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Tree species selection for land rehabilitation in Ethiopia: from fragmented knowledge to an integrated multi-criteria decision approach

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ABSTRACT

Dryland regions worldwide are increasingly suffering from losses of soil and biodiversity as a consequence of land degradation. Integrated conservation, rehabilitation and community-based management of natural resources are therefore of vital importance. Local planting efforts should focus on species performing a wide range of functions. Too often however, unsuitable tree species are planted when both ecological suitability for the targeted area or preferences of local stakeholders are not properly taken into account during selection. To develop a decision support tool for multi-purpose species selection, first information needs to be pooled on species-specific ranges, characteristics and functions for a set of potentially valuable species. In this study such database has been developed for the highly degraded northern Ethiopian highlands, using a unique combination of information sources, and with particular attention for local ecological knowledge and preferences. A set of candidate tree species and potentially relevant criteria, a flexible input database with species performance scores upon these criteria, and a ready-to-use multi-criteria decision support tool are presented. Two examples of species selection under different scenarios have been worked out in detail, with highest scores obtained for *Cordia africana* and *Dodonaea angustifolia*, as well as *Eucalyptus* spp., *Acacia abyssinica*, *Acacia saligna*, *Olea europaea* and *Faidherbia albida*. Sensitivity to criteria weights, and reliability and lack of knowledge on particular species attributes remain constraints towards applicability, particularly when many species are jointly evaluated. Nonetheless, the amount and diversity of the knowledge pooled in the presented database is high, covering 91 species and 45 attributes.

Keywords: afforestation; dryland restoration; local ecological knowledge; multi-purpose tree; rural appraisal; species selection tool

INTRODUCTION

Dryland regions all over the world are increasingly faced with huge environmental challenges and are suffering from a dramatic loss of soil and biodiversity as a consequence of long-term land degradation (Reynolds et al. 2007; White and Nackoney 2003). Integrated conservation, rehabilitation and community-based management of natural resources are therefore of vital importance, not only to maintain local biodiversity or livelihoods, but also for the protection of off-site (downstream, urban) ecosystems and livelihoods (German et al. 2006). Given the increasingly important issue of land shortage and difficulties related to limited capacity, any conservation intervention should ideally fit into a multi-functional land use, having a maximum range of benefits from a minimum investment. Undeniably, an efficient land management policy should include promotion of multi-purpose woody species through afforestation, reforestation and/or natural regeneration, as a means to enhance rural livelihoods while providing a wide range of environmental services reversing degradation (Chazdon 2008; German et al. 2006; Taddese 2001).

Nevertheless, several bottlenecks may hinder effective implementation. Often inappropriate tree species are selected for planting when both ecological suitability for the targeted area or objectives and preferences of local stakeholders (frequently farmers) are not properly taken into account (Simons and Leakey 2004), leading to negative side-effects (German et al. 2006). Moreover, since local efforts are often limited to a small pool of known species (Kindt et al. 2006), more attention should be given to valuable alternatives, performing a range of socio-economic, ecological and cultural functions. In contrast to classical plantation forestry, the selection of multi-purpose tree species for dryland rehabilitation in rural areas is much more complex and the group of stakeholders very heterogeneous (Franzel et al. 2008).

For any particular situation in a context of vegetative land rehabilitation there is hence a need to develop or use a type of framework for appropriate selection of the most suitable multi-purpose species, starting from a wide set of alternatives. To enable this (i) a broad and appropriate group of ecological, economic and social selection criteria describing species traits in terms of growth characteristics, site requirements and potential products and services, needs to be defined, and (ii) performance on each of these criteria needs to be thoroughly understood for each of the considered species, as should the relationships and trade-offs between those criteria (Franzel et al. 1996).

Several tree species reference databases and toolkits for prioritisation have been developed for various regions around the world and at different scales of implementation (e.g., Guthrie and Nygren 2007; Orwa et al. 2009; Royal Botanic Gardens 1999; von Carlowitz et al. 1991; Webb et al. 1984). Species priority setting for diversification and for selection of multi-purpose tree species in developing countries has also received wide attention in research papers, books and project reports (e.g. Franzel et al. 1996, 2008; Kindt et al. 2005, 2007; Mng'omba et al. 2008; Warner 1994, just to mention a few). Nevertheless, an all-inclusive or ready-to-use database does not exist. Limited accessibility and/or lack of detailed information, both on particular species or characteristics, are common bottlenecks (Franzel et al. 1996, 2008). Moreover, because plant performance and utility finally depend on specific environmental and social conditions, information is sometimes contradictory for different data sources.

While consulting reference databases covering the considered area and species is a must, for any particular application there is a need to perform further in-depth assessment, to modify if necessary, and to refine criteria and choices. This encompasses the need to take local conditions, uses and needs into consideration, and to incorporate additional, locally important species not yet included. Doing so, species selection can become well-matched to the specific circumstances, at the same time being applicable for a wide set of local scenarios. Such scenarios are defined as explicit situations of species selection for a concrete land use purpose (e.g. gully erosion control, firewood production or beekeeping practice). Identification of particular knowledge gaps is also crucial, and where possible these gaps need to be bridged. Besides the need to pool scientific information, it is especially important to incorporate knowledge from local stakeholders on species presence, suitability and performance, as well as on stakeholder preferences, knowledge which has received insufficient attention (Sheil and Liswanti 2006).

Hence it becomes clear that species selection can be a complex process involving a wide range of criteria and information sources. In such situation, the development of a Decision Support System (DSS) can be very helpful to deal with the large amounts of information in a consistent and objective way. Though a clear unequivocal definition is hard to find, all DSS's have in common that they are intended to interactively support decision makers in compiling useful information in order to identify problems and opportunities, and to take decisions (Gilliams et al. 2005; Reynolds and Schmoldt 2006; Sprague and Watson 1989). Multiple-criteria decision analysis (MCDA) is the group name of all types of such decision processes specifically designed to evaluate (prioritize) a list of alternatives with the help of multiple objectives (criteria) describing these alternatives (von Gadow and Bredenkamp 1992). In our particular case, those alternatives are woody species.

In this study, these issues were broadly considered for one particular African dryland area, i.e. northern Ethiopia. To contribute to an increased efficiency of tree planting efforts, we aimed at applying a conceptual framework for appropriate tree species selection in the northern Ethiopian highlands. More specifically, our objectives were:

1. To delineate both a wide set of woody species potentially suitable for the considered area, and an appropriate set of selection criteria describing species' ecological range, growth characteristics, requirements, products and services;
2. To design a comprehensible meta-database integrating fragmented scientific as well as local species-specific knowledge on these selection criteria, for the selected set of species;
3. To identify trends, relationships and particular knowledge gaps in this database, as well as to compare it with existing databases and tools;

4. To apply and evaluate two flexible decision support tools for multi-purpose species selection under different scenarios, bringing existing knowledge into appropriate practice.

