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Trial no. 1 in the arid zone series

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by

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Two trees of *Acacia nilotica* var. *cupressiformis* (seedlot no. 1223/83 from Rajasthan) in the trial. Phot: Lars Graudal 1992.

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Danida Forest Seed Centre (DFSC) is a Danish non-profit institute which has been working with development and transfer of know-how in management of tree genetic resources since 1969. The development objective of DFSC is to contribute to improve the benefits of growing trees for the well-being of people in developing countries. DFSC's programme is financed by the Danish International Development Assistance (Danida).

Preface

This report belongs to a new series of analysis reports published by the Danida Forest Seed Centre. It is the intention that the series should serve as a place for publication of trial results for the Centre itself as well as for our collaborators. The reports will be made available from the DFSC publication service and online from the web-site www.dfsc.dk. The scope of the series is in particular the large number of trials from which results have not been made available to the public, and which are not appropriate for publication in scientific journals. We believe that the results from these trials will contribute considerably to the knowledge on genetic variation of tree species in the tropics. Also, the analysis report will allow a more detailed documentation than is possible in scientific journals.

At the same time, the report presents results within the framework of the 'International Series of Trials of Arid and Semi-Arid Zone Arboreal Species', initiated by the FAO. Following collection and distribution of seed between 1983-87, a large number of trials were established by national institutions during 1984-1989. An international assessment of 26 trials took place from 1990 to 1994. DFSC is responsible for the reporting of this assessment.

This trial was established and maintained by the Empresa Brasileira de Pesquisa Agropecuaria (Embrapa) / Centro de Pesquisa Agropecuária do Trópico Semi-Arido (CPATSA), Petrolina, Pernambuca, in Brazil. The assessment team consisted of Paulo César Fernandes Lima, João Claro de Souza, Pedro José Alves, José de Assis Amaral de Lima (Embrapa/CPATSA), Agnete Thomsen (FAO) and Lars Graudal (DFSC).

The authors wish to acknowledge the help of the personnel at Embrapa/CPATSA with the establishment, maintenance and assessment of the trials, and the personnel of DFSC for their help with the data management and preliminary analyses. Drafts of the manuscript were commented on by Marcus Robbins, consultant to FAO, and Luiz Balbino Morgado, researcher at Embrapa Semi-Árido.

Abstract

This report describes results from a trial with 12 provenances of *Acacia*. The species included *A. aneura* (Australia, one provenance), *A. farnesiana* (Mexico, one provenance), *A. nilotica* (India, Senegal and Sudan, six provenances), *A. senegal* (Senegal, one provenance) and *A. tortilis* (Senegal and Sudan, three provenances). The trial was established at Petrolina - PE, Brazil in 1988 with a spacing of 3 x 4 metres, and assessed after five years in 1992. Different growth parameters were measured and subjected to analyses of variance and multivariate analyses.

The fastest growing provenances had an increment rate of 0.75 m^2 ha^{-1} y^{-1}, corresponding to a dry weight production of approximately 2 t ha^{-1} y^{-1}. The provenances with the fastest growth in basal area were of *A. nilotica*, *A. senegal* and *A. tortilis*, while *A. aneura* and *A. farnesiana* showed poor performance, partly because of a low survival.

Differences between species were not significant, but there was a large variation between provenances, and several significant differences within *A. nilotica* and *A. tortilis* were found. In *A. nilotica*, the African provenances had the highest survival, and the two best performers were provenances from Senegal and Sudan. Indian provenances were intermediate to poor. In *A. tortilis*, the provenance of the subspecies *spirocarpa* had a clearly different behaviour from the two provenances of subspecies *raddiana*.

Contents

1. Introduction

This report describes the results from trial no. 1 in a large series of provenance trials within the 'International Series of Trials of Arid and Semi-Arid Zone Arboreal Species'. The main goals of the series were to contribute to the knowledge on the genetic variation of woody species, their adaptability and productivity and to give recommendations for the use of the species. The species included in this series of trials are mainly of the genera *Acacia* and *Prosopis*. A detailed introduction to the series is given by DFSC (Graudal *et al.* 2003).

The present trial includes a number of *Acacia* species with potentials for agroforestry and/or multiple-use. *A. nilotica* is represented by six provenances, *A. tortilis* by three, whereas the species *A. aneura*, *A. farnesiana* and *A. senegal* are represented by one provenance each.

A. nilotica is a very variable species with a natural distribution covering large tracts of tropical and subtropical Africa and Asia. Nine subspecies or varieties are recognised (Brenan 1983, Ross 1979). In this trial six subspecies and varieties are represented (depending on the taxonomy, see below): *adstringens, adansonii, indica cupressiformis, indica jaquemontii, indica vediana* and *tomentosa*. The provenances are from India, Senegal and Sudan.

Taxonomy within the species is not clear, and the seed collectors of provenances in this trial have applied a taxonomy that is different by the authors quoted above. For example, subsp. *jaquemontii* from India is now considered a separate species, *A. jaquemontii*, and subsp. *adansonii* and subsp. *adstringens* are united under the name *adstringens* (Brenan 1983). Brenan also states that the subsp. *indica* constitute a separate subspecies, and that subsp. *indica* var. *cupressiformis* is rightfully the subspecies *cupressiformis*. Furthermore, subsp. *indica* var. *vediana* is considered a synonym of subsp. *subalata*, which is native to East-Africa. The occurrence of subsp. *subalata* in India could be due to crossing between two other varieties, subsp. *indica* and subsp. *hemispherica*. In this report we continue to use the terminology applied by the seed collectors.

A. tortilis is widespread in the Sahel, East Africa and Arabia (Ross 1979, Brenan 1983, von Maydell 1986, Fagg & Barnes 1990), and the provenances in this trial are from Sudan and Senegal. At present four subspecies are recognised (Brenan 1983, Fagg & Barnes 1990). In this trial the subspecies *raddiana* and *spirocarpa* are included.

2. Materials and methods

2.1 Site and establishment of the trial

The trial is located at Bebedouro, Petrolina (9°9′S, 40°22′W) in Pernambuco state, Brazil, at an altitude of 366 m. The mean annual temperature is 27 °C, and the mean annual rainfall is 553 mm (DFSC 1994). The dry period is approximately 7 months. The soils in the area are shallow latosols with low water holding capacity, low content of organic matter and phosphorous deficiency (Lima 1998). Further information is given in the assessment report (DFSC 1994) and summarised in annex 1.

The seed were sown in December 1987, and the trial was established in April 1988.

2.2 Species and provenances

The trial includes twelve provenances of five species of the genus *Acacia* (Table 1). The species *A. nilotica* is represented by six provenances of different subspecies, whereas the *A. tortilis* is represented by three provenances. The species *A. aneura*, *A. farnesiana* and *A. senegal* are represented by one provenance each. The selection of provenances represents four continents, the provenances being from Australia, Mexico, Senegal, Sudan and India. Two provenances from Rajasthan represent different subspecies, but were collected at the same site.

The provenances have been given identification numbers relating to their geographical origin (name of province or country followed by a number). The original seedlot numbers are provided in Annex 2.

2.3 The experimental design

The experimental design is a lattice design with four replicates of each provenance and 16 sub-blocks with 3 provenances each. An alternative interpretation of the design is a randomised complete block design with four blocks. Irrespective of the interpretation, there is a small error in the design, violating the assumption of independence: The sub-blocks have not been properly randomised as can be seen from the fact that the western-most provenance in each block is always the provenance Senegal35.

Within each block, each provenance is represented by 25 trees in a plot, planted in a square of 5×5 trees. The trees have a spacing of 3×4 m. The layout of the trial is shown in Annex 3. Further details are given in DFSC (1994).

2.4 Assessment of the trial

In October 1992 EMBRAPA/CPATSA, FAO and DFSC undertook a joint assessment. A detailed account of the assessment methods is given by DFSC (Graudal *et al.* 2003). The assessment included the following characters:

- Survival
- Health status
- Vertical height
- Diameter of the three largest stems at 0.3 m
- Number of stems at 0.3 m
- Crown diameter

Raw data from the assessment are documented in DFSC (1994). The plot data set on which the statistical analyses in this report are performed is shown in Annex 4. This data set includes directly observed values as well as derived variable values.

Table 1. Provenances of *Acacia* species tested in trial no. 1 at Petrolina, Brazil. Data from seed suppliers, except [1]Pélissier (1983).

Provenance identification	Species	Seed collection site	Country of origin	Latitude	Longitude	Alti-tude (m)	Annual rainfall (mm)	No. of mother trees
Australia2	*A. aneura*	Mix (CSIRO)	Australia					
Mexico01	*A. farnesiana*	Paila, Coahuila	Mexico	25°28'N	101°19'W	1040	300	
Ahmedabad1	*A. nilotica* subsp. *indica* var. *jaquemontii*	Kutch (Bhuj)	India	23°50'N	69°48'E	80	349	25
Rajahstan01	*A. nilotica* subsp. *indica* var. *vediana*	Pali (Desuri)	India	25°16'N	73°33'E	382	400	6
Rajahstan02	*A. nilotica* subsp. *indica* var. *cupressiformis*	Pali (Desuri)	India	25°16'N	73°33'E	382	400	10
Senegal12	*A. nilotica* subsp. *tomentosa*	F.C. Richard-Toll	Senegal	16°27'N	15°41'W	4	300	31
Senegal15	*A. nilotica* subsp. *adansonii*	Gabgal, Louga	Senegal	15°20'N	15°30'W		500[1]	32
Sudan09	*A. nilotica* subsp. *adstringens*	Elobeid	Sudan	13°10'N	13°14'E	570	365	25
Senegal22	*A. senegal*	Namarel, Podor	Senegal	14°46'N	16°00'W	50	333	33
Senegal35	*A. tortilis* subsp. *raddiana*	C.R.Z. Dahra	Senegal	15°20'N	15°28'W		500[1]	30
Sudan15	*A. tortilis* subsp. *spirocarpa*	Khartoum, West Nile	Sudan	15°36'N	32°33'E	330	165	25
Sudan18	*A. tortilis* subsp. *raddiana*	Elbashiri Oasis	Sudan	13°48'N	30°12'E	400	300	25

3. Statistical analyses

3.1 Variables

In this report the following nine variables are analysed:

- Survival
- Vertical height
- Crown area
- Number of stems at 0.3 m
- Basal area of the mean tree at 0.3 m
- Total basal area at 0.3 m
- Dry weight of the mean tree
- Total dry weight
- Damage score

The values were analysed on a plot basis, i.e. ratio, mean or sum as appropriate. Survival was analysed as the rate of surviving trees to the total number of trees per plot. Height, crown area, number of stems and damage score were analysed as the mean of surviving trees on a plot, as was the basal area and the dry weight of the mean tree. The total basal area and the total dry weight represent the sum of all remaining trees in a plot, expressed on an area basis. Note that the calculations of basal area are based on measurements of the three largest stems per tree.

For an unexplained reason, no diameter measurements were made for the provenance Sudan15 in block 1, which will bias estimates of basal area and dry weight. The trees of Sudan15 in block 1 were slightly smaller than trees of the same provenance in the other blocks, the average height in block 1 being 1.55 m compared to the overall average of 1.77 m for Sudan15.

The dry weight values were calculated from regressions between biomass and basal area, established in another part of this study (Graudal *et al.* in prep.). For *A. nilotica* the regression used was

$$TreeDW = e^{(2.582 \times \ln(basalarea) - 1.976)}$$

where *TreeDW* expresses the dry weight of the tree in kg tree^{-1}, and *basalarea* expresses the basal area of the tree in cm^{-2}. For *A. senegal* the regression was

$$TreeDW = e^{(2.474 \times \ln(basalarea) - 2.232)}$$

while the regression for *A. tortilis* was

$$TreeDW = e^{(2.471 \times \ln(basalarea) - 2.068)}$$

No regressions were available for the species *A. aneura* and *A. farnesiana*.

3.2 Statistical model and estimates

The statistical analysis of the trial was based on a two-step approach. The first step involved a test of species differences, whereas the second step was performed separately for each species and tested to see whether there were differences between the provenances within the species in question.

