of trees and ecosystem services provided on-farm and in the surrounding landscape. The probability of ecosystem services is conditional on ecosystem functions – denoted *P* (*service*=*function*). Once all conditional probability distributions are specified, BBN may be used to reason deductively about the probability of outcomes, i.e. given evidence about a farm's characteristics what is the likely adaptation of portfolios of trees, with multifunction traits that deliver a series of ecosystem services. Reasoning inductively, given farmer preferences for ecosystem services what are the likely functional traits that deliver these services, and what trees are associated with these traits?

Validations across the two lower quadrants reflecting scientific expert knowledge on one side and farmer expert knowledge on the other may be revealing – potential ecosystem services identified by scientists may not directly support the benefits from SPS as perceived by farmers. Linking the knowledge 'quadrants' in Fig. 1 together demonstrates how BBNs can be used as a meta-modeling platform (Barton et al., 2008). In combining multiple knowledge

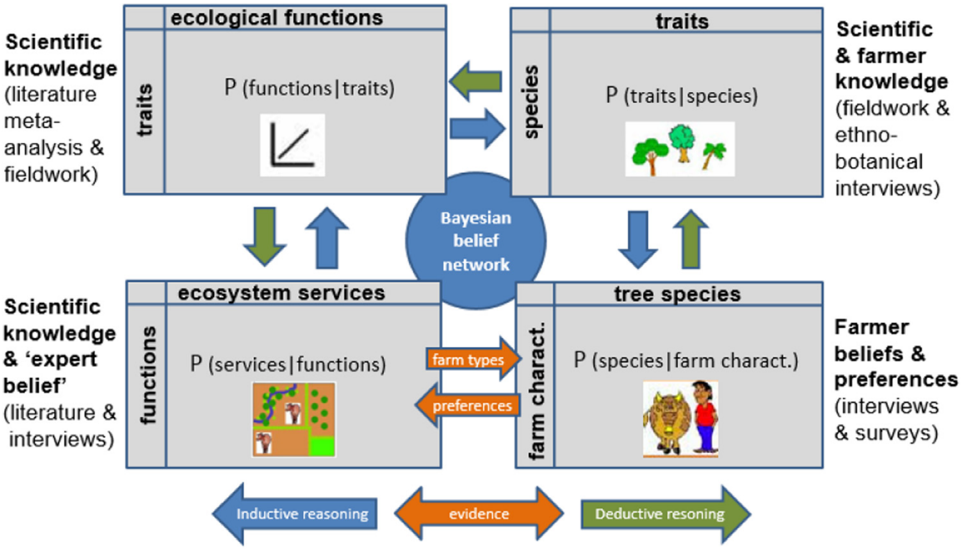

Fig. 1. Conceptual model of reasoning using a Bayesian Belief Network (BBN) integrating different knowledge domains. Each rectangle is a different knowledge domain represented by a conditional probability table P (X|Y) in the BBN. Deductive reasoning from observation of farm type counter-clockwise to ecosystem services. Inductive reasoning from observation of farmer preferences for ecosystem services clockwise to tree species portfolios.

bases a balance needs to be struck between computational efficiency, the need for communication through a compact model interface and representation of context complexity (Marcot et al., 2006). Object-oriented Bayesian network modeling (Koller and Pfeffer, 1997) makes it possible to nest complex sub-models for specific parts of a causal chain, thereby simplifying the model interface and presentation. Object-oriented modeling is a useful feature for environmental management in modeling driver-pressure-state-impact-response chains and ecosystem service cascades (Barton et al., 2012; Johnson et al., 2013). We used this approach to nest sub-networks describing the net financial returns to different tree species.

2.2. *Study area*

The study was conducted in the Department of Rivas, Nicaragua. This is a semi-arid zone at 100–200 m.a.s.l. with an average annual temperature of 26.1 °C (1971–2000), average annual precipitation of 1519 mm (INETER, 2012), and soil types dominated by vertisols and mollisols (Sánchez et al., 2004). The dry season takes place between December and the second week of May. The landscape in the study area is mainly cattle pasture with tree cover mainly as trees in pasture and live fences (Sánchez et al., 2013). The farm systems in the study area were classified as subsistence (16%), intensive (54%) and extensive (30%) (Marie, 2010). Broadly speaking subsistence farms have between 6 and 20 hectares, 2–10 heads of cattle and livelihoods are equally divided between cattle, agriculture and salaried employment. Intensive farms are mostly 20–50 hectares in size (mean 28.7 ha) with a majority of farms possessing 10–40 heads of cattle, and livelihoods based mainly on cattle, with some crops. Extensive farms vary more in size (mean of 42 ha) and cattle (mean of 29 heads), but are distinctive through the dominance of agriculture for livelihoods, secondarily cattle. Principle crops in Rivas are papaya and sugar cane on large farms and polycultures of bananas, vegetables, maize and beans on small farms (Marie, 2010; O'Toole and Aguilar-Støen, 2013). For small and medium scale cattle farmers in Nicaragua's dry Pacific region, the least costly way of feeding cattle is graze in paddocks.

In the dry season grass production stops completely (Ospina et al., 2012), requiring farmers to find other strategies for providing stable access to feed throughout the year (Sánchez et al., 2013). Risks and constraints to the farm production system vary by farm type. In subsistence farms shortages of own time, hired labour and seed ranked among the most important problems. In intensive farms labour shortage, theft of trees and alternative sources of income ranked among the most important limitations, while in extensive farms shortages of time and hired labour were the most often cited, while shortages of seed, summer pasture, water, fertilizer, alternative sources of income and lacking land title were also often mentioned (Marie, 2010). Many farmers believe a high level of tree cover leads to low pasture productivity (Marie, 2010). The vast majority of farms (87%) had tree cover less than 10%. Managing a portfolio of multifunctional trees in pastures provides a low labour input source of stable fodder, shading for cattle and secondary benefits (fire wood, building materials, fruit), addressing some of the most important limitations mentioned by farmers in the area (Sánchez et al., 2013).

2.3. *Data structure*

Fig. 2 illustrates the conceptual structure of the BBN and types of knowledge that were combined (colour legend). Primary data to populate the BBN come mainly from structured surveys of farmers, follow-up interviews of farmers with a paddock simulation board, interviews with scientists, and several secondary sources. Mosquera (2010) conducted semi-structured interviews of 76 farmers on their local knowledge of functional traits of tree species and their perceived benefits and disadvantages. Salazar (2012) conducted a structured survey of 55 of the farmers from Mosquera's sample collecting complementary information on farmers motivations, limitations and solutions for managing trees in paddocks, and knowledge of trees' costs and benefits. Structured survey questions were complemented by a semi-structured paddock simulation exercise with farmers, and semi-structured interviews with scientists on trees' functional traits and ecosystem services.

