LAND DEGRADATION & DEVELOPMENT
Land Degrad. Develop. (2017)
Published online in Wiley Online Library (wileyonlinelibrary.com) **DOI**: 10.1002/ldr.2699

MULTI-CRITERIA-BASED PLANT SPECIES SELECTION FOR GULLY AND RIVERBANK STABILIZATION IN A SUB-HUMID TROPICAL AREA

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Received 13 July 2016; Revised 21 January 2017; Accepted 21 January 2017

ABSTRACT

Selection of appropriate plant species for rehabilitation of degraded lands while fulfilling socio-economic interests of local communities is one of the decision-making challenges. This research was undertaken to select multipurpose trees, shrubs and grasses to stabilize degraded lands in the Gilgel Gibe catchment of Southwest Ethiopia, situated in the sub-humid tropics. Two multi-criteria decision analysis methods, analytical hierarchy process and simple multi-attribute rating technique, integrated in the excel-based multi-criteria tree selection tool, were used. Focus group discussions were held with experts and local communities to prioritize 40 plant species from a preselected regional pool of 129 species, using six criteria groups containing 47 individual criteria. Root characteristics of the top 9 ranked plants were studied for triangulating the multi-criteria decision analysis results. Both local communities and experts gave priority to indigenous trees over shrubs and grasses as the best five species for multipurpose use, whereas the top 5 species prioritized for riverbank stabilization contained both trees and grasses. In contrast, communities preferred indigenous trees, and experts selected grasses as the best five species for gully stabilization. The root system characterization revealed that the five top-ranked multipurpose species also have the required root characteristics for effectively reinforcing unstable slopes. However, communities prefer to plant *Eucalyptus* and *Grevillea* trees because of their short-term economic benefits although they understood the multipurpose value of indigenous plants. The trade-off between direct economic benefit and multipurpose benefits could be solved by awareness creation, incentives to communities and policy re-enforcement. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: multi-criteria; plant; root; species; stabilization

INTRODUCTION

Water-induced erosion including gullies, riverbanks, badlands and landslides are often caused by misuse of land resources and serve as an indication of severe human-induced land degradation (Cerdà, 1999; Girma, 2001; Poesen *et al.,* 2003; Broothaerts *et al.,* 2012; Martínez-Murillo *et al.,* 2013). Gullies, for example, are often directly connected to rivers or develop into badlands if untreated and deliver sediment to water bodies and affect downstream environment (Ben Slimane *et al.,* 2015). For instance, Devi *et al.* (2008) found that in Southwest Ethiopia, the Gilgel Gibe I reservoir is at risk of severe sedimentation because of soil erosion (Figure 1). They estimated that the volume of the Gilgel Gibe reservoir will be reduced by half within 12 years and would be filled with sediments within 24 years unless appropriate measures are taken. Ongoing studies that were being undertaken in the catchment indicated the severity of the siltation problem (EPA, 2011). Preliminary field surveys before the present study also clearly indicated that gullies, landslides and riverbanks are the main sources of sediment in the catchment. As Ethiopia is characterized by a rugged topography, these problems remained critical challenges being aggravated by an increasing population pressure, lack of awareness and poor land management (Girma, 2001; Muys *et al.,* 2006; de Mûelenaere *et al.,* 2014; Mengistu & Waktola, 2014; Tesfaye *et al.,* 2014; Ayele *et al.,* 2015; Lanckriet *et al.,* 2015; Mekonnen *et al.,* 2015; Kassa *et al.,* 2016; Mukai, 2016).

Rehabilitation of gullies, riverbanks and badlands is a key strategy to restore degraded lands (Blaschke *et al.,* 2000; Girma, 2001; Frankl *et al.,* 2014; Kou *et al.,* 2016) and to control sedimentation problems. The most effective and sustainable means of minimizing soil erosion *in situ* and siltation of reservoirs *ex situ* is the use of vegetation strengthened with physical soil and water conservation structures (Gyssels & Poesen, 2003; Nyssen *et al.,* 2009; Palazón *et al.,* 2014; Ferreira *et al.,* 2015; Taye *et al.,* 2015). But the suitability and effectiveness of plants to stabilize slopes are strongly species and site dependent (Abernethy & Rutherfurd, 2000; Reubens *et al.,* 2011; Ola *et al.,* 2015; Selkimäki & González-Olabarria, 2016), which requires profound knowledge of species traits and their interaction with site characteristics.

Species selection will also need to consider the species' socio-economic value for local communities, which has possibly trade-offs with erosion-controlling or soil-improving

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Figure 1. Erosion and sedimentation problems in the Gilgel Gibe catchment, Southwest Ethiopia. (A) A gully in Bulbul village, Kersa district and (B) sediment deposition in the Gilgel Gibe river near inlet to the reservoir (March, 2010). [Colour figure can be viewed at wileyonlinelibrary.com]

characteristics (Reubens *et al.,* 2011; Tesfaye *et al.,* 2015). Tesfaye *et al.* (2015) observed that the growth and survival rate of exotic species like *Eucalyptus* and *Grevillea* were significantly higher than the indigenous species in central Ethiopia, but indigenous species such as *Hagenia abyssinica* (Bruce) J. F. Gmel improved the soil properties, while *Eucalyptus* and other exotic species depleted the soil. This clearly illustrates the challenge in balancing economic interests and environmental sustainability. Many studies carried out under different environmental conditions demonstrated the intrinsic variation in plant species performance to improve the soil (Pugnaire *et al.,* 1996; Su & Zhao, 2003; Bodí *et al.,* 2011; Villacís *et al.,* 2016). Not only ecological suitability for the targeted area and environmental service but also the preferences and needs of the local stakeholders and the economic benefits are important (Sisay & Mekonnen, 2013), and this necessitates multi-criteria-based selection of appropriate species (Reubens *et al.,* 2011).

To address the aforementioned problems, we formulated the following research questions: is it possible to solve the plant species selection dilemma for land rehabilitation and multiple benefits by involving the communities in a restoration program?; does the advice of experts to select species for gully and riverbank stabilization and multipurpose use coincide with the preferences of local people?; is it possible to support the multi-criteria analysis result by experimental results on the selected species' root characteristics?; and do communities prefer exotic species instead of indigenous species for plantation because of lack of awareness or economic reasons? To address these questions, we conducted focus group discussions (FGDs) with local people and experts and performed multi-criteria analyses. Then we validated the multi-criteria results with measurements of root characteristics for the most promising multipurpose trees, shrubs and grasses. The results were interpreted with the objective of selecting suitable multipurpose plant species possessing promising intrinsic characteristics to stabilize gullies and riverbanks while fulfilling the interest of end users.

