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OBSERVATIONS ON GENOTYPE × ENVIRONMENT INTERACTIONS AND STABILITY IN THE INTERNATIONAL NEEM (*AZADIRACHTA INDICA* A. JUSS.) PROVENANCE TRIALS IN BANGLADESH AND INDIA

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ABSTRACT

Variation in plant height, collar diameter and survival rate of six neem (*Azadirachta indica*) provenances was examined at three test sites in Bangladesh and India after a growing period of about seven months in the field. Provenance means for these traits were 52.87 cm, 8.35 mm and 67.36 % at site I; 42.74 cm, 6.69 mm and 83.38% at site II; and 36.21 cm, 4.70 mm and 44.40% at site III, respectively. Significant site and provenance effects were detected in the studied traits. Three out of the six provenances changed their ranks in height growth across the three sites and showed significant Genotype × Environment interactions. Positive correlations between collar diameter and survival rate at two sites were detected among provenances. Clinal variations were observed for collar diameter, survival rate and production percentage. The regression coefficient (b_i), Wricke's ecovalance (W_i) and deviation mean squares from the regression (δ_{ij}) were used as stability parameters to determine provenance stability across the three sites. There were no significant correlations between provenance height and the stability indices. High rank correlations between b_i and δ_{ij}, and between W_i and δ_{ij} were detected. Characterization of the sites by regression methods indicated that the interactions generated were presumably due to geoclimatic factors. The applications of the three stability indices to characterize adaptive similarity or diversity between the studied provenances are discussed.

Key words: *Azadirachta indica*, clinal variation, deviation mean square, ecovalence, genotype × environment interaction, regression coefficient

INTRODUCTION

The neem tree (*Azadirachta indica* A. Juss.) is noted for its impressive range of uses in medicine, timber and fuelwood, and its role in agroforestry, crop production, air pollution and high temperature control (ANON 1986; AHMED & GRAINGE 1986; KOUL *et al.* 1990; ANON 1992; TILANDER 1993; JACOBSON 1995). It is native to the Indian subcontinent and Myanmar but the exact origin of neem is unknown. Neem has been widely distributed by introduction, mainly in the drier tropical and subtropical zone of Asia, Africa, Australia, and Central and South Americas. Here we use the term "provenance" in a broad sense, including all seed sources of neem anywhere in the world. Since neem is a naturally renewable resource producing extensive useful biomass, its genetic improvement and economic exploitation are of great interest.

Genotype × Environment (*G*×*E*) interactions are present in genetic entries (clones, families, provenances or species) if their relative performances differ when entries are grown in different environments. *G*×*E* interactions have long been recognized as a potentially serious, practical problem in plant breeding and selection, because they can reduce genetic gain (ADES & GARNIER-GÉRÉ 1996). Several authors have considered *G*×*E* interactions as a linear function of the environment (FINLAY & WILKINSON 1963; WRICKE 1962; EBERHART & RUSSEL 1966; SHUKLA 1972). Numerous analytical methods have been developed to investigate the amount, source and significance of *G*×*E* interactions in breeding programs (KNIGHT 1970; SKRØPPA 1984; COOPER & DELACY 1994; KANG & GAUCH 1996). Some of these methods condense the consistency of genotypic performance for a given trait across environments into a single parameter or "stability" index. Some indices have been suggested and their properties and inter-relationships reviewed (MATHESON & RAYMOND 1984, 1986; LIN *et al.* 1986; BECKER & LÉON 1988; WEBER *et al.* 1996). Furthermore, the indices have also been found to be correlated (PIEPHO & LOTITO 1992; WEBER *et al.* 1996). The main application of the indices has been to identify genotypes of high stability to allow sound breeding programs to be established. Breeders aim to minimize differences in response to environmental variation either by selecting for genotypic stability or minimizing environmental variability that results in *G×E* interactions (Jinks & Pooni 1988). Stability indices developed for highly homogeneous crop varieties may also be useful in identifying adaptively divergent provenances or lines.

G×E interactions in forest trees have often been studied at the provenance level (Keiding 1977; Mullin *et al.* 1980; Lindgren 1983; Matheson & Raymond 1984). The observed performance of several seed sources at different locations may be regressed against a set of environmental variables (such as latitude, longitude, altitude, temperature and rainfall) to explain the causes of the pattern of variation (Raymond & Lindgren 1988; Kundu & Tigerstedt 1997). Definition of such an environmental gradient is a prerequisite for optimal utilization of the available genetic materials. Breeding zones may be established within the natural range of clinal species to overcome the problem of *G×E* interactions and guidelines may be set for acceptable seed transfer.

The International Neem Provenance Trials have been initiated to study genetic variation, adaptation and growth of neem provenances, and to assess the resulting *G×E* interactions in multi-environment trials (Hansen *et al.* 1997). Provenance variation on morphometric and phenological traits of neem has been reported by Dwivedi (1993), Surendran *et al.* (1993), Rajwat *et al* (1994), Veerendra (1995), Gupta *et al.* (1996) and Kundu & Tigerstedt (1997). The present study is based on preliminary observations in the International Neem Provenance Trials at three sites in Bangladesh and India. The information produced could be useful in making further attempts for tree improvement. The aims of this study are: (1) to examine the magnitude of provenance variation and *G×E* interactions on plant height, collar diameter and survival rate after field planting, (2) to characterize these provenances for yield stability, (3) to characterize the contribution of the sites to the interactions, and (4) to define the relationships between the geoclimatic factors and the studied traits.

