TECHNICAL BRIEF

FUNCiTREE is a research cooperation project funded by the EU 7FP – KBBE

Issue No. 5

Towards integrating plant functional traits and ecosystem services in a model of silvopastoral systems in Senegal using Bayesian Belief Networks

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Summary

The Technical Brief illustrates how a number of different data sets from different biophysical and socio-economic studies can be integrated in a single 'meta-model' – using Bayesian belief network (BBN) software - representing local and scientific knowledge about agrosilvopastoral systems. The application is illustrated for some relatively simple datasets from the Leona study area, Senegal, in the FunciTree project. Through the example we show how BBN software can give rapid access to multiple types of knowledge and assist in reasoning about conditions under which different agrosilvopastoral practices will be more likely. We also conclude that the strengths of BBN software cannot compensate for poorly integrated study designs. BBNs can however provide a modeling framework at the beginning of an inter-disciplinary study for which spatial variables will need to be generated in common across disciplines. We recommend that further work is done to improve connectivity in the network by identifying broad environmental variables at the household survey site using GIS.

Bayesian belief networks

Bayesian networks are cyclical-directed graphs of conditional probability distributions. As such, they are a generic modelling tool both for exploring data structure and for decision analysis under uncertainty. Bayesian belief networks (BBNs) are increasingly being used in ecological, environmental and resource management modelling (Kuikka, Hildén et al. 1999, McCann, Marcot et al. 2006, Barton, Kuikka et al. 2012).

Some advantages to using BBNs for modelling scientific and local knowledge of tree multifunctionality in agrosilvopastoral systems (ASP) include (Barton, Kuikka et al. 2012):

1) Promoting social learning processes, in this case between scientists, agricultural extensionists and local farmers;
2) Better organization of distributed modelling of domains of specific knowledge, specifically farmer and scientific knowledge of constraints and possibilities for adoption of multi-functional tree species;
3) The explicit acknowledgment of model sensitivity to different levels of resolution of probability distributions, specifically the opportunity to evaluate where scientific knowledge can contribute to local knowledge about tree multifunctionality;
4) The facilitation of context-dependent decision analysis regarding adoption of ASP practices.

In this Technical Brief we provide an illustration of how BBNs have been used to. integrate knowledge from different scientific and farmer domains to study plant functional groups and uses of trees in these systems.

Senegal study site

The study area is in the Louga Region of Senegal, located between latitudes 15° 16′ 36″ N and 15° 31′ 42″ O. The rural communities of Leona and the study site are distributed across three main agroecological zones: the Niayes in the West along the coast, the continental Dieri in the East, and the transitional zone between the two.

The Niayes zone in the west covers 20% of the study area (83 km²). The area runs for 18 km along the coast. It is characterized by semi-fixed sand dunes and a band of Filao (*Casuarina equisetifolia*). The Niayes landscape consists in a series of elevated dunes and depressions with typically heavy rich sandy soils (Deck) and clay-sandy (Deck-Dior). These soils are very productive for vegetable production.

The Diéri zone covers approximately 2/3 of the Rural Community of Leona study area from the centre to the East. It is a relatively flat area with a predominance of Dior soils, and Deck-Dior soils in depressions. The Dieri zone is characterized by a larger diversity of species of Sudanese and Sahelian origin and is under the influence of hot dry winds (Harmattan).