Materials and methods

Study area

The study area (Fig. 1) is located in the Central Zone of Tigray, Ethiopia's northernmost region. With altitude ranging between 500 m a.s.l. on the eastern border with the Afar region and almost 4000 m a.s.l. in the southwest, about 53 % of the Tigray area is lowland ("*Kolla*" - less than 1500 m), 39 % is medium highland ("*Woina Degua*" - 1500 to 2300 m), and 8 % is upper highland ("*Degua*" - 2300 to 3000 m) (Hurni 1986). Large variations in topography and altitude result in different agro-ecological niches or microclimates within short distances (Causton and Venus 1981; Nyssen et al. 2005). The area on which this study mainly focuses is situated in the *Degua* and *Woina Degua* zone, more specifically in the Degua Tembien *woreda* (district) (13°39'N, 39°10'E), ca. 50 km west of Mekelle, the capital of Tigray (Fig. 1). Elevation ranges between 2100 and 2800 m a.s.l., and local geological formations, comprising limestone, sandstone and Tertiary basalt flows, form sub horizontal layers and give rise to stepped slope profiles (Nyssen et al. 2004a). Though locally highly variable, the mean annual precipitation is 778 mm, with the main rainy season (>80 % of the yearly rainfall) lasting from mid-June to mid-September, and being preceded by three months of dispersed, less intense and less predictable rains. Monthly average minimum and maximum air temperatures range from 4 to 6 °C and from 20 to 22 °C, respectively (Nyssen et al. 2008). The prevailing, small-scale agricultural system in Degua Tembien consists of integrated annual crop and livestock production in which oxen provide the draught power to plough smallholder's fields. Main crops are barley, wheat, grass pea, horse bean, lentil and teff, the latter being a cereal with very fine grains endemic to Ethiopia. In addition, vegetables, such as onions, salad, tomatoes and green pepper, are commonly grown on small, irrigated plots near the houses and adjacent to rain water harvesting ponds (Nyssen et al. 2008; Segers et al. 2008). Livestock (cattle, sheep, goats and donkeys) is very important both as a source of energy (oxen traction and manure substituting fuel wood) and as an insurance mechanism (Descheemaeker 2006; Nyssen 2001). Grassland, rangeland and exclosures are communal lands (Nyssen et al. 2008; Segers 2009).

In the highlands of this area, free grazing and encroachment of fragile relic forest fragments continue, and consumption of wood products is huge and often inefficient (Berhanu et al. 2004; Kebede et al. 2002), further aggravating the age-long problems of land degradation (Nyssen et al. 2008b, 2009). Since the 1980s, the most significant reform in natural resource management in the Ethiopian highlands has probably been the introduction of exclosures, defined as areas of natural vegetation protected from the intrusion of humans or livestock (Aerts et al. 2009; Le Houérou 2000). Such exclosures have been proven to be a successful means for on- and off-site soil and water conservation (Descheemaeker et al. 2009; Mengistu et al. 2005). Yet, after more than three decades of large-scale promotion and implementation (Shiferaw and Holden 1998), efficiency in terms of biodiversity and vegetation recovery, but also in terms of socio-economic returns, is not always indisputably successful, and social acceptance therefore precarious (Babulo et al. 2009; Bekele 2003; Muys et al. 2006). In general, it is clear that a merely natural vegetative recovery will not suffice to cope with the ever-increasing environmental pressure. An important actual challenge therefore remains to efficiently combine promotion of natural vegetation restoration with active planting of high value multi-purpose woody species.

For a long time primarily exotic evergreen species, mainly *Eucalyptus camaldulensis* and *Eucalyptus globulus*, were promoted in Ethiopia to cope with the ever-growing demand for fuel and timber, even if not without problems (Gindaba et al. 2005; Wilson 1977). It is only in the past few decades that indigenous, multi-functional woody species also slowly started to receive attention. Active tree planting could be undertaken e.g. as enrichment planting in exclosures and forest relics (Aerts et al. 2007; Gindaba et al. 2005), as on-farm agroforestry intervention, or through vegetative erosion control measures (Nyssen et al. 2004b; Reubens et al. 2009). However, although some efforts have proven to be successful, lack of aftercare and inappropriate species selection and management in general continue to result in unsustainable, inefficient planting practices with very low seedling survival rates (Aerts et al. 2007; German et al. 2006; Negussie et al. 2009; Teketay 2000).

Data collection

Inventory of potentially suitable species

In this study, a broad literature review was performed for a wide set of woody species, gathering information on a range of species-specific traits and functions, further referred to as “attributes” or “criteria” (Table 1). These were classified into specific criterion groups, hence resulting in two hierarchical selection levels (criterion groups and individual criteria). Nine such groups were defined:

1. Ecological range, i.e. those criteria delineating the climatic, topographic and agro-ecological conditions under which the species may thrive (4 criteria);
2. Species botany, i.e. a limited set of attributes roughly describing the species’ size, life form and leaf fall pattern (3 criteria);
3. Root system characteristics, i.e. those attributes characterizing the species’ root system type, size, density and strength (5 criteria);
4. Socio-economic functions, i.e. direct or potential (economic) benefits (or damage) for humans from the plant itself (13 criteria);
5. Socio-cultural values, i.e. the social basis of the species, not taking economic value into account (3 criteria);
6. Environmental services, i.e. indirect benefits (or damage) for humans and environment obtained through the influence of the growing plant on its environment or on other species (11 criteria);
7. General plant performance, i.e. the growth performance and suitability of the species to grow in the (wide) region (14 criteria);

8. Local plant performance, i.e. the suitability of the species to grow under specific local growth conditions (6 criteria);
9. Biodiversity relevance, i.e. the importance of the species to enhance or decrease associated biodiversity (2 criteria).

Data sources included publications ranging from local project reports to international journal articles, books, global databases and digital libraries. Of particular interest are initiatives such as SEPASAL of the Royal Botanic Gardens Kew (Royal Botanic Gardens 1999), the African Plants Initiative (API) of Aluka (Guthrie and Nygren 2007), and the global AgroforesTree database (AFT) of the World Agroforestry Centre (ICRAF) (Orwa et al. 2009; Salim et al. 2002; Simons et al. 2005; von Carlowitz et al. 1991). SEPASAL is an online database and enquiry service about useful "wild" and semi-domesticated plants of tropical and subtropical drylands. Aluka is an international non-profit organization collaborating with institutions and individuals around the world to produce a digital library of scholarly resources from and about Africa. A wide range of flora e.g. is now electronically available through the API. More importantly even, the AgroforesTree database has been used as a major input source, both directly and indirectly through other literature sources largely referring to it. This database summarizes taxonomy, botanical description, geographic distribution, habitat characteristics, biophysical limits, products and services, pests and diseases, propagation, tree management, growth and development, yields and harvest methods, trading and prospects for more than 500 agroforestry trees. It has been incorporated in or used as a basis for several other databases and species selection tools.