The test of species differences was based on the model:

$$X_{ijk} = \mu + species_i + provenance(species)_{ij} + block_k + \varepsilon_{ijk}$$

where X_{ijk} is the value of the trait (e.g. height) in plot *ijk*, μ is the grand mean, $species_i$ is the fixed effect of species number *i*, $provenance(species)_{ij}$ is the effect of provenance number *j* nested within species *i*, assumed to be a random effect with an expected value of zero and variance σ_{pr}^2, $block_k$ is the effect of block (replication) *k* in the trial, assumed to be a random effect (or, in the case of calculating least square means, a fixed effect), and ε_{ijk} is the residual of plot *ijk*, and is assumed to follow the normal distribution $N(0, \sigma_e^2)$. The test of species differences was performed using the Satterthwaite method for calculation of the degrees of freedom (SAS 1988b).

The test of significant differences between provenances was performed separately for the species *A. nilotica* and *A. tortilis*, based on the model:

$$X_{jk} = \mu + provenance_j + block_k + \varepsilon_{jk}$$

where X_{jk} is the value of the trait in plot *jk*, μ is the grand mean, $provenance_j$ is the fixed effect of provenance number *j*, $block_k$ is the fixed effect of block *k*, and ε_{jk} is the residual of plot *jk* and is assumed to follow a normal distribution $N(0, \sigma_e^2)$.

Since the trial was designed with a lattice design, some additional tests were performed to compare the results of a randomised complete block design (equations 4 and 5) with the lattice design. For the three variables investigated there was no advantage in using the lattice design, and the tests and estimates are therefore based on the replicate complete block model. See Annex 5 for a description and the results of these tests.

In the initial models, the co-variates were distances along the two axes of the trial, plotx and ploty, and squared values of these, plotx2 and ploty2. The co-variates were excluded successively if they were not significant at the 10% level.

Standard graphical methods and calculated standard statistics were applied to test model assumptions of independence, normality and variance homogeneity (Snedecor & Cochran 1980, Draper & Smith 1981, Ræbild 2002). Weighting of data with the inverse of the variance for the seedlots was used to obtain normality of the residuals where the seedlots appeared to have different variances. Where large provenances tended to have larger variances than small provenances, a square root transformation was used to stabilise variance (ibid., Afifi & Clark 1996).

The P-values from the tests of provenance differences were corrected for the effect of multiple comparisons by the sequential table-wide Bonferroni method (Holm 1979). The tests were ranked according to their P values, and the test corresponding to the smallest P value (P_1) was considered significant on a 'table-wide' significance level of α if $P_1 < \alpha/n$, where n is the number of tests. The second smallest P value (P_2) was declared significant if $P_2 < \alpha/(n-1)$, and so on (c.f. Kjaer & Siegismund 1996). In this case the number of tests was set to nine, thus equalling the number of variables analysed. The significance levels are indicated by (*) (10%), * (5%), ** (1%), *** (1 ‰) and n.s. (not significant).

Finally the model was used to provide estimates for the provenance values. Two sets of estimates are presented: The least square means (LS-means) and the Best Linear Unbiased Predictors (BLUPs) (White & Hodge 1989). In brief, the LS-means give the best estimates of the performance of the chosen provenances at the trial site, whereas the BLUPs give the best indication of the range of variation within the species. Since it is assumed in the calculation of BLUPs that the provenances represent a random selection, they are usually presented for the species separately. In this case we only present BLUP estimates for *A. nilotica*, since this is the only species with a larger number of provenances.

A multivariate analysis providing canonical variates, and Wilk's lambda and Pillai's trace statistics, complemented the univariate analyses (Chatfield & Collins 1980, Afifi & Clark 1996, Skovgård & Brockdorf 1998). This analysis was made with all provenances included as well as with the *A. nilotica* provenances alone.

The statistical software package used was Statistical Analysis System (SAS 1988a, 1988b, 1991, Littell *et al.* 1996). A more detailed description of the methods used for the analyses of variance is given in Ræbild *et al.* (2002), and a short description of the analysis of each variable is given in the result section.

4. Results

4.1 Survival

Survival is regarded as one of the key variables when analysing tree provenance trials, since it indicates the adaptability of the provenance to the environment at the trial site. It should be noted that survival reflects only the conditions experienced during the first years growth of the trial and not necessarily the climatic extremes and conditions that may be experienced during the life-span of a tree in the field.

Statistical analysis

The analysis of survival was straightforward, and no transformations were needed. No co-variates were significant.

Results

The average survival for the provenances was quite variable, ranging from below 30 to almost 95 %. The differences between species were not significant, but within the species there were highly significant differences between provenances (Table 2). Among the provenances with high survival were the African provenances of *A. nilotica*, the provenance of *A. senegal* (Senegal22) and the provenances Senegal35 and Sudan18 of *A. tortilis* (fig. 1). On the other hand, the provenances of *A. aneura* and *A. farnesiana*, as well as the Indian provenances of *A. nilotica* and the provenance Sudan15 of *A. tortilis* had poor survival, mostly below 50 %.

The gains by selecting the right provenance were considerable, as was indicated by the BLUP-values for *A. nilotica* (fig. 2). Senegal15 had an expected deviation from the mean of 25 percentage points, whereas the loss by choosing the provenances from Rajasthan would be around 30 percentage points – a difference of more than 50 percentage points.

Table 2. Results from analysis of variance of species and provenance differences of survival in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	4; 7	0.19	0.7	0.61	n.s.
Provenance(species)	7; 33	0.27	17.7	<0.0001	
Block	3; 33	0.11	7.2	0.0007	
Error	33	0.015			
A. nilotica					
Provenance	5; 15	0.276	21.1	<0.0001	***
Block	3; 15	0.044	3.3	0.05	
Error	15	0.013			
A. tortilis					
Provenance	2; 6	0.255	17.4	0.003	*
Block	3; 6	0.044	3.0	0.12	
Error	6	0.015			

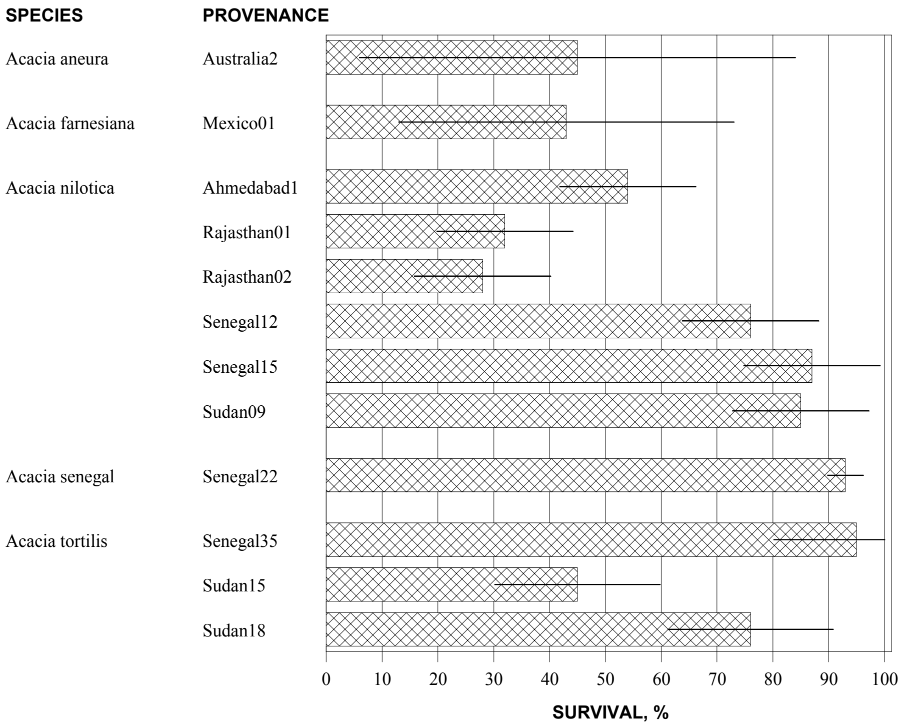

Figure 1. Survival in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are least square means with 95 % confidence limits.

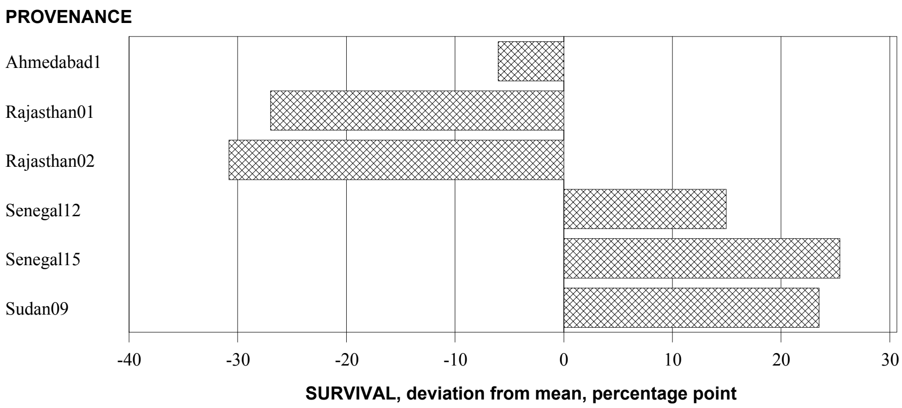

Figure 2. Best linear unbiased predictors (BLUPs) for survival in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are deviations from the mean value in percentage points.

4.2 Height

Height is usually considered an important variable in the evaluation of species and provenances, even though this depends on the main uses of the trees. Apart from indicating productivity, height may also be seen as a measure of the tree adaptability to the environment, tall provenances/trees usually being better adapted to the site than short provenances/trees. This need not always be true, as there have been cases where the tallest provenances are suddenly affected by stress with a subsequent death of the trees.

Statistical analysis

There were no problems in the analysis, and the model was based on un-transformed data. No covariates were significant.

Results

There were clear height differences between the provenances, but within the species the variation was so large that the differences between species were not significant (Table 3). Both in *A. nilotica* and *A. tortilis* the provenances were significantly different, even though the correction for multiple comparisons made this questionable in *A. nilotica*.

The provenance Sudan15 of *A. tortilis* was the smallest provenance in the trial with an average height of 1.75 m. The provenances Sudan18 and Senegal22 of the same species had heights of 2.7-2.8 m (Figure 3). In *A. nilotica* the average height varied between 2.8 and 3.7 m, with Rajasthan01 taking the lead. Mexico01 of *A. farnesiana* was at the lower end with 2.1 m, and Senegal22 (*A. senegal*) and Australia2 (*A. aneura*) were intermediate with 2.8 and 3 m, respectively.

In *A. nilotica* there were moderate height gains by selection of provenances, the predicted values varying from −8 to 13 % (Fig. 4).

Table 3. Results from analysis of variance of species and provenance differences of height in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	4; 7	1.44	2.0	0.20	n.s.
Provenance(species)	7; 33	0.731	7.2	<0.0001	
Block	3; 33	0.386	3.8	0.02	
Error	33	0.101			
A. nilotica					
Provenance	5; 15	0.460	4.0	0.02	(*)
Block	3; 15	0.184	1.6	0.23	
Error	15	0.114			
A. tortilis					
Provenance	2; 6	1.41	19.4	0.002	*
Block	3; 6	0.365	5.0	0.04	
Error	6	0.0727			

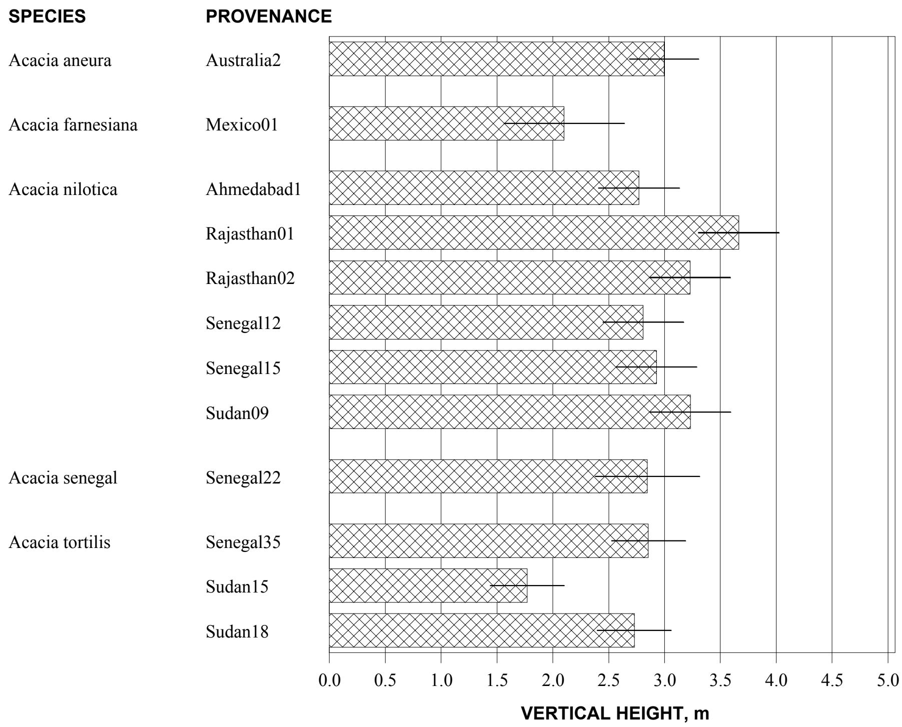

Figure 3. Vertical height in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are least square means with 95 % confidence limits.

