New Forests (2006) 31:305–320
DOI 10.1007/s11056-005-8198-6

# Seed size as a predictor of germination success and early seedling growth in 'hollong' (*Dipterocarpus macrocarpus* Vesque)

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Received 27 May 2004; accepted in revised form 24 May 2005

**Key words:** Germination time, India, Seed diameter, Seed weight, Seedling vigour

**Abstract.** In species with seeds losing viability shortly after dispersal and exhibiting inherently low germination, quick decisions are required with respect to seeds that should be selected to maximize germination success and vigorous growth of seedlings. In 'hollong' (*Dipterocarpus macrocarpus* Vesque), I address the following questions: (a) are seeds that germinate randomly distributed within a seed population, (b) are subpopulations of viable and non-viable seeds separable, (c) does seed size predict which seeds germinate and (d) does seed size predict time required for germination and seedling vigour? Two estimators of seed size, diameter and weight, demonstrated a significant positive linear relationship endorsing assumption that accumulation of mass increases with increase in diameter of seeds. A threshold for selection of potential seeds for germination could not be derived from diameter measurements since seeds in an entire range of diameter did or did not germinate. All seeds <11 g did not germinate, but this threshold lies at the far lower end of the weight range and allows rejection of only a few seeds and acceptance of many seeds that will not germinate. A risk of potential seeds being rejected or non-viable seeds being picked exists if selection was derived from either diameter or weight. However, viable seeds could be better predicted from a scatter-plot of diameter on *x*-axis and weight on *y*-axis. Seeds showed a fan-shaped scatter and those developing the lower blade of the fan did not germinate while those following the handle were successful. Hence, two subpopulations segregated, but with a fuzzy edge. Mean diameter and mean weight of germinated seeds were significantly greater than those of ungerminated seeds. Most ungerminated seeds were those that had relatively smaller weight compared to their diameter. Although some large diameter seeds with small weight did germinate, but failed to develop into seedlings. Germination time and seedling vigour parameters (height, leaf number and collar diameter) were correlated both with diameter and weight. However, weight appears to have mattered more than diameter in germination success and early seedling growth.

## Introduction

Natural regeneration of 'hollong' (*Dipterocarpus macrocarpus* Vesque) is abundant in proximity of seed-bearing trees and scarce in openings. Regeneration success is reduced by pre- and post-dispersal pest attack and explicit microsite requirements for germination and growth (Troup 1980). Weevils, especially *Alcides craessus* attack fruits to reduce germination percentage heavily (Troup 1980). Wild boars, barking deer, hog deer, sambar, and mongoose damage seeds a great deal. Hollong, a fire-adapted species, prefers mineral soil (rich sandy loam), cannot tolerate waterlogging and grows best on high tablelands and well-drained slopes. Hollong is shade loving in early stages of growth, but requires ample light for gregarious growth after it surpasses lower canopy (Rajkhowa 1960a). If seeds disperse to well-lit microsites not only light but also grasses, weeds and bamboo brakes impede germination and early seedling growth. On the other hand, if seeds disperse near or under the parent canopy, competitive conspecific or associate species' environment with the low light suppresses young established poles. Although natural mortality of established young individuals of hollong is negligible, climbers such as *Derris oblonga*, *Tapiria hirsute* and *Mezoneurum cucullatum* suffocate and kill hollong saplings and poles (Rajkhowa 1961). Hence, for flourishing germination and establishment, hollong seeds must disperse somewhat away from the parent, but arrive in shady, well-drained and bare microsites with no or little herbaceous growth. The end-result of dispersal of winged fruits of hollong is a trade-off between gravity and wind current. Gravity directs vertical movement of heavy-weighted fruits to the forest floor. However, large wings aid horizontal movement to farther distances depending upon the wind current during the event of dispersal.

Natural regeneration of hollong has been a subject of field study for over seven decades (Sen Gupta 1939; Srinivasan 1956; Mohan Lal 1960; Rajkhowa 1960a,b, 1961; Seth and Dabral 1960a,b; Vincent 1961; Roy and Kalyan Naha 1967; Troup 1980). Systematic tending is known to have encouraged regeneration of hollong. In Lakhimpur Forest Division in Assam, enhanced regeneration was noted after retention of natural seedlings, exclusion of weeds, felling or girdling of inferior trees and manipulation of lower canopy with progression of regeneration (Seth and Dabral 1960a).