The list of species considered in this review exercise was based on the species' presence in the project area or its potential for introduction, as suggested by informants (see local survey in the next section). First, a compilation was made of all trees and shrubs described as present, either during the survey for this research or during prior studies (e.g., Descheemaeker 2006; Friis 1992; Nyssen 2001; Teketay 1997, 2000; Wilson 1977). This list included both indigenous and exotic species, and both planted and naturally regenerating species on all types of land uses. In addition, those woody species highlighted during the local interviews (next section), or reported in literature as locally present or considered promising, were incorporated as well. By promising species we meant those species suited to the biophysical environment and having products of interest to farmers or products with high market demand.

We decided to focus on trees and shrubs and therefore not to include any of the Cactaceae (e.g., *Opuntia ficus-indica*), Agavaceae (e.g., *Agave sisalana*), Asphodelaceae (e.g., *Aloe* spp.), Musaceae (e.g., *Musa* spp.) or Poaceae (e.g., *Arundo donax*) highlighted during the interviews. This decision does however not imply by any means that these species are not valuable for selection.

Rural appraisal, expert questionnaires and species presence inventory

To further assess species presence and local knowledge on species-specific characteristics and functions, as well as to gain insight in people's species and function preferences, explorative field walks and participatory interviews with 45 local informants were conducted between September and December 2005. Besides 37 farmers (28 male and 9 female), eight non-farming stakeholders were included in these interviews, being local soil, water and forest conservation experts, extension agents, students and administrators. Interviews were conducted in five representative villages in a radius of 10 km around Hagere Selam town (the administrative capital of Degua Tembien), with a minimum of six interviews per village. They took place in the farmers' houses or fields. At the same time, interviews were conducted in offices or in the market of Hagere Selam, where non-farmers as well as farmers from more distant villages could be interviewed.

Local interviews could be subdivided into three particular interview components, each following a specific methodology:

- INT-a: Appraisal of the local community setting, including soil and water conditions, woody species locally found, current role of trees in the community, and problems faced related to land degradation, so as to get acquainted with the area and associated problems (Warner 1994). This was done through semi-structured individual discussions (Bernard 2006) as well as field walks in groups of 3-5 persons (Davis and Wagner 2003);
- INT-b: Prioritization (assessing relative importance) of tree-related products and services through individual interviews with direct weight ascription using small stones as counters, following Sheil and Liswanti (2006). The set of evaluated attributes (Table 1) was delineated based on the criterion groups of the literature review, and complemented with ideas raised during INT-a;
- INT-c: Assessment of species-specific occurrence, autecological characteristics (i.e. plant performance in relation and interaction with its environment), products and services (see also Table 1 for a full list) during structured group discussions (Bernard 2006) with 3-4 participants. The number of species discussed during each interview was set to a maximum of 12, selecting only species found or used in the village of the participants, and therefore well-known. Species discussed only once (6) were excluded from further survey evaluation. In that way, 31 species were considered, each of them covered in at least two discussions (Table 2).

The prioritization component of these local surveys (INT-b) was supplemented with the results of a similar exercise performed by 11 external experts, being Ethiopian (n=3) and Belgian (n=8) researchers with experience in the study area. These experts evaluated the relative importance of selection criteria for two different application scenarios (see "*Application of a multi-criteria decision tool*" further in this section), this time not by direct weighting but through a full pairwise criteria comparison. Moreover, 11 additional individual farmer interviews type INT-a and INT-b, and seven group discussions (3-5 participants) type INT-c, were performed in six different villages in the same area in May 2008, to complement and validate the initial surveys.

As a consequence of time constraints, and since semi-structured interviews allowed informants to direct the interview themselves (Bernard 2006; Love and Spaner 2005), it was impossible to obtain complete information in every single interview. Nevertheless, all questions were covered by at least 75 % of the 45 interviewees. Consistency of the answers was checked through the repetition of similar questions in a slightly different way and comparing the answers.

Species selection for further analyses

Starting from the full list of species considered during the literature review and the local interviews, those species whose requirements did not suit the conditions of the studied agro-ecological zone were excluded, taking those attributes belonging to the criterion group “ecological range” into account (Fig. 2). Only definitely unsuitable species were excluded, withholding doubtful or marginally suited species, since the true agro-ecological limitations of many species are often insufficiently understood, and hard to delineate given the complex interaction of biotic, abiotic and land management factors (Rescia et al. 1994). As such, species excluded also encompass valuable species previously present but now locally extinct (e.g., *Erica arborea*, *Prunus africana*) or species limited to lowland conditions (e.g., *Boswellia papyrifera*, *Commiphora* spp.) (Causton and Venus 1981; Teketay 2000). The resulting list is presented in Table 2.

In a next step, those species for which virtually no information was available to make a proper prioritization were excluded (Fig. 2).

Species database

The (descriptive) output of all the information collected for the species in the final species list, was synthesized into a numerical, integrated database or species x attribute matrix, summarizing species-specific occurrence, autecological characteristics, products and services (freely available upon request). For nominal variables such as soil type preference or management needs, species were classified into three to six classes defining these properties. For all other variables, ordinal scores ranging from one to ten were assigned to all species. Scores are based both on information from literature review and local interviews (mainly INT-c). Thereto, the score from literature was always taken as the base value, since it was based on a broader range of information sources. On top of replacing missing values, scores from the interviews were then used to slightly increase or decrease the literature scores, hence correcting for local conditions and use if deemed necessary. The ultimate score of many socio-economic products, e.g., construction wood, encompasses several aspects, such as quantity, quality, household use, and ability to market the product.

An important bottleneck for any such database is the absence of information for a considerable number of species x attribute combinations (Franzel et al. 1996). Nevertheless, towards further data analysis, a proper method had to be defined to fill these data gaps with an appropriate replacement value. Two types of missing values were differentiated, depending on the particular criterion considered. For one group of criteria, lack of information was interpreted as an absence of that particular characteristic or function for the considered species, since it is expected to have been mentioned otherwise. In such case, the replacement value corresponded with a low score. Most socio-economic functions, socio-cultural values and several protection functions belong to this type. For a second group of criteria, a lack of information was interpreted as if the considered species scored neither extremely negative nor extremely positive. In such case, the replacement value corresponded with a medium score. Some protection functions and many attributes related to plant performance belong to this type.

Database trends and relationships

A small set of exploratory and multivariate analyses was performed on the resulting species x criteria database in order to obtain a more detailed insight on data trends and relationships.