MATERIALS AND METHODS

The study was conducted in the catchment of the Gilgel Gibe I reservoir, Southwest Ethiopia, approximately 260 km from Addis Ababa (Figure 2). The catchment is located between 7°22′07·15″ and 8°38′09·49″N and 36°30′05″ and 37°22′32′49·13″E. The study area includes the catchment of a cascading small reservoir downstream of the main dam. Its elevation ranges between 1,096 and 3,259 m.a.s.l. (EELPA, 1996), and it has a sub-humid climate with an average annual air temperature of 19·2 °C. The average annual rainfall depth ranges between 1,300 and 1,800 mm. Sixty percent of the rainfall occurs between June and September, 30% from February to May and only 10% between October and January (EELPA, 1996).

The Multi-criteria Decision Process

There are two well-known multi-criteria decision analysis (MCDA) techniques. These are the analytical hierarchy process (AHP) (Wind & Saaty, 1980; Saaty & Vargas, 1984; Dagdeviren, 2008) and the simple multi-attribute rating technique (SMART) (Kamenetsky, 1982; Von Winterfeldt & Edwards, 1985). AHP is based on subjective judgments to the relative weight of alternatives by making pairwise comparisons indicating the relative importance of the criteria in line with the desired objectives. SMART, on the other hand, assumes ratio–scale weights by giving direct scores (0–1) to the alternatives based on the given criteria and subjective judgments (Kamenetsky, 1982; Von Winterfeldt & Edwards, 1985).

Reubens *et al.* (2011) developed a user-friendly multi-criteria tree selection tool (MCTS) (Table S1) to screen potential trees for land rehabilitation in the semi-arid tropical region of Northern Ethiopia. This MCTS tool was adapted to the context of Southwest Ethiopia and used to calculate the final score after the data input was collected via standard AHP technique and SMART. The data were generated through FGDs by participating local communities and experts specialized in natural resources management and forestry. In addition to that, field observations were made on the

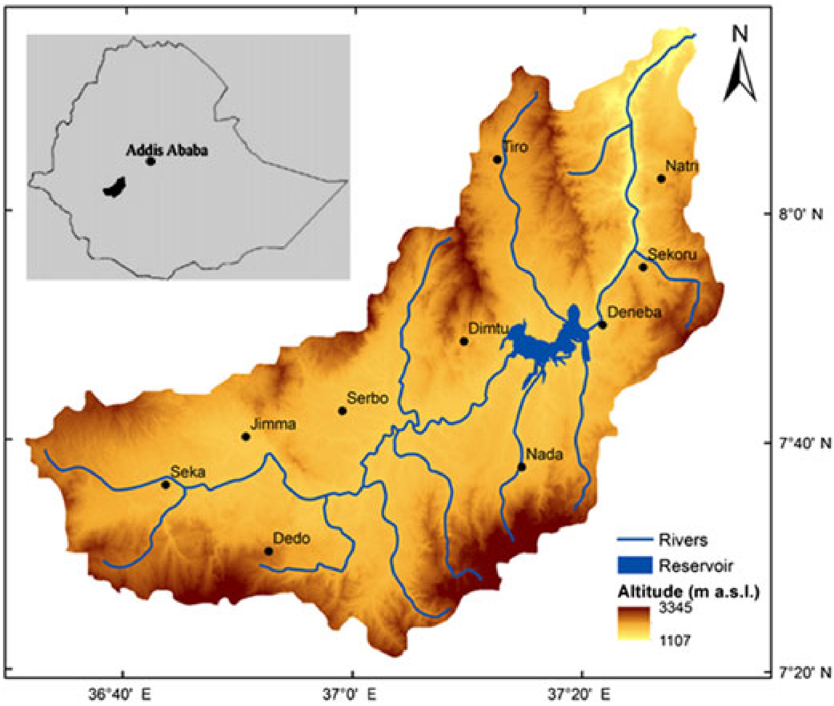

Figure 2. Map of the study areas, Dedo, Kersa (Serbo), Nada (Asendabo) and Tiro (Dimtu); the Gilgel Gibe I reservoir and its catchment (upstream from reservoir); and the upper part of the cascading Gilgel Gibe II catchment (downstream from the reservoir). The elevation map is based on Jarvis *et al.* (2008). [Colour figure can be viewed at wileyonlinelibrary.com]

root characteristics of the top 9 species to compare and contrast the MCDA result with the field data. Finally, the results of the top 9 species were interpreted and compared with scientific databases in order to triangulate the indigenous knowledge of local communities and experience of experts. This resulted in a prioritization of species for the desired objectives with special focus on land rehabilitation.

The stepwise stakeholder-driven multi-criteria selection process that we followed is illustrated in Figure 3. In step 1, a regional plant species database of 129 plant species (Table S2) was compiled based on field surveys, identification with the help of the National Herbarium of Ethiopia in Addis Ababa, expert advice and literature review (Aerts *et al.,* 2011; Reubens *et al.,* 2011). This database consists of 24 herbs, 33 shrubs, 62 trees and 10 grasses. From this database, we selected the 40 most promising plants including 19 trees, 12 shrubs and 9 grasses based on exclusion criteria such as invasiveness, least preference by the local communities and low suitability to grow on degraded lands, for further prioritization for their multipurpose use and their slope stabilization potential based on the six criteria groups and the 47 criteria (Table I).