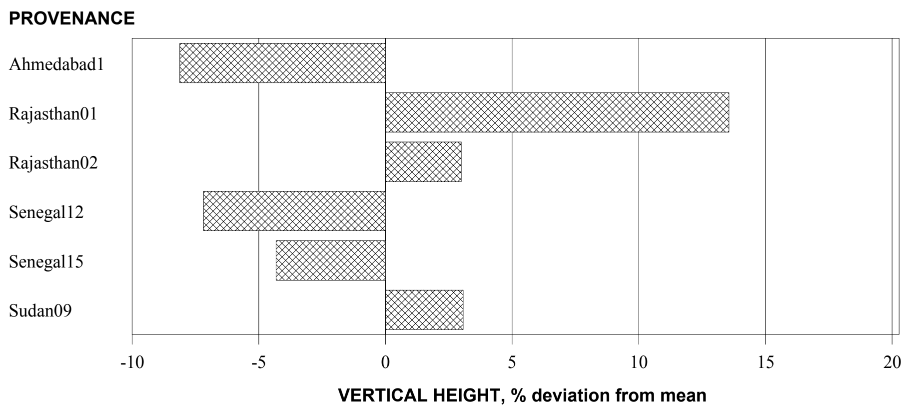

Figure 4. Best linear unbiased predictors (BLUPs) for vertical height in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations in percent of the mean value.

4.3 Crown area

The crown area variable indicates the ability of the trees to cover the ground. The character is of importance in shading for agricultural crops, in evaluating the production of fodder and in protection of the soil against erosion.

Statistical analysis

In the analysis of un-transformed data there were signs of variance heterogeneity. An analysis of data transformed by the square root gave a better distribution of the residuals, but there was still one observation (Mexico01 in block 1) which behaved like an outlier, being larger than the other plots from the same provenances. Removing the outlier had only little effect on the significance levels, and since there was no obvious explanation as to why this plot was an outlier, the tests and estimates are presented with the outlier included.

The estimates are back-transformed least square means, which imply that they will be smaller than the raw means. The advantage of this type of back-transformed means is that they give the fairest impression of the differences between provenances. In this case the differences between back-transformed means and raw means are negligible.

In the analysis of species differences and in the analysis of differences between provenances of *A. nilotica*, the co-variates ploty and ploty2 were significant or almost significant.

Results

The average crown area for the provenances varied between 4 and just below 12 m^2 tree^{-1}. As the growth space is 12 m^2 tree^{-1}, the trees in the largest provenances were almost closing the canopy above the ground. The differences between species were not significant, but within the species there were highly significant differences between the provenances of *A. nilotica* (Table 4). In *A. tortilis*, the difference between provenances was at the limit of significance, meaning that the significance disappeared when accounting for multiple comparisons.

The provenances with the smallest crown areas were Australia2 (*A. aneura*), Mexico01 (*A. farnesiana*) and Rajasthan02 (*A. nilotica*) (fig. 5). That Rajasthan02 had a small crown area was to be expected, as it is of the subsp. *indica* var. *cupressiformis,* which is known for its narrow crowns. The largest crown areas were found in the African provenances of *A. nilotica*, in Senegal22 of *A. senegal* and Sudan18 of *A. tortilis*. The rest of the provenances were intermediate. In *A. nilotica* there were quite considerable gains by choosing the largest provenances, amounting to more than 30 % compared to the mean (Fig. 6).

Table 4. Results from analysis of variance of species and provenance differences of crown area in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	4; 7	1.64	2.0	0.20	n.s.
Provenance(species)	7; 31	0.841	12.6	<0.0001	
Block	3; 31	0.946	14.2	<0.0001	
Ploty	1; 31	0.260	3.9	0.06	
Ploty2	1; 31	0.221	3.3	0.08	
Error	31	0.0667			
A. nilotica					
Provenance	5; 13	1.03	22.4	<0.0001	***
Block	3; 13	0.66	14.4	0.0002	
Ploty	1; 13	0.22	4.9	0.05	
Ploty2	1; 13	0.14	3.1	0.10	
Error	13	0.05			
A. tortilis					
Provenance	2; 6	0.425	5.7	0.04	n.s.
Block	3; 6	0.338	4.5	0.05	
Error	6	00.0742			

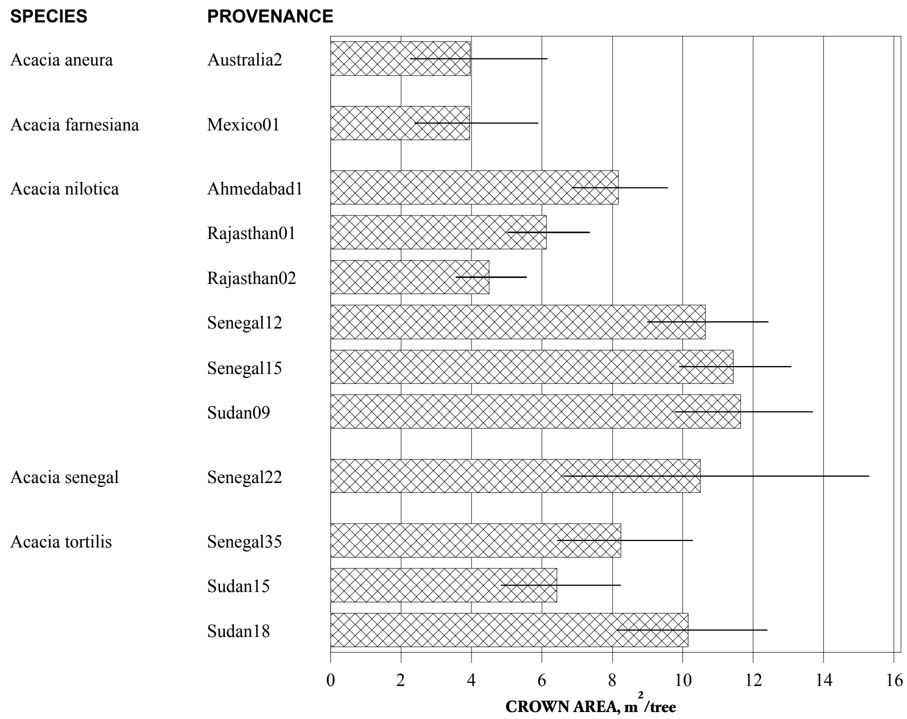

Figure 5. Crown area in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Before analysis the data were transformed with the square root, and values presented are back transformed least square means with 95 % confidence limits. Due to the transformation, the upper and lower confidence intervals have different lengths.

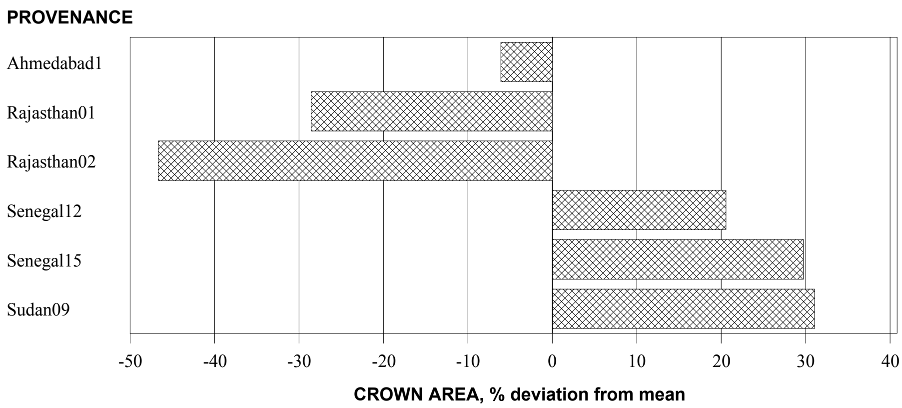

Figure 6. Best linear unbiased predictors (BLUPs) for crown area in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations in percent of the mean value.

4.4 Number of stems

The number of stems gives an indication of the growth habit of the species. Trees with large number of stems are bushy, whereas trees with only one stem have a more tree-like growth.

Statistical analysis

The first analysis suggested that there was variance heterogeneity in the data, and therefore a weight statement was applied to the data. This fulfilled the assumptions of the model. In the analyses of provenance differences within *A. nilotica* and *A. tortilis* the weights were not needed. No co-variates were significant.

Results

The average number of stems was highly variable, and differences between the species were almost significant, although the correction for multiple comparisons suggested that this could be due to random variation (Table 5). Looking at the data in fig. 7 it appeared that *A. nilotica* always had a low number of stems. In this species the differences between provenances were on the border of significance. The significance disappeared after the correction for multiple comparisons. In *A. tortilis*, on the contrary, there was a large and highly significant difference between the three provenances. The provenance Sudan15 had an average number of stems of above five, whereas the two other provenances had between 1.5 and 2 stems per tree. Sudan15 is of the subspecies *spirocarpa*, whereas the others are subsp. *raddiana*. The provenance of *A. aneura* had just below three stems per tree, whereas Mexico01 of *A. farnesiana* had an average number of stems of 4.5. The provenance of *A. senegal* had a low number of stems: only 1.7 per tree.

As the variation within *A. nilotica* was limited, the predicted gains by selection of provenances were also small. The gains varied between –7 and 13 % (fig. 8).

Table 5. Results from analysis of variance of species and provenance differences of number of stems in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	4; 7.4	53.1	3.3	0.07	n.s.
Provenance(species)	7; 33	28.7	31.4	<0.0001	
Block	3; 33	2.32	2.5	0.07	
Error	33	0.915			
A. nilotica					
Provenance	5; 15	0.0926	2.7	0.06	n.s.
Block	3; 15	0.00882	0.3	0.85	
Error	15	0.0340			
A. tortilis					
Provenance	2; 6	18.7	73.7	<0.0001	***
Block	3; 6	0.124	0.5	0.70	
Error	6	0.254			

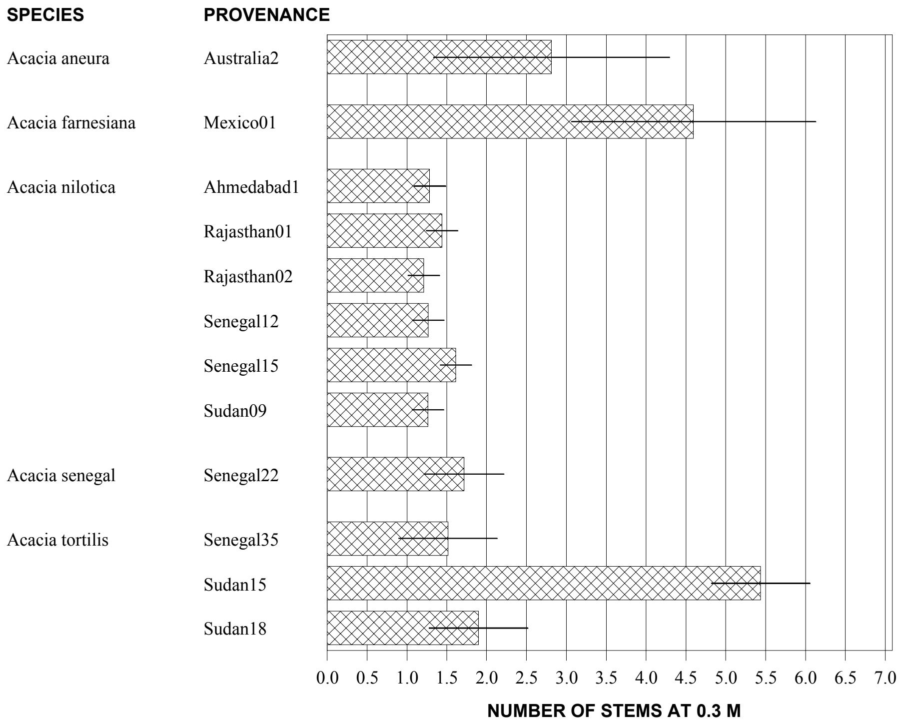

Figure 7. Number of stems in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are least square means with 95 % confidence limits.