To identify particular knowledge gaps, the percentage of missing values was calculated for every species and criterion. To evaluate how different criteria were related to each other in a positive or negative sense, Spearman's Rank correlations (Siegel and Castellan 1998) were determined between the species' criteria scores.

Based on the same species' criteria scores and following the methodology of Verheyen et al. (2003), a Ward's hierarchical clustering of a Gower similarity matrix (calculated from the complete 84 species x 45 criteria matrix) was performed to identify distinct species' clusters or "functional groups". The optimal number of emergent clusters was determined via tree validation (ClustanGraphics 8.06, Clustan Ltd. 2001), identifying five significant clusters as optimal solution. This validation compares the cluster tree obtained for the given dataset with the family of trees generated by 120 random data permutations.

In a next step, the relationships between the individual traits and the emergent cluster groups were quantified by means of Kruskal–Wallis tests in SPSS (Siegel and Castellan 1998).

Finally, a Principal Components Analysis (PCA) (Kent and Coker 1996) was used to reveal species variability in criterion scores.

Statistical analyses were performed using SPSS 15.0 (SPSS Inc., Chicago, IL), PCord 4.0 (MjM Software, USA) and ClustanGraphics 8.06 (Clustan Ltd., UK).

Multi-criteria decision analysis for species ranking and selection

To perform and evaluate the multi-criteria decision analyses on our data, a commercial software package for decision management was primarily used, i.e. Criterium DecisionPlus (CDP; InfoHarvest Inc., Seattle, USA). This is a flexible and user-friendly tool with a wide range of opportunities for data input, output, analysis and visualization. Simultaneously however, our own tool called MCTS (i.e. Multi-Criteria Tree species Selection) was applied. This freely available simplified tool, based on similar principles as CDP, was developed as a spreadsheet application and starts from a predefined but flexibly adaptable species x criteria dataset (Reubens 2010; Reubens et al. unpublished data). The idea behind developing an additional spreadsheet option was to make the whole decision process more transparent and accessible, and the valuable dataset readily available for future potential end-users, especially those prioritizing tree species in areas with similar characteristics across the East African region. MCTS consists of an introductory sheet (with general information for potential users), two input sheets (one for scoring the alternative species and one for criteria weighing, see next paragraph), three intermediate output sheets (demonstrating the results per criterion group) and one final output sheet showing the ultimate decision scores per species (Fig. 3).

For both methods, the subsequent steps followed to obtain a species ranking were (Fig. 4): (1) selecting a set of alternatives (species) and criteria, (2) building a hierarchy model, (3) scoring the alternatives, (4) weighing the criteria at the different criterion levels, and finally (5) calculating the alternative scores.

Criteria and species were selected as described above. To build the hierarchy model (Fig. 5), six out of the nine original criterion groups were further elaborated upon, i.e. the socio-economic functions, socio-cultural values, environmental services, general and local plant performance, and biodiversity relevance.

After defining this hierarchy model, assignment of individual scores to all alternatives (species) for each criterion was done using the information in the species database. In the MCTS spreadsheet, this information was integrated in the species x criteria input matrix of the tool (Fig. 3). In CDP the Simple Multi-attribute Utility Technique (SMART) was used to incorporate this information into the decision model (Belton 1986; Infoharvest Inc. 2002).

Since not all criteria or attributes are of equal importance in a decision process, weighing encompasses the evaluation of the relative importance of the different criteria at all hierarchical criterion levels. Such weights depend on the specific objective and scenario considered, and on the particular stakeholder assessing the relative importance. As an example, two scenarios for the North-Ethiopian highlands were worked out in this study. In Scenario 1, the aim was to select appropriate species for planting seedlings on private homesteads, with a strong emphasis on local plant performance and livelihood (mainly socio-economic) benefits. In this scenario, small volumes of (waste) water could be provided to the seedlings if necessary, and management may be quite intensive. In Scenario 2, species were selected for vegetative gully rehabilitation in the rural landscape, with a strong emphasis on plant performance, soil reinforcement and environmental services. Here, aftercare and protection are very limited. For both scenarios, the direct rating performed by the local stakeholders (INT-b) was first translated into a pairwise criteria comparison, which together with the other pairwise comparisons performed by the external experts was used to assess the median contrast value for each particular pair of criteria. The latter values were subsequently used for a full pairwise comparison in CDP, hence assigning a final weight. The same values, but translated into direct criteria weights, were also incorporated into the second input sheet of MCTS. All weights were positively normalized, ensuring a sum of weights equal to 1. The accumulated weight of an individual criterion over the different criterion levels (in our case two, i.e. criterion groups and attributes) can then be calculated as:

$$A_j = w_{g^j} \cdot w_j \qquad \text{(Eq. 1)}$$

where A_j is the accumulated weight of criterion "*j*", w_{gj} the weight attributed to criterion group "*g*" to which *j* belongs, and w_j the weight of *j* within its criterion group.

Following this procedure, the ultimate decision score for an alternative (species) is the sum of the scores of that alternative with respect to each of the lowest criteria weighed by their accumulated weight. In other words, the result score is calculated as:

$$D_i = \sum_{j=1}^{n} S_{ij} \cdot A_j \qquad \text{(Eq. 2)}$$

where D_i is the decision score of alternative “*i*” and S_{ij} the (normalized) score of alternative *i* on attribute *j*, and “*n*” is the total number of criteria. The same algorithm is used in CDP and MCTS.

Evaluation, validation and comparison of the species selection procedure

Since the weights attributed to the criteria in the decision model are based on personal judgments on the part of the local stakeholders and experts, it is important to understand how sensitive the model is to such weights. In other words: we are interested to understand how robust the decision results are, and what would happen if weights were slightly changed. A sensitivity analysis was therefore performed in CDP, by assessing for every criterion how much its current weight may change before the model’s preferred alternative is superseded by a different alternative. In that way, we get an idea of the sensitivity of the model, and the most critical (sensitive) criteria are determined (Infoharvest Inc. 2002; Saaty 1992).