MATERIALS AND METHODS

Seed exchange, nursery production and plantation establishment

Systematic collection and exchange of seeds by the International Neem Network have been coordinated by the FAO. Common guidelines developed by a working group of the network for nursery establishment of seedlings and experimental designs were followed (Thomsen & Souvannavong 1994). Seeds with hard shells (endocarp) were germinated in open nursery beds containing loamy-sandy soils at the nurseries of the Bangladeshi Forest Research Institute and Indian Arid Forest Research Institute. The sprouted seeds were then transferred into polybags, measuring 25.40 x 15.24 cm layflat, filled with topsoil and dry cowdung mixture (3:1). The nursery seedlings received supplementary watering whenever necessary until out-planting, 9 to 12 months later. The out-plantings were accomplished between July 28 and 30, 1996 at Charaljani (site I), on September 18, 1996 at Charkhai (site II) and between July 25 and August 5, 1996 at Jodhpur (site III).

Site conditions, experimental design and silvicultural treatments

The six common provenances or seed sources from Thailand (Tuang Luang P1, Ban Nong P2 and Doi Tao P3), Myanmar (Yezin P4), Nepal (Geta P5) and Ghana (Sunyani P6) were chosen to study *G×E* interactions. Details are given in Table 1 and Fig. 1. Descriptions of the three test sites namely, Charaljani, Charkhai (Ban

Table 1. Description of the neem provenances used in the study.

Provenance code	Provenance / seed source	Country of origin	Latitude (Lat)	Longitude (Long)	Altitude (Alt) m	Mean annual rainfall (MAR) mm	Dry season
P1	Tuang Luang	Thailand	9°09′N	99°07′E	4	1755	Jan–Apr
P2	Ban Nong Rong	Thailand	14°05′N	99°40′E	40	1145	Nov–Mar
P3	Doi Tao	Thailand	17°57′N	98°41′E	300	1250	Nov–Apr
P4	Yezin	Myanmar	19°51′N	96°16′E	100	1269	Nov–May
P5	Geta	Nepal	28°46′N	80°34′E	170	1725	Nov–Apr
P6	Sunyani	Ghana	7°21′N	2°21′W	975	1335	Dec–Mar

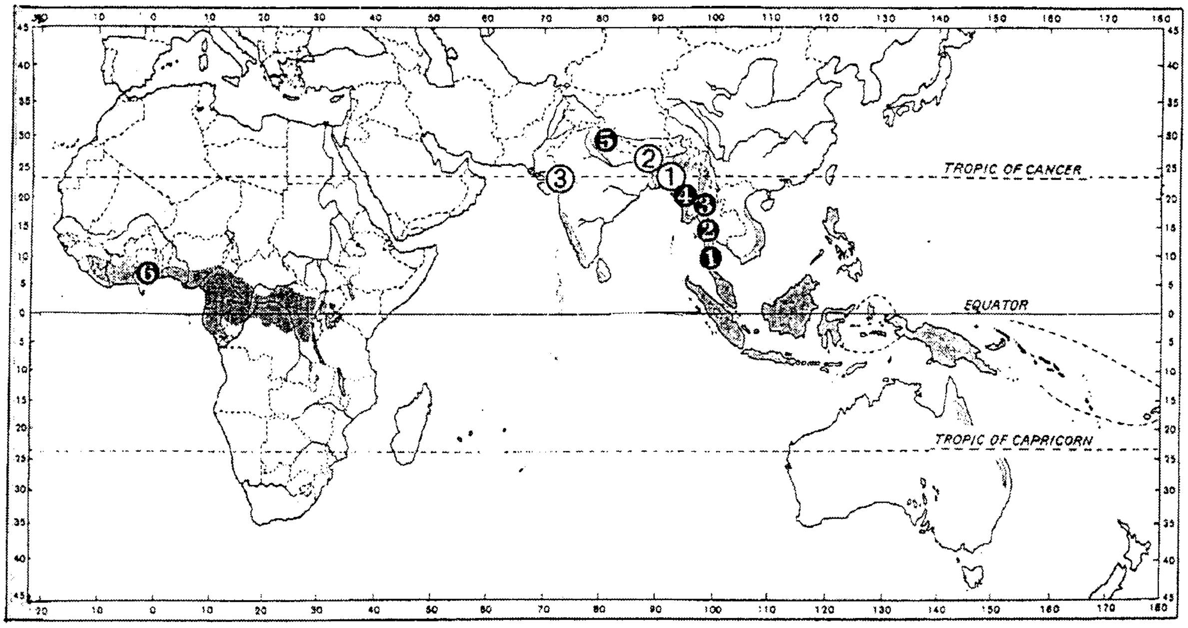

Figure 1. Distribution of the six neem provenances (❶❷❸❹❺❻) and the three sites (①②③) of the International Provenance Trials).