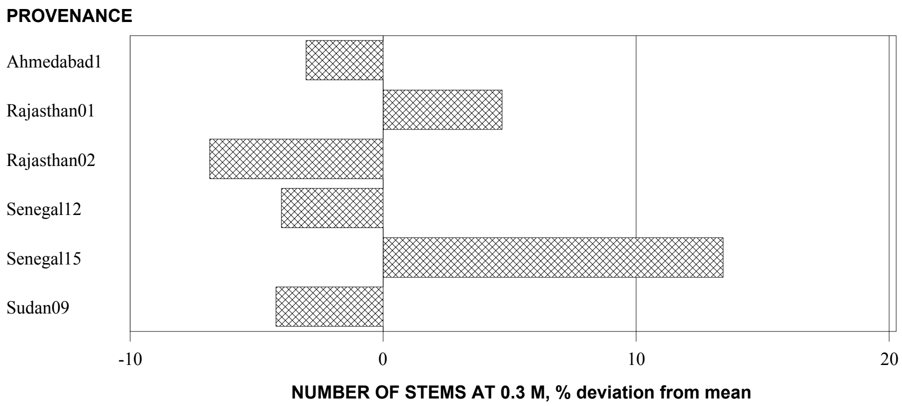

Figure 8. Best linear unbiased predictors (BLUPs) for number of stems in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations in percent of the mean value.

4.5 Basal area of the mean tree

The basal area is often used as a measure of the productivity of stands, since it is correlated to the production of wood. The basal area of the mean tree is calculated on the live trees only and gives an account of the potential basal area production of the provenance provided that all trees survive.

Statistical analysis

Again there were signs of variance inhomogeneity in the data, and a weight statement was applied to fulfil the assumptions of the model. This was not necessary in the analyses of provenance differences within the species. Similarly, the co-variate plotx2 was significant in the test of species differences, but not in the tests of differences between provenances.

It should be noted that no diameters were measured on Sudan15 in block 1, which may bias the estimates for this provenance (see section 3.1).

Results

The analysis of variance demonstrated that there were significant differences between the species with respect to basal area of the mean tree, even though the correction for multiple comparisons made the significance disappear (Table 6). However, there were large variations within the provenances, meaning that the differences between provenances (within species) were not significant in any of the species tested. The possibly significant effect of species was primarily due to the fact that *A. aneura* and *A. farnesiana* were smaller than the species *A. nilotica* and *A. senegal*.

The mean trees of *A. aneura* and *A. farnesiana* had basal areas of 32 and 27 cm^2, respectively (fig. 9). For *A. nilotica* the values ranged from 38 cm^2 (Rajasthan02 and Senegal12) to 56 in Rajasthan01. The provenance of *A. senegal* had a basal area of the mean tree of 42 cm^2, whereas the values in *A. tortilis* were varying from only 22 cm^2 in Sudan15 to 43 cm^2 in Sudan18.

Even though the differences between the provenances of *A. nilotica* were not significant, the BLUP values indicated that there would be some gains by selection of provenances (fig. 10). Compared to the mean value, the gains varied between −8 and +9 %, again with Rajasthan01 as the leader.

Table 6. Results from analysis of variance of species and provenance differences of basal area of the mean tree in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	4; 5.5	10.2	8.5	0.02	n.s.
Provenance(species)	7; 31	1.2	1.2	0.34	
Block	3; 31	5.4	5.4	0.004	
Plotx2	1; 31	14.3	14.4	0.0006	
Error	31	1.0			
A. nilotica					
Provenance	5; 15	209	1.8	0.17	n.s.
Block	3; 15	100	0.88	0.47	
Error	15	114			
A. tortilis					
Provenance	2; 5	413	1.8	0.26	n.s.
Block	3; 5	287	1.3	0.38	
Error	5	228			

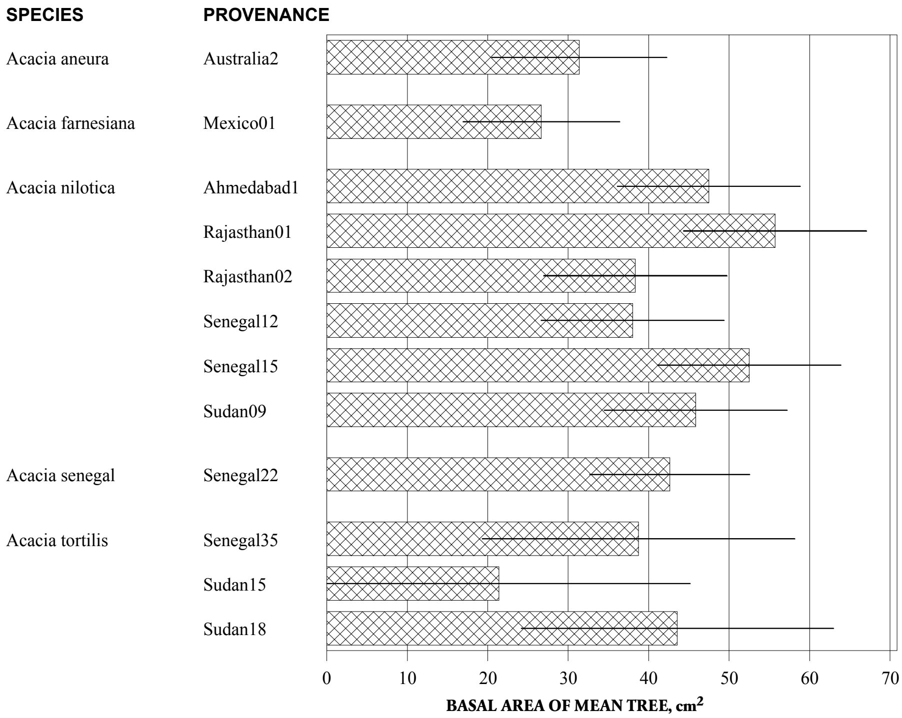

Figure 9. The basal area of the mean tree in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are least square means with 95 % confidence limits.

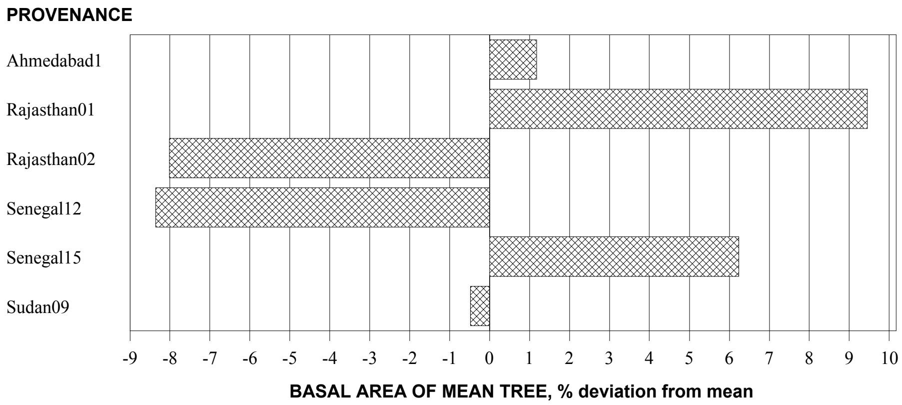

Figure 10. Best linear unbiased predictors (BLUPs) for the basal area of the mean tree in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations in percent of the mean value.

4.6 Total basal area

In comparison to the basal area of the mean tree, the total basal area accounts for missing trees and is thus a better measure of the actual production at the site.

Statistical analysis

The assumptions of the model were fulfilled in the first analysis, and no transformations or weights were used. Since no diameters were measured on Sudan15 in block 1, the estimates for this provenance may be biased (see section 3.1). No co-variates were significant.

Results

There was a large variation in the total basal areas, ranging from 0.6 to 3.8 m^2 ha^{-1}, corresponding to an average annual increment of approximately 0.75 m^2 ha^{-1}. The species were not significantly different, but there were highly significant differences within *A. nilotica* and also indications of significant differences within *A. tortilis* (Table 7).

The smallest total basal areas were found in the provenances of *A. aneura* and *A. farnesiana*, in the provenances Rajasthan01 and Rajasthan02 of *A. nilotica*, and in Sudan15 of *A. tortilis* (fig. 11). Among the highest provenances were Senegal15 and Sudan09 of *A. nilotica*, Senegal22 (*A. senegal*) and Senegal35 (*A. tortilis*).

It is interesting to note that even though the Indian provenances of *A. nilotica* have high basal areas of the mean tree (section 4.5), the poor survival means that they have small total basal areas. The large variation within this species also means that the predicted gains by selection of provenances are big (fig. 12). With Senegal15 as the leader, the predicted gains varied from −55 to +60 % compared to the mean value.

Table 7. Results from analysis of variance of species and provenance differences of total basal area in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	4; 7.0	3.87	0.8	0.55	n.s.
Provenance(species)	7; 32	4.66	10.1	<0.0001	
Block	3; 32	0.776	1.7	0.19	
Error	32	0.463			
A. nilotica					
Provenance	5; 15	4.78	14.2	<0.0001	***
Block	3; 15	1.10	3.3	0.05	
Error	15	0.336			
A. tortilis					
Provenance	2; 5	5.33	6.2	0.04	n.s.
Block	3; 5	0.588	0.7	0.60	
Error	5	0.856			

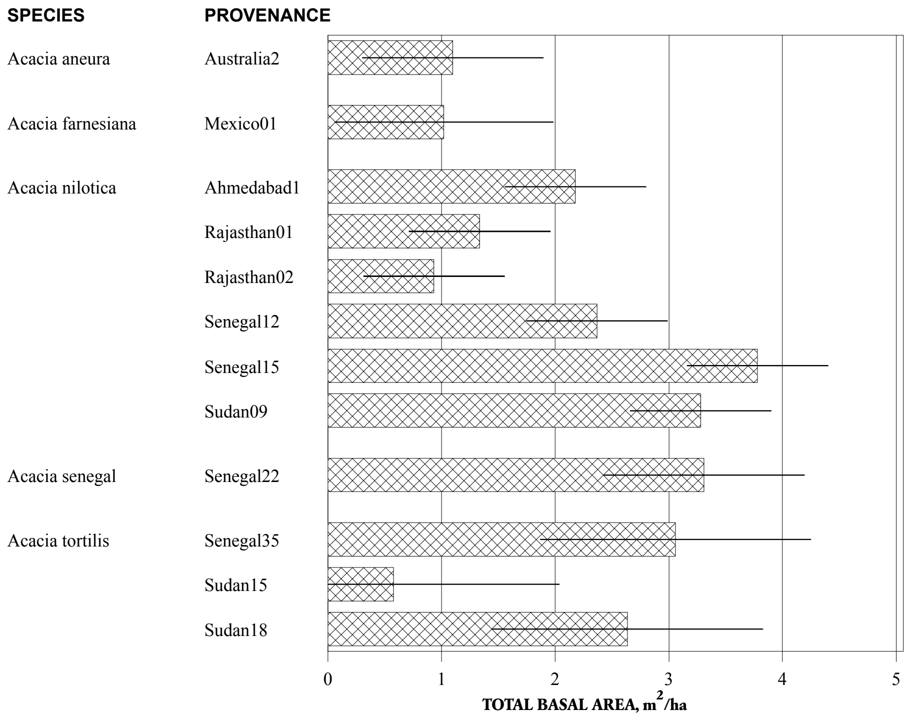

Figure 11. Total basal area in the *Acacia* species and provenances trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are least square means with 95 % confidence limits.