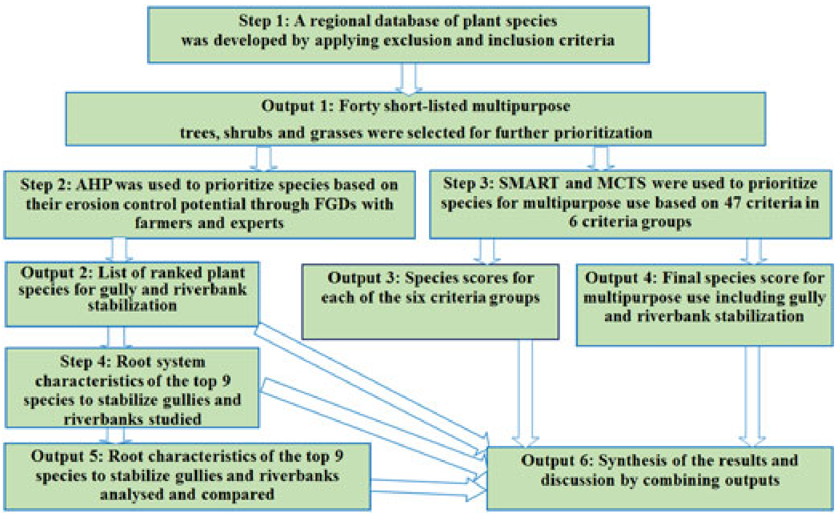

Figure 3. Scheme showing the different steps and outputs of the multi-criteria plant selection procedure. FGDs, focus group discussions; SMART, simple multi-attribute technique; AHP, analytical hierarchical process; MCTS, multi-criteria tree selection tool. [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. Criteria groups, individual criteria and corresponding normalized analytical hierarchical process scores given by the communities and experts for prioritizing potential multipurpose trees, shrubs and grasses to stabilize gullies and riverbanks

Criteria group	Description of the criteria group	Criteria	Weight from community	Weight from expert
Socio-economic function	Direct or potential (economic) benefits for humans	Firewood–charcoal	0·082	0·088
		Construction wood	**0·115**	**0·123**
		(Agricultural) tools	0·090	0·098
		Honey production	0·082	0·074
		Food	**0·108**	**0·122**
		Resin–gum–latex	0·054	0·048
		Fodder	**0·108**	**0·104**
		Medicinal use	0·082	0·073
		Dye–tannin–oil	0·062	0·038
		Fibre rope	0·062	0·066
		Cosmetic	0·041	0·038
		Non-poisonous	0·068	0·060
		Repellent	0·046	0·067
Sociocultural value	The social significance of the species	**Ceremonial value**	**0·312**	**0·198**
		Ornamental value	**0·198**	**0·490**
		Considered important	**0·490**	**0·312**
Environmental services	Indirect benefits for humans and environment obtained through the influence of the growing plant on its environment or on other species	**Protection against erosion**	**0·157**	**0·107**
		Land reclamation	**0·137**	**0·059**
		Provision of shade	**0·121**	**0·157**
		Effect on soil moisture	0·095	0·045
		Effect on nutrient availability	0·107	0·095
		Nurse plant effects	0·085	0·121
		Intercropping (agroforestry)	0·075	0·137
		Wind shelter	0·067	0·085
		Live fence	0·059	0·075
		Invasiveness	0·052	0·067
		Tolerance pests diseases	0·045	0·052
General plant performance	Growth performance and suitability of the species to grow in the (wide) region	**Drought resistance**	**0·118**	**0·139**
		Resist water logging	**0·105**	**0·122**
		Resist grazing and trampling	0·094	0·088
		Frost resistance	0·042	0·071
		Grows on nutrient-poor soil	0·085	0·086
		Grows on shallow/rocky soil	0·076	0·069
		Growth speed	0·149	0·086
		Experience with its cultivation	0·061	0·056
		Regional natural occurrence	0·048	0·092
		Ease of its sexual propagation	0·048	0·063
		Vegetative propagation	0·054	0·053
		Coppicing suitability	0·119	0·076
Local plant performance	Suitability of the species to grow under specific local conditions	**Performance on steep slopes**	**0·246**	**0·088**
		Dry/moist preferences	**0·157**	**0·112**
		Soil preferences	**0·191**	**0·140**
		Local environment suitability	**0·233**	**0·273**
		Locally planted	0·098	0·173
		Local natural occurrence	0·074	0·215
Biodiversity relevance	Importance for biodiversity	**Conservation priority**	**0·667**	**0·667**
		Indigenous/exotic	**0·333**	**0·333**

The top 18 criteria are highlighted in bold.

The FGDs with local communities were held between April 2011 and December 2012 in Dedo, Kersa, Omonada and Tiroafeta districts that were selected because of their land degradation severity, their proximity and upstream position relative to the dam. The focus groups were composed of 7–10 male and female farmers per district whose age varied between 25 and 70 years and were purposefully selected based on their active participation in agricultural extension activities. The FGDs with experts were held between April and May 2012 with 10 experts from Jimma University, Jimma Institute of Agricultural Research and District Agricultural Offices in the catchment.

The FGDs started with a discussion and confirmation of the 40 preselected species and a presentation of the species selection criteria, with a set of criteria for erosion control to be used in step 2 (Figure 3) and a second set of criteria for multipurpose use including soil erosion control to be used in step 3 (Figure 3). The use of two criteria sets was preferred to obtain a focused ranking of the preselected species based on soil and water conservation criteria before integrating with other 45 multipurpose criteria. The ranking for erosion control was based on the question 'which plant species is better among 2 species "X" and "Y" for gully or riverbank stabilization in the Gilgel Gibe I catchment?'

The AHP procedure was performed in both FGDs separately (step 2, Figure 3) and resulted in a 40 × 40 species matrices with the results of all pairwise comparisons between species in terms of their perceived suitability for gully or riverbank stabilization, but without considering other multipurpose value. A value of 2, 1/2 or 1 was given to the element on the i^{th} row and j^{th} column of the matrix when the i^{th} species was preferred, not preferred or considered equal relative to the j^{th} species, respectively (Wang & Yang, 1998; Gilliams *et al.,* 2005). The values were normalized by dividing a given matrix element value by the sum of all elements in its column, and the AHP priority value for each species was calculated by row-wise summation of the normalized values (Table S4). These sums were used to rank the species from the point of view of suitability for riverbank or gully stabilization as perceived by the two separate focus groups (output 2 in Figure 3).

In step 3 (Figure 3), we used the SMART method and processed the results with the help of the MCTS tool. Each of the 40 plant species was scored by the communities and experts in a separate FGD session for each of the 47 criteria using a decimal scale between 0 and 1. In addition, the relative weight of each of the 47 criteria was prioritized using the AHP method (step 2) in a 48 × 48 comparison matrix containing the criteria list in the first column and first row.

Similarly, the six criteria groups were also prioritized among themselves (Reubens *et al.,* 2011) in a 7 × 7 matrix. The accumulated criteria weight of an individual criterion was then calculated in the MCTS as follows:

$$A_j = W_{gj}\, W_j, \tag{1}$$

$$D_i = \sum\nolimits_{j=1}^{n} S_{ij}\, A_j, \tag{2}$$

Where: A_j = the accumulated weight of criterion j; W_{gj} = the weight attributed to criterion group g to which j belongs; W_j = the weight of j within its criterion group; D_i = the decision score of species i; S_{ij} = the normalized score of species i for criterion j; A_j = the accumulated weight of criterion j; and n is the total number of criteria. By using the two inputs, species score and the accumulated weight of criterion, the MCTS produced three different outputs. The first is the intermediate output on the relative value of each of the 40 species for the six criteria groups, and the second and third outputs are the gully and riverbank stabilization potential of each species by considering all the 47 criteria.