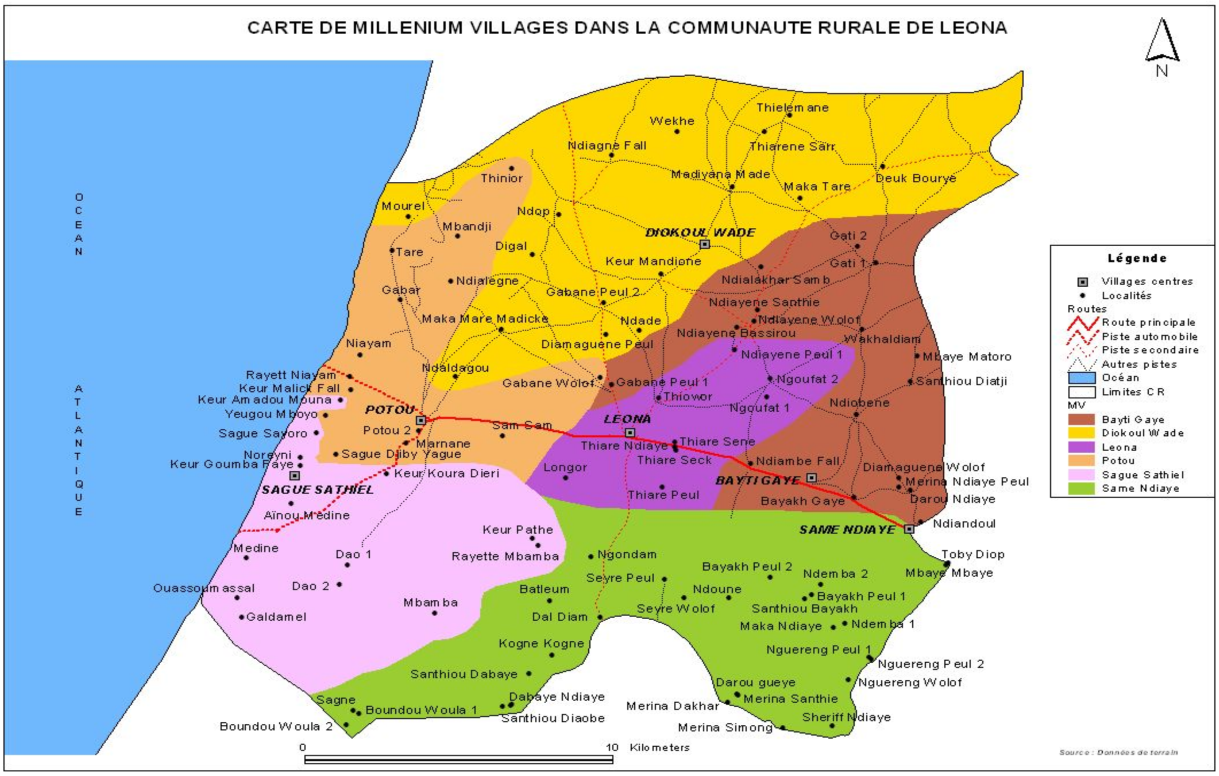

Figure 1. Villages in the study area in the community of Leona, Senegal

The "Zone Tampon" as a transitional area, combines the characteristics of Niayes and Dieri. Depressions retain rainwater, allowing some vegetable productions, tree plantations and rainfed agriculture.

The economy of the Leona study area is quite diversified. A large majority of inhabitants are involved in agriculture, in particular vegetable gardening. This is often associated with fishing. A majority of inhabitants are also involved in livestock. The main constraints in agriculture have been soil degradation, decreasing rainfall since the 1970s, lacking access to agricultural inputs, phytosanitary problems, ageing farm machinery and lacking market outlets for agricultural produce. Despite these constraints, agriculture continues to be the main source of income.

For a number of years the rural community of Leona has been home to different development projects. Management of food security has been a main concern of these projects faced with uncertainty in agriculture. Recently, the Millenium Village Project has been promoting diversification of agrosilvopastoral practices (ASP) to improve food security.

The FunciTree project has researched the extent to which ASP practices result in more multifunctional farming systems. The study of such systems is necessarily inter-disciplinary. In FunciTree, great emphasis has also been on comparing scientific knowledge of tree multifunctionality with local knowledge of different tree user groups. BBNs have been tested as one methodology for promoting integration between these knowledge systems.

Plant functional group models

The functional traits of organisms, i.e. measurable characteristics of species linked to their fitness and their effects on ecosystems, are a means to address some of the most fundamental and applied questions in ecology. Within the functional ecology framework, tree species or individuals can be grouped according to the values of their functional traits. The components of these groups possess a similar set of attributes, and are therefore expected to have similar responses to the environment, as well as similar effects on other organisms, and as a result, a similar effect on the provision of ES.

Traits related with grassland productivity and soil properties were measured on each individual tree, thus allowing us to take into account intraspecific variability in trait values both within and across soil classes. Individual trees were classified into Plant Functional Groups (PFG), which were built using hierarchical clustering processes. Clustering processes were based on the among-trees dissimilarities for the selected traits. In contrast, for traits related with fodder provision, i.e. indicators of nutritive quality, digestibility and toxicity, only a single value per species was considered. Given the high number of indicators measured for this function and the high levels of correlation between them, a Principal Component Analysis (PCA) to the species x traits matrix allowed to obtain two orthogonal axes: the first one was related to the digestibility of the plants and the second to its chemical composition and toxicity. Afterwards, a cluster analysis based on these PCA axes was performed to produce PFG for fodder provision.