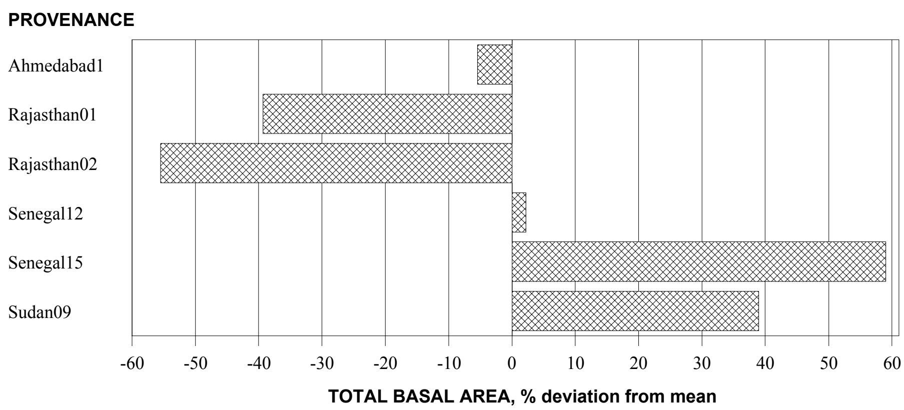

Figure 12. Best linear unbiased predictors (BLUPs) for total basal area in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations in percent of the mean value.

4.7 Dry weight of the mean tree

The dry weight of the mean tree is comparable to the average basal area in that they both are calculated on the live trees only and thus serve as a measure of the potential production at the site, provided that all trees survive. Furthermore, the two variables are linked closely together, as the basis for estimation of the dry weight is the basal area. However, an important difference is that the dry weight include a cubic term (in comparison to basal area having only a square term), meaning that large trees with a large dry mass are weighted heavily in this variable. The dry weight of the mean tree is thus the best estimate for the production of biomass at the site.

Statistical analysis

There was variance heterogeneity in the data, and in the analysis of species differences and the analysis of provenance differences within *A. tortilis* the data were weighted to fulfil the assumptions of the models. In the analysis of provenance differences within *A. nilotica*, the plots of residuals indicated that the plot of Rajasthan01 in block 4 was an outlier. However, since there were no remarks in the assessment reports justifying the exclusion of the observation, the tests and estimates are presented with the outlier. The outlier had only limited influence on the outcome of the test. No co-variates were significant.

No regressions for calculation of dry weight were available for *A. aneura* and *A. farnesiana*, and data for these species are therefore not presented.

Results

The variation of dry weight of the mean tree within provenances was quite large, and it was not possible to detect significant differences between species and provenances in the trial (Table 8). Even an additional test, excluding the species effect and thus leaving only the effects of provenances and blocks in the model, did not reveal significant differences (P=0.25, not shown).

The dry weight of the mean tree ranged from 6 to 16 kg tree^{-1}. The lowest value was found in Sudan15 (*A. tortilis*), whereas the provenances Rajasthan01 (*A. nilotica*) and Sudan18 (*A. tortilis*) had the highest values (fig. 13). Even though differences between provenances were not significant, the data indicated that in *A. nilotica* there would be some gains (~12% compared to the mean) by choosing the best provenances (fig. 14).

Table 8. Results from analysis of species and provenance differences of dry weight of the mean tree in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	2; 10.4	0.1	0.06	0.94	n.s.
Provenance(species)	7; 26	1.8	1.8	0.14	
Block	3; 26	1.9	1.8	0.17	
Error	26	1.6			
A. nilotica					
Provenance	5; 15	26.1	1.6	0.23	n.s.
Block	3; 15	14.6	0.9	0.48	
Error	15	16.6			
A. tortilis					
Provenance	2; 5	2.1	1.7	0.28	n.s.
Block	3; 5	1.3	1.0	0.46	
Error	5	1.2			

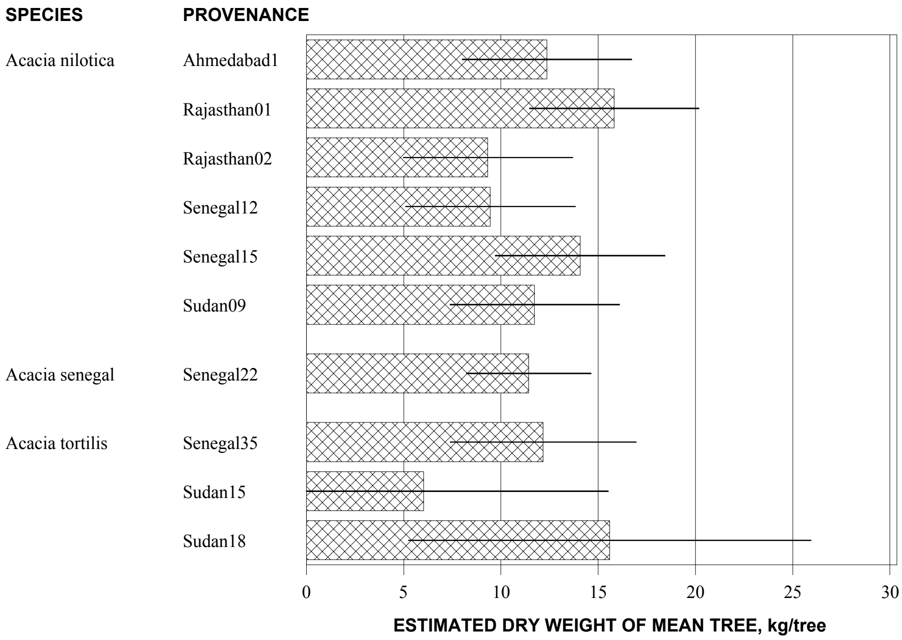

Figure 13. Dry weight of the mean tree in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are least square means with 95 % confidence limits. The data of *A. tortilis* were weighted with the inverse of the variance for the provenances before analysis, and the confidence intervals for this species are therefore of different length.

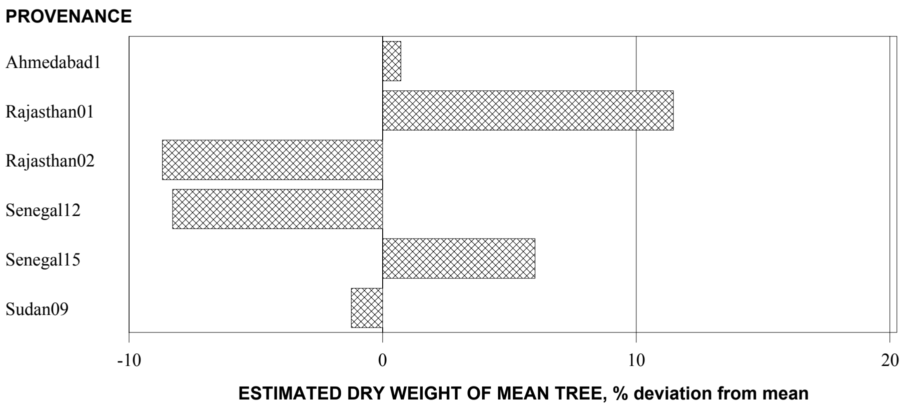

Figure 14. Best linear unbiased predictors (BLUPs) for dry weight of the mean tree in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations in percent of the mean value.

4.8 Total dry weight

In parallel with the total basal area, the total dry weight includes missing trees and gives the best measure of the total production at the site.

Statistical analysis

The analysis of species differences was performed on data without transformations or weights. In the analysis of differences within *A. nilotica*, the plots of residuals indicated that the residual of Sudan09 in block 4 was considerably higher than residuals for the other observations of the same provenance. Removing the outlier increased the significance of the provenance effect, but since there were no explanations for the outlier tendency, the test results and estimates are presented with the outlier included.

In the model for test of species differences, the co-variates ploty and ploty2 were close to significance. In the models testing for provenance differences the significance decreased, and the co-variates were removed in both cases. Note again that data for *A. aneura* and *A. farnesiana* are not available.

Results

There was a considerable variation in the production of dry weight, ranging from 1.3 t ha^{-1} to 10.1 t ha^{-1}. For the best provenance, this corresponds to an average annual growth of 2 t ha^{-1}. There were no significant differences between species, but in *A. nilotica* the difference between provenances were highly significant (Table 9). In *A. tortilis* the difference between provenances was close to being significant, but this disappeared when correcting for the effect of multiple comparisons.

Again there were signs that the provenances of *A. nilotica* from Africa were more productive than the provenances from India (fig. 15). Among the Indian provenances, Ahmedabad1 was the best, whereas Senegal15 was the best among the African provenances. The provenance of *A. senegal* was, with a production of 8.9 t ha^{-1}, also among the best. In *A. tortilis* the provenances Senegal35 and Sudan18 on average had a much higher production of biomass than the provenance Sudan15, but note that the differences were only at the limit of significance and disappeared when the correction for multiple comparisons was made.

Due to the large variation within *A. nilotica*, the predicted gains by choice of provenances were large, varying between −55 % and +60 % compared to the mean (fig. 16). Senegal15 was the provenance having the largest gain.

Table 9. Results from analysis of variance of species and provenance differences of total dry weight in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	2; 7.4	21.8	0.7	0.51	n.s.
Provenance(species)	7; 24	33.2	5.2	0.001	
Block	3; 24	5.65	0.9	0.46	
Ploty	1; 24	19.6	3.1	0.09	
Ploty2	1; 24	20.5	3.2	0.09	
Error	24	6.39			
A. nilotica					
Provenance	5; 15	33.7	11.2	<0.0001	***
Block	3; 15	8.80	2.9	0.07	
Error	15	3.00			
A. tortilis					
Provenance	2; 5	66.0	4.6	0.07	n.s.
Block	3; 5	13.1	0.9	0.50	
Error	5	14.4			

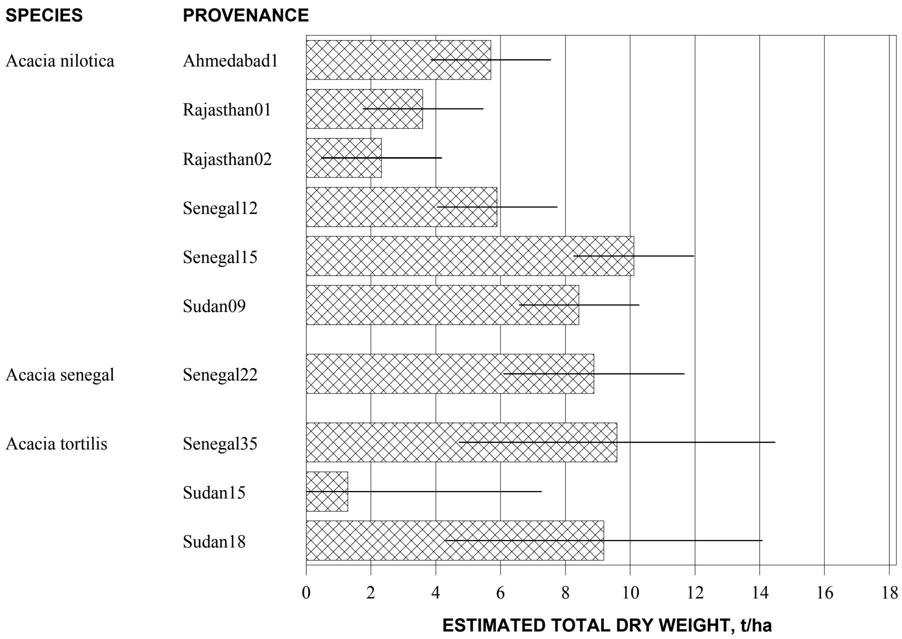

Figure 15. Total dry weight in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values presented are least square means with 95 % confidence limits.

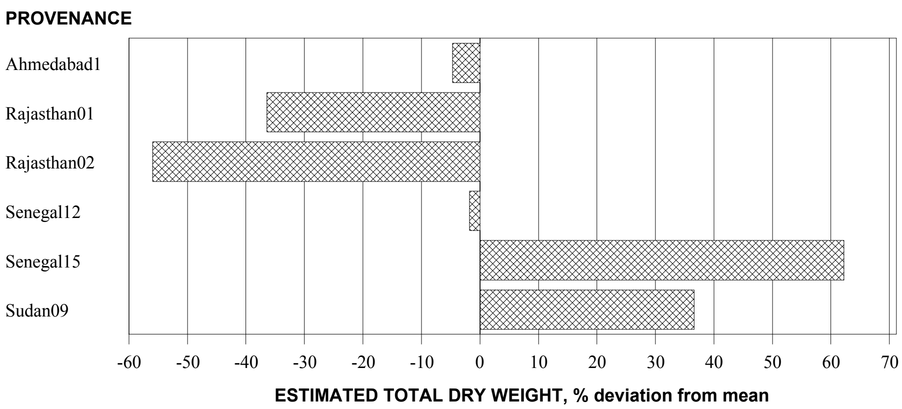

Figure 16. Best linear unbiased predictors (BLUPs) for total dry weight in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations in percent of the mean value.