2.3.1. *Farm typology*

Marie (2010) defined a farm typology – subsistence, extensive, intensive – based on farm location, area, herd size, main source of income, and main type of labour. We modelled the classification

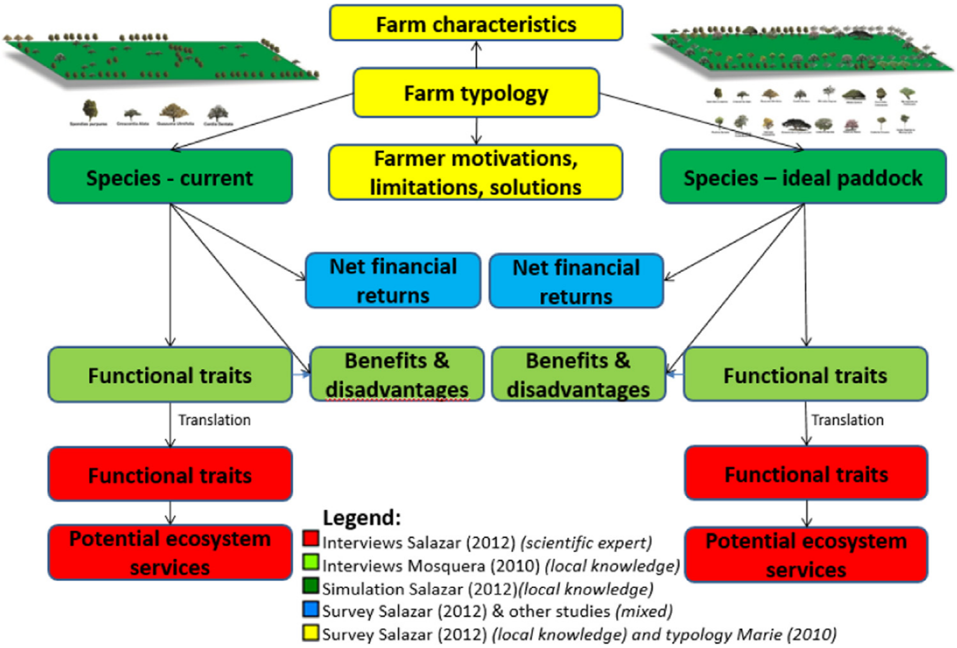

Fig. 2. Basic structure of the BBN on silvopastoral system in Rivas showing the assumptions about causality.

problem in a BBN such that physical farm characteristics are conditional on the farm typology (links from typology to characteristics) The typology by Marie (2010) was also linked to farmer characteristics in the form of their beliefs concerning limitations, motivations and solutions for adoption of tree species at the farm level as expressed in the survey by Salazar (2012) (nodes in yellow, Fig. 2). We derived conditional probability tables from the frequency of particular limitations, motivations and solutions to management of trees in paddocks mentioned by farmers in the survey by Salazar (2012) across the farm types defined by Marie (2010).

2.3.2. *Tree functional traits, benefits and disadvantages – local knowledge*

In Mosquera's (2010) interviewed farmers on their local knowledge of functional traits, perceived benefits and disadvantages of 27 tree species (light green nodes; Fig. 2). The terminology for 'functional traits' was expressed by farmers in their own words – e.g. "sombra caliente" ("hot shade") as a negative trait, or "fresco" ("fresh") as a positive trait. We used this information to specify conditional probabilities of functional traits for each tree species using local knowledge identified by Mosquera (2010). Farmers also identified six types of 'benefits' – firewood and fodder provision, erosion control, soil improvement, drought resistance and protection of water sources, and a number of 'disadvantages' in their own words (e.g. "small crown", "sparse roots"). We included conditional probability tables of trees species and benefits/disadvantages in local terminology as a complementary source of knowledge to the scientific knowledge of ecosystem services and disservices.

2.3.3. *Tree functional traits – local-to-scientific knowledge*

We defined a 'translation' node in the original Spanish version of the network to translate farmers' terminology to that used by scientists in the project (light green nodes, Fig. 2). Some local terms – e.g. "no ash", "durable", "locally adapted" – could not or were not interpreted in terms of functional traits by the experts. In these cases we assigned the scientific terms equal prior probability, i.e. 'no information'.

2.3.4. *Ecosystem services – scientific knowledge*

Salazar (2012) carried out interviews of scientific staff on the FUNCiTREE project regarding potential ecosystem services of multifunctional trees (red nodes; Fig. 2). Eight scientific experts were interviewed regarding the degree of correlation (0–1) between scientific functional traits and a longer list of ecosystem services as defined by experts (Supplementary material Table S1). Recall that scientific functional traits are conditional on an interpretation of local knowledge functional traits mentioned by farmers.

2.3.5. *Current and ideal paddock "game board"*

Using the farm typology from Marie (2010), we interviewed a representative sample of 55 farmers on the existing versus idealized composition, configuration and density of trees in the SPS as expressed in a simulation exercise (dark green nodes, Fig. 2). Detailed results are reported in Salazar (2012). Of the 27 species listed by Mosquera (2010) we used the 21 most frequently mentioned in the simulation exercise of the 'ideal' SPS carried out with farmers as part of the survey. With the aid of a 'game board' representing a typical SPS on the farm we interviewed farmers about tree composition and configuration of current and idealized paddocks (Fig. 3). Using coloured markers specific to common tree species found in pastures in the area, farmers illustrated the current composition of the typical SPS. The "game board" interviews conducted by Salazar (2012) asked farmers to modify the composition and abundance of trees until they obtained what they considered to be an "ideal" SPS in terms of species composition, spatial configuration and crown coverage of the paddock.

2.3.6. *Financial benefits and costs*

Salazar (2012) interviewed farmers regarding costs, productivity and prices for t non-timber products from paddock trees (blue nodes; Fig. 2). A BBN sub-network was constructed to calculate costs of tree planting and the net annual benefits of tree products minus management costs for live fences and trees in pasture for the current paddock and 'ideal' SPS (Supplementary material Fig. S1). Gross income and management costs were derived from the financial questions in the survey by Salazar (2012), determining net annual income per tree and for the current and ideal paddock as a whole. We based tree crown diameter node on the SILPAS project database of 1821 observations of 21 different species in the study area. We determined the number of additional trees based on information from the paddock simulation exercise. We used the number of trees per species and information on average crown size to calculate the tree crown cover percentage that would result from farmers' choices.