Finally, we created a BBN to model the effect of different trees on the provision of different ES. This BBN was divided into different sub-networks, each of them related with each to the studied ES.

Submodel –understorey

The PFGs related with the grass productivity function were based on four traits. These traits were indicators of the phenology of the tree crown (the degree of deciduousness), of the resource-use strategies (SLA and LAI) and of the size of the tree. All these traits are likely to impact the performance of the herbaceous vegetation under the tree canopy. We identified four PFG related to the performance of the understorey vegetation (Fig. 2).

The BBN submodel was built following the assumption that the effect of the trees on the herbaceous understorey can be positive (facilitation), negative (competition) or neutral, depending on two interacting features: i) the characteristics of the tree functional group; ii) the environmental characteristics. Therefore, the final outcome of the tree-understorey interaction can be either positive or negative, depending on the balance between the magnitude of facilitative and competitive effects.

The responses of the grassland were assessed by measuring above-ground productivity, grass cover and grassland species richness in paired samples, both under the tree and in an adjacent area of grassland, beyond the influence of the tree crown.

Our preliminary results confirmed that the different features of the trees in the different PFG had important implications in their

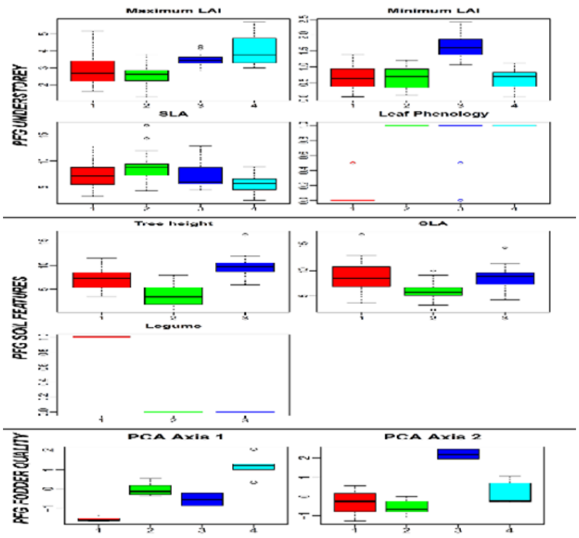

Figure 2. Mean trait values of the four tree functional groups associated with level of grassland productivity.

abundances on the two studied environmental conditions. For example, trees with a deciduous strategy and low SLA values were especially abundant in rough environmental conditions, while trees that keep a relatively high canopy cover during the dry season, and those with high SLA values, were much more abundant in benign conditions.

The submodel also showed the importance of FG–environment interactions in determining the outcome of the tree-grass interaction. In our case, the kind of effect on the grassland by trees with particular characteristics depended on whether the tree occurred in salty soils or non-salty soils. For example, trees that provide a high canopy cover during the wet season, offer protection and increase the productivity of the herbaceous layer in harsh conditions (salty soils); however, in more benign conditions, the effect of these trees was often negative, because of the reduction in light availability under the tree canopy during the wet season.

Submodel - soil properties

The three traits used to assess the associated of trees with soil formation processes were 1) tree height, a surrogate for biomass production and amount of litter deposition; 2) specific leaf area (SLA), an indicator of the degree of litter decomposability; and 3) whether the tree was a legume or not, a surrogate for N fixation capacity (Fig. 3). Legumes, which were more frequent in non-salty soils, were classified in the PFG1. Among the non-legume species, trees in PFG2 were short and had low values of SLA, and were common in salty soils. On the other hand, trees in PFG3, which were tall and had intermediate to high SLA, were mostly located in non-salty soils.

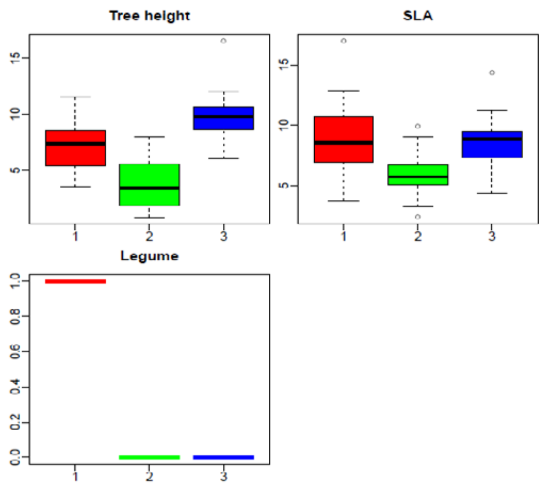

Figure 3. Mean trait values of the three tree functional groups associated with soil chemical properties.