4.9 Damage score

The damage score was determined on a scale from 0 to 3, where 0 represents no damage, 1 - light damage, 2 - moderate damage and 3 - severe damage. The cause of the damage in this trial was primarily attacks by insects.

Statistical analyses

There were signs of variance heterogeneity between the provenances, and the data were weighted to ensure that the model assumptions were fulfilled both in the analysis of species differences and in the analysis of provenances differences in *A. nilotica* and *A. tortilis*. No co-variates were significant.

Due to the somewhat artificial scale that is applied, certain problems arise. First, the scores are subjective, and it may be difficult to compare scores taken on different species, because insect attacks may have a different effect on the different species. Second, the scores are not necessarily equidistant. For example, for the growth of a tree it may mean less going from a damage score of 0 to 1 than going from a score of 1 to 2. This should be borne in mind when interpreting the results. Note also that the scale is in a way reversed: large figures denote that the damage is severe, and small values that the damage is light.

Results

Differences between the species were not significant, but within *A. nilotica* the differences between provenances were highly significant (Table 10). In *A. tortilis* the differences between provenances were at the border of significance and disappeared when corrected for multiple comparisons.

The average damage scores varied from 0.5 (in between no damage and light damage) to 1.3-1.4 (light damage to moderate damage). However, since there was variation within the provenances (or between the trees of a provenance), this means that the whole scale of damage scores was applied, and that some trees were even severely damaged. Therefore an average score of 1.3 may be serious for a provenance.

The provenances of *A. aneura* and *A. farnesiana* were in the lower end of the damage scores (fig. 17). Within *A. nilotica*, the largest differences were found between two provenances from India. The provenance having the least damage was Ahmedabad1, whereas Rajahsthan01 had the most damage. The last provenance from India and the provenances from Africa were intermediate with scores of approximately 1.0. In *A. tortilis*, the provenance Sudan15 showed the least damage.

The predicted gains from selection of provenances shows that for the provenance Ahmedabad01 an improvement of 0.35 points on the scale can be expected if this provenances is chosen in stead of an average provenance (fig. 18). On the other hand, if Rajasthan01 is chosen, a loss of 0.23 points on the damage scale is to be foreseen.

Table 10. Results from analysis of variance of species and provenance differences of total dry weight in trial 1.

Effect	DF (nominator, denominator)	MS	F-value	P-value	Bonferroni sequential tablewide correction
Test of species differences					
Species	4; 7.5	7.3	1.1	0.41	n.s.
Provenance(species)	7; 33	8.2	8.3	<0.0001	
Block	3; 33	24.7	25.0	<0.0001	
Error	33	1.0			
A. nilotica					
Provenance	5; 15	13.4	12.0	<0.0001	***
Block	3; 15	31.0	27.8	<0.0001	
Error	15	1.1			
A. tortilis					
Provenance	2; 6	8.6	5.8	0.04	n.s.
Block	3; 6	1.2	0.8	0.53	
Error	6	1.5			

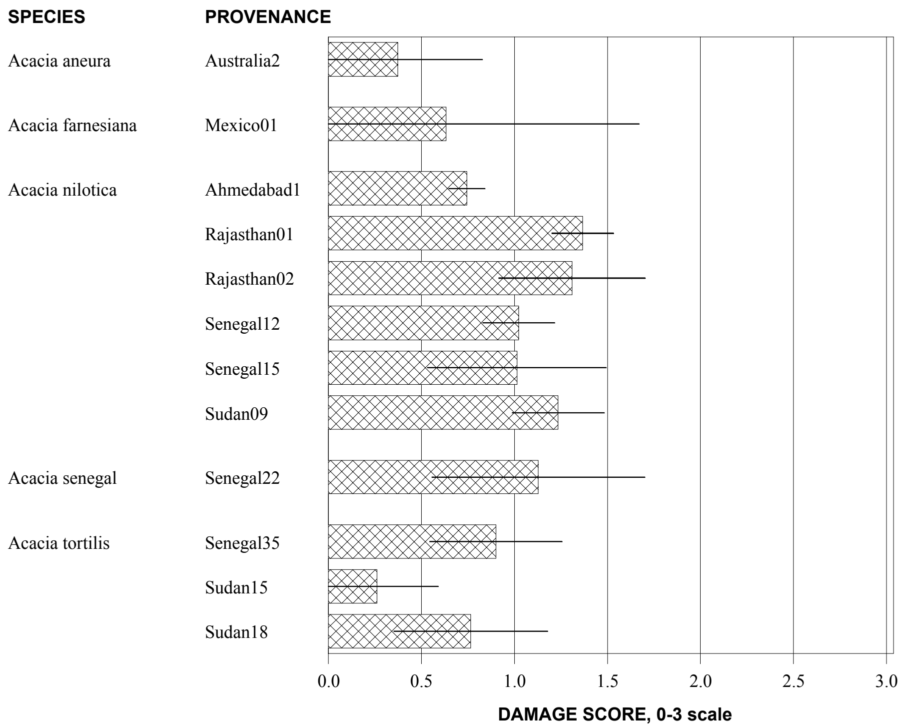

Figure 17. Damage score in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). On the scale, 0 represents no damage, whereas 3 represents severe damage. Values presented are least square means with 95 % confidence limits. Before analysis the data were weighted with the inverse of the variance for the provenances, and the confidence intervals therefore have different lengths.

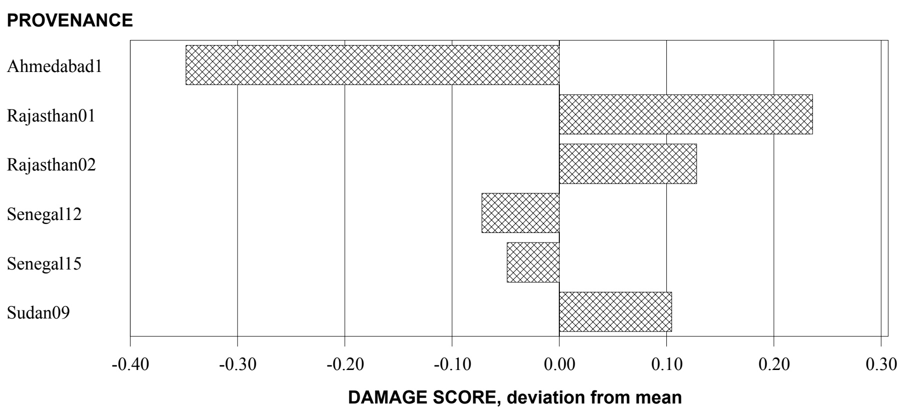

Figure 18. Best linear unbiased predictors (BLUPs) for total dry weight in the *A. nilotica* provenances in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). Values are presented as deviations from the mean value in the units of the damage score scale. Note that the scale is reverse: The best provenances are the ones with negative deviations from the mean.

4.10 Multivariate analysis of all provenances

Analysis

The multivariate analysis of all provenances included all variables analysed in the univariate analyses except for the dry weight of the mean tree and the total dry weight. Crown area was included as square root transformed data. No correction for variance heterogeneity was made.

Results

The first three canonical variates were significant, in total accounting for 97% of the variation of the data (Table 11). Differences between the provenances were highly significant (P-values for Wilk's lambda and Pillai's trace both below 0.0001).

Fig. 19 shows the plot of scores for the first three canonical variates as a plot of the second canonical variate against the first and as the third canonical variate against the first. The main part of the information is in the upper diagram, since the two first canonical variates account for 95 % of the variation. Apart from the scores, the mean values for the provenances are given together with their approximate 95 % confidence regions. In the diagram, provenances that are far apart are interpreted as being different, and if the confidence regions do not overlap, it is likely that the two provenances have different properties.

Mexico01 (*A. farnesiana*) and Australia2 (*A. aneura*) were separated from the largest cluster of provenances, which consisted of provenances of *A. nilotica*, *A. tortilis* and *A. senegal* (fig. 19). Acknowledging that the number of provenances is limited it seems that these species tend to have growth characteristics that are different from the three other species.

Of the three provenances of *A. tortilis*, Sudan18 and Senegal35 were found in the large cluster of provenances. Both these provenances are of the subspecies *raddiana*. The last provenance, Sudan15, is of the subspecies *spirocarpa*, and was located far away from the others. The provenances of *A. nilotica* were found in two groups, one with the two provenances from Rajasthan and one with the rest.

Table 11. Results from the canonical variate analyses of all provenances for the first three canonical variates in trial 1.

Canonical variate no.	1	2	3
Proportion of variation	0.72	0.23	0.03
Significance, P-value	<0.0001	<0.0001	0.01

	Raw canonical coefficients			Standardised canonical coefficients			Canonical directions		
Canonical variate no.	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Survival	7.4	3.9	-1.8	2.1	1.1	-0.5	1.0	2.0	-3.0
Height	-1.2	-2.7	-2.1	-0.7	-1.5	-1.2	1.9	-3.8	-3.3
Crown area	3.5	2.0	2.4	2.1	1.2	1.5	2.8	3.2	2.2
Number of stems	-2.6	0.73	-0.16	-3.5	1.0	-0.2	-7.8	5.2	4.6
Basal area of the mean tree	0.11	-0.01	0.065	1.5	-0.1	0.9	47.5	-26.8	55.5
Total basal area	-1.9	0.46	-1.2	-2.2	0.6	-1.5	5.3	6.6	-8.2
Damage score	0.82	-0.41	1.0	0.4	-0.2	0.5	1.5	-1.6	1.2

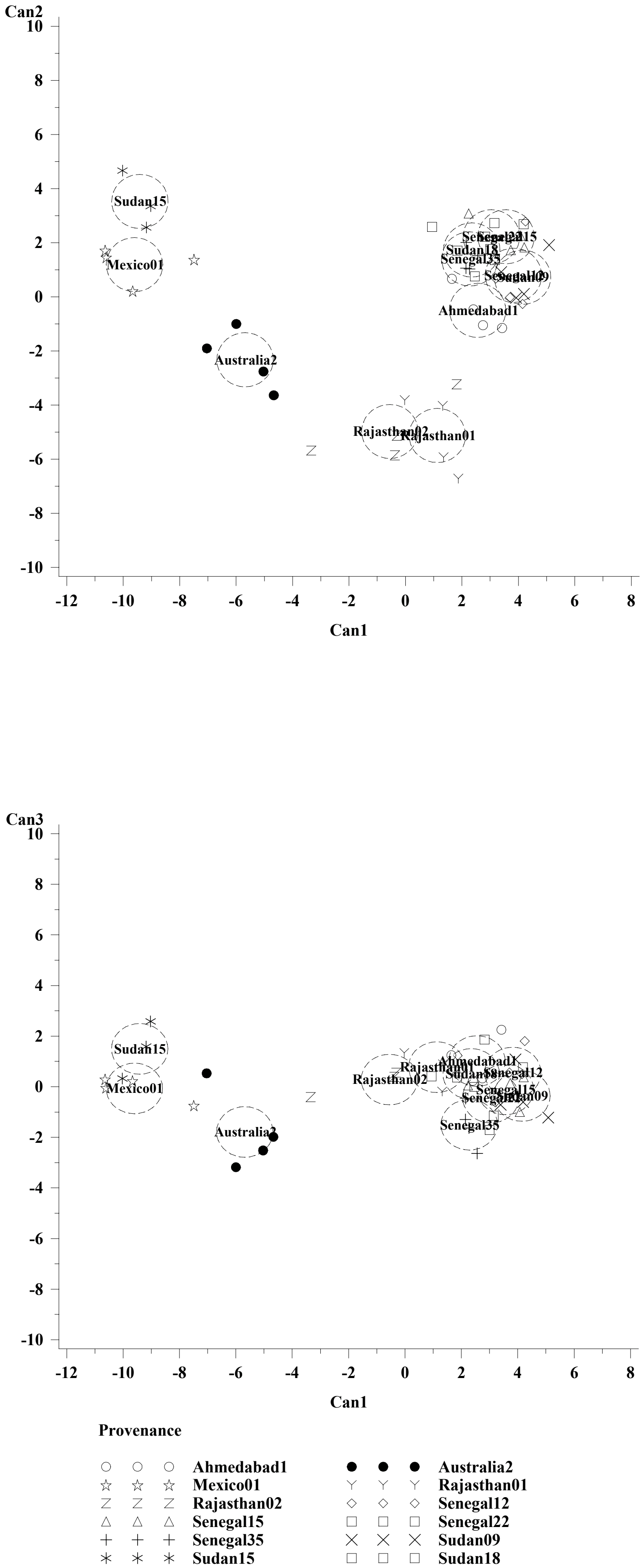

Figure 19. Score plot of the first and the second canonical variate (upper figure) and of the first and the third canonical variate (lower figure) from the canonical variate analysis for the 12 provenances in the *Acacia* species and provenance trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). The variables survival, height, crown area, number of stems, basal area of the mean tree, total basal area and damage score were included. Each provenance is marked at the mean value and surrounded by a 95 % confidence region.