As discussed in the Data Collection section, the AgroforesTree database (AFT) has been used as a major input source for the database developed in this case study. Besides AFT, another very broad species reference guide including a species selection tool, is the Forestry Compendium (CABI FC; CAB International 2005). To date, the CABI FC harbors information on more than 22,000 species occurring worldwide. To our knowledge, nowhere such a vast amount of existing but fragmented information has been compiled into one database, this comprehensive integration being the main strength of the compendium. Although very useful and time-saving, the CABI FC has purposely not been used for developing our own database and MCTS-tool, so as to enable utilizing it for comparison afterwards. Using a free institutional trial version (2007 Edition © CAB International, Wallingford, UK), we evaluated which species of our final list (Table 2) were found in the CABI FC. Furthermore the CABI FC selection tool (Webb et al. 1984) was applied. This tool encompasses about 1300 woody species and reproduces a fully ordered list of these species, completely ranked according to a set of specified selection criteria and the relative importance attributed to the latter. Selection criteria include: country or region, latitude, altitude, rainfall, air temperature, soil properties, silviculture, land uses as well as preferable woody and non-woody products. One can also choose to select planted or naturally growing species. Besides a representation of the suitability for each of the selected criteria, the output encompasses links to the Pest search module, aimed at assessing the risk for selected tree species of actual or potential attack by pests, which is likely to influence the final choice of species (Webb et al. 1984). Species selection outputs obtained through our MCTS-tool for three different scenarios, i.e. without criteria weighing, with criteria weighted towards promoting private planting, and with criteria weighted towards promoting gully rehabilitation, were compared to those obtained using CABI FC. For the latter, Ethiopia was specified as the country and repeated selections were made defining slightly variable altitude and rainfall characteristics within the range for the study area, as well as silviculture, woody and non-woody product specifications.

Results

Selected species

From the full original species list represented in Table 2, seven species (nearly 8 %) were excluded from further analysis for lack of available information, i.e. *Abutilon longicuspe, Calpurnia aurea, Grewia ferruginea, Manilkara butugi, Psydrax schimperiana, Pterolobium stellatum* and *Sheffleria abyssinica*. A total of 84 potentially suited species, belonging to 43 different families, was hence withheld. Sixty-seven of these species are found in the study area and three are not but were suggested by local informants as being promising. The Fabaceae were the largest family, with 19 species represented.

Trends in interviews and questionnaires

Local knowledge and preferences

Regardless of any specific scenario, local stakeholders particularly consider utility of species for construction wood or (agricultural) tools as very important. Similarly, growth speed and drought resistance are greatly appreciated plant attributes (Table 3).

Species that are well known and therefore preferably selected for discussion during INT-c, include *Olea europaea* subsp. *cuspidata*, *Acacia abyssinica*, *Eucalyptus* spp., *Cordia africana* and *Rumex nervosus*. On the other hand, species which are up to now poorly understood by local stakeholders encompass the locally increasingly valued (Mengistu et al. 2002) fodder species *Sesbania sesban* and *Leucaena leucocephala*.

Plant attributes or functions which are rarely known or for which available information is probably unreliable given the high variability in response between different stakeholders, include all root system characteristics and ecological traits such as flowering period. On the other hand, socio-economic or relevant environmental functions like utility for firewood, construction wood, fodder or shade, are thoroughly understood, with respondents often even making a differentiation of several quality levels. Noteworthy, knowledge on medicinal uses is not widespread, such uses only being mentioned by a limited number of stakeholders.

Some findings from the semi-structured discussions (INT-a) considered relevant in the framework of our database and MCTS tool are also briefly summarized here, even if it is outside the scope of this manuscript to thoroughly discuss the output of these discussions.

The local informants considered the following species as overall most important (in decreasing order): *Olea europaea* subsp. *cuspidata*, *Eucalyptus* spp., *Cordia africana*, *Juniperus procera*, *Acacia etbaica*, *Ficus vasta* and *Acacia abyssinica*. Though jointly determined by a range of criteria, the available amount (particularly for *Eucalyptus* and *Acacia* spp.) and quality (particularly for *Cordia*, *Juniperus*, *Ficus* and *Olea*) of wood, mainly for use as construction wood or firewood, were the most important reasons behind this species prioritization. Similarly, *Acacia abyssinica*, *Eucalyptus* spp., *Acacia etbaica*, *Agave* *sisalana* and *Olea europaea* subsp. *cuspidata* were most repeatedly mentioned as being naturally present or frequently planted.

Expert priorities

Regardless of the considered scenario, local plant performance was considered relatively most important (Table 1). For scenario 1 greatest value was furthermore attributed to the socio-economic functions, more particularly to construction wood and firewood and charcoal. Environmental services highly appreciated for scenario 1 were the utility for live fencing or shade, as well as increased water and nutrient availability.

Besides local plant performance, general plant performance and environmental services got the greatest relative weight for scenario 2. This time, environmental services highly appreciated were protection against soil erosion and land reclamation. The most appreciated socio-economic values were firewood and charcoal, fodder, and honey production. For both scenarios, attributes of general plant performance receiving the greatest relative weight were growth speed, resistance to grazing, coppicing ability and drought resistance (Table 1).

Integrated database: strengths, constraints, patterns

Particular knowledge gaps

In general, for only 60 % of all attributes evaluated, was information found for more than half of the considered species. Most outstanding are the root system characteristics, for which information was hardly ever available. Especially with regard to root strength or density, data were found for less than 3 % of the considered species. For about 20 % of all species, a rough description of a root system type is given, and for nearly 50 % rooting depth and/or lateral spread are reported. Other criteria, for which information was only found for 25 up to 45 % of all species, were a set of ecological or plant performance attributes, including species air temperature range and performance on nutrient-poor, steep, shallow or rocky soils. Also the effects of a particular species on soil water status (information was available for less than 30 % of all species) or nutrient availability (less than 45 %) were poorly described.

The other way around, for only 30 % of all species, was information found for more than 70 % of the considered attributes. Half of these were exotics and/or considered important, locally or nationally. Besides those species which were excluded because of lack of information (marked in Table 2), the fewest data could be traced for *Cussonia spicata*, *Allophylus abyssinicus* and *Mimusops kummel*. Species considered important but for which information was found for less than 50 % of all attributes, include *Albizia schimperiana*, *Diospyros abyssinica* and *Ficus vasta*.

Nevertheless, as discussed in the Material and Methods section for missing values, it is noteworthy that in many cases no information was found merely because the considered species simply does not hold a particular characteristic or function, or at least not in an outstanding way.

Attribute relationships

Without elaborating upon the detailed results, some of the most significant correlations (Spearman rank correlation coefficient $\rho > 0.4$) reveal the following trends. Generally, given the strong positive correlations between the attributes concerned, species which are considered important are also often locally and/or regionally cultivated, and provide construction wood and/or good shade. Species providing shade are frequently also those species with an ornamental or wind shelter function. Obviously protection against soil erosion and use in land reclamation are attributes going hand in hand, as do nurse plant effects (i.e. the facilitation of seedling establishment by increasing fertility or soil moisture, or offering protection against high irradiance, temperature or predation), agroforestry applications, and increasing soil moisture and nutrient availability. Species performing well on shallow soils also perform well on steep slopes, those increasing soil humidity are often also droughtresistant, and those suitable for coppicing frequently resist grazing well. Furthermore, suitability for construction wood and for agricultural tools are positively associated, as are ornamental functions and presence of tannins or oils. Species growing fast and/or frequently cultivated are often exotics.

