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REGULAR ARTICLE

Establishment and management of woody seedlings in gullies in a semi-arid environment (Tigray, Ethiopia)

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Abstract In the north Ethiopian highlands, gully erosion is a significant land degradation process. Although the protective role of vegetation has been demonstrated in many studies, efforts previously made in using woody species for erosion control in the research area are limited, and when applied, survival of the planted seedlings was very low. Lack of experience and fundamental knowledge on species autecology and traits are two important bottlenecks. This study therefore aims at better understanding seedling establishment and growth in a context of tree plantings, with the view to further control gully erosion in a semi-arid environment. To this end survival, growth and development of seedlings of *Acacia etbaica* Schweinf., *Sesbania sesban* (L.) Merr. and *Dodonaea angustifolia* L.f. were monitored during 26 months in a field trial under different site conditions and treatments. The experiment was established at two sites characterized by topographic and edaphic conditions (Vertisol and sandy colluvium) representative for the study area. At each site, seedlings were subjected to different treatments of watering, sheltering and planting position (gully floor, sidewall and shoulder), and a large set of plant growth variables was regularly monitored. Height and biomass growth was fastest for *Sesbania*, even if affected by different pests. Regardless of the species, plants growing in the (nutrient-rich) Vertisol site had a higher survival rate and an overall better development. Shelter protection significantly increased survival and resulted in taller seedlings. Notwithstanding these general trends, treatment effects were often varying over time and strongly influenced by specific edaphic conditions. Generally, *Acacia* performed best on gully shoulder and wall, *Sesbania* on the gully floor and *Dodonaea* on shoulder positions. Recommendations for planting practice and follow-up research are discussed.

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Introduction

In the north Ethiopian highlands intense land degradation and deforestation have had and continue to have important effects on loss of topsoil by sheet, rill and gully erosion as well as on landsliding (Nyssen et al. 2004). Such processes result in an irreversible loss of soil fertility and constitute a severe threat for sustainable agriculture and forestry, especially in developing countries (Karambiri et al. 2003). Gully erosion is responsible for significant on-site soil losses, and once developed, gullies transfer runoff and sediment rapidly from uplands to lowlands and further down the drainage system, resulting in off-site consequences such as flooding and sediment deposition in river channels and reservoirs (Haregeweyn et al. 2008; Poesen et al. 2003).

There exists no such thing as a universally suited measure against gullying. To prevent gullying or to rehabilitate or stabilize an existing gully, it is important to first understand its principle causes and dynamics, and to take into account local soil and environmental conditions (Roose et al. 2000). The construction of physical structures such as dry masonry or gabion check dams is the most widely used gully control technique applied in northern Ethiopia. Nevertheless, these structures become less effective over time, and in some situations the check dams lead to piping in the gully sidewalls and concentrated flow bypassing the dam (Nyssen et al. 2004). Moreover, check dams often lead to increased gully bed erosion downstream because of a “clear water effect” (Boix-Fayos et al. 2007; Castillo et al. 2007). Correct design and construction, careful maintenance, and complementary techniques are therefore needed (Nyssen et al. 2004). In that context, biological measures complementing physical structures could result in sustainable and effective control.

The protective role of vegetation has long been recognized and proven: vegetation reduces water erosion by intercepting rainfall, increasing water infiltration, reducing runoff volume and velocity, and stabilizing the soil by roots (e.g. De Baets et al. 2006; Gyssels et al. 2005; Nilaweera and Nutalaya 1999; Reubens et al. 2007). Since different types of vegetation have different effects, depending for example on the depth, strength and density of their rooting system (Nilaweera and Nutalaya 1999; Reubens et al. 2007; Roose et al. 2000), a mixture of species to control a wide range of soil loss processes is generally most beneficial (Reubens et al. 2007). Trees in particular are useful in integrated, multipurpose management practices, as they generally perform a wide range of socio-economic, ecological and cultural functions. This versatility makes them highly appropriate for curbing land degradation in northern Ethiopia.

The most basic solution would be to fence or guard certain areas along gullies, allowing natural vegetation restoration. However, bottlenecks for natural regeneration in semi-arid areas like this are seed (dispersal) limitation, recruitment limitation (especially along gullies abiotic growth conditions are difficult) or a combination of these factors (Aerts et al. 2006; Jordano and Godoy 2002). To catalyze recovery and because of the general shortage of land as well as the huge need for valuable wood products in the study area (Nyssen et al. 2008; Taddese 2001), such a set-aside strategy should include managed planting of high value multipurpose woody species mixed with naturally regenerating vegetation.

At present, vegetative management of gully erosion is rarely implemented in northern Ethiopia since it requires a substantial effort and careful protective management that is not always realistic given the still very widespread free-grazing system (Taddese et al. 2002). Moreover, for many woody species detailed knowledge on species autecology (i.e. the relation and interactions with its environment) and functional traits is currently missing. In order to effectively implement vegetative measures, more fundamental knowledge and more experience are needed with regard to species suitability, bottlenecks impeding plant establishment, and suitability of treatments and growth conditions, especially in the critical initial growth stages. This study therefore aims at better understanding seedling establishment and growth in a context of tree plantings, with the view to further control gully erosion in a semi-arid environment. To this end we studied the survival, growth and development of three important multifunctional species (*Acacia etbaica* Schweinf, *Sesbania sesban* (L.) Merr. and *Dodonaea angustifolia* L.f.) under a set of representative site conditions and plant treatments, in order to a) assess species-specific seedling establishment and growth characteristics in a nutrient-rich and nutrient-poor situation; b) identify effects of specific treatments on seedling establishment and growth in both situations; c) understand changes of growth and effects through time; and d) assess type and magnitude of seedling growth bottlenecks. From those insights, we intend to provide some general principles, rules and recommendations for species management in the presented context, in order to define efficient planting practices for further erosion control.

Materials and methods

Study area

The study area (13°84′N, 39°81′E) is located in the Dogu'a Tembien *woreda* (district) in the Central Zone of the Tigray Regional National State, northern Ethiopia, ca. 50 km west of Mekelle (Fig. 1a). Elevations range between 2,200 m and 2,600 m above sea level, 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. 2004). The average yearly precipitation is 778 mm and the main rainy season (>80% of the yearly rainfall) lasts from mid-June to mid-September, preceded by a less predictable smaller rainy season between March and May. Average monthly temperatures range from 4–6°C minimum to 20–22°C maximum (Nyssen et al. 2008). Agriculture in Dogu'a Tembien consists exclusively of small-scale family farms. On average, the families in the study area use two or three parcels of cropland, with a combined area between 0.5 ha and 0.75 ha. Grassland, rangeland and exclosures (i.e. areas where natural vegetation is protected from the intrusion of humans or livestock; Aerts et al. 2009) are communally owned (Nyssen et al. 2008).

Species selection

Three woody species were carefully selected for experimentation, manageable within the project time, space and budget constraints. The initial selection of these species was based on a multi-criteria decision approach taking into account indicators of ecological suitability, socio-economical functions, protection functions and root characteristics. To enable such an approach, a comprehensive tree species database was developed for northern Ethiopia, based on scientific as well as local ecological knowledge, that provided information on species-related characteristics and that enabled assessment of the relative importance of selection criteria (Moeremans 2007). Given the context of usage for gully reclamation, the main criteria used were drought resistance as well as resistance to temporary water logging, fast above- and belowground development, socio-economic relevance, and local availability of seedlings.

The selected species have the following characteristics (based on Bekelle-Tesemma 1993; Dharani 2002; Fichtl and Admasu 1994; Maundu and Tengnäs 2005; Noad and Birnie 1989; Royal Botanic Gardens 2007; World Agroforestry Centre 2002):

1. *Acacia etbaica* Schweinf. [Tigrigna (local language): seraw; E: no common English name] is a monoecious tree or shrub, indigenous and very common in the research area. It is a leguminous, calciphyl and drought-resistant species, having re-sprouting characteristics and a good capacity to be used for recovering degraded land. *A. etbaica* is an important source of good firewood, providing also the pillars and beams to hold the heavy earthen roofs of houses in northern Ethiopia. Vegetative propagation is perfectly possible.
2. *Sesbania sesban* (L.) Merr. [Tigrigna: sesbania; E: River bean or Egyptian rattle pod] is an exotic but naturalized, very fast growing shrub and a prolific seeder, under natural conditions found along rivers or in moist or swampy sites. It tolerates dry eroded soil as well as seasonal or permanently waterlogged, saline, acidic and alkaline soil conditions. *S. sesban* is a nitrogen-fixing soil fertility improver, also having the ability to stabilize the soil with its deep taproot system. It is especially known for high-quality green manure and fodder, but also serves as a source of firewood and charcoal, as light construction wood or for making ropes. It is sensitive to several infections and diseases.
3. *Dodonaea angustifolia* L.f. [Tigrigna: tahses; E: Hop bush or Sand olive] is an indigenous tree or shrub growing in a variety of habitats from riverine forest to shallow, rocky soils or arid marginal areas.

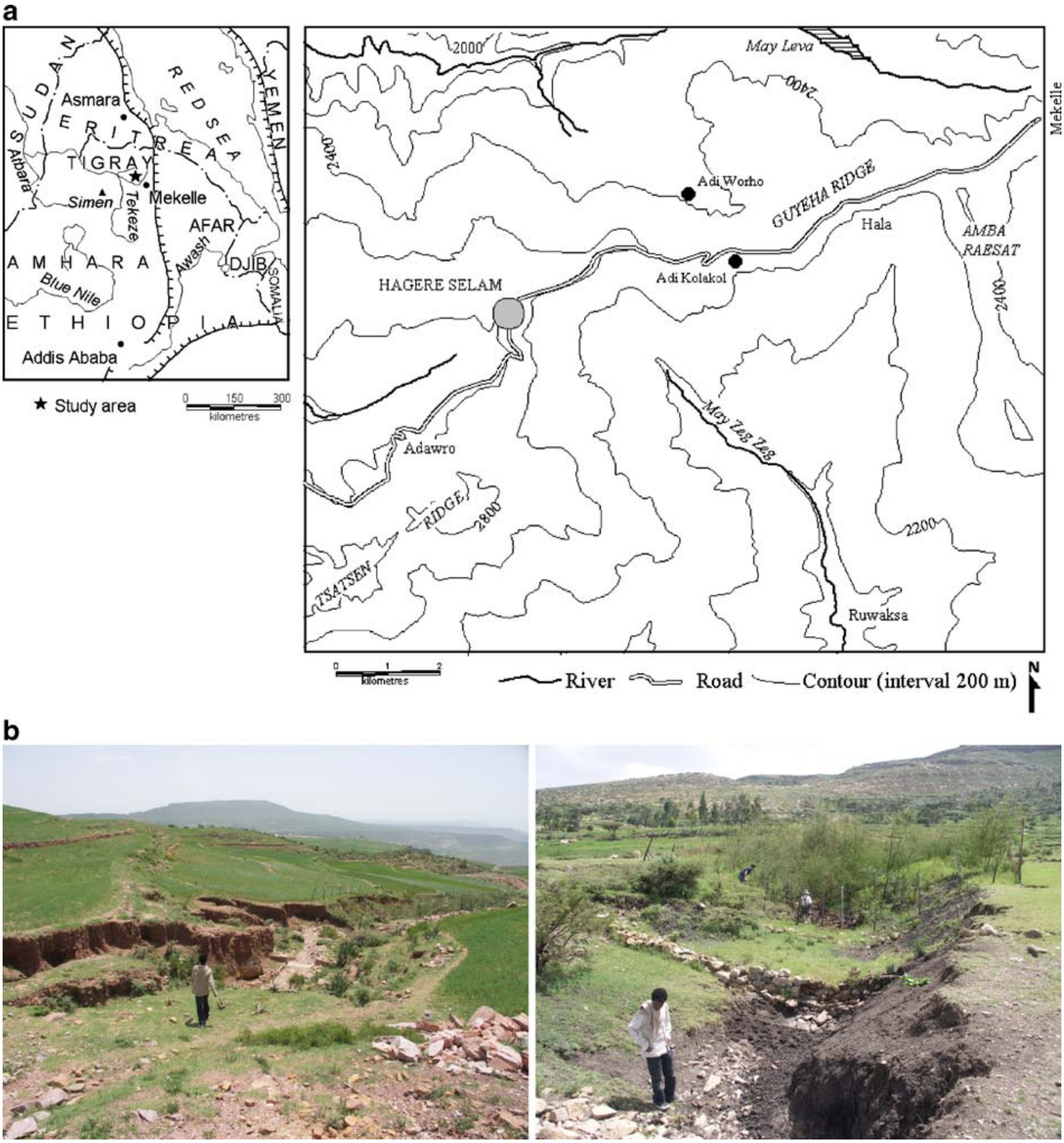

Fig. 1 Study area and experimental sites. **a** Map location of the study area. **b** Overview of both study sites comprising the fenced gully parts: *Left* = Adi Kolakol gully in sandy colluvium, *Right* = Adi Worho gully in Vertisol, with steep limestone cliff in the background