2.3.7. *Validation as an extension tool*

Eight interviews were conducted with extensive (2), intensive

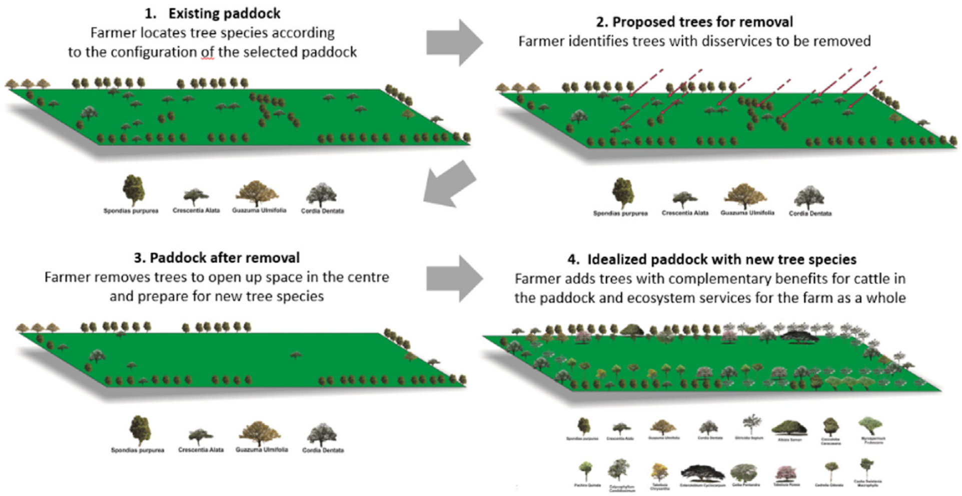

Fig. 3. Example of the process of defining the current SPS and adaptation to the ideal SPS Source: Salazar (2012). Graphic design by Juan Guillermo Martínez Souza.

(3) and subsistence (3) farmers from the same study area in Rivas, but who had not participated in Mosquera"s (2010) and Salazar's (2012) samples. The farmers were asked about the benefits of paddock trees they would seek in improving their paddocks, and the tree species they considered appropriate to achieve this. Their selection of trees was compared to the tree combination predicted by the BBN based only on information about farm type and the farmers' stated needs.

2.4. Model structure

For constructing our overall model we used the licenced software Hugin Developer v8.1. (www.hugin.com). The resulting network in Hugin software identifies tree composition, density and arrangement in an idealized pasture based on the following information provided by the farmers and scientific experts: (1) the types of ecosystem services desired by the farmer, (2) functional traits of trees desired by the farmer or recommended by experts, (3) expected financial income and costs, (4) average crown size of selected species, (5) tree density desired by the farmer, (6) species composition selected by the farmer. The network is presented in high resolution in Supplementary material (Fig. S2).

The network contains nodes that 'translate' terminology of the ecosystem services cascade regarding 'benefits' perceived by farmers into the 'ecosystem service', 'ecosystem function' and 'ecosystem structure' terminology used by researchers. The directionality of the links in the network illustrates the underlying assumption, regarding network causality. This determines what is meant by 'deductive' and 'inductive' types of analysis. The network can be used to determine species composition in an idealized pasture conditional on the ecosystem services desired by the farmer, requirements for financial return and farm typology.

3. Results

3.1. Online model

A selection of the BBN's marginal conditional probability distributions can be inspected in a web front-end extract of the model at http://funcitree.hugin.com/pastures. The web front-end version of the BBN illustrates a selection of model nodes demonstrating how a model can be made widely available using the HUGIN Web Service API[1].

3.2. Farmer preferences for the ideal silvopastoral system

The paddock simulation exercises showed that farmers preferred increasing tree density in live fences over increasing tree density within pastures. They preferred trees that grow easily, that have specific economic values, and generally seek to remove species with few uses, as well as species that reduce pasture productivity due to excessive shading. As observed in the conditional probability distributions, the ecosystem services most frequently mentioned by farmers included ensuring dry season fodder availability for animals, diversifying farm products such as fence posts, supply of construction materials and firewood and enhancing scenic beauty to the surroundings.

According to Esquivel et al. (2007), pasture productivity may start to decline as crown cover exceeds 30% or more. Current pasture tree cover averages 15% whereas farmers indicate that they would like tree cover of around 42% on average in simulation exercises. The typical farmer places most additional trees in live fences. This suggests that while farmers are willing to accept some pasture productivity decline in return for benefits to cattle from shading, shading effects are preferred when shared with neighbouring pastures. The typical farmer surveyed had 12 trees ha^{-1} in live fences, but added 36 trees in the idealized plot, aiming for a density of 48 trees ha^{-1}. In addition, the average farmer maintained 7 trees dispersed in the pasture but added 18 in the idealized pasture. In live fences, the most common species were *Cordia dentata*, *Guazuma ulmifolia* and *Spondias purpurea*. In the idealized model of live fences farmers mostly added *Pachira quinata*. At the time of the survey, the most common trees dispersed in pasture were *G. ulmifolia* and *Cordia alliodora*, whereas in the idealized pastures, farmers tended to add *Gliricidia sepium*, *P. quinata*, *C. dentata*. The financial returns for the ideal SPS as expressed by farmers showed relatively little variation across different kinds of ecosystem service profiles (Table S2, Supplementary material). This may reflect that there was relatively little variation in the tree species selected for the ideal pasture.

3.3. Ecosystem service profiles – farm system diagnostics using BBN

Fig. 4 shows how the preferred ecosystem services sought by a subsistence farmer with the desirable functional traits together determined the optimal combination of trees. In this example, *C. dentata* (59%), *G. sepium* (15%), and *C. candidissimum* (11%) were the most likely species to meet these preferences, with five other species being preferred with lower probabilities. Fig. 4 provides an example of combining inductive – 'bottom-up' – and deductive – 'top-down' – reasoning about an ideal portfolio of trees for a context specific silvopastoral system. For example, an extension agent may specify that he/she wants a diagnosis of the likely portfolio of tree species that meets farmer preferences for 'shade', 'animal nutrition' and 'firewood' in an idealized pasture. In an inductive mode of reasoning – against the causal direction of the links in the network – an extension agent could determine likely functional traits. The most likely functional traits to describe the desired trees in our data were “cool shade” (14%), “grass grows” (below the crown) (10%), and “hard firewood” (6%). In a deductive mode of reasoning – using the same direction as the causal links – the extension agent would specify that the desired portfolio of trees be determined for a specific type of farmer, in this case a 'subsistence' farmer.