During approximately 1900–1970, massive selection felling of hollong occurred for veneer, railway sleepers, and electric and telecommunication poles (Srinivasan 1956; Troup 1980). Most often during 1970 and 1996, i.e., until the Supreme Court of India enforced a blanket ban on clearfelling in northeastern region of India, selection-felling rules were overlooked and clear felling was done. Reforestation of cleared lands was a challenge to the silviculturists. Raising seedlings in nurseries requires minimizing costs (energy and money) by selection of seeds that germinate and establish healthy seedlings. However, no such attempt has been made. In this study, I address the following questions: (a) are seeds that germinate randomly distributed within a seed population, (b) are subpopulations of seeds that will germinate and will not germinate separable, (c) does seed size predict the seeds that germinate, and (d) does seed size predict time required for germination and seedling vigour? The results have implication in reforestation programmes of species with large variation in seed size, short viability after dispersal and inherently low germination, such as hollong that require quick selection of seeds that would give rise to vigorous seedlings to curtail investment in sowing seeds not expected to germinate and establish seedlings.

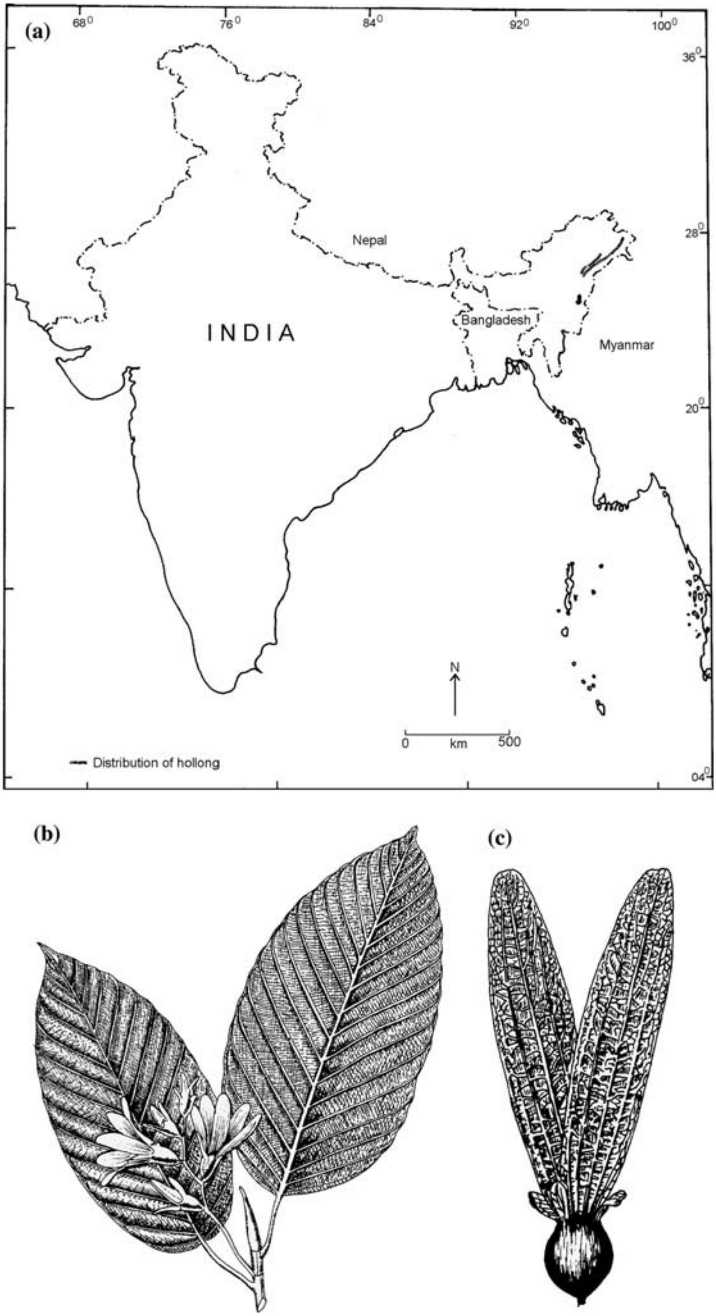

*Figure 1.* (a) Geographical distribution of hollong in Indian sub-continent. (b) A flowering twig of hollong. (c) A mature fruit of hollong with two calyx lobes developed into wings and three undeveloped lobes.

## Materials and methods

### *Fruit collection*

Fruits were collected from the Proposed Deomali Elephant Reserve (PDER), a celebrated home of hollong. PDER (95°10′–95°40′E longitude, 26°55′–27°15′N latitude) is located at the tri-junction of the States of Arunachal Pradesh, Assam and Nagaland (Figure 1). Ripe fruits of hollong falling early in spring were collected from the forest floor on March 08, 2002. Two hundred fruits were collected, sealed in polythene bags and transported to the laboratory. The persistent calyx was excised at the pericarp level. When necessary the pedicel was excised too. Henceforth, excised fruits shall be referred to as 'seeds'.