Similarly to the grassland productivity function, the BBN submodel for the soil properties function was built following the next assumptions: i) the effect of the trees on 5 soil properties (i.e. soil pH, carbon, nitrogen, conductivity and content of mycorrhiza spores) depends on the characteristics of the tree functional group, ii) the net effect of the tree on the soil could be either positive or negative, and iii) the net effect of the trees on soil properties is a function of the environment.

The results show that trees considerably increased soil N, C and conductivity, but these effects were independent of the considered PFG and of the environment. These results are in agreement with studies in the literature and with other analyses conducted with FUNCiTREE data on the effect of trees on the soil.

Submodel - fodder

The trait values in the analysis of the fodder provision function were species averages obtained from the CIRAD database prior their incorporation into the FUNCiTREE trait base; therefore intraespecific variability in trait values was not taken into account for the construction of PFG for fodder quality. We used Principal Component Analysis (PCA) to sort the species according to the trait presented in Table 1. Species were sorted into 4 areas in the ordination diagram, along a gradient of digestibility associated to PCA axis I and with content of N and tannins associated to PCA axis II (Fig. 4).

At a second stage, the species were grouped into four PFG using hierarchical clustering. The four groups showed clear differences in the averages and ranges of scores on PCA I and II. Afterwards, the BN model was built under the assumption that the livestock preferences for the different tree species depend on its functional traits. We considered the preferences of three different livestock species: cattle, sheep and goats. Based on expert opinions about the preference of the fodder by livestock, tree species were classified into three groups according to the preference of each of the livestock species: "Highly preferred", "Average" and "Non-preferred". It is important to remark that this model differ from the others, because it did not consider the effect of the environment on the livestock preferences, since neither the trait information nor the livestock preferences information were linked with environmental data.

Almost 50 % of the species in the data set belonged to a PFG with intermediate digestibility

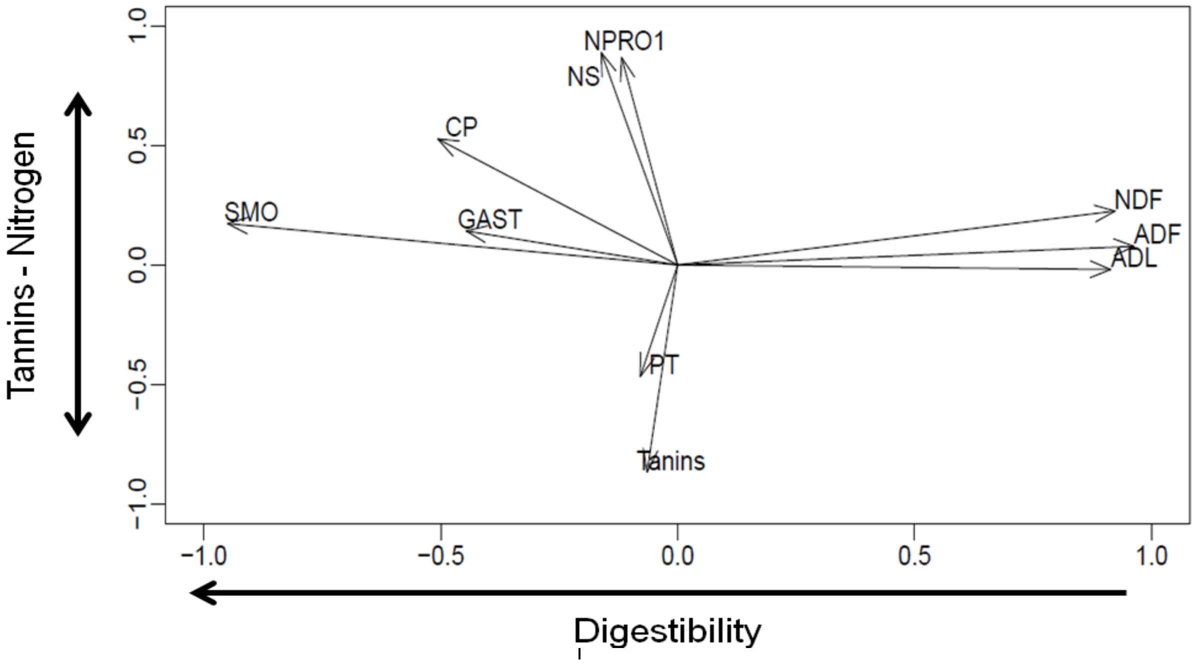

Figure 4. Ordination diagram resulting from a Principal Component Analysis (PCA) of agroforestry species based on trait values associated to forage quality.