4. Discussion

Our analysis demonstrates how BBNs can be used to join local and scientific knowledge databases on silvo-pastoral systems in support of agricultural extension work matching farmer stated needs with the tree species composition, densities, and traits that meet those needs. Baynes et al. (2011) discuss how the ability of BBNs to accommodate imprecise estimates of qualitative variables is highly advantageous in extension work, which by definition is concerned with subjective human values and attitudes. For example, farmers' needs expressed through a semi-structured interviews could be classified using local terminology for functional traits and linked to e.g. quantitative information on tree cover. Landuyt et al. (2013) argue that integrated models can become structured libraries of existing scientific knowledge enabling the identification of knowledge gaps. For example, conditional probability tables can be rapidly inspected to observe whether there is wide variation in preferred tree species, and whether there are particular farm conditions or farmer needs which will significantly shift preferences. Wide variation and little sensitivity to farm

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[1] The HUGIN Web Service API is distributed with the Hugin Researcher or Developer software. Users can develop and host their own web front-end to a BBN developed in HUGIN. We required assistance from the company Hugin Expert to deploy the web front-end model.

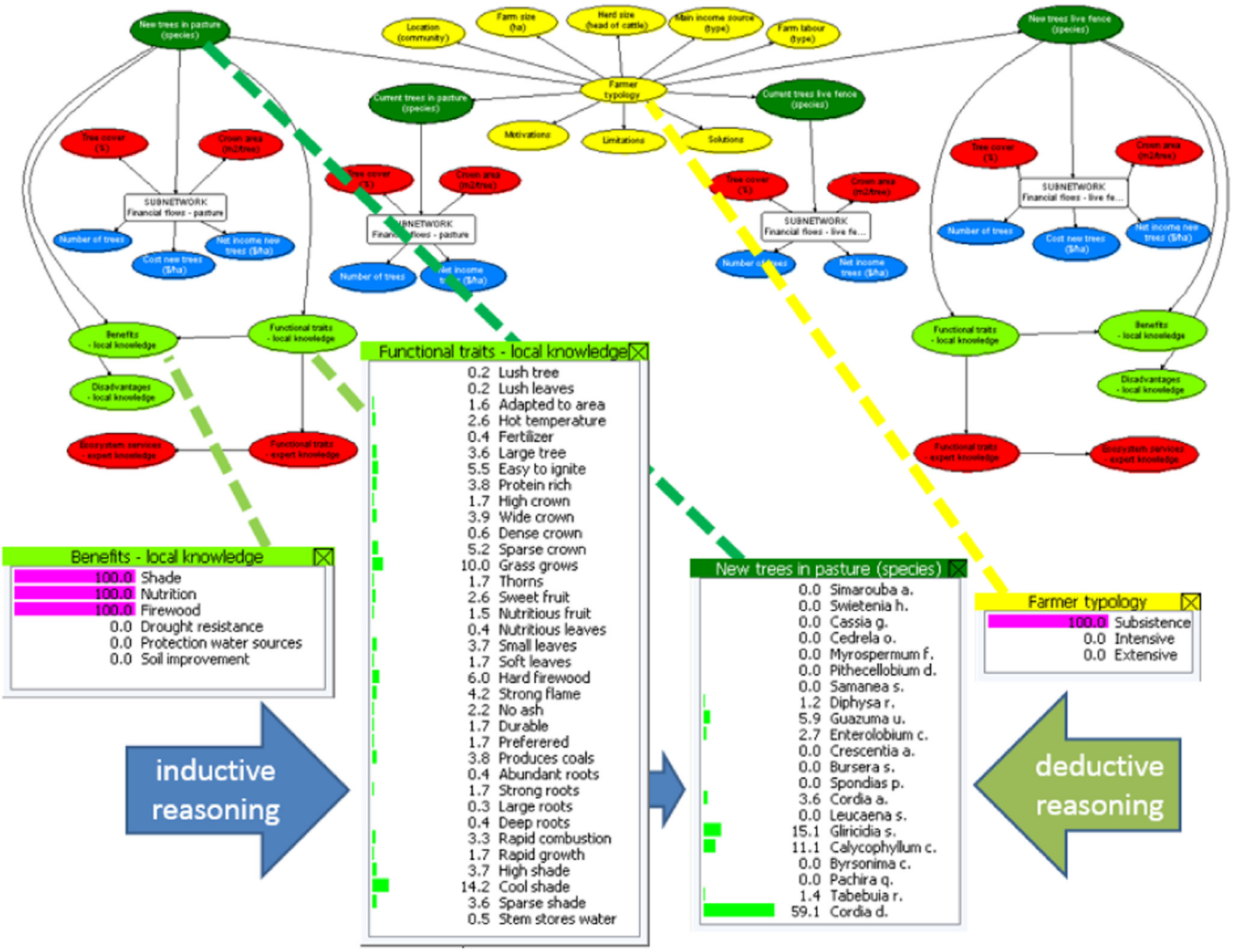

Fig. 4. Example of combining inductive and deductive lines of reasoning using the BBN as an expert system. Ideal tree species portfolio conditional on a subsistence farmer's preferences for 'shade', 'nutrition' and 'firewood'.

context indicate to the extension worker that there is too little information to apply predefined 'solutions' to the farmer. However, compared to these ambitions for an 'expert system' on SPS adaptation some key variables are still missing from our model. Specifically, those that can incorporate scientific knowledge with quantitative assessments of the functional performance of tree species (Pérez Almario et al., 2013), identifying potential new functions and uses of silvopastoral trees, and thus better informing choices among conflicting values.

Farmers are continually working towards their 'ideal' SPS. Our analysis shows how a number of constraints such as limited access to labour and capital make the current SPS different from the ideal. These constraints are only captured indirectly through the farmer typology node in our model, which differentiates labour availability, but not access to credit. Farmers have a limited budget and will not experiment with new technologies at high risk. The calculation of average annual net income for a 25-year cycle of paddock management, does not accurately reflect financial barriers to implementation. Compared to agricultural returns, returns from increasing tree density take longer to materialize. For example, the farmer must wait at least 2 years for any benefits of *G. sepium* to be reflected in farm budgets (Alonso et al., 2001; Thangata and Alavalapati, 2003). In this sense, the 25-year expected net financial return estimates have limited relevance for decisions to introduce a new species or not for subsistence farmers' that are credit constrained.

Current pasture tree cover in the area averages 15%, whereas farmers indicate that they would like tree cover of around 42% on average in simulation exercises. The paddock simulation exercise does not illustrate a decrease in pasture productivity. It assumes that farmers mobilise their own knowledge of the relationship between crown size and pasture productivity when reconfiguring to their 'ideal' paddock. Had we introduced the paddock exercise with information on pasture quantities or qualities decreasing depending on tree crown size farmers may have provided different responses regarding tree density.