Table 2. Description of sites of the international neem provenance trials in Bangladesh and India included in the study

Site	Latitutde	Longitude	Altitude (m)	MAR (mm)	Dry season	*MMRH (%) range	Temperature °C	
							max	min
I Charaljani, Bangladesh	24°43' N	90°26' E	19	2246	Nov–Mar	56–85	29.9	20.4
II Charkai, Bangladesh	25°28' N	88°54' E	37	1695	Nov–Apr	46–83	30.8	19.7
III Jodpur, India	24°40' N	71°15' E	224	250	Mar–Jun	55–63	46.0	2.0

Site	Topography and soils	Original vegetation types
I Charaljani, Bangladesh	Flat to very gentle sloping. Brown forest soils derived from Plio-Pleistocene sediments. Clay loam to clay, pH 5.0–5.5	Moist deciduous *Shorea robusta* forests. Associates: *Adina, Albizia, Emblica, Syzigium, Terminalia*
II Charkai, Bangladesh	Flat to very gentle sloping. Brown forest soils derived from Plio-Pleistocene sediments. Clay loam to clay, pH 5.0–6.0	Moist deciduous *Shorea robusta* forests. Associates: *Albizia, Anthocephalus, Bombax, Miliusa*
III Jodpur, India	Flat to gentle sloping. Sandy loam, reddish brown. Moderately acid soil, pH 5.5–6.5	Dryland savanna forest, savanna dotted with xerophytes. Associates: *Prosopis, Acacia, Zizyphus*

gladesh) and Jodhpur (India) are presented in Table 2. The three sites were different in edaphic and climatic conditions and could be classified as optimum, intermediate and stress environments on the basis of mean annual rainfall (MAR), temperature (maximum and minimum) and soil conditions. Site I is characterized by a high MAR, moderate temperatures and clay loam soils. Site III is characterized by low MAR, extreme temperatures with winter frost. Site II is intermediate between the afore-mentioned sites.

The experimental design at each site was a randomized complete block design replicated in four blocks. Each provenance was represented in each block by 25 seedlings per plot. The seedlings were planted in pits (30 x 30 x 30 cm) with a spacing of 3 x 3 m square. Four periodic weedings were performed. A hoeing was done to enhance the soil aeration in site II in December, 1996.

Measurements

Observations on growth traits and survival rate were made on February 7 (site I), 24 (site II), and January 21 (site III), 1997 after a growing period of about eight months in the field. The evaluation of the trial included the following measurements and registrations: (a) Height (HT): height of the plant was measured as the distance between the soil surface and the tip of the terminal bud; (b) Collar diameter (CD): diameter of the stem at the soil surface as measured with a vernier caliper; (c) Survival rate (SV%): plant survival rate was calculated as number of survived plants divided by total plants planted and multiplied by 100.

Statistical analyses and concepts

Mean values and coefficient of variation were based on plot means. Differences among sites and provenances were established by analyses of variance (ANOVA) using SAS software (version 6.11) PROC GLM (SAS Institute Inc. 1996) with type III estimation of sum of squares. Whenever the differences were significant in the ANOVA, the means were separated using the Tukey's Honestly Significant Difference (HSD) test (P = 0.05). Variance components were obtained by using an option REML in the SAS VARCOMP program. Data on SV% were subjected to arcsin transformation in order to normalize the variance (FOWLER & COHEN 1990). Data from the three sites were combined and the following statistical model was used to analysis them. Site and provenance effects were considered to be fixed and other sources of variation were treated as random.

$$X_{ijk} = \mu + G_i + E_j + (GE)_{ij} + B_{k(j)} + \varepsilon_{ijk} \qquad [1]$$

where X_{ijk} = observed value of a given character for an individual measurement of the *k*th plant of the *i*th provenance at site *j*, μ = overall mean, G_i = genotypic effect (*i*th provenance), E_j = environmental effect (*j*th site), $(GE)_{ij}$ = genotype (*i*th provenance) x environmental (*j*th site) interaction effect, $B_{k(j)}$ = effect of replicates *k* at site *j*, ε_{ijk} = random error.

*G*x*E* interactions were further characterized by provenance stability analyses.

Correlations and simple regressions

The Pearson's product-moment correlations among the studied traits were computed by using the provenance means of an individual site. Simple linear regressions analyses were also performed to determine the relationships between the performance and provenances. Spearman's rank-order correlations among stability indices were computed because the stability parameters can not be assumed to be normally distributed (BECKER 1981; PIEPHO & LOTITO 1992).