It grows and regenerates easily, and can be an aggressive colonizer. Nevertheless, it is an interesting, drought-resistant soil improver and a good hedge species for dry areas. Its extensive shallow root system makes it also useful for effective erosion control. Furthermore, *D. angustifolia* is an important bee plant, providing good quality firewood and charcoal as well as hard and heavy wood used for poles, timber, tool handles and walking sticks, and has wide-ranging medicinal uses.

Prior to transplanting to the field, all seedlings were raised at the Endayesus tree nursery (Mekelle University) in small polyethylene tubes (5.25 cm diameter, 15 cm deep) filled with a substrate of local black soil and sieved river sand mixed with organic material. The open bottom of the polyethylene tubes allowed undisturbed taproot growth and prevented the development of long lateral roots. In the field, seedlings were planted with the substrate attached to the roots but without the polyethylene tubes. At the time of transplanting, seedling age was 17 months, 3 months and 8 months for the *Acacia*, *Sesbania* and *Dodonaea* seedlings, respectively. Despite these relatively large differences in age, average length of all seedlings was ca. 20 cm at the time of transplanting, and taproot length did not exceed 17 cm. Measurements started in August 2006, and the results of the first 26 months (until October 2008), including three rainy seasons, are presented here.

Site selection and description

The experiments were conducted in two *kushets* (villages): Adi Kolakol and Adi Worho, further referred to as AK and AW respectively (see Fig. 1). Sites were selected in agreement with the local communities and with suitable gully dimensions and homogeneity in soil as well as environmental conditions as most important selection criteria (Table 1).

The site in AK comprises a gully developed in a soil consisting mainly of sandy colluvium (average thickness around 1.5 m) covering a Vertisol. This gully is situated downstream from a culvert of the Mekelle-Adwa road (Fig. 1a) and has been the subject of a road impact study (Nyssen et al. 2002). Absolute peak runoff discharge recorded during the observation period was 1.85 $m^3 s^{-1}$, corresponding to an absolute maximum water level of 50 cm in the gully floor. Initiated by the road culvert, this gully is still active. The gully side wall slope is relatively steep (± 60°) in the upper part, but gradually reduces towards the lower part of the site (Fig. 1b).

In AW, the site with a gully is located in a lower slope position. Peak runoff discharge recorded during the experiment was 1.90 $m^3 s^{-1}$, corresponding to an absolute maximum water level of 52 cm in the gully floor. This active gully is a well-developed channel, initiated in a Calcic Vertisol at the bottom of a steep limestone cliff. Expansion is partially caused by piping. The gully side-wall is sloping (35–60°) along its entire length (Fig. 1b). At both sites, prior overgrazing resulted in a degraded natural vegetation cover. No side-wall reshaping took place.

Experimental setup

Both field trial sites (each approximately 950 m²) were fenced to prevent destruction by grazing, browsing or trampling (see Fig. 1b). Within these sites, the tree seedlings were planted inside and on the shoulder (i.e. the soil surface bordering the gully channel) of the gully, following a systematic planting design (Fig. 2b). Four experimental treatment factors, expected to have an influence on seedling establishment and growth, were taken into account: (a) species (three levels); (b) watering (Water; two levels: low and high volume of manual watering during the dry season); (c) sheltering (Shelter; two levels: unsheltered seedlings versus seedlings individually protected by an open, ca. 35 cm high shelter of dry Giant reed [*Arundo donax* L.] stalks—see Fig. 3); and (d) gully position (Position; three levels: gully floor, gully sidewall, and gully shoulder). Sheltering resulted in an average illuminance reduction of 65%, as compared to unsheltered seedlings (measured with a photovoltaic luxmeter—data not shown). Watering volumes were determined through testing and feedback evaluation. At the onset of the experiment, seedlings of low and high watering treatment received 1 l and 4 l twice a week respectively. When initial survival was assured, these volumes were gradually reduced to 0 l and 1.5 l twice a week after 1 year. No water was provided during the main rainy season.

At each site, seedlings were planted in an organized way, repeated over six 'experimental plots' running across the gully channel (Fig. 2b). Every such plot consisted of 72 seedlings, equally distributed over the three species, the two shelter treatments and the three gully position treatments. Of the six experimental plots, three full plots received a high and three a low volume of water, which finally resulted in 12 replicates per species-treatment combination. The same setup was repeated at both sites.

Table 1 Summary of gully site characteristics

Variable	Adi Kolakol	Adi Worho	P-value
Environmental characterisation			
Altitude (m a.s.l.)	2425	2260	
Hillslope inclination (°)	17	8.5	
Hillslope aspect (−)	SE	NNE	
Catchment area (ha)	8.0	45.0	
Surrounding landuse (−)	rangeland & cropland	rangeland	
Yearly rainfall (mm year−1) (2006–2008)	630	800	
Average monthly min air temperature (°C) (2006–2008)	11.0	12.8	
Average monthly max air temperature (°C) (2006–2008)	24.6	29.4	
Peak flow discharge (m^3 s−1)	1.85	1.90	
Peak flow shear stress (Pa)	1434	754	
Soil characterisation (mean ± s.d.)			
Soil water content (g g−1) dry period	0.080±0.004	0.134±0.003	<0.001**
Soil water content (g g−1) wet period	0.159±0.005	0.236±0.005	<0.001**
Soil bulk density (g cm−3)	1.52±0.23	1.20±0.13	<0.001**
Clay (%)	32.37±2.15	41.89±2.15	0.007**
Silt (%)	26.46±1.34	38.55±1.34	<0.001**
Sand (%)	41.46±2.65	19.57±2.65	<0.001**
pH—H2O	6.84±0.53	7.21±0.11	0.049*
Pav (ppm)	1.46±0.59	1.99±1.38	0.376
CaCO3—equivalent (g/100 g)	2.18±1.72	17.73±4.59	<0.001**
ECw (μS·cm−1)	109.68±37.64	202.20±106.64	0.019*
CEC (cmolc/kg soil)	17.29±5.12	49.49±4.40	<0.001**
K (cmolc/kg soil)	0.44±0.10	0.83±0.15	<0.001**
Ca (cmolc/kg soil)	15.97±5.41	40.47±2.73	<0.001**
Mg (cmolc/kg soil)	1.21±0.34	9.75±3.64	<0.001**
Corg (g/100 g)	0.57±0.08	1.70±0.32	<0.001**
Ntot (g/100 g)	0.064±0.006	0.085±0.006	0.035*

Pav available phosphorus; *ECw* Electrical conductivity; *CEC* Cation Exchange capacity; *Corg* Organic carbon; *Ntot* total nitrogen
*$P<0.05$; **$P<0.01$

Evaluation methodology

Environmental and soil conditions

A broad set of soil and environmental variables was measured to characterize between-site and within-site heterogeneity.

Rainfall (using five rain gauges) and minimum and maximum air temperature (in two locally constructed, well-ventilated Stevenson shelters) were monitored on a daily basis throughout the duration of the experiment, following the methodology of Nyssen et al. (2005). In the rainy season, runoff discharge in the gullies at both sites was measured during every rainfall event. To this end, a rectangular masonry channel 2 m wide and 10 m long was shaped in the gully floor immediately upstream of the fenced sites. Repeated measurements of flood height and width, as well as mean flow velocity (by recording the travelling time of a floating object between the start and endpoint of the channel) allowed calculating instant discharge. At both sites slope gradient (with a clinometer), aspect (using a compass), gully morphology (e.g. local expansion, wall slope and orientation),

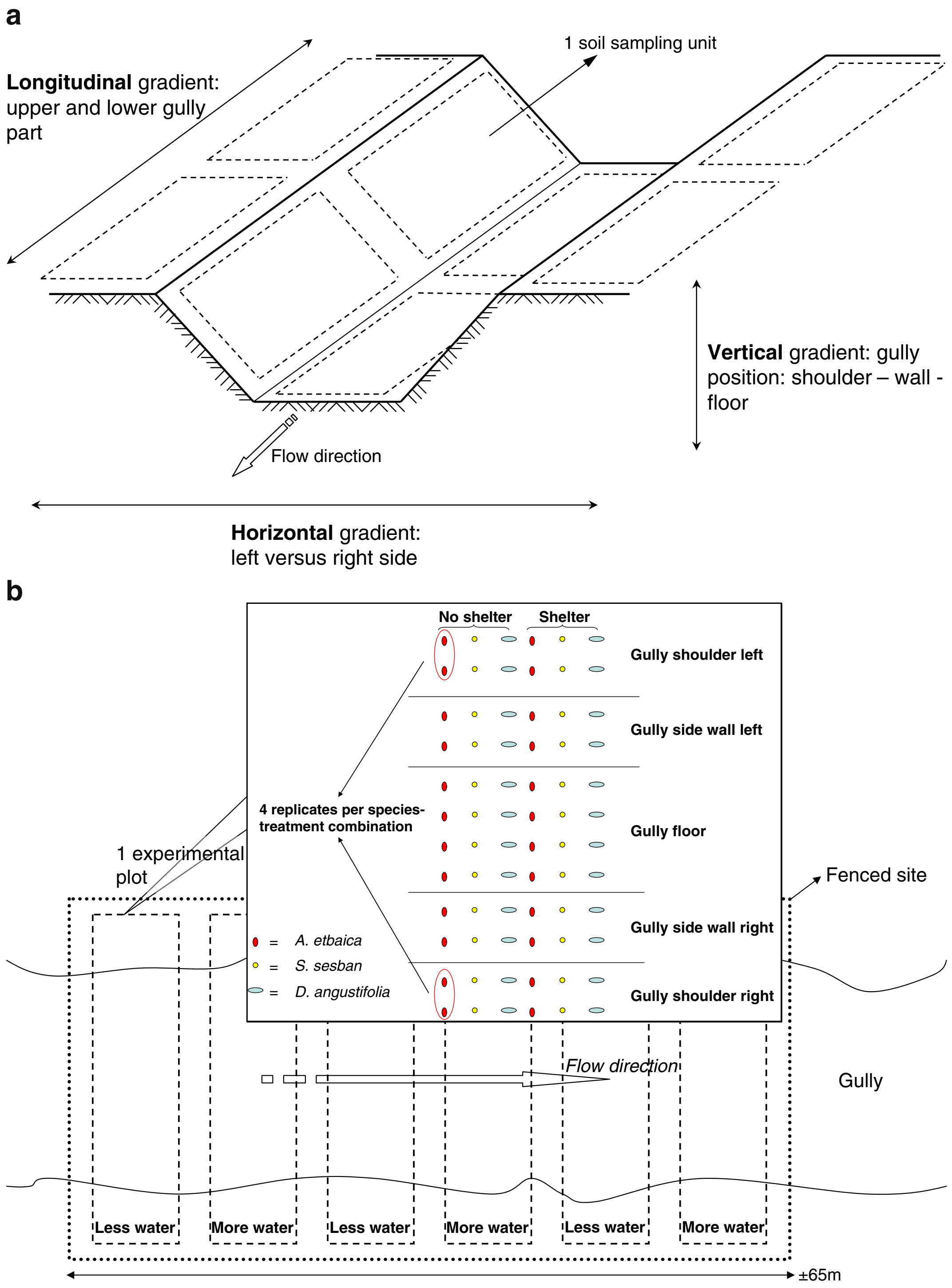

Fig. 2 Experimental setup at each gully. **a** location of ten soil sampling units, **b** treatment setup with six experimental plots