and high contents of tannins. Livestock preference data showed that these trees are highly consumed by goats, whereas they are to a large extent rejected by cattle. The second most abundant in the dataset encompassed trees with low average digestibility values and intermediate contents of tannins and Nitrogen. Species in this group were well accepted by cattle, but not particularly preferred by goats. These results indicate that a large portion of the species occurring in the area have relatively low value as fodder. This was especially so for the salty soils, where the group with the lowest contents of tannins and relatively easy to digest, was remarkably less abundant than in non-salty soils.

Submodel – uses and agroforestry practices

A survey questionnaire was applied to 56 farmers from 7 villages in the Niayes zone, 4 villages in the transition "Zone Tampon" and 4 villages from the contintental Dieri zone. Farmers from the Niayes area associated with the nature reserve were selected after their participation in a focus group. Farmers participating in the Tampon and Dieri villages were selected at random.

The questionnaire contained a large number of questions on socio-economic background, characteristics of the farm production system and agrosilvopastoral practices (ASP). The survey was exploratory and aimed at providing data for testing the integration of socio-economic farm characteristics with biophysical characteristics. A small sample approach was used to test whether BBNs provide useful information for sample sizes typically lower than what is used in econometric models representing the population.

Our preliminary data analysis found that very few socio-economic characteristics of the farm and farmer could explain the specific adoption of ASP or the selection of specific tree species. This may have been due to the small sample size combined with the large heterogeneity resulting from the spatial sampling strategy.

Table 1. Most probable configurations of uses and agroforestry practices

Agroforestry practice	Uses	Joint probability of most probable configurations
plantation	forrage	0.34
trees in field	forrage	0.14
plantation	firewood	0.08
plantation	pharmacopoeia	0.08
regeneration	forrage	0.06
trees in field	food	0.06
trees in field	firewood	0.04
trees in field	construction	0.04
regeneration	food	0.03
plantation	food	0.03
regeneration	firewood	0.02
trees in field	pharmacopoeia	0.02
plantation	construction	0.02
trees in field	fertilisation	0.01

We decided to illustrate the meta-modeling approach with two of the key variables from the survey: agroforestry practice and uses / provisioning ecosystem services of trees. ASP included 'live fences' , conserving 'trees in field', 'plantations' and 'natural regeneration' . Uses included 'firewood', 'forage', 'pharmacopeia', 'construction', 'food', 'live fence', and 'fertilization'. Table 1 describes the most probable combinations of uses of trees and ASP practices found in the sample. Forrage associated with plantations and trees in field were the most common combinations. Forrage is by far the most common of the uses of trees in the sample with 53% of respondents reporting some type of forage.

A meta-model in a Bayesian belief network

Fig. 5 provides an overview of the BBN network linking databased on plant function groups, their environmental, soil and understory characteristics and data on animal and human preferences in silvopastoral systems.

Fig. 5 shows how data on tree species used in agrosilvopastoral systems and agrosilvopastoral practices from the survey were integrated with datasets on plant functional groups(PFG). Tree species is described by the node "species" observed in botanical fieldwork and "useful species" and "ASP species" reported in the surveys. The two species lists do not coincide, making it necessary to include both nodes in the meta-model. The species list from the plant functional group studies was longer. Species that were not mentioned by farmers in the survey were designated "other".

Another characteristic of the network worth noting is the lack of links between soil and understory characteristics and species observed in the survey. Ideally choice of useful species and AFP would be conditional on environmental factors. However, the socio-economic surveys were not conducted on the same plots that produced the plant functional group data. The two studies were carried out separately and at different stages in the project, indicating a limitation in study design. This can be corrected in further model development by

for tree species, PFG, uses and agrosilvopastoral practices. The distributions as shown represent the characteristics of the samples in the study. It is worth noting that all nodes are described by discrete states. This means that analysis of the network is non-parametric.

The data show the representation of tree species in the plant functional group studies. These were predominantly sampled in Niayes type environment. Some PFG dominate. From the "Uses" node we see that forage uses (53%) dominate followed by firewood (14,6%) and pharmacopeia uses(10,8%).