Trees in SPS have cultural values. These are enhanced by farmer management, which in turn modify their functional traits. Crown size is an example of cultural values co-determining changes in tree density in pastures (Zapata et al., 2013). Species with wide crowns occupy greater surface areas and reduce pasture productivity (Rusch et al., 2014), and farmers seem to be aware of these constraints, but the preferences revealed through the interviews disclose multiple values attached to the trees. For example, species such as *Enterolobium cyclocarpum* and *Albizia saman* which have crown diameters that can reach 25–40 m, provide ample fruit for animal fodder, but are not preferred by farmers due to their wide crown. However, while farmers tend not to add these species, they also are not keen to remove them from existing pastures. Species with a crown size above the average represent 20% of the trees chosen by farmers for the idealized pasture, including *Cassia grandis*, *A. saman*, *E. cyclocarpum*, *P. quinata*, *Leucaena* sp, and *G. ulmifolia* (Salazar, 2012). Despite its large crown size, *P. quinata* is the third most common species in study area pastures. Farmers mention other characteristics that may outweigh the disadvantages of shading such as high survival rates, rapid growth, commercial demand for wood and utility as fence posts. However, trees with large crown size are believed by farmers to have important scenic value enhancing the landscape view, and pertaining to an idealized vision of what a Nicaraguan pasture looks like. The Guanacaste (*E. cyclocarpum*) has a large parasol shape when grown in open pastures and is emblematic of Nicaragua. Farmers in the area have learned methods of thinning large crowns that reduce limiting effects of shading of pasture while maintaining the aesthetics of large crowns. BBNs are acyclic (Kjærulff and Madsen, 2013) and such dynamic management interactions are only captured implicitly through farmers' choices of trees for the ideal pasture based on their cultural ideals and knowledge of how tree crowns can be managed.

In this study, we show how to use BBN to combine deductive reasoning including farm context, with inductive reasoning regarding farmer motivations in order to determine a potential portfolio of tree species to be included in farm planning and management. This complements research on adoption of SPS technologies aimed at deductively predicting the probability of a particular farming practice given farm(er) characteristics (Scherr, 1995; Ayuk, 1997; Lapar and Pandey, 1999; Adesina et al., 2000; Thangata and Alavalapati, 2003; Mercer, 2004). A BBN approach combining deductive and inductive reasoning is reminiscent of recommendations from climate adaptation research in agroforestry (Verchot et al., 2007), calling for multi-scale assessments combining internal adoption factors linked to individual's preferences and capacities, and external contextual factors. The focus of our particular BBN is nevertheless on tree selection at the paddock level. The knowledge bases we use capture the contribution of tree composition and density, but do not explicitly capture tree spatial configuration in pastures, as highlighted by Gret-Regamey et al. (2013). In order to simulate regulating and supporting services, tree portfolios in paddocks would need to be coupled with biophysical models at farm and catchment scale that evaluate the impact of tree arrangement within pastures on service provision.

The overall structure of the Bayesian belief network has some notable differences from the ecosystem services cascade framework representing a structure-function-service-benefit-value causal cain (Haines-Young and Potschin, 2010). Farmers express knowledge of income from marketable non-timber forest products (e.g. firewood, fruit) directly linked to different tree species. Similarly, management costs of trees are directly associated with tree species in farmers interviews. The bias introduced by this particular structuring of the BBN is that information on net income from trees in paddocks appears more certain than information regarding ecosystem service provision, which appears in the model as an indirect response modulated by tree functional traits. Also, farmer knowledge collected by Mosquera (2010) did not follow the ecosystem service cascade framework, but was nevertheless incorporated in the network. In the latter study, farmers associate benefits and disadvantages directly with tree species without the intermediate step of identifying the species traits producing them. Our BBN assumes that a functional interpretation of the species underlies the farmers' choices, but in interviews conducted by Mosquera (2010) farmers conceptualize them as species, not as functional types. A relevant question is therefore, “what is the value added to extension services of using a causal framework of *structure – functional trait – ecosystem service* ”? A number of alternative portfolios of trees can have similar likelihoods of meeting farmers' preferences for services. We would therefore argue that the ecosystem cascade logic is a useful way to structure information about tree species' complementarity when a large number of tree species with multiple services are available for local adaptation and utilization.

A functional approach can also help identify redundancy in fulfilling specific functions, a feature that may help increase farm and regional level resilience, as pointed out by Biggs et al. (2012). This enables extension services to offer a portfolio of options according to farm context and farmer preference, rather than the utilization of a single ‘best fit’ option applied across farm typologies. Such an approach simultaneously facilitates meeting specific farmers' needs, as well as supporting the maintenance of tree diversity in conservation hotspots. We also think a functional traits approach is useful for identifying regulating, supporting and cultural services that are not immediately tangible from a single species, but are best achieved through complementary species combinations. For example, studies on the use of native trees in silvopastoral systems in seasonally dry tropical regions indicate that few trees are multi-functional, that no trees fill all the important functions identified by the farmers, and that there is a large degree of functional complementarity among tree species (Clinquart, 2010). Furthermore, farmer preferences may be expressed through a large number of functional traits using local terminology, but the combination of preferred traits may correspond to a more limited list of tree species capable of meeting farmer needs with a reduced number of multifunctional species. We show how this information can be organized transparently in the conditional probability tables of a BBN facilitating a portfolio approach to extension interaction with farmers and farmer communities.

Valuation is not a final node in the causal chain of our model, contrasting with studies applying the ecosystem service cascade in BBN (Haines-Young, 2011; Landuyt et al., 2013; McVittie et al., 2015). In the knowledge bases we use to populate the BBN, farmers express their preferences as lists of benefits and disadvantages, with no information on the relative importance of one ecosystem service over another. Even so, when the binary responses from a population of farmers' are combined in a BBN, it results in a ranking of preferred species. This is based on the likelihood that species have ecosystem service-related functional traits as perceived across the collective local knowledge of a population of farmers. The more frequently an association between tree functional trait and ecosystem service is mentioned by these farmers, the higher its posterior probability of inclusion in the idealized pasture. This is reminiscent of voting rules reflecting the importance of criteria, as used in outranking approaches in social multi-criteria decision analysis (Munda, 2008). In fact, in using farmer preferences to specify a portfolio of trees, we are using the BBN for the same purpose as a multicriteria decision analysis (MCDA). Although MCDA's use of explicit weights for the relative importance of ecosystem services would be an unfamiliar question for farmers, it would not be difficult to model in a BBN. Relative probabilities could be assigned different ecosystem service benefits in lieu of the binary choices (0 or 1) shown in Fig. 4. Going even further, a complete weighting of ecosystem services could be obtained using pairwise weighting of ecosystem services, in what is called an analytical hierarchy process (AHP) as illustrated by Poppenborg and Koellner (2014) for crop choices. However, caution is needed because different weighting approaches have different assumptions about preferences.