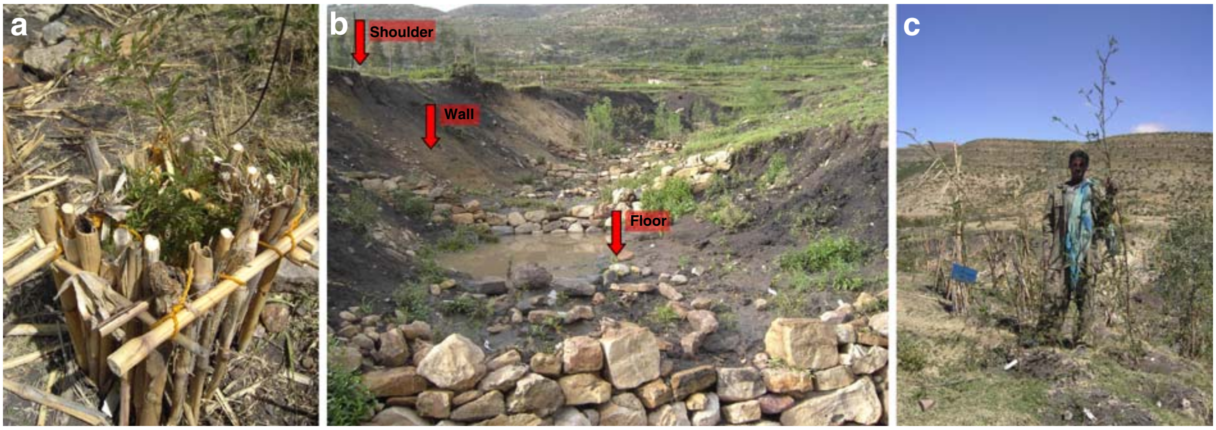

Fig. 3 Illustration of the experiment: **a** 8 month old *A. etbaica* seedling with shelter; **b** indication of gully positions in Adi Worho; **c** *S. sesban* seedling towering high above the others, 3 months after planting

land use (including grazing pressure and human disturbance) and upstream gully drainage area (mapped using a Trimble RTK 5800 GPS device) were measured. Two detailed soil profile descriptions were made at every site, followed by soil classification using World Reference Base (IUSS Working Group WRB 2006).

A more detailed sampling strategy was used to collect samples for soil physical and chemical analysis, with samples at two depth intervals (0–15 cm and 15–30 cm) collected on the gully shoulder, wall as well as floor positions, at both sides of the gully (left and right, facing down slope) and at two positions along the main gully axis, resulting in ten soil sampling units or a total of 20 samples per site (see Fig. 2a). These were used for the determination of available phosphorus (P_{av}) in a sodium hydrogen carbonate extract (Olsen's method), carbonate content ($CaCO_3$) (titrimetric), texture by dispersion, decantation and sedimentation, Cation Exchange Capacity (CEC) and exchangeable bases following the Silver-thiourea method, electrical conductivity (EC_w) and pH in a H_2O solution, and total carbon (C_{tot}) and nitrogen content (N_{tot}) with the Dumas combustion method using a Solid Carbon Analyser (Vario Max C/N apparatus—Elementar Analysensysteme GmbH, Germany). Organic carbon content (C_{org}) was calculated by subtracting the carbon present as $CaCO_3$ from the total carbon content. Kopecky cylinders were used to take samples for soil bulk density determination. Soil water content (SWC) was determined gravimetrically at least once per season, covering the soil sampling units defined above.

Non-destructive repeated measurements of seedling growth response

Seedling *survival* was assessed weekly. Both disappeared (eroded by the flood or covered by sediment) and visibly dead seedlings were considered as mortality. Plant growth was monitored by recording *length* (measured along the main plant axis), *base diameter* (D_{base}—assessed in two perpendicular directions using a digital calliper), number of stems (N. stems), *number of twigs* (N.twigs), *crown dimension* (crown—measured in two perpendicular directions and calculated as area of an ellipse), presence of *flowers* and presence of *fruit*. For a subset of ten leaves per plant, the *leaf dimensions* (leaf length and width) were measured as well.

These growth characteristics were initially evaluated on a monthly basis, then every 3–6 months, resulting in a total of nine evaluation moments during the course of the experiment (Fig. 4).

Destructive seedling measurements

With a 1 year interval (in October 2007 and October 2008), a limited number of destructive plant samples (each time 24 seedlings, i.e. four replicates per species per site) was collected. After measurement and removal of the aboveground part, roots were manually excavated. Subsequently, all plant material was divided into leaves, stem + branches and roots, which were first weighed fresh and then oven-dried for at least 24 h at 70°C to obtain dry mass. For a subset of these plants, fresh leaf size was assessed using a Leaf

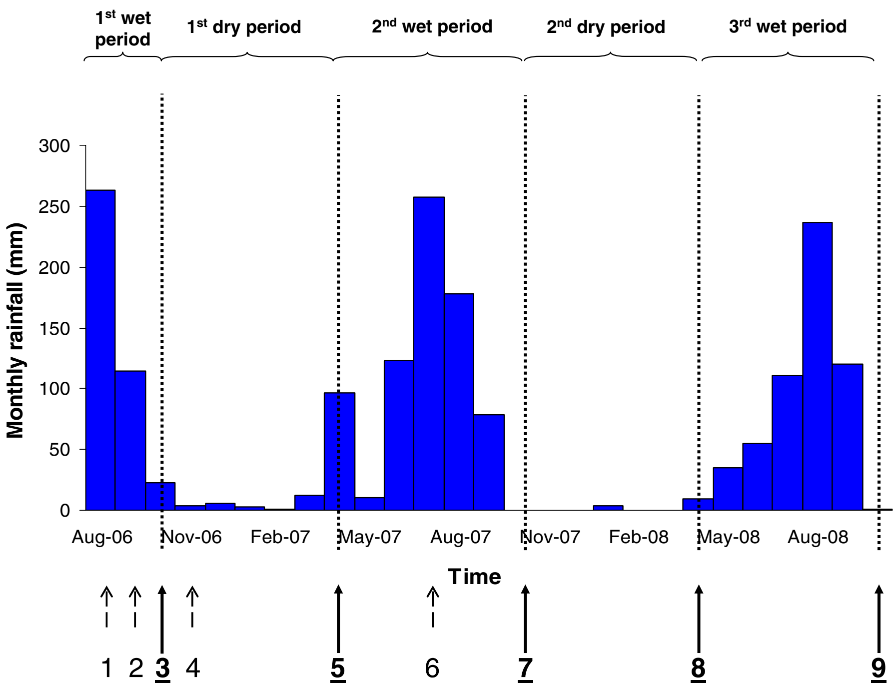

Fig. 4 Monitoring scheme in relation to dry and wet periods, with indication of monthly rainfall. *Bold* and *underlined* numbers indicate evaluation moments used for Repeated Measures Analysis

Area Meter (CI-202 Area Meter with Scanman head, logitech. CID, Inc.). Though not included in ANOVA-analyses due to the small number of replicates, these biomass and leaf area assessments were useful for calculation of derived plant growth characteristics.

Derived plant growth characteristics

A forward linear regression approach was used to derive species-specific allometric relations estimating average individual leaf area (A_L) and total above-ground biomass (BM) of all seedlings at all evaluation moments. The following regression formulas were finally most suited:

(a) for leaf area (A_L, cm²):

· *S. sesban*:	$A_L=0.410 \cdot L_L-23.565$	$R^2=0.90$; $P<0.001$, $N=10$
· *D. angustifolia*:	$A_L=0.006 \cdot L_L \cdot W_L$	$R^2=0.99$; $P<0.001$, $N=60$

with L_L=leaf length (mm) and W_L = leaf width (mm).

(b) for aboveground biomass (BM, g):

· *A. etbaica*:	$BM=0.664 \cdot D \cdot L-6.996$	for AK and	
	$BM=0.503 \cdot D \cdot L-6.996$	for AW	$R^2=0.95$, $P<0.001$, $N=12$.
· *S. sesban*:	$BM=3.532 \cdot (D^2 \cdot L)^{0.621}$	for AK and	
	$BM=3.532 \cdot (D^2 \cdot L)^{0.733}$	for AW	$R^2=0.98$, $P<0.001$, $N=12$.
· *D. angustifolia*:	$BM=0.409\ (D^2 \cdot L)^{0.980}$		$R^2=0.99$, $P<0.001$, $N=10$.

with $D = D_{base}$ (cm) and L = length (cm).

Absolute as well as relative growth rates for length (AGR_L, mm day^{-1} and RGR_L, mm cm^{-1} day^{-1}, respectively), D_{base} (AGR_D, µm day^{-1} and RGR_D, µm mm^{-1} day^{-1}) as well as biomass (AGR_W, g day^{-1} and RGR_W, g g^{-1} day^{-1}) were calculated for every period between two evaluation moments, with the following equations used in the classical approach (Grime and Hunt 1975):

$$AGRx = \frac{X2 - X1}{t2 - t1}$$

and

$$RGRx = \frac{\ln(X2) - \ln(X1)}{t2 - t1}$$

where X_1 and X_2 are the values of plant length, D_{base} or biomass at times t_1 and t_2.

Furthermore, the following seedling traits were assessed: root-shoot ratio (R:S; g g^{-1}); leaf, stem and root dry matter content (LDMC, SDMC, RDMC; dry mass per unit fresh leaf, stem or root mass; %); and leaf, stem and root mass fractions (LMF, SMF, RMF; dry leaf, stem or root mass per unit dry plant mass; g g^{-1}).

Statistical analyses

Analysis of variance (ANOVA) was used to assess effects of site and treatments on plant growth performance. Kolmogorov-Smirnov and Levene's tests were used to test normality and to check for homogeneity of variances, respectively. If required, variables were transformed.