Hugin software includes a functionality for "value of information" analysis (VOI). VOI evaluates the amount of shared information between different discrete nodes in the network, akin to a correlation analysis for continuous variables. Fig. 7 shows that the node

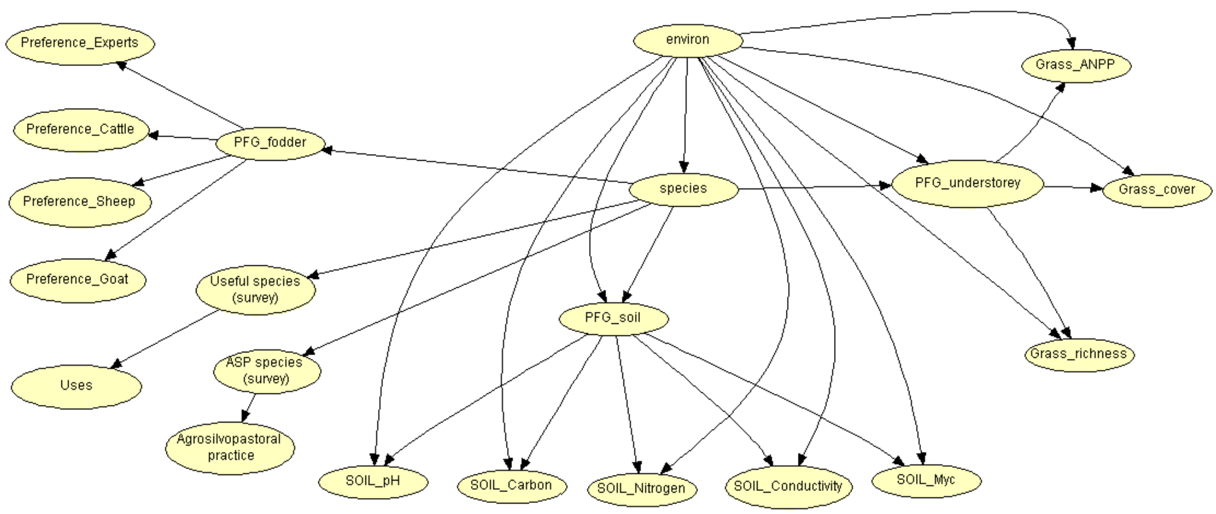

Figure 5. An overview of the meta-model integrating several different databases on plant functional groups and data on agroforestry practices and uses

assigning soil characteristics to the survey data locations based on existing soil maps.

Fig. 5 thus illustrates that the only information shared by the different studies are the tree species lists.

Fig. 6 provides a view of the Hugin software interface showing the probability distributions

for "uses" shares most information – aside from the 'useful species' and 'ASP species' – with plant functional group for fodder, soil and understory. This reflects the structure of the network rather than any significant patterns in the data. The node uses is weakly informative of the nodes for fodder preferences of sheep, goat, cattle. This is a weak validation that the survey data coincides with experimental data on forage preferences. Finally, the data on understorey and soil characteristics have almost no information on what kind of uses can be expected of trees.

Fig. 8 shows a similar analysis carried out for the node “species”. This explains to what extent other nodes provide any information on the species. Discarding ‘useful species’ and ‘ASP species’ which are correlated by definition, it is interesting to note that PFG_fodder and PFG_soil are substantially more informative of species than PFG_understory. Surprisingly, agrosilvoral practices are more informative of farmers knowledge of species than uses.

Fig. 9 illustrates how reasoning can be carried out in a BBN. In the example we are interested in identifying the tree species most likely to provide fodder and be ‘trees in field’. *Boscia senegalensis* (40,84%) is most likely, followed by *Sclerocarya birrea* (13,23%) and *Faidherbia albida* (12,58%). The graph conditional probability distributions can also be evaluated in relative terms. In the case of the “environ” and “PFG_” nodes we have illustrated how “forage”