To crosscheck the multi-criteria analysis approach, we studied the top 9 ranked plant species for their intrinsic root characteristics relevant for slope stabilization (Abernethy & Rutherfurd, 2001; Gyssels & Poesen, 2003; De Baets *et al.,* 2007; De Baets *et al.,* 2009; Ni *et al.,* 2015; Ola *et al.,* 2015). Three mature plants of each of the nine species were selected from the Gilgel Gibe I catchment semi-natural forest in an open landscape. To excavate roots, a circular trench was dug at 1.5 m radius from the stem of the trees and shrubs until 1 m deep following a procedure described in De Baets *et al.* (2009) and adapted to our field situation (Figure 4b). Then the excavation continued towards the stem for quantifying the relevant root characteristics. For the grass species, the whole root system was excavated as their root system is manageable. Root density, root area ratio (RAR), root tensile strength (*Tr*) and root cohesion (*Cr*) were quantified based on the procedures indicated in Method S1 and Figure 4b, c and d.

Data Analysis

Cluster analysis was conducted on the average value of the MCTS intermediate output of the six criteria groups versus the 40 plant species using SPSS version 19 (IBM Corp. 2010) using the method of average linkage between groups and squared Euclidean distance to measure similarity. Analysis of variance was performed on the measured root characteristics using Minitab version 16 (Minitab 16 Statistical Software 2010). Multiple comparisons of species were performed using Tukey's family error rate at $p = 0{\cdot}05$ level of significance for mean separation.

RESULTS

Among the six criteria groups 'biodiversity relevance', local plant performance and sociocultural value showed the highest scores among the six criteria groups (Table I). Within these important criteria groups, the criteria conservation priority and performance on steep slopes were considered to be the most important of all 47 criteria (Table I).

The AHP comparisons evaluating the potential for gully or riverbank stabilization of the preselected 40 plant species are presented in Table II. The local communities prioritized the tree species *Albizia gummifera*, *Syzygium guineense*, *Acacia abyssinica*, *Eucalyptus camaldulensis* and *Eucalyptus globulus* as the top 5 species to stabilize gullies, whereas the experts prioritized grasses, particularly *Chrysopogon zizanioides, Pennisetum purpureum, Cynodon dactylon, Pennisetum macrourum* and *Pennisetum clandestinum* as the top 5 to stabilize gullies. For riverbank stabilization, *Salix subserrata*, *P. purpureum*, *Cyprus elegantulus*, *Rhus natalensis* and *Saccharum officinarum* were selected as the top 5 species by the experts, whereas local communities selected *Sa. subserrata*, *Erythrina abyssinica*, *R. natalensis*, *P. macrourum* and *P. purpureum* as the top 5 species.

The multi-criteria analysis result for gully and riverbank stabilization potential of each species is given in Table III. Communities prioritized the tree species *S. guineense*, *Ac. abyssinica, A. gummifera*, *Ficus vasta* and *Vernonia amygdalina* as the top 5 species for multipurpose use, whereas experts prioritized tree species *Ac. abyssinica*, *A. gummifera*, *Cordia africana*, *S. guineense* and *F. vasta* as the top 5 species, respectively.

Root system characteristics of some of the top-ranked species are summarized in Table IV. *Ac. abyssinica* and *A. gummifera* are the top 2 species for increasing soil cohesion, the most informative variable to differentiate species for their contribution to soil shear strength (*Cr*) as it combines RAR and *Tr* values. The result revealed that the aforementioned top 2 prioritized species by AHP and MCTS ranked top in root characteristics as well. *Grevillea robusta* has significantly higher ($p < 0{\cdot}001$) root tensile strength than all species followed by *C. zizanioides* and *P. macrourum*, respectively (Table III). *S. guineense*, which stood third based on AHP and MCTS, has relatively high root density (46·4 kg m^{-3}) although its *Tr* and RAR value is relatively low.

Figure 4. Illustration of the field and lab measurements during root characterization. (A) Horse-tail-type root system of *Salix subserrata* with numerous thin roots, which help the species to reinforce the soft alluvial flood plain along riverbanks, (B) circular trench excavated to determine root density and root area ratio of *Albizia gummifera*, (C) profile wall method for determining root area ratio; and (D) root samples of four diameter classes of *A. gummifera* roots ready for tensile strength measurement. [Colour figure can be viewed at wileyonlinelibrary.com]

DISCUSSIONS

Plant Species Selection Dilemma for Land Rehabilitation and Multipurpose

Local communities selected indigenous plant species rather than exotic species for multipurpose use and land rehabilitation (Tables II and III). Among the selected indigenous plants, *S. guineense* was prioritized as the best species for gully stabilization and the second species for riverbank stabilization followed by the nitrogen-fixing legumes, *A. gummifera* and *Ac. abyssinica*. In agreement with this, the World Agroforestry Centre database (Orwa *et al.,* 2009) (Table S3) described that *S. guineense* is a multipurpose tree used for food, apiculture, timber production for building, bridge construction, medicine, firewood, charcoal, shade tree, ornamental and evergreen tree. Cerdà & Garcia-Fayos (1997) stated that one of the most critical challenges in the rehabilitation of badlands is the poor survival rate of the planted species on the infertile soils. *S. guineense* was scored as the number one species to grow on severely degraded conditions. As a continuation of this species-screening study, we established the top 18 plants on a degraded gully in the study area and confirmed that *S. guineense* is the most successful species than any other tree species to survive in a severely degraded gully (under publication process).

However, local communities consistently prefer to plant the exotic *Eucalyptus* and *Grevillea* species because of their economic return although they understood the multipurpose value of indigenous plants. Addressing this economical versus ecological benefit dilemma requires policy re-enforcement, incentives, by-laws and awareness creation on long-term values of indigenous species. In line with this, Muys *et al.* (2006) stated that sustainable land management choices must be based on multiple criteria decision-making and economic evaluation techniques, rather than focusing on short-term economic gain.