For those plant variables repeatedly assessed throughout the course of the experiment, a Repeated Measures Analysis (RMA) was performed. This ANOVA procedure analyzes groups of related dependent variables that represent measurements of the same attribute at different times, by defining a within-subject factor (Time). The latter is assigned a number of factor levels corresponding to the number of evaluations taken into account for the studied attribute (maximum nine). In most cases, five fixed evaluations, each with an interval of 6 months between two subsequent evaluations, were selected. Although the main rainy season generally is concentrated between mid-June and mid-September (Nyssen et al. 2008), these 6-month intervals (October–April–October) more or less corresponded with a dominantly 'dry' or 'wet' period, enabling also differentiation of climate-related effects (see Fig. 4 for an overview). This procedure made it possible to assess overall trends and effects, as well as to elaborate upon changes or effects in any specific time period. Bonferroni's test was applied for post-hoc analysis.

Kaplan-Meier survival analysis was used to estimate plant survival rate, but also to assess rates of fruiting and flowering at each point in time, and treatment effects thereupon.

Environmental variables, soil physical and chemical characteristics as well as soil water content (further referred to as soil characteristics) were expected to be significantly different between both sites and therefore to play a major role in plant growth performance. In that perspective, both a Principal Components Analysis (PCA) (Kent and Coker 1996) and multivariate analysis of variance with soil characteristics as dependent variables were used to reveal spatial variability in soil conditions. In addition, given its dynamic nature, differences in SWC between both watering treatment levels were evaluated during the dry period.

Non-parametric statistics (Siegel and Castellan 1988) were used where needed.

Statistical analyses were performed using SPSS 15.0 (SPSS Inc., Chicago, IL) and PCord 4.0 (McCune and Mefford 1999).

Results

Species-specific plant traits, survival and growth

Although trends differed between both sites (see next paragraph), *Sesbania* had the lowest overall mortality (18%), whereas mortality of *Acacia* (30%) and *Dodonaea* (32%) were similar (Fig. 5). Mortality rate for *Dodonaea* was especially high in the first weeks after planting (August–September '06). Later, two more mortality peaks were experienced, during the summer rains of '07 and '08. On the other hand, except for a small mortality peak at the onset of the experiment, both *Sesbania* and *Acacia* remained relatively unaffected during the first year, but later experienced several moderate mortality peaks (see Fig. 5).

Tables 2 and 3 provide an overview of species-specific growth characteristics. Differences in growth between species were very pronounced, with *Sesbania* clearly being the fastest developing, as reflected in all plant growth characteristics. In the first 26 months, dry mass increased at an average rate of 118 g $month^{-1}$ for *Sesbania* as opposed to 1.2 g $month^{-1}$ and 3.1 g $month^{-1}$ for *Acacia* and *Dodonaea*, respectively (Table 2). Plant mass fraction values indicated how *Sesbania* invested relatively less in leaf biomass and more in aboveground woody biomass,

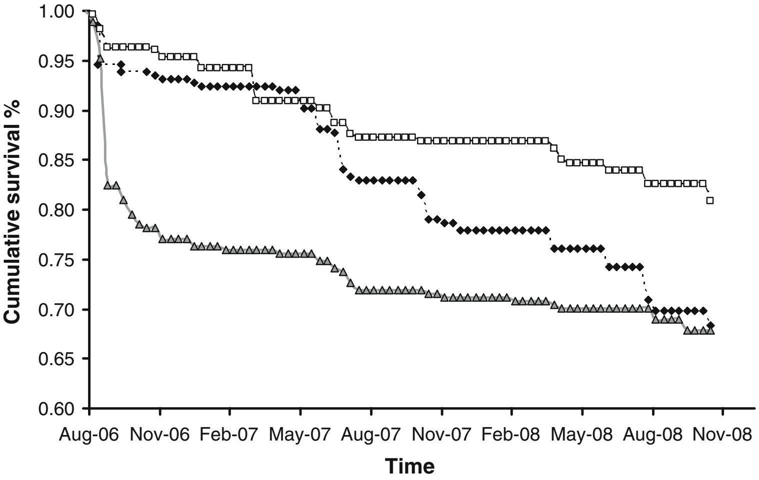

Fig. 5 Cumulative survival rate for the three species. *Black diamonds*: *A. etbaica*, *Grey triangles*: *D. angustifolia*, *White squares*: *S. sesban*

whereas *Acacia* invested most of its resources in root biomass.

The three species differed not only in growth, but also in speed of flowering, fruiting and regeneration, with *Sesbania* clearly being fastest and most prolific: within 2 months after planting 14% of all *Sesbania* seedlings in AW were flowering, followed soon by AK (28% after 3 months). Seedlings bore fruit for the first time after less than 8 months (87% in AW, 51% in AK). Soon, new seedlings spontaneously established in AW (not in AK), with more than 1,850 seedlings observed (average of two seedlings per m²) immediately after the rainy season of 2007 (data not shown). Nevertheless, only 25% of those new seedlings survived the 2nd dry period. For *Dodonaea*, it took until the 3rd wet period before significant numbers of seedlings were flowering or fruiting. For *Acacia* seedlings flowering or fruiting rarely took place within these first few years, with only a few observations in AW, first noticed during the 2nd rainy season.

In addition to the regularly measured plant characteristics, it was also observed how both *Acacia* and *Sesbania* seedlings were capable to re-sprout after being cut at the base. *Acacia* seedlings also re-sprouted after being completely buried by sediment deposits (2–10 cm) on the floor.

Finally, the three species differed also in the way they responded to the different treatments attributed.

Table 2 Relevant biomass characteristics (mean ± standard deviation over repeated measurements) with representation of the non-parametric test results indicating species differences

Variable (unit)	*Acacia*	*Sesbania*	*Dodonaea*	χ^2	P-value
RGRW (g g^{-1} day^{-1})	0.003±0.007^a	0.012±0.004^b	0.005±0.008^a	16.595	0.000**
AGRW (g month^{-1})	1.18±1.79^a	118.05±169.17^b	3.09±4.70^a	14.595	0.000**
LDMC (%)	49.67±9.86^a	47.52±16.86^{ab}	39.85±11.53^b	6.857	0.032*
SDMC (%)	54.25±8.98^a	48.74±8.04^b	57.69±6.35^a	14.171	0.001**
LMF (g g^{-1})	0.21±0.07	0.10±0.06	0.29±0.09	1.286	0.257
SMF (g g^{-1})	0.30±0.09	0.66±0.05	0.46±0.12	0.818	0.366
RMF (g g^{-1})	0.50±0.10	0.21±0.04	0.25±0.11	0.333	0.564

Values followed by a different character are significantly different from each other at a significance level of 0.05 with Wilcoxon–Mann–Whitney test

RGRW and AGRW relative and absolute growth rate biomass, respectively; *LDMC*, *SDMC* leaf or stem + branch dry matter content, defined as dry mass per unit fresh leaf or stem + branch mass, respectively; *LMF*, *SMF* and *RMF* leaf , stem + branch and root mass fraction, respectively, defined as dry mass per unit dry plant mass

*$P<0.05$; **$P<0.01$ (Kruskall-Wallis)

Table 3 Summary of relevant plant growth characteristics (mean ± standard deviation) for the three species, with representation of the ANOVA-test results indicating site effects

Variable (unit)	*Acacia*			*Sesbania*			*Dodonaea*		
	Adi Kolakol	Adi Worho	P-value	Adi Kolakol	Adi Worho	P-value	Adi Kolakol	Adi Worho	P-value
Length (cm)^a	46.34±2.99	63.76±3.07	<0.001**	197.55±11.08	353.27±9.79	<0.001**	59.53±4.84	126.17±4.42	<0.001**
Dbase (mm)^a	11.78±0.82	16.61±0.89	<0.001**	49.19±3.55	82.54±3.14	<0.001**	9.92±0.78	17.29±0.72	<0.001**
L/D (−)^a	55.61±1.78	62.46±1.92	0.903	72.29±2.77	76.61±1.92	0.605	80.29±1.94	90.63±1.78	<0.001**
N.twigs (−)^b	4.9±0.4	7.7±0.4	<0.001**	7.7±5.1	54.5±3.8	<0.001**	5.3±1.8	22.1±1.8	<0.001**
Crown (m^2)^a	0.20±0.03	0.27±0.03	<0.001**	3.46±1.42	12.05±1.01	<0.001**	0.12±0.05	0.58±0.05	<0.001**
AL (cm^2)^b	-	-	-	15.67±0.51	20.97±0.45	<0.001**	4.52±0.12	5.87±0.11	<0.001**
BM (g)^a	34.47±4.08	42.56±4.60	0.393	687±956	7342±643	<0.001**	31.84±15.04	183.04±15.59	<0.001**
RGRL (mm cm^{-1} day^{-1})^b	0.007±0.001	0.010±0.001	0.146	0.055±0.003	0.051±0.002	0.336	0.011±0.001	0.023±0.001	<0.001**
RGRD (μm mm^{-1} day^{-1})^b	0.900±0.128	1.714±0.442	<0.001**	5.555±0.217	5.588±0.166	0.903	2.174±0.156	2.943±0.145	<0.001**
RGRW (g g^{-1} day^{-1})^b	0.002±0.000	0.006±0.001	0.004**	0.011±0.000	0.012±0.000	0.066	0.005±0.000	0.008±0.000	<0.001**

Values followed by a different character are significantly different from each other at a significance level of 0.05 with Bonferroni's test

Length length of seedling, measured along the main plant axis; *Dbase* base diameter, measured in two perpendicular directions; *L/D* ratio of length and Dbase; *N.twigs* number of twigs; *Crown* crown dimension calculated as area of elips; *AL* average individual leaf area; *BM*: dry mass; *RGR*: relative growth rate

[a] mean & s.d. from last measurement (after 26 months)

[b] mean & s.d. average values over all repeated measurements

Further analyses were therefore performed separately per species.

Differences in site conditions and their effect on plant growth performance

The results of the PCA and manova (Table 1) revealed that almost all soil characteristics were significantly different between both sites, with a higher water and nutrient availability in the Vertisol area of AW when compared to the sandy colluvium in AK. PCA also revealed a clear clustering of soil units per site (Fig. 6). Variance could not be explained by a limited number of soil characteristics, but is determined by a wide set of (intercorrelated) variables including exchangeable bases, texture, stoniness, carbon content and SWC. Although SWC in AK is remarkably lower for seedlings under low (0.048± 0.010 g g^{-1}) than for those under high watering (0.093±0.013 g g^{-1}), this could not be proven statistically. In AW, no effect of watering treatment on SWC was observed. The significant site effect mentioned above (68% and 48% wetter in AW than in AK during dry and wet periods, respectively) appeared therefore to be relatively more determining than the effect of the watering treatment.