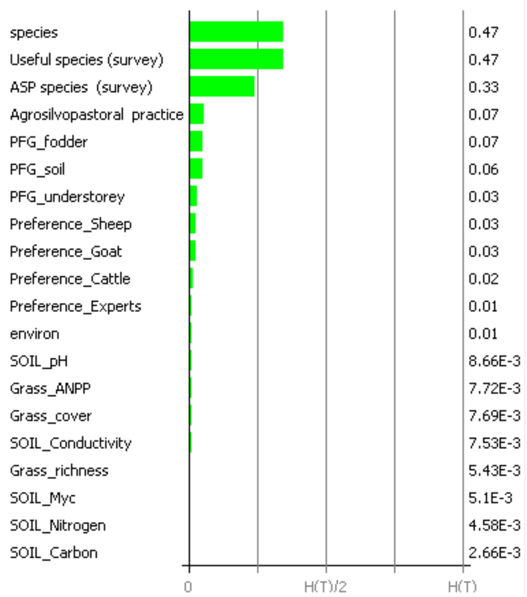

Figure 7. Mutual information between “Uses” and other nodes in the network

and “trees in field” as conditions change the likelihood that specific plant functional groups will be represented (thin dark green lines) relative to the overall sample characteristics (broad light green lines). For example, tree species in fields useful for forage are somewhat more likely to be found in “salty soil” environments than “Niayes”

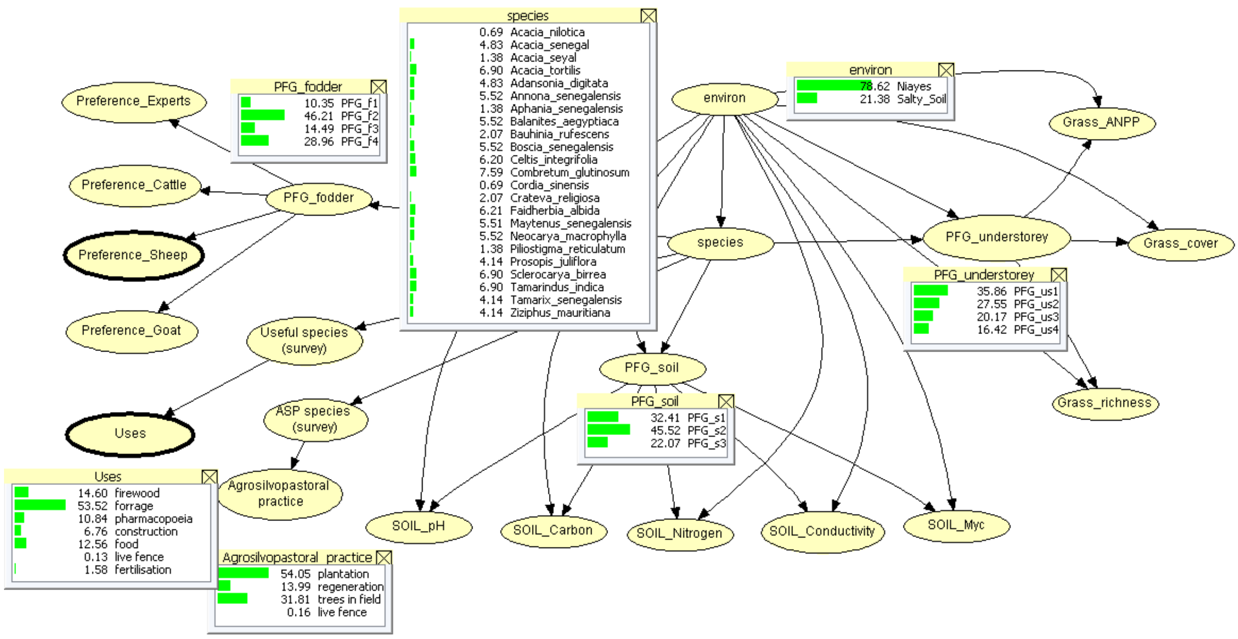

Figure 6. Tree species and states of “use”, “agroforestry practice” and “plant functional group” nodes

environments relative to the overall sample.

Further work

Further work will be conducted to improve the knowledge base by taking advantage of GIS data to characterize the environmental context of the household survey data. The only environmental distinction that was used in the ecological networks is whether the soils are salty or not. GPS data on the village will be used to locate the villages in available soil maps. This means that "ASP species" and "used species" can be made conditional on the "environment" node and possibly on some more specific soil characteristics included in PFG_soil.

Additionally, the information on the relevant functional trait values for the "ASP species" and the "used species" can be searched in existing trait databases (such as the TRY database) in order to include these species in the different "PFG_" nodes.