Stability parameter concepts

Although there are many biometrical studies of stability models and parameters, they do not provide sufficient predictive information for ranking of genotypes or on how a variety responds to a range of environments. We have chosen three widely used stability parameters, namely (a) the *regression coefficient* (b_i), (b). *Wricke's ecovalance* (W_i) and (c) *mean squares deviation from the regression* (δ_{ij}) proposed by FINLAY & WILKINSON (1963), WRICKE (1962) and EBERHART & RUSSEL (1966), respectively (Table 3).

a. *Regression coefficient* (b_i)

The regression approach is very often used in analyzing *G*x*E* interactions. The regression coefficient is a standardized description of covariance of the effect of environments and of *G*x*E* interactions. The regression coefficient reflects that proportion of genotypic stability associated with the capacity of a genotype to perform relatively better in unfavorable than in favorable environments (HANSON 1970). In this approach the yield of a specific genotype in a given environment is regressed on another measure of the environment. Regression coefficients (b_i) are estimated using the following regression model:

$$y_i = a + bx_i + e_i \qquad [2]$$

where y_i is the provenance value at site *i*, *a* is the intercept of the provenance, x_i is mean of all provenances at this site, and *e* is the unknown error. A b_i value close to 1 indicates average stability; a higher value, low stability; and a lower value, high stability. Furthermore, a genotype with a high yield over all environments and a regression coefficient close to 1 is regarded as being well-adapted to all environments compared to a genotype with the same regression coefficient but a low overall mean yield. The latter is regarded as being poorly adapted to all environments. A genotype which has a regression coefficient higher

Table 3. Formulae used to compute stability indices of the six neem provenances

Stability index	Formula
Coefficient of regression	$b_i = 1 + \dfrac{\sum_{j=1}^{g} (x_{ij}-\bar{x}_{i.}-\bar{x}_{.j}+\bar{x}_{..})(\bar{x}_{.j}-\bar{x}_{..})}{\sum_{j=1} (\bar{x}_{.j}-\bar{x}_{..})^2}$
Ecovalence	$W_i = \sum_{j=1}^{e} (x_{ij}-\bar{x}_{i.}-\bar{x}_{.j}+\bar{x}_{..})^2$
Deviation mean squares from the regression	$\delta_{ij} = (E-2)^{-1}[\sum_{j=1} (x_{ij}-\bar{x}_{i.}-\bar{x}_{.j}+\bar{x}_{..})^2-(b_i-1)^2\sum_{j=1} (\bar{x}_{.j}-\bar{x}_{..})^2]$

X_{ij} is the mean of provenance *i* (*i* = 1, ..., e) in *j* (*j* = 1, ... , *g*) environment, and $X_{i.}$, $X_{.j}$ are the marginal means of provenance *i* and environment *j*, and *X* is the grand mean; b_i is the regression coefficient (FINLAY & WILKINSON 1963), W_i is the ecovalence (WRICKE 1962), δ_{ij} is the deviation mean squares from the regression (EBERHART & RUSSEL 1966) of the *i*th provenance at the *j*th environment, and *E* is the number of environments

than 1 but a low overall mean yield is well-adapted only to favorable environments and a genotype with a regression coefficient lower than 1 but with a moderate overall mean yield is adapted to unfavorable environments as described by FINLAY AND WILKINSON (1963).

b. *Wricke's ecovalance* (W_i)

Ecovalence measures the contribution of a genotype to the *G*×*E* interactions. It reflects the capacity of a genotype to yield more consistently among environments than other genotypes. The ecovalence strongly depends on the environments included in the test and the breeder can manipulate the ecovalence by choosing specific locations. A genotype with high ecovalence $W_i = 0$ is regarded as stable in all environments.

c. *Mean square deviation from the regression* (δ_{ij})

In addition to the ecovalence, the deviation mean squares δ_{ij} describe the contribution of genotype *i* to *G*×*E* interactions. A low δ_{ij} indicates a good fit to the linear model. For ranking purposes, the choice of desired δ_{ij} value depends on the specific goal, while independently of the objective, the δ_{ij} values of the stable genotypes are zero.

Interrelationship of the three stability parameters

The three parameters could be used as additional variables for selection. They are related by the following equation and there is generally a high correlation between W_i and δ_{ij} (WRICKE & WEBER 1986):

$$W_i = (b_i-1)^2(SS_{loc})/g + r\Sigma_j\delta_{ij} \qquad [3]$$

where SS_{loc} is the usual sum of squares of locations, *g* is the number of genotypes and *r* is the number of replications.

RESULTS

Variation among the provenances

Simple statistical parameters [mean and coefficient of variation (CV)] for the traits at the three sites with the statistical significance at the 5% level for the combined sites means are presented in Table 4. Sites I, II and III showed the highest, medium and lowest performance, respectively, for all traits, except the highest SV% (83.38) at site II. There was a considerable variation in HT and CD across the three sites. Provenance P3 was significantly different (P = 0.05) from the others in height growth. The provenance ranking at the three sites are presented in Table 5. Provenances P1, P2 and P4 changed ranks at different sites while P3, P5 and P6 did not show any change.