Even if many of these relationships or trade-offs may be considered evident, it is valuable to understand them, since they may enable estimating species potential or constraints from a limited set of known characteristics.

Cluster analysis and PCA

Fig. 6 represents the ordination of the considered species along the first two principal axes of the PCA, explaining 22.3 % of the initial variance. The first axis of the PCA was positively correlated with performance on nutrient poor soil (0.22), ornamental value (0.25), resin-gum-latex (0.23), dye-tannin-oil (0.21), experience with cultivation (0.27), local planting (0.25), protection against soil erosion (0.25) and wind shelter (0.28). In summary this axis could be interpreted as a “protection” axis (against wind and water), a “planting experience” axis, and a “non-woody socio-economic value” axis. The second axis of the PCA is positively correlated with nutrient increase (0.33), intercropping (0.33), increased water availability (0.33), and nurse plant effects (0.32). In summary, this is a “plant nursing-soil improvement” axis.

Five species groups were identified by means of Ward’s hierarchical clustering, and are relatively clearly delineated on the ordination graph (Fig. 6).

1. Even if not uniformly valid for all member-species, group 1 (e.g., *Olea europaea*, *Euclea racemosa*, *Ficus vasta*, *Maytenus* spp.) could be described as including indigenous species with a good local performance, often with a high biodiversity value and socio-economically relevant. Half of them have an important ceremonial value.

2. Group 2 (e.g., *Acacia etbaica*, *Afrocarpus falcatus*, *Ricinus communis, Mimusops kummel*) is a group with a mixed set of attributes, often with a sub-optimal growth performance. This group includes several species for which little information was available.
3. Group 3 (e.g., *Nicotiana glauca*, *Ehretia cymosa*, *Rumex nervosus* and *Rosa abyssinica*) mainly includes naturally (frequently fast-) growing species, indigenous or naturalized, rarely cultivated and with a low socio-economic, protection or socio-cultural value. Again, this group includes several species for which little information was available.
4. Group 4 (e.g., *Acacia abyssinica*, *Cordia africana*, *Dodonaea angustifolia*, *Faidherbia albida*) mainly includes indigenous, naturally growing species adapted to harsh conditions, often with a socio-cultural importance, high protection and reclamation value, and an excellent agroforestry potential. The upper-right position of this group on the ordination graph (Fig. 6) confirms the overall relevance of its member-species.
5. Group 5 (e.g., *Sesbania sesban*, *Cupressus lusitanica*, *Grevillea robusta*, *Eucalyptus* spp.) mainly includes fast-growing, locally planted (coppiceable) exotics, with a good performance on poor soil, and a high protection and socio-economic value. Several species are however susceptible to pests and/or diseases (e.g., *Sesbania*, *Cupressus*), have an adverse effect on water availability and a low conservation or biodiversity relevance.

Species with a notable position on the ordination plot (red numbers in Fig. 6), are *Eucalyptus camaldulensis* (indicated as “1” on the graph) and *Eucalyptus globulus* (2), having an extremely low nursing potential and an adverse effect on nutrient and water availability (as opposed to for example *Leucaena leucocephala* (3) or *Faidherbia albida* (4)), but with a very high protection value against wind, water erosion and landslides, and socio-economic relevance (contrary to for example *Nicotiana glauca* (5) or *Sida schimperiana* (6)). Cluster membership of all species is represented in Table 2. Clustering results seem to be quite sensitive to small changes in trait values.

Multi-criteria decision tools for species selection

Resulting species prioritization in Criterium DecisionPlus and MCTS

A summary of the ranking of species for both methods (CDP and MCTS) and in both scenarios is shown in Table 4. Selection analysis is based upon the weights as presented in Table 1. Generally, differences in performance or significance for two subsequently ranked species are not very high, as indicated by the small stepwise variations in score (see also next section). Both *Dodonaea angustifolia* and *Cordia africana* are always found among the top three priority species, for both scenarios and methods. *Eucalyptus* also scores well, particularly for private planting (Scenario 1). Remarkably, *Olea europaea*, usually considered the number one priority species in the study area, is displaced at the top by *D. angustifolia*, *C. africana* and a few other species. While for private planting its position is still within the top seven, particularly for gully rehabilitation (Scenario 2) *Olea*'s score is not as high as expected, with e.g. the fodder species *Sesbania sesban* and *Leucaena leucocephala*, as well as several *Acacia* species doing better. Other highly valued species for both scenarios include *Acacia abyssinica* and *Acacia saligna*. *Acacia seyal* and *Juniperus procera* are highly ranked for scenario 1, and *Ficus sycomorus* and *Faidherbia albida* for scenario 2. Several of the highly valued tree species, such as *Faidherbia albida*, *Leucaena leucocephala* and *Sesbania sesban*, are frequently used for agroforestry development in sub-Sahara Africa (Owino 1992).

Pie charts in which the pie radii represent criterion (group) scores for the considered species and pie width varies according to the relative weight attributed to the considered criterion (group), enable visual assessment of the species performance for all criteria (criterion groups), and the relative importance of each such criterion (group) in the overall evaluation. Examples of such pie charts have been set up for a few highly-valued species with regard to the gully rehabilitation scenario (Fig. 7). In that way, it becomes clear for example that *D. angustifolia* scores high for all criterion groups except for biodiversity relevance, which is never given a high relative weight, hence not affecting the top position for this species. Valuation for *C. africana* is similar, with a higher biodiversity relevance but somewhat lower general plant performance. Besides a low biodiversity relevance, mainly the low score for environmental services reduces the importance of the otherwise highly valued *Eucalyptus* species for gully rehabilitation. Indeed, *Eucalyptus* species may seriously decrease soil water and nutrient availability, which might result in additional soil cracking and piping (Gindaba et al. 2005; Wilson 1977). Despite very high scores for biodiversity relevance and socio-economic & socio-cultural values, *Olea*'s plant performance (particularly growth speed) and environmental services were slightly lower than for a few other species. Since plant performance and environmental services are given a high relative weight, *Olea* is displaced at the top.

Model sensitivity

Without elaborating upon the detailed results, the sensitivity analysis in CDP indicated that one should not focus too much upon the exact ranking of a species, since this may be affected by small changes in weight attribution to the criteria. Sensitivity of the decision models is therefore assumed to be relatively high, even if the general trends are quite robust. For the private planting scenario, the criteria or criterion groups most sensitive to changes appeared to be (in decreasing order of sensitivity): biodiversity impact, environmental services, food, vegetative propagation, cosmetic use, frost resistance, performance on steep slopes, socio-cultural value and local plant performance. For the gully rehabilitation scenario, which is generally slightly less sensitive, biodiversity impact, coppicing, socio-cultural value, invasiveness, local and general plant performance are most sensitive.

