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Assessing ecosystem services from multifunctional trees in pastures using Bayesian belief networks

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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.

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