Comparing Experts' and Communities' Species Preferences

The overall results reveal that preference of experts and communities is satisfactorily matched in prioritizing plant species for their multipurpose use and for riverbank stabilization with slight variation in scoring. However, there was a big difference among the two discussion groups in the

Table II. Analytical hierarchical process scores (and their rank in brackets) giving the suitability of 40 plant species for gully and riverbank stabilization in Southwest Ethiopia as assessed by local communities and groups of experts

Species	Family	Gully stabilization		Riverbank stabilization	
		Local communities	Experts	Local communities	Experts
Acacia abyssinica Hochst. ex Benth	*Fabaceae*	**0·043 (3)**	0·028 (15)	0·018 (29)	0·020 (25)
Agave sisalina Perrine	*Agavaceae*	0·030 (14)	0·032 (11)	0·016 (32)	0·014 (36)
Albizia gummifera (J. F.Gmel.) C. A. Sm.	*Fabaceae*	**0·046 (1)**	0·034 (9)	0·025 (20)	0·022 (22)
Arundinaria alpina K. Schum.	*Poaceae*	0·025 (19)	0·019 (26)	0·035 (10)	0·033 (9)
Arundo donax L.	*Poaceae*	0·027 (17)	0·019 (26)	0·037 (8)	0·035 (8)
Carissa spinarum L.	*Apocynaceae*	0·022 (23)	0·018 (28)	0·026 (18)	0·012 (40)
Chrysopogon zizanioides (L.) Nash	*Poaceae*	0·034 (9)	**0·045 (1)**	0·015 (33)	0·031 (10)
Cordia africana Lam.	*Boraginaceae*	0·022 (23)	0·024 (19)	0·020 (26)	0·021 (24)
Croton. macrostachyus Hochst. ex Ferret et Gal.	*Euphorbiaceae*	0·021 (25)	0·023 (21)	0·021 (24)	0·020 (25)
Cynodon dactylon (L.) Pers.	*Poaceae*	0·029 (15)	**0·042 (3)**	0·028 (16)	0·018 (28)
Cyperus elegantulus Steud.	*Cyperaceae*	0·013 (37)	0·015 (33)	0·040 (6)	**0·041 (3)**
Enthada abyssinica Steudel ex A. Rich.	*Fabaceae*	0·020 (27)	0·014 (36)	0·018 (29)	0·013 (39)
Erythrina abyssinica Lam. ex DC.	*Fabaceae*	0·029 (15)	0·033 (10)	**0·045 (2)**	0·025 (19)
Eucalyptus camaldulensis Dehnh.	*Myrtaceae*	**0·041 (4)**	0·020 (25)	0·023 (22)	0·024 (21)
Eucalyptus globulus Labill.	*Myrtaceae*	**0·039 (5)**	0·013 (38)	0·024 (21)	0·018 (28)
Euphorbia tirucalli L.	*Euphorbiaceae*	0·031 (12)	0·031 (13)	0·013 (38)	0·022 (22)
Ficus lutea Vahl.	*Moraceae*	0·016 (34)	0·015 (33)	0·027 (17)	0·015 (34)
Ficus ovata Vahl.	*Moraceae*	0·013 (37)	0·021 (23)	0·030 (14)	0·029 (11)
Ficus palmata Forssk.	*Moraceae*	0·015 (35)	0·018 (28)	0·031 (13)	0·027 (14)
Ficus thonningii Blume	*Moraceae*	0·018 (30)	0·021 (23)	0·022 (23)	0·026 (17)
Ficus vasta Forssk.	*Moraceae*	0·014 (36)	0·027 (16)	0·029 (15)	0·027 (14)
Grevillea robusta A. Cunn. ex R. Br.	*Proteaceae*	0·038 (6)	0·024 (19)	0·014 (36)	0·014 (36)
Jatropha curcas L.	*Euphorbiaceae*	0·032 (11)	0·022 (22)	0·012 (40)	0·018 (28)
Leucaena leucocephala (Lam.) de Wit	*Fabaceae*	0·035 (8)	0·036 (7)	0·019 (28)	0·025 (19)
Meisa lanceolata Forssk.	*Myrsinaceae*	0·019 (29)	0·013 (38)	0·013 (38)	0·018 (28)
Millettia ferruginea (Hochst.) Baker	*Fabaceae*	0·020 (27)	0·025 (18)	0·021 (24)	0·026 (17)
Musa domestica G. E. Rumphius	*Musaceae*	0·023 (22)	0·016 (31)	0·032 (12)	0·037 (6)
Pennisetum clandestinum Hochst. ex Chiov	*Poaceae*	0·026 (18)	**0·039 (5)**	0·018 (29)	0·014 (36)
Pennisetum purpureum Schumach.	*Poaceae*	0·031 (12)	**0·040 (4)**	**0·041 (5)**	**0·043 (2)**
Pennisetum macrourum (Nees) Benth	*Poaceae*	0·033 (10)	**0·043 (2)**	**0·043 (4)**	0·017 (32)
Persea americana Miller	*Lauraceae*	0·018 (30)	0·016 (31)	0·014 (36)	0·016 (33)
Rhus natalensis Krausus	*Anacardiaceae*	0·017 (33)	0·014 (36)	**0·044 (3)**	**0·040 (4)**
Saccharum officinarum L.	*Poaceae*	0·024 (21)	0·015 (33)	0·036 (9)	**0·038 (5)**
Salix subserrata Wild.	*Salicaceae*	0·012 (40)	0·012 (40)	**0·046 (1)**	**0·045 (1)**
Sapium ellipticum (Hochst.) Pax	*Euphorbiaceae*	0·018 (30)	0·026 (17)	0·026 (18)	0·028 (13)
Sesbania sesban (L.) Merr.	*Fabaceae*	0·037 (7)	0·037 (6)	0·020 (26)	0·027 (14)
Syzygium guineense (Willd.) DC.	*Myrtaceae*	**0·044 (2)**	0·035 (8)	0·033 (11)	0·036 (7)
Trichocladus ellipticus Eckl.& Zeyh	*Hamelidaceae*	0·013 (37)	0·017 (30)	0·040 (6)	0·029 (11)
Vernonia amygdalina Del.	*Asteraceae*	0·021 (25)	0·032 (11)	0·015 (33)	0·020 (25)
Vernonia colorata (Willd.) Drake	*Asteraceae*	0·025 (19)	0·029 (14)	0·015 (33)	0·015 (34)

A value of 0 indicates not suitable, and a value of 1 means most suitable. The five highest scores in each column are given in bold.

selection of species for gully stabilization as communities preferred trees, while experts preferred grasses among the top 5 species (Table II and III).