The AHP approach assumes that decision criteria – the ecosystem services in this case – are *independent* of one another, and *completely compensating* (Munda, 2008). The independence assumption applied to provisioning services from trees implies that preferences for provisioning services are not correlated with preferences for cultural or regulating services. Cultural practices with tree crowns show that cultural services are co-dependent on other services, as discussed more generally by e.g. Chan et al. (2012). The complete compensation assumption implies that the reduction of one ecosystem service could be compensated by increase in another service. A lacking willingness to make trade-offs is an empirical question, but such lexicographic preferences are a common phenomenon in cultural services (Chan et al., 2012). These strong assumptions in AHP can to some extent be addressed in a BBN. By explicitly modeling ecosystem services' inter-dependence in conditional probability tables a BBN can address the assumption of criteria *independence* in an MCDA – our modeling of ecosystem services as probable combinations of functional traits is an example of inter-dependence between ecosystem services from trees in paddocks. Whether the use of probabilities as weights in a BBN also assumes that there is *complete compensation* between ecosystem services assessment criteria is an empirical question.

A limitation of our study is that we did not carry out extensive field-testing of the model to the level where we can say 'this is an expert system that could be put into operation'. Our eight validation interviews with farmers confirmed that tree portfolios indicated by the BBN were consistent with those selected by farmers who had not participated in previous studies. More generally, this raises the questions of how to validate object-oriented Bayesian Networks combining different fields of knowledge. Metrics for evaluating performance and uncertainty of BBNs in ecology have been tested mostly on single species population models (Kuhnert et al., 2010; Marcot, 2012) used for *tactical* and *operational* decision-contexts (Barton et al., 2012). We recognize that our combination of multiple knowledge bases aimed at linking local farmer and research languages on ecosystem services is of a more exploratory nature. Sutherland (1983) calls this a *directive* approach to exploring causal model structure, where less emphasis is given on the detailed estimation of conditional probabilities by the data, and the focus is more on relational rather than logical reasoning. To move our model to tactical use as an 'expert system' we would need to further disentangle the different sources of uncertainty – linguistic, epistemic and variability – from the elicited responses by farmers (Kuhnert et al., 2010). Nevertheless, the interactive linking of knowledge bases and online access (http://funcitree.hugin.com/pastures) could still be useful for training purposes, for researchers or extension workers who are new to the Rivas study area, and to build upon for future extension work.

5. Conclusions

Farmers' knowledge is built on experience over long time spans and integrating multiple dimensions, which are difficult to cover in scientific surveys that address specific questions in isolation, with data collected in relatively short periods. BBNs are a generic modeling tool that enable the integration of different sources of knowledge complemented and updated over time. Collecting data from several studies from a single study area we use a BBN to describe farm and farmer characteristics, and functional characteristics, ecosystem services and disservices of trees in silvopastoral systems of Rivas, Nicaragua. We illustrate how the BBN can integrate different domains of scientific and farmer knowledge; both primary data collected in farmer interviews and previously published results. Rather than a field validated expert system for SPS we demonstrate two desirable properties of such an 'expert system': a predictive, deductive analysis and a diagnostic, inductive analysis. The case study demonstrates how interactive farmer interviews can be integrated in a BBN. The 'paddock simulation exercise' used qualitative participatory landscape visualization techniques to provide probabilistic information for scenario analysis and Bayesian inference. We integrated a knowledge database on costs and benefits with biophysical assessment of SPS, which may be useful for extension services. The ability to differentiate advice by farmer typology can also make extension more context adapted. Our BBN model illustrates how linguistic differences in the definition of scientific knowledge and local farmer knowledge of tree functional traits may be one explanation for differences in understanding of the more abstract notion of ecosystem services. Finally, we demonstrate another useful property of an expert system by making the BBN available online for consultation and support in fieldwork.

Farmer adaptation in a multi-functional approach requires different extension tools from those used in traditional approaches that communicate single practices and recommendations. BBNs seem well suited to synthesize farmers' multi-functional understanding of silvopastoral systems. Diagnostics and systematic updating of knowledge are particularly interesting features of BBN that are not found in other types of models of ecosystem services. Bayesian inference may also prove to be a useful technique in matching individual ecosystem service demand to potential supply in a multi-criteria decision analysis. BBNs make both inductive and deductive analysis in ecosystem services cascades possible.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2016.03.002.

References

Adesina, A.A., Mbila, D., Nkamleu, G.B., Endamana, D., 2000. Econometric analysis of the determinants of adoption of alley farming by farmers in the forest zone of southwest Cameroon. Agric. Ecosyst. Environ. 80, 255–265.

Aguilera, P.A., Fernández, A., Fernández, R., Rumi, R., Salmeron, A., 2011. Bayesian networks in environmental modelling. Environ. Model. Softw. 26, 1376–1388.

Alonso, M., Ibrahim, M., Gómez, M., Prins, K., 2001. Potencial y limitaciones para la adopción de sistemas silvopastoriles para la producción de leche en Cayo Belice. Agroforestería en las Américas 8, 24–27.

Ayuk, I.T., 1997. Adoption of agroforestry technology: the case of live hedges in the central plateau of Burkina Faso. Agric. Syst. 54, 189–206.

Barton, D.N., Kuikka, S., Varis, O, Uusitalo, L., Henriksen, H.J., Borsuk, M., de la Hera, Á., Farmani, R., Johnson, S., Linnell, J.D.C., 2012. Bayesian networks in environmental and resource management. Integr. Environ. Assess. Manag. 8, 418–429.

Barton, D.N., Saloranta, T., Moe, S.J., Eggestad, H.O., Kuikka, S., 2008. Bayesian belief networks as a meta-modelling tool in integrated river basin management – pros and cons in evaluating nutrient abatement decisions under uncertainty in a Norwegian river basin. Ecol. Econ. 66, 91–104.

Baynes, J., Herbohn, J., Russell, I., Smith, C., 2011. Bringing agroforestry technology to farmers in the Philippines: identifying constraints to the success of extension activities using systems modelling. Small-Scale For. 10, 357–376.

Biggs, R., Schlueter, M., Biggs, D., Bohensky, E.L., BurnSilver, S., Cundill, G., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., Leitch, A.M., Meek, C., Quinlan, A., Raudsepp-Hearne, C., Robards, M.D., Schoon, M.L., Schultz, L., West, P.C., 2012. Toward principles for enhancing the resilience of ecosystem services. Annu. Rev. Environ. Resour. 37, 421–448.