The combined analyses of variance (Table 6) indicated very highly significant site effects on all traits (HT, CD and SV%). A very highly significant prove-

Table 4. Statistical parameters used to compare the six neem provenances in three environments

Site	Trait	Statistical parameter	P1	P2	P3	P4	P5	P6	All provenances
I **Charaljani** **Bangladesh** *Optimal environment*	Height (cm)	Mean	65.12	49.46	41.10	54.16	51.14	56.27	52.87
		CV	5.30	11.22	13.48	7.07	9.74	3.16	15.84
	CD (mm)	Mean	8.90	9.26	8.62	8.25	6.72	8.32	8.35
		CV	10.87	11.30	8.70	12.56	12.03	4.35	13.42
	SV%	Mean	74.03	66.63	57.40	58.85	68.35	79.18	67.36
		CV	15.05	6.41	7.25	15.73	13.61	10.84	15.97
II **Charkai** **Bangladesh** *Intermediate environment*	Height (cm)	Mean	40.72	42.89	34.13	50.15	42.76	46.35	42.74
		CV	19.61	5.22	27.85	13.23	3.19	2.94	16.88
	CD (mm)	Mean	8.02	7.83	6.70	6.37	5.45	7.10	6.91
		CV	18.43	5.34	26.86	6.85	5.28	4.17	18.16
	SV%	Mean	84.26	84.11	82.79	84.25	80.62	84.25	83.38
		CV	0.00	0.31	3.50	0.03	9.02	0.03	3.77
III **Jodhpur** **India** *Stress environment*	Height (cm)	Mean	43.65	30.43	29.51	41.64	34.77	42.22	37.04
		CV	15.13	25.99	16.45	6.42	20.18	12.91	21.34
	CD (mm)	Mean	4.89	5.24	4.45	4.44	4.72	4.45	4.70
		CV	14.83	15.18	6.48	9.95	27.37	16.26	15.93
	SV%	Mean	49.20	34.10	52.24	33.11	44.89	52.85	44.40
		CV	34.32	25.27	17.99	12.87	56.75	42.75	37.68
Combined sites	Height	Mean	49.83	40.93	34.91	48.65	42.89	48.28	44.25
	CD		7.27	7.44	6.59	6.36	5.63	6.62	6.65
	SV%		69.17	61.61	64.14	58.65	64.62	72.09	65.05

Means with the same superscript letters are not significantly different at $P = 0.05$ (Tukey's HSD test); CV, coefficient of variation.

Table 5. Rank of the six neem provenances based on height at three sites

Provenance	Final rank	Rank at site		
		I	II	III
P1	1	1	5	1
P4	2	3	1	3
P6	3	2	2	2
P5	4	4	4	4
P2	5	5	3	5
P3	6	6	6	6

nance effect was observed for HT and CD, with a significant effect on SV%. A significant site x provenance interaction effect was observed only for HT.

Provenance stability analyses

The values of each stability index calculated for each provenance and overall provenance mean height are presented in Table 7. A plot of provenance mean heights against the site means together with the estimated regression lines is shown in Fig. 2. The results indicate that provenances (P4 and P6) with a lower slope of regression than the average had superior height at the stress site (III) and average or poor performance on optimal or intermediate sites (I and II, respectively). Provenances P1, P3 and P5 showed below average, above average and average stability, respectively. A plot of the three stability parameters (b_i, δ_{ij} and W_i) against the provenance means is presented in Figs. 3a, 3b and 3c, respectively. Provenances P4 and P6 falling in the lower, right hand sides proved to be superior according to the three stability parameters. A plot of

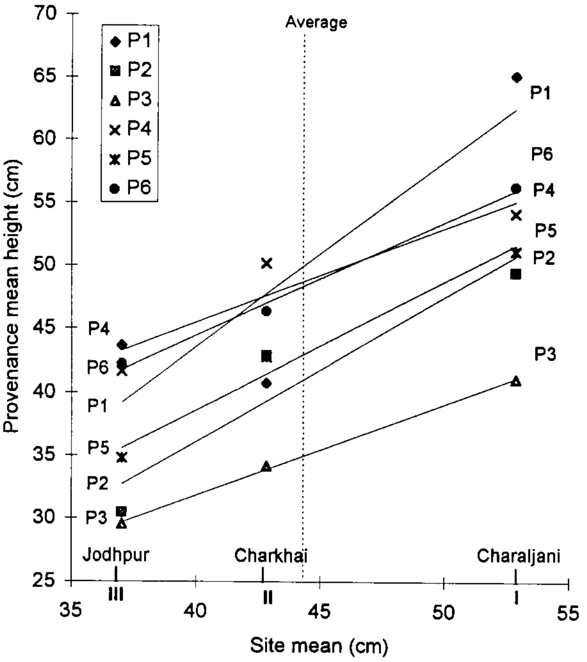

Figure 2. Plot of provenance mean height for the six neem provenances against site mean with corresponding regression lines.

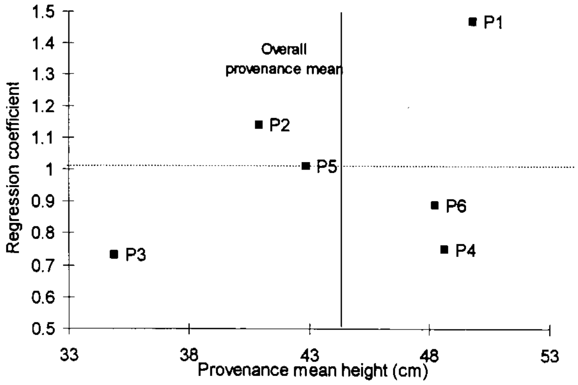

Figure 3a. Relationships between regression coefficients and provenance means of the six neem provenances.