Experts prioritized grasses such as *C. zizanioides* and *P. purpureum* as first and second best species for effective gully stabilization (Table II) although these grasses scored very low for multipurpose use (Table III). Communities prioritized trees among the top 5 species for gully stabilization. In agreement with the experts' preference, several authors confirmed that *C. zizanioides* reduces soil erosion and siltation problems very effectively in the Tropics (Boonyanuphap, 2013; Amare *et al.,* 2014).

Both experts and communities score trees like *A. gummifera, Ac. abyssinica* and *S. guineense* as the top species for multipurpose use. Similarly, Hines & Eckman (1993) and Munishi *et al.* (2001) reported that the two species are nitrogen-fixing species suitable for intercropping with any other vegetation including crops, grasses, trees and shrubs and result in a fertile and sustainable mosaic farming system and offer multipurpose use for the end users.

The top species for riverbank stabilization selected by both communities and experts was *Sa. subserrata*. Likewise, several researchers reported that the species is a widely used plant to stabilize riverbanks all over the world (Gray & Sotir, 1996; Leden, 1996; Linderson *et al.,* 2007). Locally, *Sa. subserrata* is performing better than any other species along riverbanks under natural conditions although there is no purposeful plantation or management of the species so far. The root studies also revealed that this species possesses

Table III. The multi-criteria score given by communities and experts for gully and riverbank stabilization to the 40 prioritized plant species

	Family	Gully		Riverbank	
		Community	Experts	Community	Experts
Acacia abyssinica	***Fabaceae***	**0·674 (2)**	**0·588 (1)**	**0·678 (2)**	**0·595 (1)**
Agave sisalina	*Agavaceae*	0·48 (29)	0·376 (40)	0·482 (30)	0·385 (40)
Albizia gummifera	***Fabaceae***	**0·674 (3)**	**0·565 (2)**	**0·676 (3)**	**0·577 (2)**
Arundinaria alpina	*Poaceae*	0·553 (14)	0·496 (9)	0·557 (14)	0·524 (8)
Arundo donax	*Poaceae*	0·533 (20)	0·421 (31)	0·537 (19)	0·460 (20)
Carissa spinarum	*Apocynaceae*	0·597 (6)	0·447 (20)	0·601 (6)	0·451 (27)
Chrysopogon zizanioides	*Poaceae*	0·419 (40)	0·421 (32)	0·422 (40)	0·456 (22)
Cordia africana	***Boraginaceae***	**0·537 (17)**	**0·552 (3)**	**0·541 (17)**	**0·561 (3)**
Croton macrostachyus	*Euphorbiaceae*	0·464 (33)	0·430 (28)	0·466 (33)	0·446 (31)
Cynodon dactylon	*Poaceae*	0·555 (13)	0·399 (38)	0·560 (11)	0·428 (37)
Cyprus elegantulus	*Cyperaceae*	0·435 (38)	0·408 (35)	0·438 (39)	0·438 (34)
Enthada abyssinica	*Fabaceae*	0·580 (9)	0·432 (26)	0·584 (9)	0·452 (26)
Erythrina abyssinica	*Fabaceae*	0·582 (8)	0·489 (11)	0·586 (8)	0·494 (11)
Eucalyptus camaldulensis	*Myrtaceae*	0·555 (11)	0·441 (24)	0·558 (13)	0·438 (33)
Eucalyptus globulus	*Myrtaceae*	0·555 (12)	0·453 (19)	0·558 (12)	0·453 (25)
Euphorbia tirucalli	*Euphorbiaceae*	0·522 (22)	0·458 (18)	0·524 (22)	0·471 (18)
Ficus lutea	*Moraceae*	0·535 (18)	0·459 (17)	0·539 (18)	0·471 (17)
Ficus ovata	*Moraceae*	0·591 (7)	0·510 (7)	0·595 (7)	0·533 (6)
Ficus palmata	*Moraceae*	0·546 (15)	0·418 (33)	0·549 (15)	0·446 (32)
Ficus thonningii	*Moraceae*	0·562 (10)	0·427 (29)	0·566 (10)	0·450 (30)
Ficus vasta	***Moraceae***	**0·605 (4)**	**0·528 (5)**	**0·606 (5)**	**0·556 (5)**
Grevilea robusta	*Proteaceae*	0·493 (25)	0·486 (12)	0·497 (24)	0·487 (13)
Jatropha curcas	*Euphorbiaceae*	0·476 (31)	0·435 (25)	0·479 (31)	0·450 (29)
Leucaena leucocephala	*Fabaceae*	0·455 (37)	0·431 (27)	0·460 (37)	0·428 (36)
Maesa lanceolata	*Myrsinaceae*	0·459 (36)	0·397 (39)	0·462 (35)	0·426 (39)
Millettia ferruginea	*Fabaceae*	0·544 (16)	0·515 (6)	0·546 (16)	0·520 (9)
Musa domestica	*Musaceae*	0·492 (26)	0·461 (16)	0·497 (25)	0·475 (16)
Pennisetum macrourum	*Poaceae*	0·479 (30)	0·410 (34)	0·483 (29)	0·459 (21)
Pennisetum purpureum	*Poaceae*	0·462 (35)	0·472 (14)	0·462 (36)	0·493 (12)
Pennisetum clandestinum	*Poaceae*	0·523 (21)	0·402 (37)	0·527 (21)	0·427 (38)
Persea americana	*Lauraceae*	0·466 (32)	0·504 (8)	0·471 (32)	0·525 (7)
Rhus natalensis	*Anacardiaceae*	0·463 (34)	0·445 (22)	0·465 (34)	0·450 (28)
Sacharum officinarum	*Poaceae*	0·484 (28)	0·427 (30)	0·489 (28)	0·453 (24)
Salix subserrata	*Salicaceae*	0·515 (23)	0·463 (15)	0·517 (23)	0·480 (14)
Sapium ellipticum	*Euphorbiaceae*	0·534 (19)	0·447 (21)	0·537 (20)	0·454 (23)
Sesbania sesban	*Fabaceae*	0·434 (39)	0·474 (13)	0·439 (38)	0·476 (15)
Syzygium guineense	***Myrtaceae***	**0·688 (1)**	**0·543 (4)**	**0·690 (1)**	**0·557 (4)**
Trichocladus ellipticus	*Hamelidaceae*	0·492 (27)	0·402 (36)	0·492 (27)	0·435 (35)
Vernonia amygdalina	***Asteraceae***	**0·602 (5)**	**0·494 (10)**	**0·607 (4)**	**0·509 (10)**
Vernonia colorata	*Asteraceae*	0·494 (24)	0·443 (23)	0·496 (26)	0·467 (19)

Values in brackets are ranks corresponding to each species. The five highest scores in each column are given in bold.