Casals, P., Romero, J., Rusch, G.M., Ibrahim, M., 2013. Soil organic C and nutrient contents under trees with different functional characteristics in seasonally dry tropical silvopastures. Plant Soil 374, 643–659.

Chan, K.M.A., Satterfield, T., Goldstein, J., 2012. Rethinking ecosystem services to better address and navigate cultural values. Ecol. Econ. 74, 8–18.

Clinquart, P., 2010. Representations et usages des espèces ligneuses: une approache par les trait fonctionnels pour une ingénierie eds systemes agroforestiers en zones arides et semi-arides. Cas des parcs agroforestiers de la zone de Tiby au Mali. Mémoire de stage de fin d'études.

Cramb, R.A., 2005. Farmers' strategies for managing acid upland soils in Southeast Asia: an evolutionary perspective agriculture. Agric. Ecosyst. Environ. 106, 69–87.

Espeleta, J.F., West, J.B., Donovan, L.A., 2004. Species-specific patterns of hydraulic lift in co-occurring adult trees and grasses in a sandhill community. Oecologia 138, 341–349.

Esquivel, H., Ibrahim, M., Harvey, C., Benjamin, T., Sinclair, F., 2007. Impacts of dispersed trees in pastures on fodder quantity and quality to cattle in seasonally dry ecosystems. CATIE, Turrialba, Costa Rica.

Esquivel, M.J., Harvey, C., Finegan, B., Casanoves, F., Skarpe, C., 2008. Effects of pasture management on the natural regeneration of neotropical trees. J. Appl. Ecol. 45, 371–380.

Gonzalez-Redin J., Luque S., Poggio L., Smith R. and Gimon A., Spatial Bayesian belief networks as a planning decision tool for mapping ecosystem services trade-offs on forested landscapes, Environmental Research Volume 144, Part B, January 2016, Pages 15–26.

Gret-Regamey, A., Brunner, S.H., Altwegg, J., Christen, M., Bebi, P., 2013. Integrating expert knowledge into mapping ecosystem services trade-offs for sustainable forest management. Ecol. Soc. 18.

Haines-Young, R., 2011. Exploring ecosystem service issues across diverse knowledge domains using Bayesian Belief Networks. Prog. Phys. Geogr. 35, 681–699.

Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being. In: Raffaelli, D., Frid, C. (Eds.), Ecosystem Ecology: a New Synthesis. Cambridge University Press, Cambridge, pp. 110–139.

Harvey, C.A., Chacón, M., Donatti, C.I., Garen, E., Hannah, L., Andrade, A., Bede, L., Brown, D., Calle, A., Chara, J., Clement, C., Gray, E., Hoang, M.H., Minang, P., Rodríguez, A.M., Seeberg-Elverfeldt, C., Semroc, B., Shames, S., Smukler, S., Somarriba, E., Torquebiau, E., van Etten, J., Wollenberg, E., 2014. Climate-smart landscapes: opportunities and challenges for integrating adaptation and mitigation in tropical agriculture. Conserv. Lett. 7, 77–90.

Harvey, C.A., Komar, O., Chazdon, R., Ferguson, B.G., Finegan, B., Griffith, D.M., Martinez-Ramos, M., Morales, H., Nigh, R., Soto-Pinto, L., Van Breugel, M., Wishnie, M., 2008. Integrating agricultural landscapes with biodiversity conservation in the Mesoamerican hotspot. Conserv. Biol. 22, 8–15.

Ibrahim, Muhammad, Guerra, Leonardo, Casasola, Francisco, Neely, Constance, 2010. Importance of silvopastoral systems for mitigation of climate change and harnessing of environmental benefits. Grassland carbon sequestration: management, policy and economics 11, 189.

INETER, 2012. Boletines Meteorológicos. Managua, Nicaragua.

Johnson, S., Marker, L., Mengersen, K., Gordon, C.H., Melzheimer, J., Schmidt-Kuntzel, A., Nghikembua, M., Fabiano, E., Henghali, J., Wachter, B., 2013. Modeling the viability of the free-ranging cheetah population in Namibia: an object-oriented Bayesian network approach. Ecosphere 4 (art90).

Joshi, L., Wibawa, G., Sinclair, F.L., 2001. Local Ecological Knowledge and Socio-economic Factors Influencing Farmers' Management Decisions in Jungle Rubber Agroforestry Systems in Jambi, Indonesia. World Agroforestry Centre (ICRAF).

Kjærulff, U.B., Madsen, A.L., 2013. Bayesian Networks and Influence Diagrams: a Guide to Construction and Analysis, 2nd ed. Springer, New York, USA.

Koller, D., Pfeffer, A., 1997. Object-oriented Bayesian networks Pages 302–313. In: Proceedings of the Thirteenth Annual Conference on Uncertainty in Artificial Intelligence. Providence, Rhode Island, USA.

Kuhnert, P.M., Martin, T.G., Griffiths, S.P., 2010. A guide to eliciting and using expert knowledge in Bayesian ecological models. Ecol. Lett. 13, 900–914.

Kuikka, S., Hildén, N., Gislason, H., Hansson, S., Sparholt, H., Varis, O., 1999. Modeling environmentally driven uncertainties in Baltic cod (*Gadus morhua*) management by Bayesian influence diagrams. Can. J. Fish. Aquat. Sci. 56, 629–641.

Landuyt, D., Broekx, S., D'hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M., 2013. A review of Bayesian belief networks in ecosystem service modelling. Environ. Model. Softw. 46, 1–11.

Lapar, M.L.A., Pandey, S., 1999. Adoption of soil conservation: the case of Phillippine uplands. Agric. Econ. 21, 241–256.

Levasseur, V., Olivier, A., Steven, F., 2009. Facteurs d'adoption de la haie vive améliorée au Mali. Cah. Agric. 18, 1–6.

López, F., Gómez, R., Harvey, C., López, M., Sinclair, F.L., 2007. Toma de decisiones de productores ganaderos sobre el manejo de los árboles en potreros en Matiguás, Nicaragua. Agroforestería en las Américas 45, 93–99.

Marcot, B.G., 2012. Metrics for evaluating performance and uncertainty of Bayesian network models. Ecol. Model. 230, 50–62.

Marcot, B.G., Steventon, J.D., Sutherland, G.D., McCann, R.K., 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Can. J. For. Res. – Revue Canadienne De Recherche Forestiere 36, 3063–3074.