Seedling mortality rate after 26 months was 22.5% in AW and 30.9% in AK. In AK, mortality was significantly higher for *Dodonaea* (39%) than for *Acacia* (26%) and *Sesbania* (27%), whereas in AW, mortality was highest for *Acacia* (35%), followed by *Dodonaea* (25%), and with a remarkably lower mortality for *Sesbania* (9%). Despite these relatively small differences in mortality, differences in plant

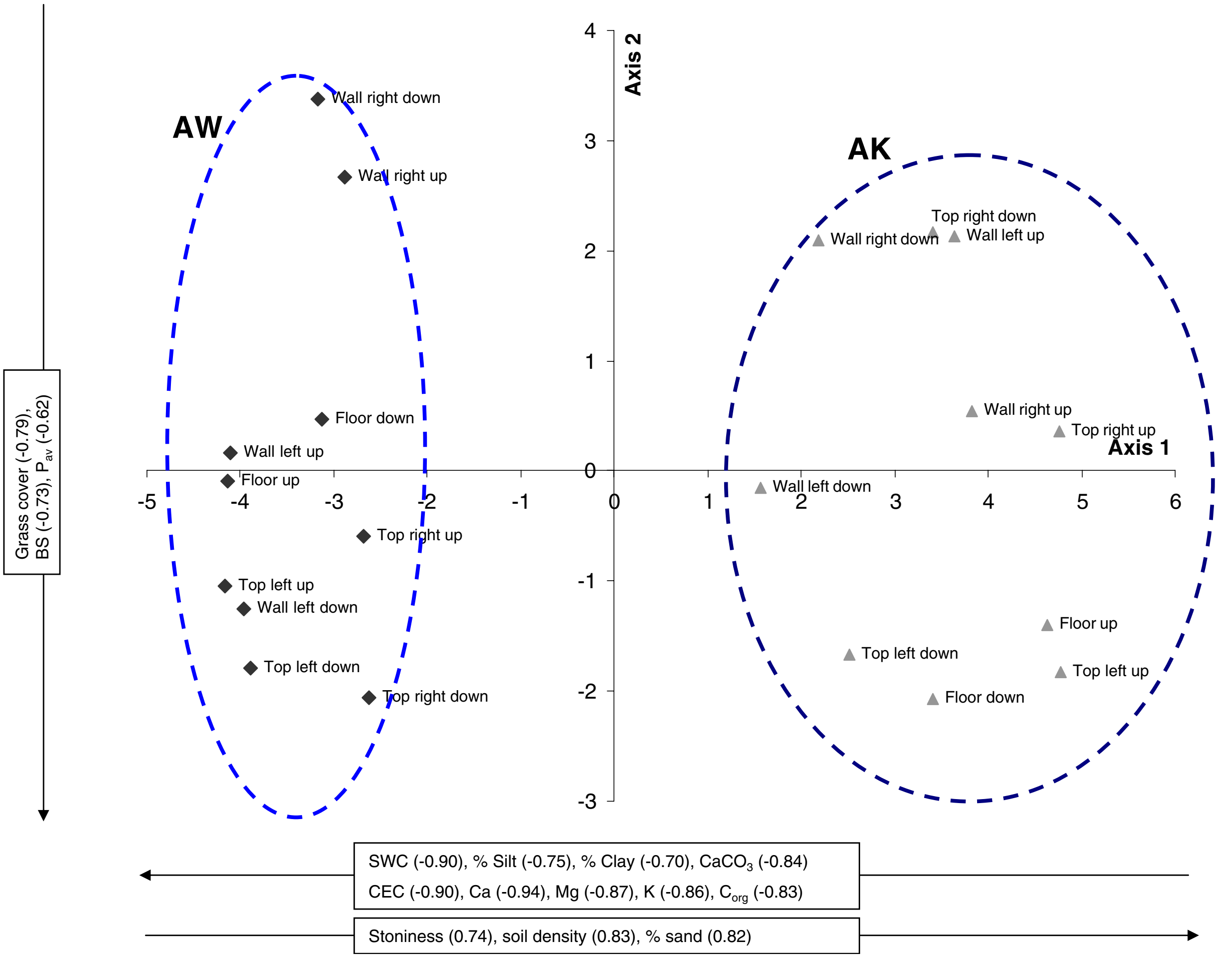

Fig. 6 PCA results based on soil characteristics. *Black diamonds*: sampling units in AW, *grey triangles*: sampling units in AK

growth performance between both sites were very pronounced for all species, with an overall significantly better performance in the Vertisol area of AW (Table 3 and Fig. 7). Presence of fruit and flowers was also significantly higher in AW than in AK for all species.

In Fig. 7, the bigger the differences in curve slope between the different treatment levels for a certain species are, the more important the considered treatment effect was in that specific time interval. Though depending on the species and plant characteristic considered, the main differentiation between both growth sites generally took place during the 1st year after planting, after which the established trend was either maintained or decreased gradually.

An exploratory multi-factor analysis including Site, Position, Shelter and Watering as factors (details not shown), revealed how Site not only determined the main differentiation in plant growth characteristics, but also frequently interacted with other treatments, especially with Position. This could explain why certain treatment effects were different for both sites. In the remainder of this article, evaluation of treatment effects is performed separately for each site.

Treatment effects on plant mortality and regeneration

At both sites, mortality for *Acacia* and *Dodonaea* was highest on the gully floor: of all dead *Acacia* seedlings, 72% (in AK) and 44% (in AW) were found on the floor. For *Dodonaea* this ratio reached 57% and 94%, in AK and AW respectively (data not shown). For *Sesbania* the same effect was only found in AW, where 75% of all mortality took place on the floor. Sheltering significantly increased the survival rate at both sites and in all gully positions. This effect was strongest for *Acacia* seedlings, for which 67% (in AK) and 79% (in AW) of all dead seedlings had no shelter. For *Dodonaea* a similar trend was observed, whereas *Sesbania* was not significantly affected. Watering treatment only affected *Sesbania* mortality in AK, with a significantly lower mortality for those seedlings receiving more water.

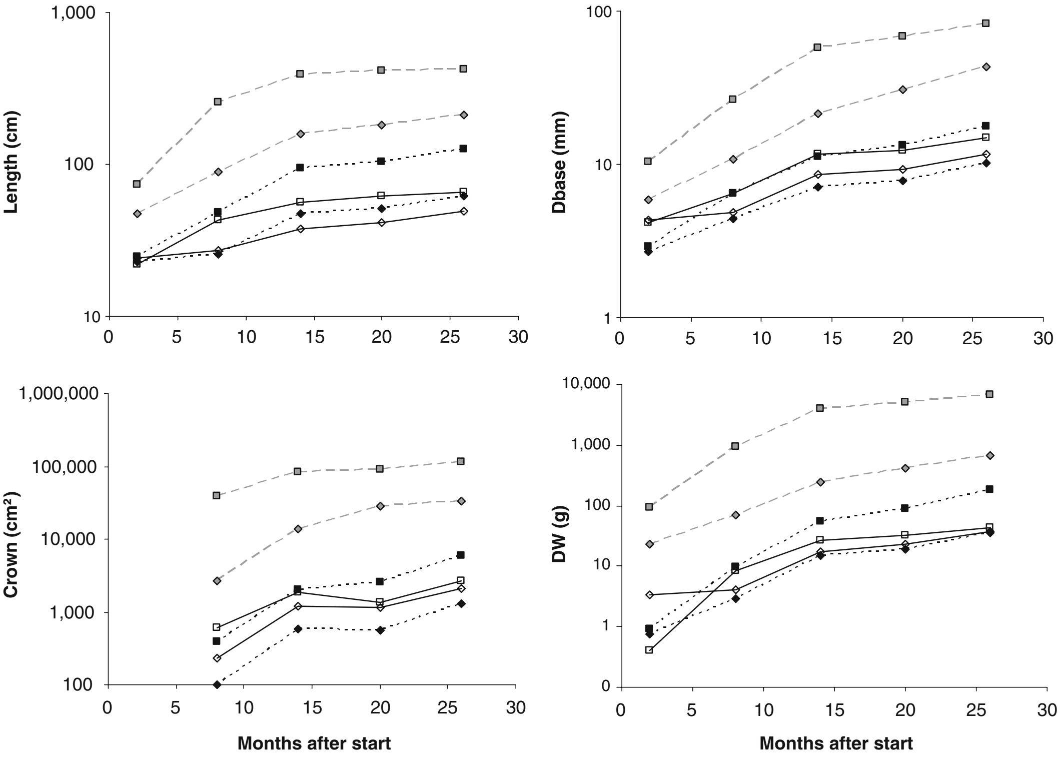

Fig. 7 Site effect on species performance through time. *White* symbols (*full line*): *A. etbaica*; *grey* symbols (*interrupted line*): *S. sesban*; *black* symbols (*dotted line*): *D. angustifolia*. *Diamonds*: Adi Kolakol; *squares*: Adi Worho

Sesbania seedlings on the floor bore significantly faster and more fruit than those on shoulder and wall positions. Sheltering also had a significant influence on flowering, with a slightly higher flowering incidence for unsheltered *Sesbania* seedlings as compared to sheltered ones. Even more, flowering time distribution was affected by sheltering, with unsheltered seedlings flowering faster (data not shown).

Time and treatment effects on plant growth

Generally, five time levels (3, 5, 7, 8 & 9; see Fig. 4) were taken into consideration for RMA procedures (output in Tables 4 and 5). Exceptions were the variables N.twigs and crown, as a result of measurement limitations at certain moments. Unless differently stated, mean and standard deviation values mentioned are those of the last evaluation (after 26 months), while P-values are average values over all measurement moments included in the RMA. Representative growth graphs indicating time and treatment effects are shown in Fig. 8.

Time effects

Time levels correspond with evaluation moments, being transitions from a dominantly wet to a dry period or vice versa (Fig. 4). For all species, nearly all growth variables were affected by the within-subject factor Time (Table 4), indicating a significant change. In most cases, within-subject contrasts (not shown) revealed that these changes took place between all Time levels, demonstrating a change that was not temporarily or interrupted, but rather constant. Nevertheless, changes did not necessarily take place at a continuous rate: in Figs. 7 and 8, different slopes between different evaluation moments indicate dissimilar rates of change. For variables such as length, D_{base}, BM and N.twigs, changes corresponded with an increase or growth, whereas average values of crown or individual leaf size often fluctuated, following an increasing trend during wetter and a decreasing one during dry periods. Absolute and relative growth rates for *Acacia* and *Dodonaea* were also characterized by such fluctuating behavior (with often higher rates during wet periods), although the main trend of all RGR's for the three species by and large was a gradual decrease through time.

Time effects significantly interacted with one or more between-subject factors (Position, Shelter and/or Watering) (Table 4), although within-subject contrasts (not shown) indicated that these Time × Factor interactions did not hold between all Time levels. Similarly, between-subject factor effects on growth variables were generally not significant between all Time levels. These observations indicate that changes over time were different dependent on the level of certain interacting factors taken into consideration, and/or that between-subject factor effects were time-dependent. For most plant characteristics, effects mentioned below were generally strongest during the 1^{st} dry season or at least during the 1st year after planting (Fig. 8).

Growth responses in Adi Kolakol

Gully position effects

Gully position affected plant characteristics of all species, with the exact responses being species-dependent. Both for *Acacia* and *Dodonaea*, seedling performance was best on the gully shoulder, as evidenced by a significantly affected Length, D_{base}, L/D, N.twigs and Crown for *Acacia*, and D_{base}, L/D, Crown, RGR_D and RGR_W for *Dodonaea*. For *Sesbania*, performance was least on the wall and more or less similar on shoulder or floor, depending on the plant characteristic considered.

Sheltering effects

Responses to sheltering were most pronounced for *Acacia*, with a significantly higher length, RGR_L and L/D, and a significantly lower D_{base}, RGR_D and N. twigs for sheltered seedlings. *Dodonaea* seedlings were affected in the same way, but only for length, RGR_L and L/D. *Sesbania* was least affected by sheltering, with only a slightly lower A_L and a higher length and RGR_L for sheltered seedlings.