Table IV. Measured mean values of root characteristics for nine studied plants

Species	RAR (n = 3–9)	*Tr* (MPa) (n = 30)	*Cr* (kPa) (n = 3–9)	Root density (kg m^{-3}) (n = 90)
	Mean ± SD			
Acacia abyssinica	$0·0059 \pm 0·0006^{a}$	$36 \pm 11·9^{b}$	250 ± 20^{a}	33 ± 5^{bc}
Albizia gummifera	$0·003 \pm 0·0003^{ab}$	$41 \pm 23·5^{b}$	117 ± 9^{bc}	38 ± 9^{abc}
Chrysopogon zizanioides	$0·003 \pm 0·0004^{ab}$	42 ± 17^{ab}	128 ± 28^{b}	$0·08 \pm 0·01^{e}$
Grevillea robusta	$0·004 \pm 0·0016^{b}$	$55 \pm 38·2^{a}$	141 ± 44^{b}	$38 \pm 9·6^{abc}$
Pennisetum macrourum	$0·002 \pm 0·001^{bc}$	$41 \pm 33·5^{ab}$	46 ± 15^{de}	$0·05 \pm 0·01^{e}$
Rhus natalensis	$0·001 \pm 0·0004^{bc}$	$34 \pm 18·3^{b}$	35 ± 16^{e}	$6·0 \pm 0·4^{e}$
Salix subserrata	$0·002 \pm 0·0007^{bc}$	$36 \pm 15·1^{b}$	99 ± 31^{bcd}	$11 \pm 0·6^{de}$
Syzygium guineense	$0·002 \pm 0·002^{b}$	$31 \pm 14·5^{b}$	63 ± 47^{cde}	$46 \pm 1·6^{ab}$
Trichocladus ellipticus	0·003 ± 0·0004b	$36 \pm 20·8^{b}$	102 ± 15^{bcd}	$3 \pm 0·6^{e}$

Different letters between species (within a column) indicate significant differences at a $p < 0.05$ level of significance.
RAR, root area ratio; *Tr*, root tensile strength; *Cr*, root cohesion; RD, root density.

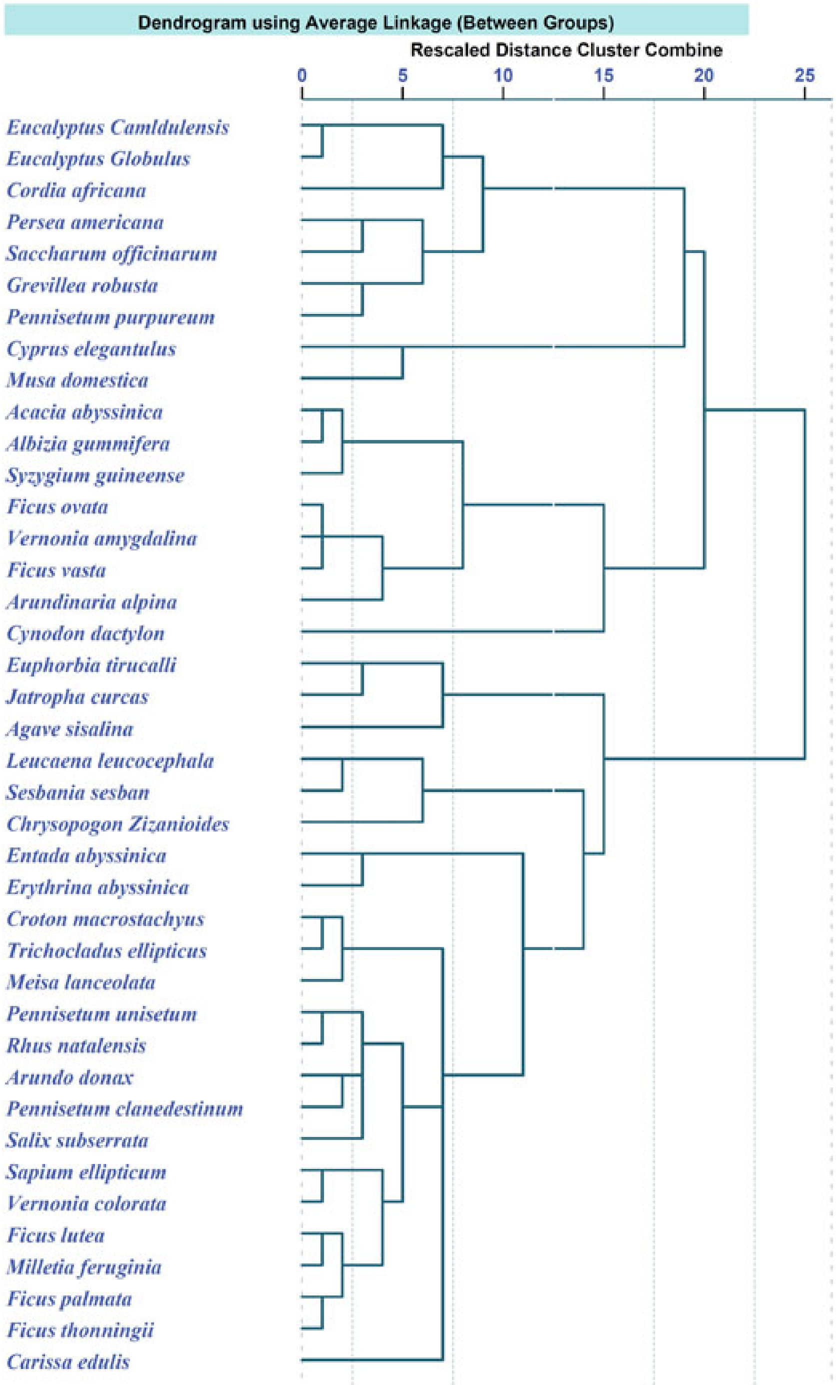

Figure 5. Hierarchical clustering of plant species using the six criteria groups (socio-economic function, sociocultural value, environmental service, general plant performance, local plant performance and biodiversity relevance), which were used in the multi-criteria tree selection spreadsheet by using the average of multi-criteria scores given by the local communities and experts. [Colour figure can be viewed at wileyonlinelibrary.com]

very thin and numerous roots with a horse tail-like thin roots, where each of the secondary and tertiary roots develops several smaller roots to anchor the alluvial soil near rivers (Figure 4a). This makes the species a very promising candidate for riverbank stabilization campaigns in the sub-humid tropics like Southwest Ethiopia.