4.11 Multivariate analysis of *A. nilotica*

To investigate the differences within *A. nilotica* in detail, a second analysis including only the provenances of *A. nilotica* was made. As the dry weight estimates were available for this species, the analysis included all variables. Again crown area was included as square root transformed data, and no correction for variance heterogeneity was made.

Results

In this analysis only two canonical variates were significant, accounting for 86 % of the variation (Table 12). The difference between provenances was highly significant (P-value for Wilk's lambda=0.0007 and P-value for Pillai's trace=0.0005).

The provenances of *A. nilotica* in the trial all represent different subspecies. It appeared from the score plot that the growth habits of Sudan09 (subsp. *adstringens*) and Senegal15 (subsp. *adansonii*) were quite similar (fig. 20). Also Ahmedabad1 (subsp. *indica* var. *jaquemontii*) and Senegal12 (subsp. *tomentosa*) were close to each other. The provenances Rajasthan01 (subsp. *indica* var. *vediana*) and Rajasthan02 (subsp. *indica* var. *cupressiformis*) were separated both from each other and from the other provenances. Apart from these differences there could be a geographical pattern as well, the provenances from India and Africa being located opposite to each other.

Table 12. Results from the canonical variate analyses of *A. nilotica* provenances for the first two canonical variates in trial 1.

Canonical variate no.	1	2
Proportion of variation	0.75	0.11
Significance, P-value	0.0007	0.04

	Raw canonical coefficients		Standardised canonical coefficients		Canonical directions	
Canonical variate no.	**1**	**2**	**1**	**2**	**1**	**2**
Survival	12.8	-32.7	3.5	-8.9	0.9	-0.3
Height	-1.2	1.2	-0.5	0.5	-0.6	2.6
Crown area	4.2	0.09	2.4	0.05	1.8	-0.2
Number of stems	3.5	4.9	0.7	1.0	0.3	0.8
Basal area of the mean tree	0.49	-0.66	5.6	-7.5	7.1	51.8
Total basal area	5.1	38.1	6.0	45.1	3.8	1.1
Dry weight of the mean tree	-2.7	-11.4	-8.8	-36.8	10.2	4.0
Total dry weight	-0.82	1.9	-3.5	8.1	2.1	18.2
Damage score	-0.21	2.1	-0.1	0.9	-0.4	1.4

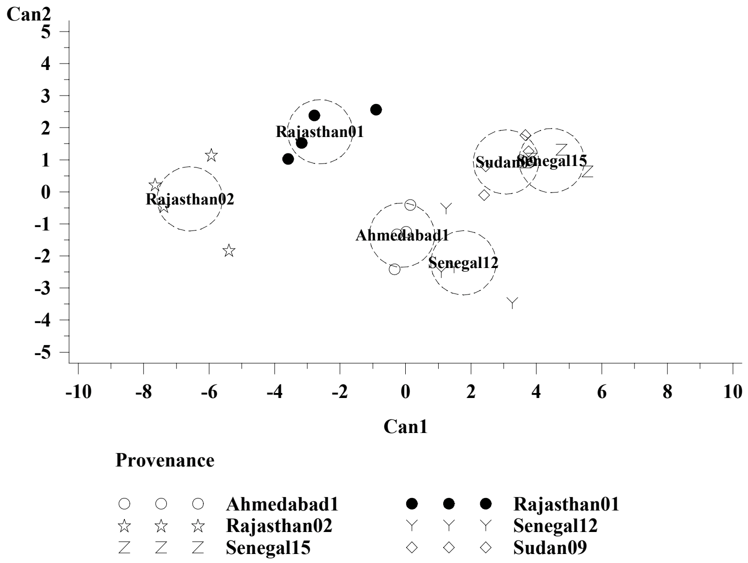

Figure 20. Score plot of the first and the second canonical variate from the canonical variate analysis for the provenances of *A. nilotica* in the trial at Petrolina, Brazil (Trial no. 1 in the arid zone series). The variables survival, height, crown area, number of stems, basal area of the mean tree, total basal area, dry weight of the mean tree, total dry weight and damage score were included. Each provenance is marked at the mean value and surrounded by a 95 % confidence region.

5. Discussion and conclusions

Productivity

The best provenances of *A. nilotica*, *A. senegal* and *A. tortilis* had produced a biomass of 8-10 t ha^{-1}, which corresponds to an annual production of 1.6 – 2 t ha^{-1} during the first five years at a spacing of 3x4 metres. Compared to the *Prosopis* trials at Petrolina this is a relatively high production. Brazil2 (*P. juliflora*), the best producing provenance of *Prosopis* at Petrolina in the trials included in this series, had an annual production of biomass of 1.6 t ha^{-1}. It appears that a range of *Acacia* species, including at least the three species mentioned above, could have a satisfactory production at the site.

Species differences

In the univariate analyses there were only few signs of differences between species, and when the tests were corrected for multiple comparisons by the sequential Bonferroni tablewide method, all differences became non-significant. In the multivariate approach, it seemed that the provenances of *A. farnesiana* and *A. aneura* were far apart from the main group of the three other species. However, judging the performance of a species by testing only one provenance is tricky, since other provenances within the same species could be better adapted to the site. Thus conclusions have to be given at the provenance level rather than at the species level.

Provenance differences

There were several highly significant differences between the provenances in the trial. The survival was quite variable, which in turn influenced many of the other variables. Even though the variation in basal area of the mean tree was modest, the differences in survival meant that the total basal area and total dry weight varied with a factor of 10 from the smallest to the largest provenance.

From the trial it is clear that certain provenances have a poor performance at the site. These provenances include Australia2 (*A. aneura*), Mexico01 (*A. farnesiana*), the *A. nilotica* provenances from Rajasthan, and Sudan15 of *A. tortilis*. On the other hand, the provenances Senegal15 and Sudan09 (*A. nilotica*), Senegal22 (*A. senegal*) and Senegal35 (*A. tortilis*) had an impressive growth and should be considered for further testing. An unclear factor in the choice of provenances is the attacks by insects. Even though there were significant differences between the provenances, the damage was not concentrated on certain groups of provenances. There are theoretical difficulties in the analysis of the damage to trees as it is difficult to make an objective evaluation of degree of impact the damage has to a tree, and the subject deserves more attention.

Analysing differences within the species revealed two interesting facts. In *A. nilotica*, both the univariate and the multivariate analyses indicated that there were important differences between the provenances. Since each variety was represented only once, the interpretations should be cautious, but a few things deserve mention. First, the provenances from Rajasthan were collected at the same site and did not separate clearly from each other even though representing two different varieties (subsp. *indica* var. *cupressiformis* and subsp. *indica* var. *vediana*). In the multivariate analysis, the provenances came out separately, but still in the same end of the diagram (fig. 20). During the assessment it was noted that the trees of Rajasthan02 was a mixture of trees of both the 'normal' and the narrow erect 'cupressiformis' crown type. If we assume that seed of this provenance was collected on trees of 'cupressiformis' type, this leads us to the conclusion that the 'cupressiformis' form is truly a variety and not, as suggested by Brenan (1983), a subspecies.

Second, the provenances Sudan09 (subsp. *adstringens*) and Senegal15 (subsp. *adansonii*) were placed together in the multivariate analysis even though being separated by a wide distance geographically. According to newer taxonomy (Brenan 1983) the two subspecies are considered as being the same (see introduction). Third, these two provenances were slightly separated from the third provenance from Africa, Senegal12, of the subspecies *tomentosa*. This subspecies tolerates inundation and appear to be restricted to habitats along rivers and seasonally flooded areas, whereas subsp. *adstringens* is found predominantly in wooded grassland, on deep sandy-loamy soils (von Maydell 1986, Ross 1979, Fagg & Barnes 1990). Fourth, the African provenances seemed to perform better than the provenances from India, although Ahmedabad1 was close to Senegal12. The material is sparse, but this could be a hypothesis worth further testing.

In *A. tortilis* it was clear that the provenance Sudan15 of the subspecies *spirocarpa* was different from the provenances of the subspecies *raddiana*, even though one of these provenances was also of Sudanian origin. This points to the variability within the species.

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Annex 1. Description of trial site

Name of site:	Bebedouro, Petrolina - PE Latitude: 9°9'S Longitude: 40°22'W Altitude: 365.5 m
Meteorological stations:	Local (5 km (Establishment Report 1988)) Petrolina (9°23'S, 40°29'W, 370 m (FAO 1985))
Rainfall:	Annual mean (period): 553 (11 years - period not given (Establishment Report 1988))
Rainy season:	November-April (Establishment Report 1988) Type: Intermediate (FAO 1985) Length (days): 60 (FAO 1985)
Dry months/year	Establishment Report 1988: No. of dry months (<50 mm): 7 No. of dry periods: 1
Temperature (°C):	Establishment Report 1988: Annual mean: 27 Coldest month: 18 (minimum) Hottest month: 40 (maximum)
Wind:	Speed: 1.4 (FAO 1985)
Topography:	Flat/gentle
Soil:	Type: Latosols, low water holding capacity, low organic matter (Lima 1986) and stony Depth: Shallow (Lima 1986)
Climatic/agroecological zone:	Semi-arid
Dominant natural vegetation:	'Caatinga', deciduous woodland
Koeppen classification:	BSh

Annex 2. Provenances of *Acacia* species tested in trial no. 1 at Petrolina, Brazil.

The plot numbers refer to the seedlots in the map of the trial, see Annex 3.