Watering effects

The only statistically significant effect of the watering treatments was found for *Dodonaea*, which had a higher L/D for those seedlings receiving more water. Any other notable effect was absent, although Watering sometimes interacted with other factors.

Table 4 P-values demonstrating effects of position, shelter, watering and time on plant growth variables at both study sites

A. Adi Kolakol

Acacia etbaica

Source of variation	Length	Dbase	L/D	N.twigs	Crown	BM	RGRL	RGRD	RGRW
Within-subject effects									
Time	**<0.001**	0.065	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Time × Position	**0.036**	0.126	0.511	0.147	**0.006**	0.963	**0.004**	0.339	0.570
Time × Shelter	**<0.001**	**<0.001**	**<0.001**	**0.036**	**0.001**	0.443	**0.033**	0.685	0.990
Time × Watering	0.595	0.076	0.499	**0.001**	0.132	0.215	0.546	0.143	0.589
Between subject effects									
Position	**0.017**	**0.001**	**0.233**	**0.010**	**0.001**	0.499	0.575	0.190	0.516
Shelter	**0.032**	**<0.001**	**<0.001**	**0.005**	0.283	0.343	**0.003**	**0.033**	0.530
Watering	0.908	0.079	0.086	0.522	0.170	0.665	0.556	0.286	0.459
Position × Shelter	0.098	0.066	0.225	0.055	**0.016**	0.790	0.829	0.180	0.784
Position × Watering	0.163	0.502	0.556	**0.022**	**0.007**	0.094	**0.044**	0.447	0.060
Shelter × Watering	0.515	0.363	0.908	0.494	0.720	0.439	**0.021**	**0.043**	0.669

Sesbania sesban

	Length	**Dbase**	**L/D**	**N.twigs**	**Crown**	**LA**	**BM**	**RGRL**	**RGRD**	**RGRW**
Within-subject effects										
Time	0.974	0.711	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Time × Position	0.342	**0.002**	0.599	**0.013**	**0.004**	0.067	**0.007**	0.155	0.528	0.738
Time × Shelter	**<0.001**	0.842	0.153	0.079	**0.001**	0.054	**0.002**	0.257	0.430	0.294
Time × Watering	0.178	0.442	0.545	0.859	0.102	0.345	0.785	0.510	0.353	0.608
Between subject effects										
Position	0.465	**0.008**	**0.023**	0.077	**0.014**	0.308	0.322	0.134	**0.021**	**0.016**
Shelter	0.241	0.636	**0.030**	0.098	0.831	**0.003**	0.244	**0.002**	0.153	**0.018**
Watering	0.886	0.414	0.092	0.530	0.410	0.547	0.168	0.210	0.830	0.687
Position × Shelter	0.703	0.661	0.735	0.882	0.968	0.805	0.167	0.172	0.575	0.588
Position × Watering	0.202	0.710	0.219	0.852	0.298	0.448	0.274	**0.011**	0.087	0.053
Shelter × Watering	0.165	0.648	0.154	0.986	0.623	0.712	**0.020**	0.443	0.985	0.693

Dodonaea angustifolia

	Length	**Dbase**	**L/D**	**N.twigs**	**Crown**	**LA**	**BM**	**RGRL**	**RGRD**	**RGRW**
Within-subject effects										
Time	**0.018**	**0.002**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Time × Position	0.360	0.144	0.088	0.107	0.293	0.572	0.508	0.538	0.668	0.587
Time × Shelter	**<0.001**	0.759	**<0.001**	0.432	**0.036**	**0.003**	0.699	**0.040**	0.533	0.858
Time × Watering	0.895	0.382	0.171	0.097	0.054	**<0.001**	0.550	0.858	0.345	0.603
Between subject effects										
Position	0.374	**0.001**	**0.018**	**0.044**	0.082	0.761	**0.003**	0.179	0.544	0.866
Shelter	**0.039**	0.146	**<0.001**	0.535	0.335	0.905	0.727	**<0.001**	0.432	0.374
Watering	0.969	0.178	**0.040**	0.698	0.984	0.800	0.436	0.964	0.219	0.291
Position × Shelter	0.487	0.708	0.222	0.664	0.476	0.490	0.589	0.099	0.874	0.585
Position × Watering	**0.047**	0.429	**0.038**	0.370	0.231	0.243	0.478	**0.001**	0.401	0.068
Shelter × Watering	0.751	0.312	**0.005**	0.807	0.914	0.769	0.578	0.174	0.966	0.757

Table 4 (continued)

Source of variation	Length	Dbase	L/D	N.twigs	Crown	BM	RGRL	RGRD	RGRW
B. Adi Worho									
Acacia etbaica									
Within-subject effects									
Time	0.171	**0.001**	**<0.001**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**<0.001**	**0.003**
Time × Position	**0.004**	**0.020**	**0.008**	0.366	0.302	0.457	**0.033**	0.849	0.999
Time × Shelter	**0.005**	**<0.001**	**<0.001**	0.064	0.281	0.945	**<0.001**	**0.036**	0.548
Time × Watering	0.458	0.624	0.217	0.275	0.760	0.533	0.414	0.826	0.097
Between subject effects									
Position	**0.010**	0.111	**0.013**	0.216	**0.053**	**0.002**	**0.019**	**0.031**	0.382
Shelter	0.590	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.490	0.973	**<0.001**	0.091
Watering	0.276	0.811	0.471	0.611	0.371	0.535	0.242	0.217	0.077
Position × Shelter	0.574	0.310	0.253	0.487	**0.465**	0.254	0.849	0.775	0.655
Position × Watering	0.946	0.230	0.916	0.273	**0.687**	0.438	0.559	0.336	0.318
Shelter × Watering	0.166	0.606	0.947	0.904	0.368	0.577	0.277	0.391	0.631

Sesbania sesban

	Length	**Dbase**	**L/D**	**N.twigs**	**Crown**	**LA**	**BM**	**RGRL**	**RGRD**	**RGRW**
Within-subject effects										
Time	**<0.001**	**0.016**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Time × Position	**<0.001**	**<0.001**	0.232	**<0.001**	**<0.001**	0.027	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Time × Shelter	0.759	0.600	0.021	0.050	0.570	**<0.001**	0.591	0.056	0.078	0.230
Time × Watering	0.886	0.422	0.862	0.245	0.083	**0.033**	0.847	0.288	0.732	0.490
Between subject effects										
Position	**<0.001**	**<0.001**	**0.038**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**0.001**	**<0.001**	**<0.001**
Shelter	0.275	0.887	**0.017**	0.274	0.935	**0.001**	0.960	0.183	0.253	0.878
Watering	0.999	0.405	0.584	0.694	0.475	**0.006**	0.871	0.801	0.649	0.923
Position × Shelter	0.411	0.987	0.070	0.785	0.349	0.761	0.793	0.282	0.722	0.359
Position × Watering	0.154	0.635	0.081	0.569	0.239	0.080	0.593	0.208	0.637	0.923
Shelter × Watering	0.559	0.866	0.894	0.887	0.236	0.342	0.495	0.208	0.940	0.736

Dodonaea angustifolia

	Length	**Dbase**	**L/D**	**N.twigs**	**Crown**	**LA**	**BM**	**RGRL**	**RGRD**	**RGRW**
Within-subject effects										
Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Time × Position	**<0.001**	**0.011**	**<0.001**	0.246	**0.023**	0.586	0.090	0.118	0.145	0.784
Time × Shelter	0.249	**0.001**	**<0.001**	0.198	0.115	0.682	0.393	0.050	0.056	0.140
Time × Watering	0.298	0.813	0.336	0.705	0.293	0.384	0.988	0.293	0.941	0.969
Between subject effects										
Position	**0.006**	0.083	**0.001**	0.296	**0.031**	0.840	0.260	**<0.001**	0.243	0.071
Shelter	0.180	**0.001**	**<0.001**	0.121	0.936	0.522	0.159	0.113	0.362	0.928
Watering	0.860	0.188	0.525	0.667	0.683	**0.018**	0.381	0.461	0.991	0.811
Position × Shelter	0.643	0.491	0.431	0.707	0.585	0.872	0.876	0.141	0.648	0.574
Position × Watering	0.351	0.113	0.542	0.726	0.379	0.059	0.280	0.128	0.045	0.111
Shelter × Watering	**0.010**	0.061	0.442	0.093	**0.034**	**0.016**	**0.029**	0.051	0.191	0.116

Results were analysed using GLM repeated measures and univariate anova. Bold: $p<0.05$

Table 5 Summary of relevant plant growth characteristics (mean ± standard deviation) for both sites, represented per factor level for the three species

A. Adi Kolakol											
Gully position effects	***Acacia***				***Sesbania***				***Dodonaea***		
Variable (unit)	**Shoulder**	**Wall**	**Floor**		**Shoulder**	**Wall**	**Floor**		**Shoulder**	**Wall**	**Floor**
Length (cm)^{a}	52.54±3.30a	45.31±3.33ab	42.28±5.18b		225.66±21.68	169.20±25.01	247.38±31.55		62.27±4.11	59.16±4.44	57.40±7.72
Dbase (mm)^{a}	14.28±0.94a	10.53±0.95b	10.51±1.47b		45.13±6.41ab	27.71±7.40a	63.44±9.34b		11.68±0.79a	8.57±0.84b	9.49±1.48ab
Crown (m^{2})^{a}	0.32±0.04a	0.19±0.03a	0.08±0.06b		3.26±0.86a	1.80±0.99b	4.98±1.23ab		0.15±0.03	0.12±0.03	0.09±0.05
AL (cm^{2})^{b}	-	-	-		16.29±0.71	14.81±0.82	16.54±1.02		4.57±0.17	4.40±0.17	4.55±0.29
BM (g)^{a}	51±6	27±6	24±9		652±156	492±198	1109±213		45±8a	25±9b	25±15ab
RRW (g g^{-1} day^{-1})^{b}	0.003±0.000	0.002±0.000	0.003±0.001		0.004±0.000ab	0.004±0.000a	0.005±0.000b		0.005±0.000	0.004±0.000	0.004±0.001
Shelter effects	***Acacia***			***Sesbania***			***Dodonaea***				
Variable (unit)	**shelter**	**no shelter**		**shelter**	**no shelter**		**shelter**	**no shelter**			
Length (cm)^{a}	51.81±2.85	41.61±3.68		234.88±22.70	193.28±20.35		68.34±3.76	50.88±5.35			
Dbase (mm)^{a}	8.93±0.81	14.61±1.05		42.44±6.72	48.41±6.02		9.37±0.72	10.46±1.03			
Crown (m^{2})^{a}	0.17±0.03	0.22±0.04		3.64±0.90	3.06±0.79		0.12±0.03	0.12±0.02			
AL (cm^{2})^{b}	-	-		17.45±0.75	14.31±0.66		4.49±0.14	4.52±0.21			
BM (g)^{a}	28±5	39±6		827±169	676±140		32±7	31±10			
RGRW (g g^{-1} day^{-1})^{b}	0.003±0.000	0.003±0.000		0.004±0.000a	0.005±0.000b		0.004±0.000	0.005±0.000			
B. Adi Worho											
Gully position effects	***Acacia***				***Sesbania***				***Dodonaea***		
Variable (unit)	**Shoulder**	**Wall**	**Floor**		**Shoulder**	**Wall**	**Floor**		**Shoulder**	**Wall**	**Floor**
Length (cm)^{a}	51.82±7.42a	81.10±6.58b	60.66±7.46ab		299.08±27.47a	441.45±26.06b	540.90±29.32b		104.81±6.75a	144.97±6.62b	132.91±13.28ab
Dbase (mm)^{a}	16.57±1.87	19.94±1.64	12.80±1.86		55.11±10.07a	77.92±11.57b	124.11±11.57c		17.45±1.02	19.90±0.98	13.85±2.00
Crown (m^{2})^{a}	0.23±0.06	0.39±0.06	0.19±0.06		5.14±2.10a	10.80±2.05b	20.22±2.31c		0.39±0.08a	0.81±0.08b	0.54±0.15ab
AL (cm^{2})^{b}	-	-	-		18.76±0.65a	22.23±0.63b	21.73±0.71b		5.77±0.18	5.90±0.17	5.92±0.33
BM (g)^{a}	38±8a	66±7b	34±8b		3357±1325a	6710±1257b	11961±1568b		140±22	257±22	145±45
RGRW (g g^{-1} day^{-1})^{b}	0.005±0.001	0.004±0.001	0.002±0.001		0.005±0.000a	0.006±0.000b	0.007±0.000c		0.006±0.000	0.007±0.000	0.006±0.001
Shelter effects	***Acacia***			***Sesbania***			***Dodonaea***				
Variable (unit)	**shelter**	**no shelter**		**shelter**	**no shelter**		**shelter**	**no shelter**			
Length (cm)^{a}	65.62±4.61	63.44±6.88		440.63±21.97	413.46±23.16		132.09±6.68	123.04±8.57			
Dbase (mm)^{a}	11.67±1.15	21.21±1.72		483.89±8.59	87.54±8.59		14.54±1.00	19.54±1.29			
Crown (m^{2})^{a}	0.21±0.04	0.33±0.06		11.72±1.73	12.39±1.79		0.53±0.07	0.63±0.10			
AL (cm^{2})^{b}	-	-		19.52±0.55	22.29±0.53		5.95±0.16	5.77±0.22			
BM (g)^{a}	36±5	57±8		6950±1117	7735±1152		134±24	228±28			
RGRW (g g^{-1} day^{-1})^{b}	0.005±0.001	0.003±0.001		0.006±0.000	0.006±0.000		0.007±0.000	0.007±0.000			