Based on the hierarchical cluster analysis, the 40 species were clustered into eight groups at a rescaled clustered distance of 10 (Figure 5). The third cluster from the top, which contains *A. gummifera*, *Ac. abyssinica*, *F. ovata*, *F. vasta* and *C. africana*, includes the top species for multipurpose use with high relevance for environmental services, biodiversity conservation and regional and local plant performance. All these species are the most prominent, naturally occurring species in the region under negligible management by humans. Special conservation focus and priority have to be given for this group to utilize their multipurpose potential in the region.

Evidence from Root Characteristics Supporting the Multi-criteria Decision Analysis Results

The top 2 selected species for multipurpose use, *A. gummifera* and *Ac. abyssinica*, and the top grass selected by experts for gully stabilization, *C. zizanioides*, had high root cohesion value (Table IV), supporting the MCDA results. In agreement with this, *A. gummifera* is reported as one of the most preferred species by experts and local communities in various tropical areas for its multipurpose use and for its root characteristics (Hines & Eckman, 1993; Munishi *et al.,* 2001). The World Agroforestry Centre database (Orwa *et al.,* 2009) also documented that *A. gummifera* is a prominent tree in agroforestry systems of humid tropical environments. Similarly, *Ac. abyssinica* is listed as key multipurpose species in tropical environments because of its deep root system, exceptional coppicing ability, nitrogen fixation, fodder value for animals in time of drought and increasing soil fertility by easily decomposing litter fall among other criteria (Hines & Eckman, 1993; Sisay & Mekonnen, 2013).

However, a species prioritized for general multipurpose use may not perform successfully under field conditions to stabilize gullies and riverbanks. Hence, depending on the context, weights should be given to specific criteria. In cases where soil rehabilitation is extremely important, characteristics expressing their effectiveness should be prioritized above other multipurpose uses and vice versa. The use of a mixture of the prioritized species in guaranteeing success rate in survival and effectiveness while simultaneously creating opportunity for other uses and functions might be a better option to avoid the species selection dilemma.

Integrating the AHP, SMART, MCTS and field tests in the multi-criteria analysis gives a better understanding on the decision process. Certain fast growing and economically more attractive species may dominate the ecosystems because of less understanding or lack of consciousness about the long-term environmental benefits of the slow-growing multipurpose species. Comparing and contrasting different species for a specific purpose (AHP) procedure and for multipurpose use (SMART and AHP) are important to understand the value of each species and to make optimal decisions through continuous awareness creation, demonstrations, incentives, payment for environmental services, carbon trade and other similar options for communities. The excel-based MCTS tool helps to simplify the analysis process as the decision-making tool is freely available upon request from the authors (Reubens *et al.,* 2011).

Based on the findings, we recommend further study on the effectiveness and suitability of the prioritized species under field condition to clarify and support the multi-criteria analysis output. The MCDA technique of plant selection is recommended for different agro-ecological regions to compile indigenous knowledge and to integrate it with new scientific advancements related to land rehabilitation and the multipurpose use of vegetation. In addition, we recommend detailed investigation on the composition of the natural self-sustaining biodiversity along the undisturbed riverbanks as an additional scientific input to the multi-criteria-based study to restore severely degraded riverbanks and gullies.

CONCLUSIONS

The multi-criteria analysis on the relative importance of 40 plant species revealed that trees are selected as superior over shrubs and grasses for multipurpose use in Sub-humid Tropics, Southwest Ethiopia. Trees such as *A. gummifera*, *Ac. abyssinica* and *S. guineense* were the top-preferred species by experts and local communities for their multipurpose value. The root characteristics of these top 3 species also confirmed their promising root features to reinforce unstable slopes. Experts gave higher priority to grasses than to trees and shrubs for gully stabilization, whereas communities prefer trees for the same purpose. *Sa. subserrata* and *P. macrourum* were prioritized as the best for riverbank stabilization by experts and communities, but their multipurpose value is low compared with other species. *Eucalyptus* and *Grevillea* are less preferred by the experts based on multi-criteria analysis and highly preferred by communities for private plantation because of economic reasons. Hence, when multi-functionality is used as a guideline in species selection, it should also be evaluated to what extent the multiple functions can also effectively be used by the local communities in a context of efficiency and cost-effectiveness. The trade-off between direct economic benefit and multipurpose benefits could be solved by awareness creation, incentives to communities and policy re-enforcement.

ACKNOWLEDGEMENTS

We thank VLIR-UOS for financial support through the IUC-JU program. We are grateful to the agricultural experts in Jimma Agricultural Research Center and Jimma University, and local communities and district administrators of Kersa, Omonada, Tiroafeta and Dedo districts who participated in the focus group discussions and facilitated the data collection process. Finally, we would like to express our gratitude to Mr. Roc Padro Caminal who helped with the root characterization study and Ms. Jennifer Roelens for her help in improving quality of the images used in this paper.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web site:

Table S1. Example of the input sheet for species scores in the multictiteria tree selection tool (MCTS) for ten of the forty spcies and six of the 47 comparison criteria (Adapted from Reubens *et al.* 2011).

Table S2. Southwest Ethiopia plant species database that was used as the regional species pool for further screening on their potential for gully and riverbank stabilization in Gilgel Gibe catchment. T = tree, S = shrub, H = herb and G = grass. From the listed 130 species, the 40 most promising species (highlighted in bold) were selected and further prioritized. Source: Belachew *et al.* 2010; Aerts *et al.*, 2011; Own identification, Flora of Ethiopia, Addis Ababa University Herbarium).

Table S3. Database with information on multipurpose trees, shrubs and grasses in Southwest Ethiopia preselected for gully and riverbank stabilization based on scientific literature and local experience for the top fifteen prioritized species.

Table S4. Overview of the normalized values of the pairwise comparison table of AHP by taking only seven species as example. All of the 40 species of trees, shrubs and grasses were compared in a 40 × 40 comparison matrix. The scores were added per row and the rank was calculated for each species.

Method S1. Procedures used to quantify Root Density (RD), Root Area Ratio (RAR), Root Tensile Strength (Tr) and Soil cohesion due to roots (Cr).