Comparison with existing databases and selection tools

Fifty-four percent of all considered species in the present case study (Table 2) were also recorded in the AgroforesTree (AFT) database. Even if the corresponding figure was 87 % in the CABI FC database, for 50 % of all species information was limited to a taxonomic description and a distribution map, so the CABI FC provided information on ecology, functions and uses for only for 37 % of the species.

When comparing species selection outputs of our MCTS-tool with the CABI FC selection tool, some notable trends could be observed. Since in the CABI tool no species are actually excluded, but always a fully ordered list of all species in the FC database is provided, only a fixed number of top-ranked species should be considered as relevant for the scenario dealt with. In our comparison, we broadly considered the top 100 ranked species on this list. Whatever the selected scenario, an average of only 24-27 % of all species in this top 100 were also found in our own species list, only 32 % was actually found in the study area, and more than 50 % were (non-naturalized) exotic species. The latter was reduced to an average of 36 % when "naturally growing" was added as a selection criterion. Generally, this top 100 species list in CABI included about 20 *Acacia* species and 20 *Eucalyptus* species, 14 and 7 of which returned in every selected scenario, respectively. Highly-rated species also found in our species list included *Acacia seyal*, *Croton macrostachyus*, *Cupressus lusitanica*, *Dodonaea angustifolia*, *Erythrina abyssinica*, *Eucalyptus globulus*, *Faidherbia albida*, *Juniperus procera*, *Sesbania sesban*, and *Syzygium guineense*. Other highly valued species not in our list were *Acacia angustissima*, *Acacia mearnsii*, *Entada abyssinica*, *Leucaena pallida* and *Terminalia brownii*.

Noteworthy, there were no significant correlations between the final species priority scores for both tools.

DISCUSSION

The importance and challenge of a holistic approach

Since land degradation in dryland regions may be caused by and affect a wide range of environmental and anthropogenic aspects, an integrated approach is needed to deal with this problem in an effective way, incorporating different criteria, disciplines as well as present and future potential stakeholders. Sustainable management of natural resources may be hindered not only by incomplete biophysical understanding, technical bottlenecks, land shortage or difficulties related to limited capacity, but also by policy-related shortcomings (Pausewang 2002) or insufficient insight in objectives and actions of the different stakeholders (Segers et al. 2008). If planting trees is perceived as a way to establish rights to land (or extend right of exclusion) in the community being examined, care has to be taken not to suggest niches or spatial arrangements of tree planting that will create or worsen land tenure problems, especially for the most vulnerable groups in the community (Warner 1994). Hence, acceptance and success of tree planting and land rehabilitation activities depend upon the amount of attention given to local environmental and social conditions, cultural values, and people’s needs and knowledge (Zubair and Garforth 2006). Involving local people in the design, implementation, and evaluation of such activities will further contribute to their success (Franzel and Scherr 2002).

The present case study aimed at integrating several aspects of such a holistic approach into an appropriate procedure for selecting multi-purpose tree species. The key aspects were a broad set of species to start from, a wide range of criteria for evaluation, and knowledge from an extensive set of literature sources and different groups of local stakeholders. Such an approach nevertheless demands time, and is not without difficulties. It is out of our scope to discuss the challenges of integrating local knowledge, but the qualitative and holistic nature of it often hampers its incorporation into a scientific quantitative, analytical but fractionated knowledge framework (Bernard 2006). Similarly, information from the literature, research guidelines and recommendations may be fragmented and hence difficult to synthesize, not to mention the ample knowledge gaps (see section “common knowledge gaps”). Estimating the value of a particular species is further complicated by the fact that principal uses vary from region to region (Franzel et al. 2008), at least partly explaining contradictory statements in literature. The challenge of an appropriate and user-friendly tree species selection procedure is to combine simplicity, transparency, participation and analytical rigour in order to ensure that the right species are chosen for the right place (Franzel et al. 2008).

The importance of a correct use and interpretation of reference databases and tools

In the present case study, two databases elaborated upon in detail are the global AgroforesTree database (AFT) and the CAB International Forestry Compendium (CABI FC), both covering a wide range of tree species. These references present methodological guidelines and encompass an enormous richness of species information, often hard to find elsewhere. They hence offer enormous time-saving opportunities. Nevertheless, the output generated is habitually relatively rough and broad-scaled, and based on limited and local data. For many species lack of sufficient (site-specific) information remains a major constraint. These references should hence be used and their output be interpreted in accordance with their intended purpose, i.e. offering species-specific information along with the possibility to obtain a first, rough delineation of potentially interesting species for a particular application. As stated by Webb et al. (1984), users are reminded that expert knowledge, and experimentation where required, must be used jointly with any results obtained from searches in species selection tools in order to arrive at fully-informed decisions.

As an example, it was demonstrated in this study how information for only 54 % of all species in our selection list was found in the AFT database and 37 % in the CABI FC. Moreover, when species selection procedures were performed under CABI FC for similar scenarios as those worked out in this study, very different results were obtained, with many of the prioritized species being exotics or species found outside the study area. It must be noted however that the focus of the AFT database is particularly on tree species suitable for agroforestry, which is why some species of our list may not be incorporated. Similarly, we worked with a trial version of CABI FC, with potentially better results being expected in the full version.

State of the art: common knowledge gaps

It appeared to be difficult to clearly delineate species-specific agro-ecological ranges, with systematic research on biophysical limits largely missing for many species, and existing literature sources often providing dissimilar information. This further complicated assessment of species suitability for the study area and is in line with the notion that little is known about the ecology and distribution of many African tree species (Kindt et al. 2007). Not only may true agro-ecological limitations of a species depend upon the phenotype considered, they are generally hard to delineate given the complex interaction of biotic, abiotic and land management factors (Rescia et al. 1994). Moreover, there is no common definition of the term ‘biophysical limit’: it is usually not clear whether it refers to the limit at which the tree can survive at all, the limit at which the tree performs less well than in other areas, or somewhere in between these two definitions. Human impact on species distribution and abundance has been enormous (Darbyshire et al. 2003; Kindt et al. 2007), and the threshold between true exotics and naturalized species is not always clear. Furthermore, micro-climatic conditions may deviate from regional averages, with for example topographical aspects affecting temperature, wind speed and rainfall distribution (Nyssen et al. 2005).