Marie, C., 2010. Of Trees and Pastures – Management of Woody Resources and the Social Dynamics in La Chocolata, Rivas, Nicaragua. CIRAD, Montpellier, France.

McCann, R.K., Marcot, B.G., Ellis, R., 2006. Bayesian belief networks: applications in ecology and natural resource management. Can. J. For. Res. – Revue Canadienne De Recherche Forestiere 36, 3053–3062.

McVittie, A., Norton, L., Martin-Ortega, J., Siameti, I., Glenk, K., Aalders, I., 2015. Operationalizing an ecosystem services-based approach using Bayesian Belief Networks: an application to riparian buffer strips. Ecol. Econ. 110, 15–27.

Mercer, D.E., 2004. Adoption of agroforestry innovations in the Tropics: a review. Agrofor. Syst. 61, 311–328.

Mosquera, D., 2010. Conocimiento local sobre bienes y servicios de especies arbóreas y arbustivas en sistemas de producción ganadera de Rivas, Nicaragua. CATIE, Turrialba, Costa Rica.

Munda, G., 2008. Social Multi-Criteria Evaluation for a Sustainable Economy. Springer-Verlag, Berlin, Heidelberg.

O'Toole, D., Aguilar-Støen, M., 2013. Ecología histórica de la ganadería y usos de la tierra asociados en Muy Muy y Belén, Nicaragua. Agroforestería en las Américas 50, 114–121.

Ospina, S., Rusch, G.M., Pezo, D.A., Casanoves, F., Sinclair, F.L., 2012. More stable productivity of semi natural grasslands than sown pastures in a seasonally dry climate. PLoS One 7, e35555.

Pérez Almario, N., Ibrahim, M., Villanueva, C., Skarpe, C., Guerin, H., 2013. Diversidad forrajera tropical: rasgos funcionales que determinan la calidad nutricional y preferencia de leñosas forrajeras para su inclusión en sistemas de alimentación ganadera en zona seca. Rev. Agroforestería de las Américas 50, 44–52.

Poppenborg, P., Koellner, T., 2014. A Bayesian network approach to model farmers' crop choice using socio-psychological measurements of expected benefits of ecosystem services. Environ. Model. Softw. 57, 227–234.

Rogers, E.M., 2003. Diffusion of Innovation, 5th ed. Free Press, New York, USA.

Ruiz, F., Gómez, R., Harvey, C., 2005. Caracterización del componente arbóreo en los sistemas ganaderos de Matiguás, Nicaragua. Nitlapán, Managua, Nicaragua.

Rusch, G.M., Zapata, P.C., Casanoves, F., Casals, P., Ibrahim, M., DeClerck, F., 2014. Determinants of grassland primary production in seasonally-dry silvopastoral systems in Central America. Agrofor. Syst. 88, 517–526.

Sadoddin, A., Letcher, R.A., Jakeman, A.J., Newham, L.T.H., 2005. A Bayesian decision network approach for assessing the ecological impacts of salinity management. Math. Comput. Simul. 69, 162–176.

Salazar, A., 2012. Modelo experto para el análisis de la adopción de árboles en pasturas del trópico seco de Nicaragua. CATIE, Turrialba, Costa Rica.

Sánchez, D., Rusch, G.M., Villanueva, C., Barton, D.N., Salazar, A., 2013. ¿Cómo incrementar la multifuncionalidad en potreros? Agroforestería en las Américas 50, 122–130.

Sánchez, F., López, M., Medina, A., Gómez, R., Harvey, C., Vílchez, S., Hernández, B., López, F., Joya, M., Sinclair, F., Kunth, S., 2004. Importancia ecológica y socioeconómica de la cobertura arbórea en un paisaje fragmentado de bosque seco de Belén, Rivas, Nicaragua. Revista Encuentro (NI), vol. 68, pp. 14.

Sauceda, M., 2010. Impacto del arreglo espacial del componente arbóreo en sistemas silvopastoriles sobre el nivel de sombreado y la conectividad estructural de los agropaisajes en los municipios de Belén y Matiguás, Nicaragua. Magister Scientiae in Tropical Agroforestry. CATIE, Turrialba.

Scherr, S.J., 1995. Economic factors in farmer adoption of agroforestry: patterns observed in Western Kenya. World Dev. 23, 787–804.

Souza de Abreu, M.H., 2002. Contribution of Trees to the Control of Heat Stress in Dairy Cows and the Financial Viability of Livestock Farms in the Humid Tropics. CATIE, Turrialba, Costa Rica.

Sutherland, J., 1983. Normative predicates of next-generation management support systems. IEEE Trans. Syst. Man Cybern. 13, 279–297.

Thangata, P., Alavalapati, J., 2003. Agroforestry adoption in Southern Malawi: the case of mixed intercropping of *Gliricidia sepium* and maize. Agrofor. Syst. 78, 57–71.

Uusitalo, L., 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecol. Model. 203, 312–318.

Varis, O., 1997. Bayesian decision analysis for environmental and resource management. Environ. Model. Softw. 12, 177–185.

Verchot, L.V., Van Noordwijk, M., Kandji, S., Tomich, T., Ong, C., Albrecht, A., Mackensen, J., Bantilan, C., Anupama, K.V., Palm, C., 2007. Climate change: linking adaptation and mitigation through agroforestry. Mitig. Adapt. Strateg. Glob. Change, 901–918.

Villacís, J., 2003. Relaciones entre la cobertura arbórea y el nivel de intensificación de las fincas ganaderas en Río Frío, Costa Rica. CATIE, Turrialba, Costa Rica.

Villanueva, C., Ibrahim, M., Harvey, C., Sinclair, F., Gómez, R., López, M., Esquivel, H., 2004. Tree resources on pastureland in cattle production systems in the dry pacific region of Costa Rica and Nicaragua. In: Mannetje, L.T., Ramírez, L., Ibrahim, M., Sandoval, C., Ojeda, N., Ku, J. (Eds.), The Importance of Silvopastoral Systems for Providing Ecosystems Services and Rural Livehoods. Autonomous University of Yucatán, Mérida, Mexico, pp. 183–188.

Villanueva, C., Ibrahim, M., Harvey, C.A., Sinclair, F.L., Muñoz, D., 2003. Decisiones claves que influyen sobre la cobertura arbórea en fincas ganaderas de Cañas, Costa Rica. Agroforestería en las Américas 10, 39–40.

Zapata, P., Rusch, G., Ibrahim, M., DeClerk, F., Casanoves, F., Beer, J., 2013. Influencia de los árboles en la vegetación herbácea de sistemas ganaderos del trópico seco de Nicaragua. Agroforestería en las Américas 50, 30–36.