Conclusions

Through the example, we show how BBN software can give rapid access to multiple types of knowledge and assist in reasoning about conditions under which different agrosilvopastoral practices will be more likely. We also conclude that the strengths of BBN software cannot compensate for poorly integrated study designs. BBNs can however provide a modeling framework at the beginning of an inter-disciplinary study for which spatial

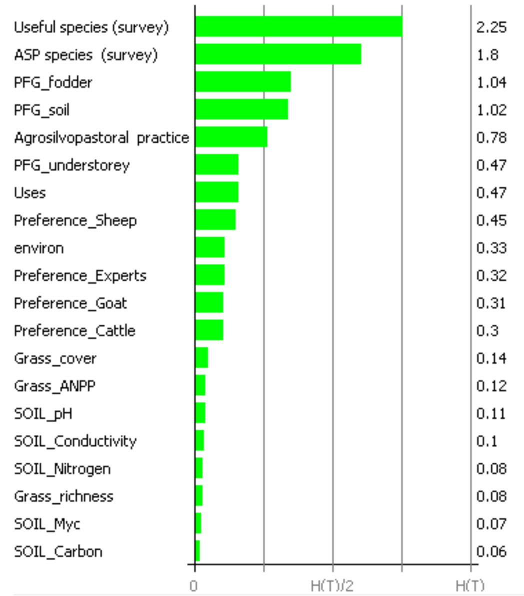

Figure 8. Mutual-information between "Species" and other nodes in the network

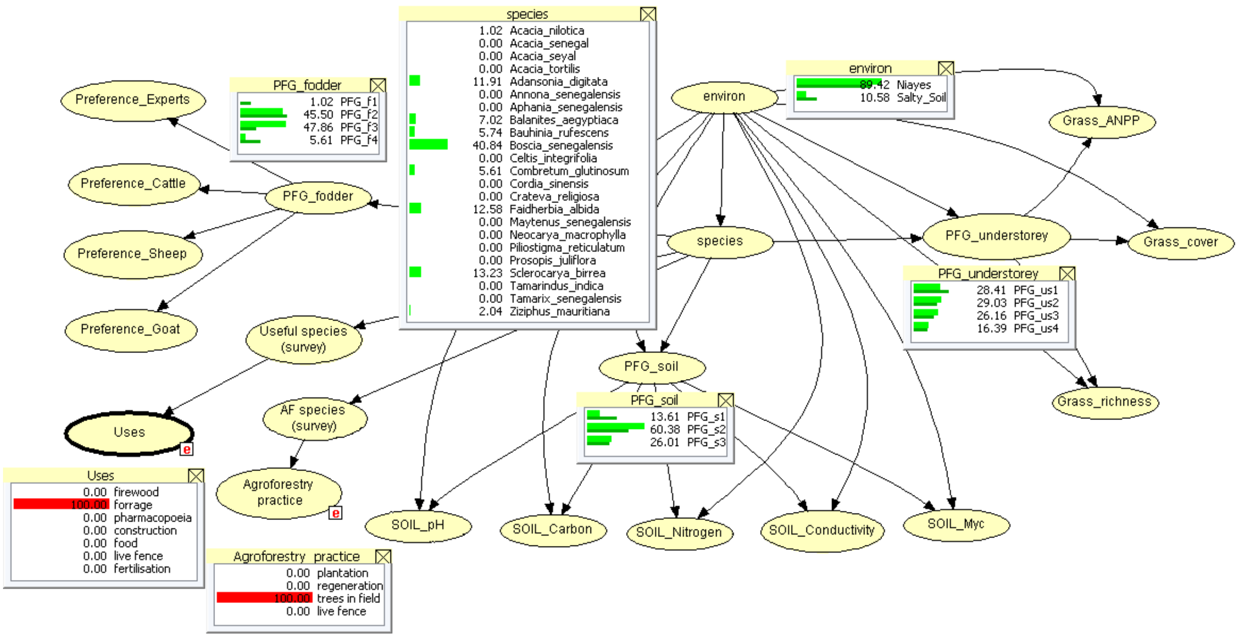

Figure 9. The relative importance of plant functional groups (relative to the sample population) conditional on farms with traditional silvopastoral practices ("forage" and "trees in field").

variables will need to be generated in common across disciplines. We will carry out work to improve connectivity in the network by identifying broad environmental variables at the household survey site using GIS.

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An ecological framework for sustainable and adaptable agro-forestry systems in landscapes of semi-arid ecoregions.

Based on the principles of functional ecology, FUNCiTREE addresses the provision of multiple services of silvopastoral systems (SPS) in semi-arid regions in Africa and Central America. FUNCiTREE aims to provide farmers in the regions with a portfolio of regionally suitable tree species that are capable of providing multiple services. The project integrates theories and concepts from agroforestry and ecological science and will provide a scientifically based model for the design of modernized SPS.

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