Provenance	Seedlot numbers			Provenance information							
	DFSC	Country of origin	Plot	Species	Origin	Country of origin	Latitude	Longitude	Altitude (m)	Rainfall (mm)	No. of mother trees
Australia2	-	Mix of 3 lots	9	*A. aneura*	Mix (CSIRO)	Australia					
Mexico01	1270/84	3	10	*A. farnesiana*	Paila, Coahuila	Mexico	25°28'N	101°19'W	1040	300	
Ahmedabad1	1076/82		7	*A. nilotica* subsp. *indica* var. *jaquemontii*	Kutch (Bhuj)	India	23°50'N	69°48'E	80	349	25
Rajahstan01	1217/83		6	*A. nilotica* subsp. *indica* var. *vediana*	Pali (Desuri)	India	25°16'N	73°33'E	382	400	6
Rajahstan02	1223/83		12	*A. nilotica* subsp. *indica* var. *cupressiformis*	Pali (Desuri)	India	25°16'N	73°33'E	382	400	10
Senegal12	1037/82	82/625	3	*A. nilotica* subsp. *tomentosa*	F.C. Richard-Toll	Senegal	16°27'N	15°41'W	4	300	31
Senegal15	1202/83	83/766	5	*A. nilotica* subsp. *adansonii*	Gabgal, Louga	Senegal	15°20'N	15°30'W			32
Sudan09	1112/83	1/1983	4	*A. nilotica* subsp. *adstringens*	Elobeid	Sudan	13°10'N	13°14'E	570	365	25
Senegal22	1035/82	82/559	2	*A. senegal*	Namarel, Podor	Senegal	14°46'N	16°00'W	50	333	33
Senegal35	1197/83	83/836	1	*A. tortilis* subsp. *raddiana*	C.R.Z. Dahra	Senegal	15°20'N	15°28'W			30
Sudan15	1045/82	3/82	8	*A. tortilis* subsp. *spirocarpa*	Khartoum, West Nile	Sudan	15°36'N	32°33'E	330	165	25
Sudan18	1240/84	6/1983	11	*A. tortilis* subsp. *raddiana*	Elbashiri Oasis	Sudan	13°48'N	30°12'E	400	300	25

Annex 3. Layout of the trial

Layout of blocks and plots in the field The numbers correspond to the seedlots given in Annex 2:

y	BLOCK 1			BLOCK 2			BLOCK 3			BLOCK 4			
4	1	5	9	1	6	11	1	7	12	1	10	8	
3	2	6	10	5	2	12	2	11	8	9	2	7	
2	3	7	11	9	3	8	5	10	3	6	3	12	
1	4	8	12	10	7	4	9	6	4	5	11	4	
	1	2	3	4	5	6	7	8	9	10	11	12	x

Individual tree positions in each plot (each tree indicated by its local tree number):

y						
5	5	6	15	16	25	
4	4	7	14	17	24	
3	3	8	13	18	23	
2	2	9	12	19	22	
1	1	10	11	20	21	
	1	2	3	4	5	x

Annex 4. Plot data set

Species codes: aan: *A. aneura*, afa: *A. farnesiana*, aniada: *A. nilotica* subsp. *adansonii*, aniads: *A. nilotica* subsp. *adstringens*, aniincu: *A. nilotica* subsp. *indica* var. *cupressiformis*, aniinja *A. nilotica* subsp. *indica* var. *jaquemontii*, aniinve: *A. nilotica* subsp. *indica* var. *vediana*, anito: *A. nilotica* subsp. *tomentosa*, ase: *A. senegal*, atora *A. tortilis* subsp. *spirocarpa*, atosp: *A. tortilis* subsp. *spirocarpa*.

Block	Plotx	Ploty	Species	Provenance	Survival	Height	Crown area	Number of stems	Basal area of the mean tree	Total basal area	Dry weight of the mean tree	Total dry weight	Damage score
					%	m	m^2 $tree^{-1}$	no. $tree^{-1}$	cm^2 $tree^{-1}$	m^2 ha^{-1}	kg $tree^{-1}$	t ha^{-1}	0-3 scale
1	3	4	aan	Australia2	76	3.04	3.52	3.11	28.6	1.81			0.21
1	3	3	afa	Mexico01	60	2.55	4.85	5.80	34.9	1.74			1.47
1	2	4	aniada	Senegal15	92	2.67	10.35	2.00	54.9	4.21	15.1	11.5	0.83
1	1	1	aniads	Sudan09	80	3.01	9.17	1.35	43.5	2.90	11.1	7.4	1.80
1	3	1	aniincu	Rajasthan02	40	3.19	2.51	1.20	52.2	1.74	13.9	4.6	2.20
1	2	2	aniinja	Ahmedabad1	68	2.96	7.18	1.12	49.8	2.82	13.1	7.4	1.06
1	2	3	aniinve	Rajasthan01	40	2.79	3.65	1.40	45.9	1.53	11.7	3.9	1.70
1	1	2	anito	Senegal12	100	2.69	6.34	1.20	37.1	3.09	9.2	7.7	1.64
1	1	3	ase	Senegal22	92	2.42	6.84	1.87	35.8	2.75	9.2	7.1	1.43
1	1	4	atora	Senegal35	96	2.28	6.26	1.50	29.7	2.38	8.9	7.1	0.54
1	3	2	atora	Sudan18	92	2.03	6.03	2.09	24.8	1.90	6.9	5.3	0.74
1	2	1	atosp	Sudan15	68	1.55	5.30	6.00					0.41
2	4	2	aan	Australia2	52	2.92	2.61	2.15	23.6	1.02			0.23
2	4	1	afa	Mexico01	48	1.97	2.69	4.92	25.7	1.03			0.81
2	4	3	aniada	Senegal15	84	3.15	12.01	1.52	63.7	4.46	17.7	12.4	1.33
2	6	1	aniads	Sudan09	88	3.19	9.71	1.36	49.2	3.61	12.6	9.3	1.09
2	6	3	aniincu	Rajasthan02	28	3.41	5.19	1.14	27.8	0.65	6.0	1.4	1.43
2	5	1	aniinja	Ahmedabad1	64	2.89	7.10	1.25	54.0	2.88	14.7	7.8	0.81
2	5	4	aniinve	Rajasthan01	52	3.92	7.66	1.46	42.5	1.84	10.6	4.6	1.62
2	5	2	anito	Senegal12	72	3.15	9.72	1.06	37.8	2.27	9.2	5.5	0.94
2	5	3	ase	Senegal22	92	2.91	12.05	1.78	42.7	3.27	11.5	8.8	1.26
2	4	4	atora	Senegal35	96	2.99	7.63	1.63	36.6	2.93	11.2	8.9	1.08
2	6	4	atora	Sudan18	88	3.37	11.66	1.82	54.2	3.97	18.7	13.7	1.41
2	6	2	atosp	Sudan15	32	1.83	6.48	5.25	28.0	0.75	8.1	2.2	0.25
3	7	1	aan	Australia2	20	2.78	5.30	4.00	39.5	0.66			0.80
3	8	2	afa	Mexico01	16	1.75	3.56	4.00	20.1	0.27			0.00
3	7	2	aniada	Senegal15	96	2.73	10.51	1.46	39.6	3.17	9.6	7.7	1.00
3	9	1	aniads	Sudan09	80	3.14	10.84	1.25	33.3	2.22	7.7	5.1	1.05
3	9	4	aniincu	Rajasthan02	36	2.91	6.51	1.00	36.5	1.09	8.8	2.7	1.11
3	8	4	aniinja	Ahmedabad1	36	2.87	10.81	1.44	43.8	1.31	11.3	3.4	0.78
3	8	1	aniinve	Rajasthan01	20	3.72	6.97	1.40	52.0	0.87	13.7	2.3	1.40
3	9	2	anito	Senegal12	64	2.98	10.89	1.44	41.5	2.21	10.7	5.7	1.06
3	7	3	ase	Senegal22	96	2.97	12.28	1.96	50.9	4.07	14.1	11.3	1.21
3	7	4	atora	Senegal35	100	2.98	9.00	1.52	42.6	3.55	13.5	11.2	0.84
3	8	3	atora	Sudan18	68	2.54	9.01	1.47	22.1	1.25	6.0	3.4	0.41
3	9	3	atosp	Sudan15	56	1.91	7.17	6.00	29.4	1.27	8.7	3.8	0.21

Block	Plotx	Ploty	Species	Provenance	Survival	Height	Crown area	Number of stems	Basal area of the mean tree	Total basal area	Dry weight of the mean tree	Total dry weight	Damage score
4	10	3	aan	Australia2	32	3.24	4.69	2.00	33.9	0.90			0.25
4	11	4	afa	Mexico01	48	2.14	4.91	3.67	26.0	1.04			0.25
4	10	1	aniada	Senegal15	76	3.16	14.11	1.47	51.8	3.28	13.9	8.8	0.89
4	12	1	aniads	Sudan09	92	3.60	16.50	1.09	57.3	4.39	15.5	11.9	1.00
4	12	2	aniincu	Rajasthan02	8	3.40	4.96	1.50	36.8	0.25	8.5	0.6	0.50
4	12	3	aniinja	Ahmedabad1	48	2.36	8.72	1.33	42.2	1.69	10.5	4.2	0.33
4	10	2	aniinve	Rajasthan01	16	4.23	7.52	1.50	82.3	1.10	27.3	3.6	0.75
4	11	2	anito	Senegal12	68	2.42	13.24	1.38	35.6	1.90	8.7	4.6	0.44
4	11	3	ase	Senegal22	92	3.09	11.35	1.26	41.1	3.15	10.9	8.3	0.61
4	10	4	atora	Senegal35	88	3.17	10.36	1.41	46.0	3.38	15.1	11.1	1.14
4	11	1	atora	Sudan18	56	2.98	15.00	2.21	73.1	3.41	30.8	14.4	0.50
4	12	4	atosp	Sudan15	24	1.80	6.83	4.50	20.5	0.41	5.5	1.1	0.17

Annex 5. A comment on the lattice design

Trial no. 1 follows the structure of a lattice design and actually matches the design of a 3x4 rectangular lattice given by Burley & Wood (1976) exactly. However, the design is not randomised according to the recommendations given by Burley & Wood. For example it appears that the provenance Senegal35 is located in the upper left corner of each replicate block. Such non-random designs may introduce systematic errors in the analysis. Ideally, the subplots should be randomised within the blocks, and the provenances should be randomised within subplots (see Burley & Wood 1976 and Cochran & Cox 1957 for details). Modern computer software will produce these kinds of designs in a less laborious manner (Williams & Matheson 1994). These authors also provide up-to-date information on imbalanced block designs. In the following analyses it is assumed that the lack of randomisation does not influence the estimates.

For the variable plot survival an analysis of the effects of the lattice design was made. In the following, the terminology follows Williams & Matheson (1994), meaning that the *Replicate* denote what is usually termed 'block' in the analysis (values from 1 to 4), and *Block* denote the smaller plots (subblocks, the incomplete blocks, values from 1 to 16). Three models were compared (here we ignore the effect of species):

$$X_{ij} = \mu + \mathit{Provenance}_i + \mathit{Replicate}_j + \varepsilon_{ij} \quad (1)$$

representing the complete randomised block design,

$$X_{ik} = \mu + \mathit{Provenance}_i + \mathit{Block}_k + \varepsilon_{ik} \quad (2)$$

representing the incomplete block design (lattice), and finally

$$X_{il} = \mu + \mathit{Provenance}_i + \mathit{Suprablock}_l + \varepsilon_{il} \quad (3)$$

where *Suprablock* is a new class variable made by adding two neighbour blocks of one replicate. The suprablocks have the double number of provenances compared to the blocks, but only half the number compared to the replicates, *i.e.* their number is eight.

The three models differ in the degree to which they model the environmental variation. Whereas model (1) gives a coarse evaluation of the environmental variation, model (2) gives a fine evaluation (small blocks), and model (3) is intermediate in this respect. On the other hand the residual degrees of freedom decrease when more parameters are included, and since model (2) with small blocks contains the most parameters, the number of residual degrees of freedom is smallest in this model (see table below).

The results of different models may be estimated at two levels: The significance of the included effects and the precision on the parameter estimated in the model. Results from the analysis of survival are given in the table below.

It follows that the effect of provenance was highly significant in all cases. However, the F-value for provenance was slightly higher in the suprablock model (model 3) than in model (1). The lattice design model (model 2) had the lowest F-value for provenance.

The precision of the estimates for the provenance effects (given by the width of the 95 % confidence intervals) was highest in the replicate block model and lowest in the lattice model. The suprablock model was almost as precise the replicate block model. Similar results were obtained by analysis of vertical height. For the variable crown area, the precision on the estimates was largest in the supra-block model (data not shown).

From this analysis we may conclude that the lattice design has improved neither the significance nor the precision of the estimates. The gain in modelling of the environment does not compensate for the loss in degrees of freedom on the error term. However, compared with the replicate block model, the suprablock model gives the same or perhaps even better results, the precision being almost the same and the significance levels slightly

Model	Effect	DF (effect)	F	P	DF (error)	95 % confidence limits
(1)	Provenance	11	15.8	<0.0001	33	0.125
	Replicate	3	7.22	0.0007	33	
(2)	Provenance	11	12.0	<0.0001	21	0.152
	Block	15	2.12	0.06	21	
(3)	Provenance	11	16.4	<0.0001	29	0.130
	Suprablock	7	4.14	0.003	29	

higher. Thus in this case (and for this variable) an intermediate block size may improve the outcome of the trial.

Irrespective of this analysis it is important to stress that there are potential gains in precision by using the lattice design, especially in cases where there are clear environmental gradients in the trial area. It is also important to note that these gains come free of charge – there are no differences in the establishment costs, and if there is no beneficial effect of the lattice design (as in this trial), there will be nothing wrong in analysing the trial as a replicate block design.

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