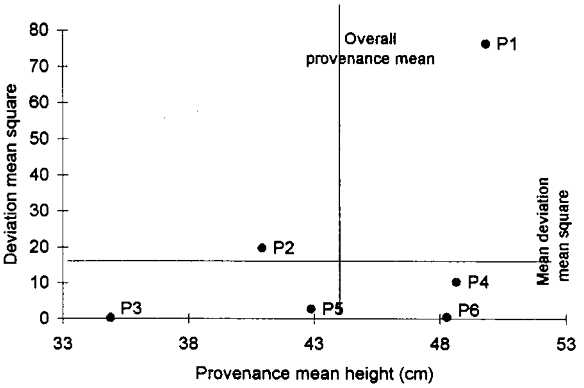

Figure 3b. Plot of deviation mean squares against provenance means.

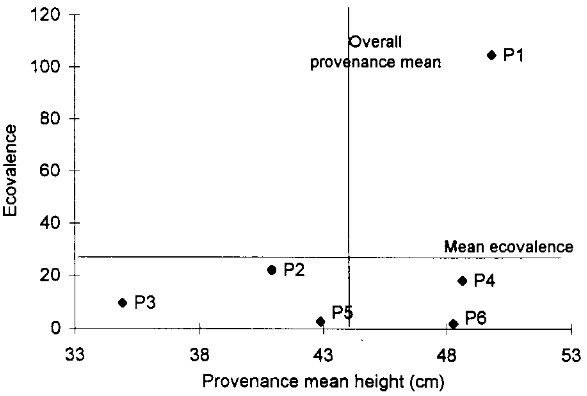

Figure 3c. Plot of ecovalence against provenance means.

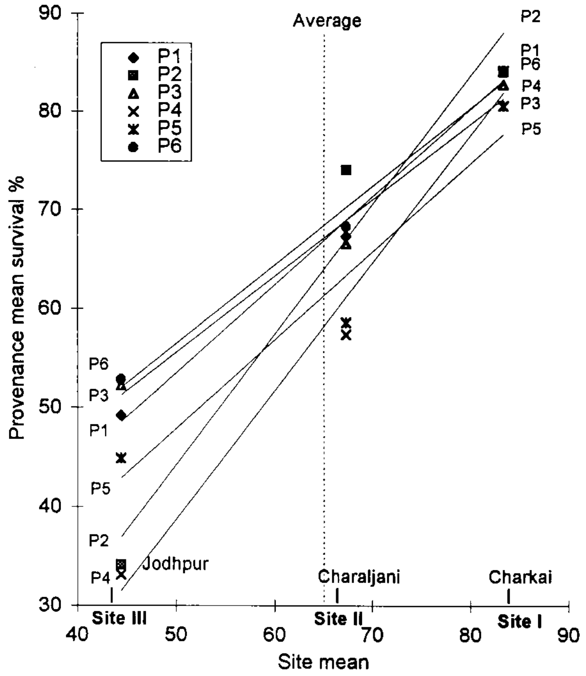

Figure 4. Plot of provenance mean survival % for the six neem provenances against site mean with corresponding regression lines.

regression lines between provenance mean survival rates and site means is shown in Fig. 4. Provenances (P1, P3 and P6) with a lower than average slope had superior survival rates at stress or poor site, while provenances (P2, P4 and P5) with significantly steeper than average slopes had poor survival rates at stress site.

The Spearman's rank-order correlations for HT and the three stability indices are presented in Table 8. No index was significantly correlated to mean height. Significant correlations (r = 0.83) between b_i and δ_{ij}, and between W_i and δ_{ij} were observed.

Table 6. Combined analyses of variance on height (HT), collar diameter (CD) and survival percentage (SV%) of the six neem provenances tested at three sites of Bangladesh and India

Traits	Source	df	Mean Square	F-value	Variance component (%)
HT	Site	2	1540.35	49.11***	–
	Block (site)	9	22.48	0.72***	0.00
	Provenance	5	400.47	12.77*	–
	Site x Provenance	10	63.77	2.03*	8.47
	Error	45	31.36		29.88
	Total	71			
CD	Site	2	80.85	107.95***	–
	Block (site)	9	0.93	1.24	0.03
	Provenance	5	5.16	6.89***	–
	Site x Provenance	10	1.01	1.35	0.07
	Error	45	0.75		0.75
	Total	71			
SV %	Site	2	9215.13	112.63***	–
	Block (site)	9	288.02	3.52**	34.37
	Provenance	5	288.93	3.53*	–
	Site x Provenance	10	160.60	1.96	19.70
	Error	45	81.82		81.82
	Total	71			

*, Significant at $P < 0.05$; **, significant at $P < 0.01$; ***, significant at $P < 0.001$.