Also the effect of a particular species on soil water status is generally poorly described. It is indeed difficult to generalize the influence of perennial woody components in semiarid areas on soil water dynamics (Kizito et al. 2006). Soil-tree hydrological interactions are a complex issue, with the overall balance of fluxes largely dependent on a wide range of specific plant (e.g., root system depth, plant physiology), site (e.g., land use, management, soil conditions), seasonal and/or climatic conditions (Bruijnzeel 2004; Burgess et al. 1998). Probably most systematic however, was the lack of information on root characteristics, even for very well-known or economically important species such as *Olea europaea* or *Cordia africana*. This is not a surprising result, since quantitative research on root system characteristics has been very limited, primarily because of methodological difficulties

(Reubens et al. 2007). Nevertheless, insight in rooting characteristics is crucial towards application both for agroforestry in general and soil erosion control.

For many species there is still a lack of sufficient information on environmental range, characteristics and/or functions, a problem which holds true particularly for tropical tree species (Simons and Leakey 2004; Teketay 2000). Moreover, information is often mainly descriptive, and species' characteristics or functions are mentioned as being "present" or "absent" (e.g., used or not used for firewood or charcoal production), without further differentiating distinct levels of function performance (such as the quality or available biomass for firewood or charcoal production). Finally, it is noteworthy to remark that different literature sources frequently get their information from one and the same original study or database. Hence, not every additional literature source should be regarded as adding new information to the pool of knowledge.

Opportunities and constraints of the species selection framework applied

As much as for any other application, the latter shortcomings evidently had serious consequences for the decision model presented in this particular study, the output of which is not only sensitive to the weights assigned to the criteria (as assessed in the sensitivity analysis), but also depends on the reliability of the species-criteria input scores. Even if as much information as possible has been collected and a lot of attention has been paid to consistency while attributing scores to the alternative species for each criterion, these scores often merely remain a translation of a qualitative description into an ordinal value. Small changes in these scores may therefore result in a different model output. Moreover, contradictory information from different data sources and the wide range of missing values further increase variability. Finally, the informants are often quite heterogeneous and the analysis must take into account the views of different strata such as men and women, members of different ethnic groups and socio-economic categories. In conclusion, the values assigned to the ratings of the alternatives are not precise but have considerable uncertainty associated with them (Saaty 1992).

Through performance of an uncertainty analysis, determining upper and lower cutoff levels, mean values and/or standard deviations for all ratings, a statistically sound decision model could be obtained, in which the probability of a certain outcome is assessed in more detail. However, at present no uncertainty analysis was performed for our particular dataset, since it is very difficult to accurately assess the potential variability of every individual score. It is nevertheless important to take such uncertainty into account when evaluating the decision model. The general trends and rough ranking of the alternatives rather than the exact position of a particular species versus its neighbor should be considered towards application, as is also confirmed by the often very minute differences in final species scores between neighboring alternatives.

Two other complications are worth mentioning concerning the calculation of scores and their use in recommending species for planting. First, a species may perform well on nearly all criteria, and thus obtain a high score, but poor performance on a single criterion, such as susceptibility to disease, may render it unsuitable for planting. Second, if informants view a species as important or having high benefits, it does not necessarily mean that they wish to plant it. For example, farmers may have high regard for a fruit tree yet have little or no interest in planting it because it is already available in abundance and there is no market for surplus fruits.

Notwithstanding all these constraints and uncertainties, the amount and diversity of the knowledge pooled in the database developed is huge, covering not less than 91 species and 45 attributes. As such, the species selection tool coupled to this database could serve as a catalyst for bringing existing knowledge into appropriate practice, at any decision level and for a broad range of scenarios.

Conclusions and implications for practice

The main objective of this study was to provide a conceptual framework for multi-criteria tree species selection in degraded African semiarid areas, using the northern Ethiopian highlands as a case study. Thereto, first of all a wide set of woody species potentially suited for the considered area, and an appropriate set of ecological, economic and social selection criteria describing species' growth characteristics and requirements, products and services, were defined. Next, a comprehensive meta-database integrating fragmented scientific as well as local knowledge on species-specific ecological ranges, characteristics and functions was designed and evaluated. Finally, both an existing and a new, flexible DSS for multi-purpose species selection under different scenarios are described, each having its strengths and constraints. Within the bounds of the presented MCTS tool, the user is free to add or remove species or criteria and to change species' scores or criteria weights, in line with the particular conditions considered and any local scenario aimed at. Although the idea is to provide a flexible output for a specific situation, recommendations cannot and should not be in too much detail, as this would create the impression that the impact is perfectly understood in great detail, while that is not the case.

It is furthermore noteworthy that the current results are only directly applicable to the Degua Tembien district and other Tigray districts under similar agro-ecological conditions. Nevertheless, the MCTS-tool could serve as a base for a broad set of applications in different situations, applicable not only in the study area but, if properly dealt with, in the East African region at large. Any such expansion should include consideration of new species and local conditions and knowledge. Moreover, species' functioning may be slightly different.

Though not extensively discussed here, a next vital step prior to planting is the feedback evaluation of the tree selection made (Warner 1994): does the tree fit the conditions to be met? What is the expected (positive as well as potentially negative) social, ecological and economical impact? It is essential that such final assessment is made together with local stakeholders, particularly those user groups potentially vulnerable to land or tree use restrictions (e.g., landless farmers, women) (Raintree and Warner 1986). Finally, we repeat that appropriate tree species selection is just one out of a wide range of conditions to be fulfilled towards sustainable land rehabilitation in dryland regions. Tree seedling planting interventions are of little value unless other problems such as inappropriate seedling raising or planting, lack of aftercare, lack of stakeholders' participation and lack of attention to farmers' views and needs are jointly dealt-with. To end with a famous anonymous quote: "*The best time to plant a tree was 20 years ago. The second best time is now*". Rather than waiting until all knowledge gaps are bridged, at many places interventions are required now, using the currently available understanding to the best of one's ability.

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Figure captions

Fig. 1. Study area.

Fig. 2. Scheme for initial species selection, prior to further prioritization.

Fig. 3. A view of the input sheet for species scores in MCTS. Column A stands for the species list, row 6 represents the criteria list. Species scores for each criterion are presented in the green matrix. Species, criteria and scores may all be adapted by the user.

Fig. 4. Schematic representation of the multi-criteria decision process.

Fig. 5. Hierarchic model.

Fig. 6. Principal Components Analysis ordination graph with representation of the cluster groups. *Black triangles*: group 1, *white squares*: group 2, *black stripes*: group 3, *black crosses*: group 4, *grey diamonds*: group 5. See text for description of the groups. A small set of notable species is indicated with an encircled number: *Eucalyptus camaldulensis*: 1, *Eucalyptus globulus*: 2, *Leucaena leucocephala*: 3, *Faidherbia albida*: 4, *Nicotiana glauca*: 5, *Sida schimperiana*: 6.

Fig. 7. Pie charts for a set of highly-valued tree species, regarding scenario 2 (gully rehabilitation). Radius represents criterion group score (scale 0-100) for the considered species, pie width varies in line with the relative importance attributed to the considered criterion group.