Values followed by a different character are significantly different from each other at a significance level of 0.05 with Bonferroni's test

Length length of seedling, measured along the main plant axis; *Dbase* base diameter, measured in two perpendicular directions; *Crown* crown dimension calculated as area of elips; *AL* average individual leaf area; *BM* dry mass; *RGRw* relative growth rate dry mass

[a] mean & s.d. from last measurement (after 26 months)

[b] mean & s.d. average values over all repeated measurements

Growth responses in Adi Worho

Gully position effects

As in AK, responses to gully position were species-dependent. For all species, growth was generally least on the gully shoulder. This was most evident for *Sesbania*, with virtually all growth characteristics affected and best performance on the gully floor. Performance of both *Acacia* and *Dodonaea* was best on the wall.

Sheltering effects

For all species, responses to sheltering were very similar to those observed in AK. Again effects were most pronounced for *Acacia*, with a significantly higher L/D and a significantly lower D_{base}, RGR_D, N. twigs and crown for sheltered seedlings. For *Dodonaea* seedlings, a significantly higher L/D and a significantly lower D_{base} were observed, whereas *Sesbania* was least affected, with only a slightly lower A_L and a higher L/D for sheltered seedlings.

Watering effects

The only plant characteristic significantly affected by the watering treatments was A_L, which for both *Sesbania* and *Dodonaea* was significantly higher for those seedlings receiving less water.

For more details we refer to Tables 4 and 5, and to Fig. 8.

Discussion

Trends in plant survival and growth

Post-planting stress together with flooding during the first month after planting resulted in an initial mortality peak for all species, most evidently for *Dodonaea* (Fig. 5). For *Acacia* and *Dodonaea*, such a mortality peak caused by flooding returned every rainy season, although with a gradually reduced impact. In addition, more irregular intermediate peaks were observed, which could be interpreted in different ways. Drought stress might have played a role here, certainly for *Sesbania* seedlings. As a result of its fast growth and the relatively small within-plot planting distance, part of *Sesbania* mortality might also have been the result of self-thinning (2nd degree competition). *Sesbania* also appeared to be susceptible to different pests, reducing vitality. Several as yet unidentified types of scale insects (*Coccoidea*) and caterpillars (*Lepidoptera*) were frequently noticed on the branches. Later, rodents (rats, rabbits or squirrels) also ate its bark. Although probably reducing growth and vitality, this did not frequently result in mortality. Besides *Sesbania*, in AW at least 25 *Acacia* seedlings suffered seriously from being uprooted at night by unidentified rodents (as observed by the guards), making uprooting the highest cause of mortality of *Acacia* in AW.

Results demonstrated some pronounced differences in plant growth and biomass allocation between the studied species. However, differences in biomass allocation could not be proven statistically, due to the low number of destructive replicates. Moreover, root biomass was probably underestimated for the extended root network of *Sesbania* seedlings.

While difficult to generalize, two main trends of time differentiation in growth and effects can be distinguished. First of all, especially for *Acacia* and *Sesbania*, between-subject factor effects were usually strongest in the 1st year after planting, during which growth was generally high. Secondly, especially for *Acacia* and *Dodonaea*, plant growth and development appeared to be higher during wet rather than during dry periods, a commonly observed tree growth trend in African (semi-)arid areas (Broadhead et al. 2003). This indicates that between-subject factor effects depended for example on the growth development stage or specific weather conditions. It was furthermore observed that RGR declined as plants grew, in accordance with previous observations (Turnbull et al. 2008).

Originally, the shelter treatment was designed to reduce overexposure to sunlight. However, it quickly became clear that sheltering had several other protective advantages, such as the capture of rough plant material (branches, grass) transported by the flood, the physical barrier protection against the flood, and the ability to avoid browsing by rodents if constructed properly. It is important to keep the shelter open at the top, in order not to hinder the growth of the plant itself. Growth response to sheltering was straightforward: for all species, having a shelter resulted in a smaller D_{base} and a higher L/D. This might be

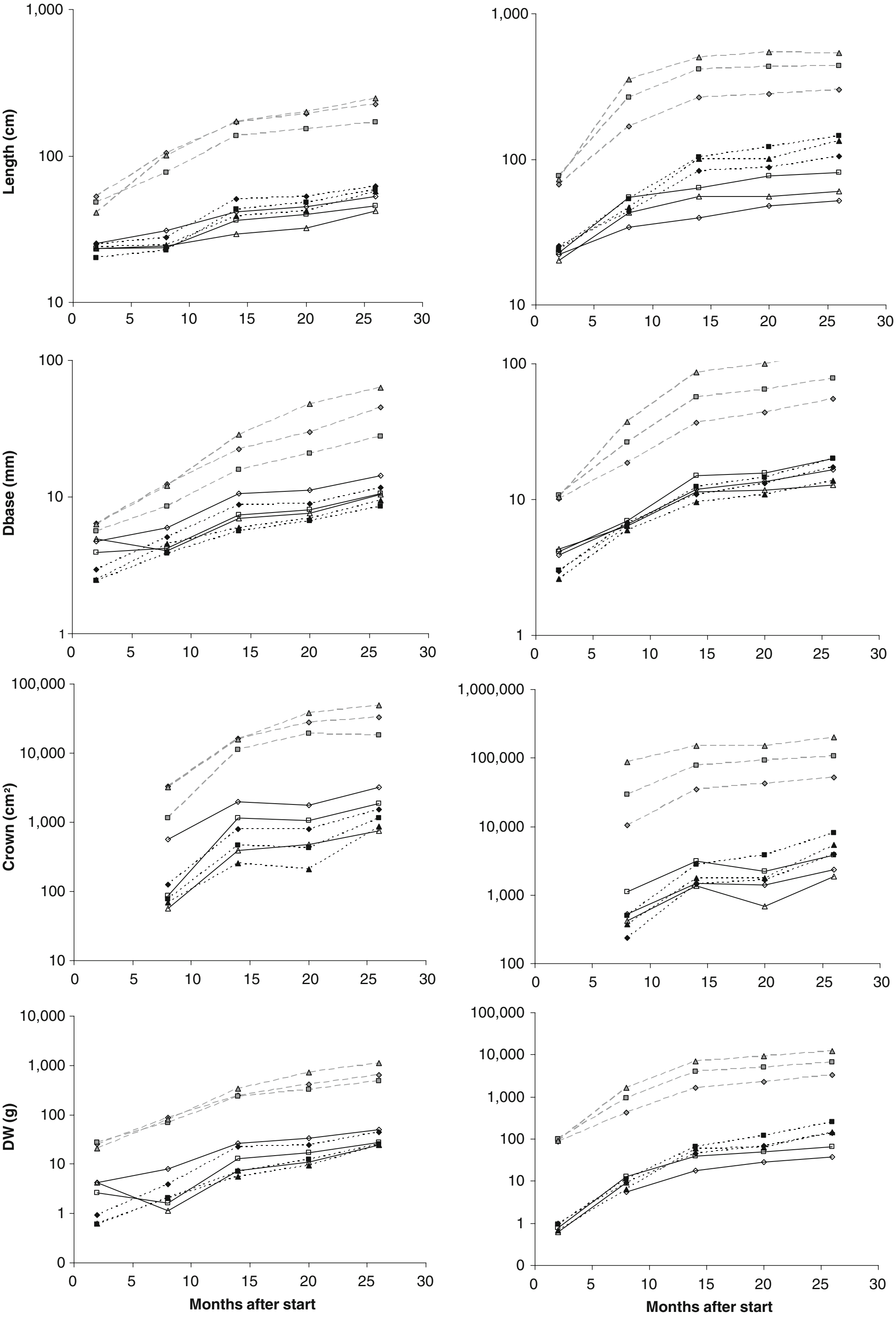

Fig. 8 Effects of gully position on species performance through time. *Left*: AK, *right*: AW. *White* symbols (*full line*): *A. etbaica*; *grey* symbols (*interrupted line*): *S. sesban*; *black* symbols (*dotted line*): *D. angustifolia*. *Diamonds*: shoulder; *squares*: wall; *triangles*: floor

interpreted as a trend in which the plant rushes to grow towards the light and invests relatively more in an increase in height, as was previously also observed for the more commonly used plastic tube shelters (West et al. 1999). On the other hand, this could also be considered as a thigmomorphogenetic response, in which unsheltered seedlings are more exposed to wind disturbance, resulting in a reduced height and thicker stem diameter (Jaffe 1973; Read and Stokes 2006; Reubens et al. 2009). While for *Acacia* and *Dodonaea* it often took a few months before the sheltering effects became clear, generally, for *Sesbania*, these effects gradually decreased through time or sometimes even completely disappeared as a result of their fast growth by which they quickly escaped from the low shelter. Knowing that the important beneficial effects of sheltering are strongest in the initial growth stage, but that biomass development may well be suppressed in the long term, it is suggested to carefully remove (or at least not to reinforce) the shelters once seedlings are firmly fixed in the soil and reached a considerable length.