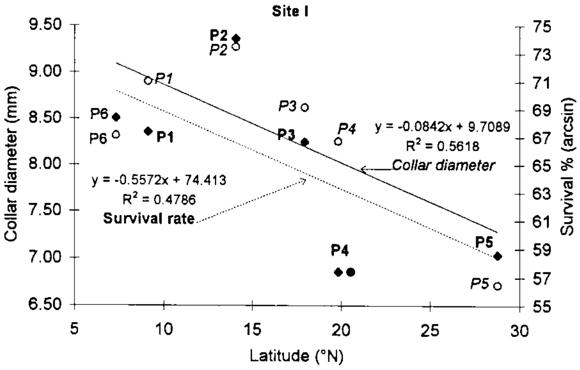

Figure 5a. Plot of collar diameter and survival rate for the six neem provenances against the latitude of origin with corresponding regression lines at site I. Provenances values for the CD and SV% are represented as *P1* to *P6* ($r = -0.75$) and **P1** to **P6** ($r = -0.65$), respectively.

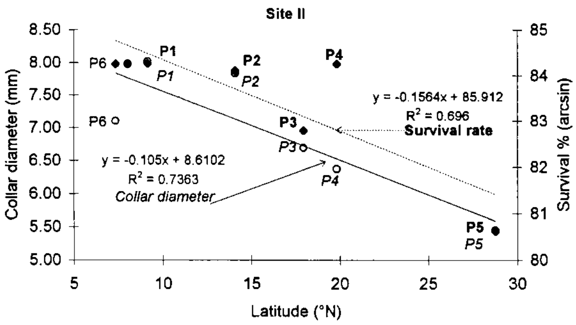

Figure 5b. Plot of collar diameter and survival rate for the six neem provenances against the latitude of origin with corresponding regression lines at site II. Provenances values for the CD and SV% are represented as *P1* to *P6* ($r = -0.75$) and **P1** to **P6** ($r = -0.65$), respectively.

Interdependence among characters

The Pearson's product-moment correlations coefficient (r) and significance probabilities for studied traits at the three sites are presented in Table 9. Strong positive correlations ($r = 0.74$ and 0.79) were observed between CD and SV% at sites I and II, respectively. Correlation between HT and CD was weak at the three sites. At the individual site level, there were strong negative relationships between Lat and CD ($R^2 = 0.56$), and between Lat and SV% ($R^2 = 0.48$) at site I (Fig. 5a). Further strong relationships between Lat and CD ($R^2 = 0.73$) and between Lat and SV% ($R^2 = 0.67$) at site II were observed (Fig. 5b).

A correlation matrix for combined provenance means of the studied traits and geoclimatic data is summarized in Table 10. Strong negative correlations between Lat and CD (r = –0.77) and between Lat and SV% (r = –0.59) were observed. A strong positive

Table 7. **Stability index for each neem provenance for height**

Provenance	Provenance mean height (cm)	Regression coeffcient (b_i)	Ecovalence (W_i)	Deviation mean square (δ_{ij})
P1	49.83	1.47^{NS}	104.71	76.32
P2	40.93	1.14^{NS}	22.19	19.67
P3	34.91	0.73*	9.63	0.26
P4	48.65	0.75^{NS}	18.24	10.21
P5	42.89	1.01^{NS}	2.64	2.63
P6	48.28	0.89*	1.99	0.43
Mean	44.25	0.99^{NS}	26.57	18.25

$^{NS.}$ Not significantly different at $P < 0.05$; *, significant at $P < 0.05$.

Table 8. The Spearman's rank-order correlation coefficients for the variable height (HT) and the three stability indices of the six neem provenances

Stability index	HT	b_i	W_i
b_i	0.43^{NS}		
W_i	0.31^{NS}	0.54^{NS}	
δ_{ij}	0.60^{NS}	0.83*	0.83*

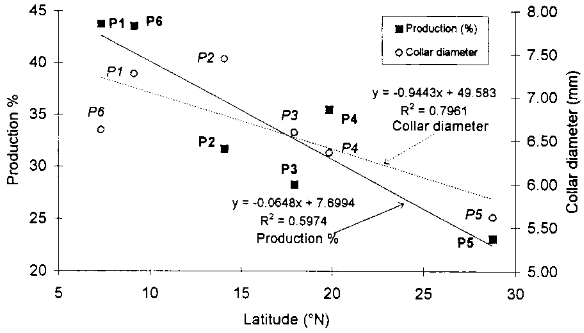

Figure 6. Regression lines showing the relationships between latitude and production % (HT×SV%) on the one hand and latitude and collar diameter on the other hand. Provenance values for the production % and collar diameter (combined analysis) are represented as **P1** to **P6** and *P1* to *P6*, respectively.

correlation was also detected between Alt and SV% (r = 0.64). At the combined site level, strong negative relationships between Lat and CD (R^2 = 0.80) on the one hand, and Lat and production % (R^2 = 0.60) on the other were revealed (Fig. 6).

DISCUSSION

The variation among provenances in growth and survival rate observed in the present study indicates the potential benefits of choosing the best provenance for a site. Site means of traits decreased with increasing altitude, and decreasing rainfall and temperature. Seedlings and young trees are often sensitive to extremes of cold and drought (SHELBOURNE 1972). Poor performance of growth traits examined in this study at site III was most likely due to extreme temperatures and low rainfall.