Although the lack of differentiation in watering treatment during the rainy seasons was expected to be masking effects, no significant watering effects were observed even when only taking dry periods into account. Results from other (albeit unfenced) trials in the same area (Aerts et al. 2007) however indicated a very low survival rate for seedlings which were not given any additional water to overcome the first dry season, even if these were drought-resistant species. The ability to develop deep roots and to access soil moisture is decisive for seedling survival, regardless of species-specific drought tolerance. The absence of effects of watering treatment here, is probably a consequence of (1) too small treatment differentiation, and/or (2) the fact that water availability for seedlings was not only determined by the volume provided during the dry season in our treatments, but by a mixture of factors including soil water holding capacity, gully position, irregular aboveground runoff, and belowground percolation and lateral soil water transfers. In addition, one can expect a gully site to have a higher SWC than the surrounding area because of its topographic position. Given the effort needed to provide water on a regular basis, and the general shortage of water towards the end of the dry season, watering should be kept to the absolute minimum required. This minimum will depend upon the planted species, the climate conditions (with ET_0 to be taken into account) and the soil conditions (with higher requirements in dry, sandy soils).

Underlying mechanisms and relative importance of soil and environmental conditions

The underlying mechanisms for both site and position effects may well have been similar. Gully position effects could be a result of differences in sunlight or wind exposure, as well as of differences in flood stress, soil shear stresses or soil characteristics such as water and nutrient availability, which are both site- and position-related. More generally stated, as also observed for watering, the effects of the imposed treatments on plant growth performance were not unequivocal, but depended on the specific growth conditions.

Different groups of environmental characteristics could be distinguished (Table 1): climatic, topographic, or soil physical and chemical characteristics. In addition, soil water content is another, more dynamic soil characteristic, affected by seasonality, environment, as well as by the manual watering treatments. All of these might have influenced plant growth performance in some way. Despite slightly better climatic conditions in Adi Worho (higher mean air temperatures, slightly more rainfall), variation in climate conditions was relatively small, and it is probable that the influence of other soil and environmental characteristics, particularly nutrient and water availability, have been relatively more significant.

Values for these soil characteristics (Table 1) were in line with previous observations in the same area (Descheemaeker et al. 2006; Nyssen et al. 2008). Generally, soil characteristics in Tigray are highly variable, controlled by topography and underlying geological formation (Nyssen et al. 2008). More than 50% of the soils is shallow, very low in organic matter, extremely deficient in both total nitrogen and available phosphorus, but moderately sufficient in potassium (Beyene et al. 2005).

As for gully position, given the different responses depending on the site and species evaluated, it remains difficult to assess a single explanation for the observed trends. It was hypothesized that in general water and nutrient availability would have been higher on the gully floor, where a lateral flux of water and nutrients is expected. Such a trend could have explained why *Sesbania* performed better on the gully floor. Although this is at least part of the explanation, it could not be incontestably proved in the current setup. More replicates at different sites, in which differences in sunlight or wind exposure, flood stress, or soil shear stresses are also assessed in more detail, would therefore be interesting.

In conclusion, although attention was paid to homogeneity in growth conditions, apart from the imposed treatment factors, at each site additional natural heterogeneity also had an influence on seedling development, complicating interpretation of some results. This is the fate of a field trial under natural conditions, certainly on dynamic and heterogeneous landforms like gullies, as contrasted to strictly controlled laboratory or greenhouse experiments. Nevertheless, in real life plant establishment unavoidably takes place in such a complex scenario, where many abiotic and biotic factors act simultaneously and interactively. Therefore understanding these interactions is often even more important than being able to separate individual effects (Gomez-Aparicio et al. 2008).

In this respect, variability in plant growth performance could be differentiated into three main components: (1) a determinate component expressing the trends and effect of the imposed treatments; (2) a determinate component set by additional (spatial) variability in environmental characteristics; and (3) a random undetermined component (including measurement errors).

Species-specific bottlenecks and recommendations

In our sites, *Acacia etbaica* performed best on the gully shoulder and wall positions. Developing a taproot (Windey 2007), it could be an interesting species for stabilization of the gully walls. On the shoulder, if managed as a dense shrub, *Acacia* is suitable for development of a natural fence around vulnerable places where vegetation recovery has to be given a chance. On the other hand, given its robustness and capacity to re-sprout, which was also previously observed (World Agroforestry Centre 2002) and is a well-known characteristic of many *Acacia* species (Noad and Birnie 1989), it could also be an interesting species for frequently disturbed sites or gully bottoms where sediment is being deposited. As a very common species in the research area, its use to reclaim degraded lands (World Agroforestry Centre 2002) should be uncomplicated. Initial sheltering may well be important to protect the seedlings from uprooting by rodents.

Sesbania sesban above- and belowground development was very fast, even though the research area (about 2,500 m a.s.l.) is not the species' optimum, i.e. between 200 m a.s.l. and 500 m a.s.l. (Noad and Birnie 1989). The observations correspond with its description as a short lifespan shrub species with an initially very fast growth rate gradually decreasing through time (Mekonnen et al. 2006; Mengistu et al. 2002). The fast reproduction is in line with its specification as a prolific seeder, with germination rates of about 80% (Maundu and Tengnäs 2005). It appears to be a species suited to wall and floor stabilization where its growth is best and its mortality low. Its rapid early growth rate could also be exploited by intercropping it with other slower establishing species for earlier yields. As a coppiceable species (Noad and Birnie 1989) the ability to re-sprout after cutting is not surprising. Coppicing yields useful wood material, with cutting frequencies reported of three to four cuts per year. Similarly, pollarding at young age is probably desirable to stimulate investment in fresh leaf development, and to keep the plant strong and its growth rate high. Maintaining a healthy status is important since *Sesbania* is susceptible to pests and diseases. Similar problems have been observed in several semi-arid lowland regions of eastern and southern Africa, where the establishment of *Sesbania sesban* has either failed, or substantial crop losses have been incurred, because of the activities of root-knot nematodes, leaf eating beetles (*Mesoplatys ochroptera* Stäl), caterpillars (*Lepidoptera*), weevils (*Curculionoidea*) as well as several species of bacteria and fungi (Sileshi et al. 2000; World Agroforestry Centre 2002). Despite its interesting characteristics, *Sesbania* should be used carefully and moderately: it is an exotic species with an invasive behavior (Wagner et al. 1999).

Dodonaea angustifolia had its best development on gully shoulder positions. Although this species is said not to be browsed by cattle (Bekelle-Tesemma 1993), and could hence serve as a natural fence around the gully, browsing (especially by goats and donkeys) was observed in the study area. Its extensive shallow root system makes it useful in soil binding and erosion control (Bekelle-Tesemma 1993; Royal

Botanic Gardens 2007). *Dodonaea* is a dominant species in exclosures in the study area, actively and easily regenerating (Mengistu et al. 2005), and with a fairly fast biomass increase.

Experimental limitations, extension and long-term follow-up

Though extensive, this study had its limitations, of which the duration of the experiment and the limited number of species and situations were the most important. Nevertheless, in this study we covered the first 2 years of seedling growth, including three rainy seasons. If seedlings survive this first, most critical stage (Sanchez-Gomez et al. 2008) and establish well, there is a high probability to further develop without major problems. Similarly, species were carefully selected and may have important traits in common with other species, which will therefore belong to an identical functional group. In that context, one could assume *A. etbaica* and *D. angustifolia* to be representative of a wider set of relatively drought resistant shrub or (evergreen) tree species, whereas *S. sesban* could be a prototype of fast-growing, nutrient-fixing fodder species. Species belonging to one functional group could then be expected to respond in a similar way to treatments. Nevertheless, such similarities cannot be taken for granted without further investigation. As a general principle, attention should be given to fast-growing multipurpose species, including promising species which are currently rarely used.

The treatments for this study were selected taking into account local conditions and an effort- and cost-effective approach. Of course, other treatment strategies are possible, and it would be especially interesting to study the effects of nutrient availability and pocket fertilization in more detail. Furthermore, once rates of plant establishment and growth for specific species and sites are well-understood, it would be interesting to assess economic feasibility.

It is noteworthy that this experiment was designed for multi-disciplinary, long-term follow-up, implying evaluation of other aspects not addressed here. These include assessment of natural vegetation growth, soil strength and root reinforcement, and evolution of gully morphology. Furthermore, in a second experimental phase (since August 2007; Woldekidan, unpublished data), three additional woody species were subjected to a similar experimental evaluation, i.e. *Cordia africana* Lam., *Psidium guajava* L. and *Faidherbia albida* (Delile) A. Chev, all selected through a similar multi-criteria decision approach. Treatments and setup were the same, except for an additional zero-watering treatment, included because of the lack of watering differentiation in the former experiment. Here as well, seedling survival and growth were mainly determined by differences in growth conditions at both sites. Fifteen months after planting, *Faidherbia* had the lowest overall survival rate (44%), whereas survival of *Cordia* and *Psidium* were similar (60%). The surprisingly low survival rate for *Faidherbia* might at least partly be explained by inconvenient nursery practices (e.g. long length of stay in the nursery, taproot pruning, no hardening), stressing the crucial role of a proper seedling handling (Aerts et al. 2007). *Psidium* had a significantly lower survival when zero watering was applied. *Cordia* seedlings performed best on the gully wall, whereas *Psidium* and *Faidherbia* were less affected by the gully position. *Cordia* and *Faidherbia* responded to sheltering in a similar way as observed in the presented study. Despite the introduction of a zero-watering treatment, watering level rarely affected plant growth.

Towards implementation

Successful examples of gully erosion control using locally available resources or woody vegetation in other (semi-)arid environments, such as South China (Li et al. 2004; Sheng and Liao 1997; Xu et al. 2008), the Sahelian region (Ribolzi et al. 2006; Wardman and Salas 1991) or the Mediterranean region (Arabi 2006; Quinton et al. 2002), prove that there is a good potential for effective implementation of such measures in rural development programs, in a way which can even be economically beneficial in the long term. Nevertheless, failures are common if (1) the objectives and actions of the different actors playing a role in the implementation of such programs are not thoroughly understood (Segers et al. 2008), and (2) measures are not inspected regularly for necessary repair, inappropriate species are selected, or treatment and planting conditions are unsuited. As for the former, planning and implementation of soil and water conservation often suffer from over-ambition, upward accountability and a top-down blanket approach (Segers et al. 2008).

Above all, keeping out grazing and browsing animals from restoration sites is the most critical trigger for a successful plant establishment (Aerts et al. 2007; Negussie et al. 2008; Nyssen et al. 2008). It is not only a precondition when aiming at effective seedling plantings, but it also allows natural vegetation to recover and hence protect the soil against further erosion.

Conclusions

Except for a few attempts in for example Burkina Faso, Mali and Algeria (Bourougaa and Monjengue 1989), which often had good results but lacked an appropriate statistical approach, this experiment is one of the first (reported) systematic studies on seedling establishment and plant growth performance in the framework of gully erosion control in African semi-arid areas.

Survival, growth and development of seedlings in gullies strongly depend upon their treatment and the growth conditions under which they are planted. For all species in this study, plant growth performance at any time was significantly ($P<0.01$) different between both growth sites, with an overall higher survival rate and better performance in the nutrient-rich Vertisol area of Adi Worho.

The exact effects of treatment in terms of gully position, sheltering and watering were mainly determined by the considered species and site. Gully position effects were especially different for *Sesbania* (which had an overall better performance on the gully floor) when compared to both other species. Sheltering effects were more straightforward, and proved to fulfill an important protective role. Remarkably, the different watering treatments almost did not affect survival or growth performance of any of the examined species. Given the complex interaction of factors determining overall seedling water availability, more highly differentiated watering treatments in a controlled research setup are needed to determine species- and site-specific watering thresholds.

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