Strong correlations between CD and SV% detected in this study at sites I and II suggest that there is a good opportunity to select seedlings with larger CD in order to secure early establishment. Seedlings with a smaller CD often suffer more from moisture stress than those with a larger CD (MCGRATH & DURYEA 1994). Accordingly, culling (seedling grading) of seedlings prior to out-planting is a vital step for tree improvement. Our results conform with the studies of LONG & CARRIER (1993) and DHURIA (1995).

The results of regressions between the geographical factors with the provenance means of individual sites as well as with the overall provenances means suggest a clinal variation among the provenances in CD and SV%, and production percentage and CD, respectively. The strong relationships between Lat with CD and SV% at sites I and II suggest that geographical factors could influence growth and survival of neem. KUNDU & TIGERSTEDT (1997) reported the clinal variation in neem provenances related to Lat and MAR. RAYMOND & LINDGREN (1990) suggested the combination of HT growth and survival rate into a single index and proposed that production rate may be useful in defining growth. Similar results on clinal variations by KHASA *et al.* (1995) have also been reported on *Racosperma auriculiforme* and *R. mangium*.

Our results of stability analyses are generally consistent with relationships found in various crops where δ_{ij} and W_i are strongly correlated, while b_i and W_i are not (BECKER & LÉON 1988; PIEPHO & LOTITO 1992; WEBER *et al.* 1996). The low correlations between HT and both δ_{ij} and W_i in the present study could be explained by the low proportion of interaction revealed by the joint regression.

Table 9. The Pearson's product-moment correlation coefficients among the studied traits of the six neem provenances at three sites. Provenance means of each site have been used in the analyses. I, II and III are the three sites

	HTI	HTII	HTIII	CDI	CDII	CDIII	SV%I	SV&II
HTII	0.46							
HTIII	0.88*	0.61						
CDII	0.09	–0.18	–0.05					
CDII	0.41	–0.14	0.16	0.91**				
CDIII	0.16	–0.13	–0.31	0.38	0.54			
SV%I	–0.08	–0.40	–0.35	0.74	0.79*	0.60		
SV%II	0.35	0.27	0.38	0.86*	0.79*	0.09	0.46	
SV%III	0.05	–0.54	0.12	–0.13	0.02	–0.40	0.16	–0.18

*, Significant at $P < 0.05$; **, significant at $P < 0.01$; ***, significant at $P < 0.001$.

Table 10. The Pearson's product-moment correlation coefficients (r) among the studied traits and geoclimatic data of the six neem provenances. The combined provenance means have been used in the analyses

Traits	HT	CD	SV%
CD	0.07		
SV%	0.36	0.12	
Lat	–0.38	–0.77	–0.59
Alt	0.11	–0.21	0.64
MAR	0.31	–0.44	0.37

The 'r' values are not significantly different at $P < 0.05$.

In our present study, the provenance with a lower regression coefficient than average had superior height on the poor site and average or poor performance on good sites. Provenances with a lower coefficient line than average had superior survival rate on poor sites, while provenances with steeper slopes than the average had poor survival. The high survival rates at sites I and II may be due to more favorable planting conditions. On the other hand, a high mortality rate in site III indicates a stress environment. The results of the regressions for HT and SV% followed the interpretation of Finlay & Wilkinson (1963). These results also correspond to similar studies reported by Lindgren (1983), Clair & Kleinschmit (1986) and Khasa *et al.*(1995).

The significant provenance x site interactions revealed in this study indicate that provenances show different relative performances on the different sites. Several studies on other species, such as *R. auriculiforme* and *R. mangium* (Khasa *et al.* 1995), tropical pines and eucalypts (Matheson & Raymond 1984; Otegbeye & Samarawira 1991; Wright *et al.* 1991) accord with the results of the present study. In our study, the ratio of the variance component of provenance x site and provenance is 0.3. In the examples by Lindgren (1984) for forest trees, the relation varied between 0 to above 3 with most cases below 1. For cereals, it varied between 1.4 and 8.9. Shelbourne (1972) has suggested that when the relation is above 0.5 the interaction is a serious threat to the breeding program. We found a moderate impact of *G*x*E* interactions within species, though the earliness of the present evaluation casts some doubt on the reliability of *G*x*E* estimates. Over the long run, however, the *G*x*E* interactions effect must be considered at later stages of the provenance testing program as suggested by Barnes *et al.* (1984).

Our data suggest that temperature, rainfall, soil types, latitude and altitude are the distinct environmental factors interacting with genotypes. When several environmental factors influence yield, it is difficult to identify which is the limiting factor(s) for the *G*x*E* interactions (Skrøppa 1984). In this study, the three sites differ in both rainfall and temperature. Probably these are the major factors causing interactions in height growth.

Over the short term, breeding zones may be set up in environmentally homogeneous areas and the best genotypes selected for them. This may reduce cost and considerably increase the genetic gain because the best materials are selected. Another possibility is to select stable provenances for a long term breeding program. For practical purposes, this strategy of selecting provenances that are adapted to the average site may be applicable in neem. But breeding neem only for stable provenances may involve a reduction in genetic gain and consequently genetic erosion. Therefore, breeding for composite traits such as disease and drought resistant, higher limnoid content in the seeds and high dry-matter production for the common interests may be recommended.

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