### *Seed germination and seedling growth*

Fresh seeds were measured for diameter using a calliper to 0.1 mm precision and weight using a Sartorius digital balance to 1 mg precision. Measured seeds were labelled and stored in a paper bag until sowing. Seeds were sown without any nutrition supplement in polythene bags on March 11, 2002. Polythene bags (16 cm diameter, 22 cm length, with drainage holes) were filled with a mixture of lateritic loam and sand (1:1 ratio), placed in a nursery shade house, watered regularly and examined daily for germination. Since germination is hypogeous, confounding effects of cotyledonary photosynthesis on early growth of seedlings are minimal.

Seeds were considered germinated as early as the radicle emerged on the soil surface (Figure 2a and b). The time between germination and development of first pair of leaves was recorded as 'leaf emergence time' (Figure 2c and d). Germination ceased 66 days after sowing. Ungerminated seeds were retrieved to confirm death. Shoot height, root collar diameter and leaf number were measured (Figure 2e). Shoot height was measured between the shoot tip and placental joint. Collar diameter was measured just above the placental joint. Growth of all surviving seedlings was measured on two occasions, namely, on August 12, 2002 marking the growth that had occurred during the wet summer and on November 11, 2002 marking the growth that had occurred during autumn. One of the seeds produced two seedlings (Figure 2f), but was discarded from the analyses.

### *Data analyses*

Quantitative analyses are based on seed size measured as diameter and weight. Seeds were classified in three diameter classes: small ( <3 cm), intermediate (≥3 to <3.5 cm) and large (≥3.5 cm) (diameter ranged between 2.53 and 4.06 cm).

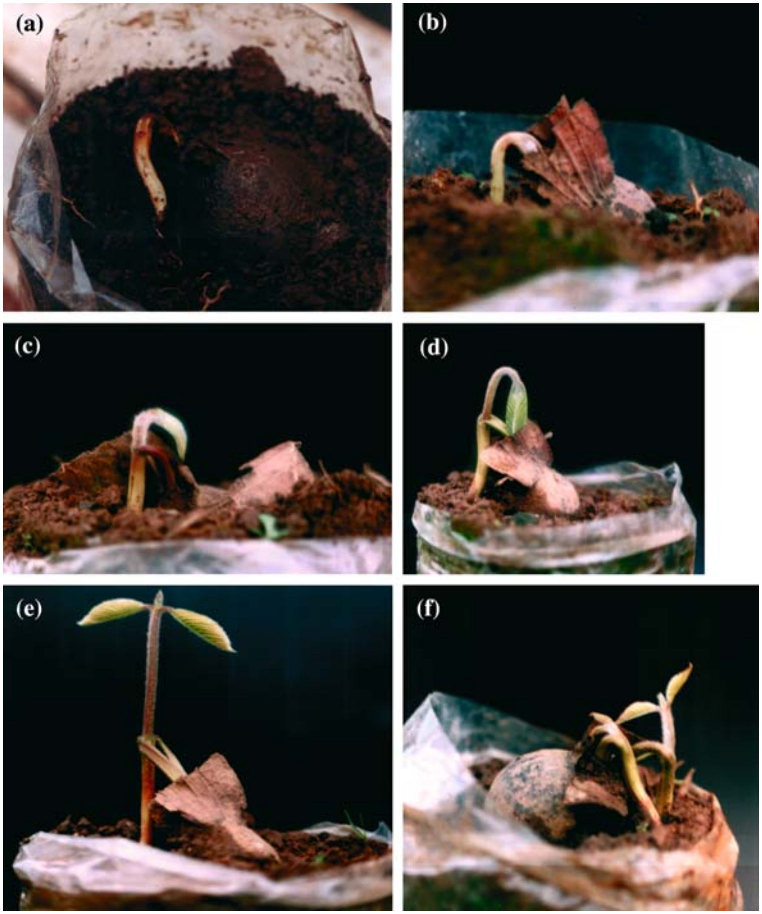

*Figure 2.* Images depicting stages of seed germination and early seedling growth of hollong. (a) An excised seed showing emergence of radicle. (b) Geotropic movement of radicle. (c) Emergence of plumule. (d) First pair of cotyledonary leaves flushing. (e) A complete seedling still receiving nourishment from reserves in the seed. (f) An aberration with emergence of two seedlings from a single seed.

Similarly, seeds were classified in three weight classes: light ( <17 g), intermediate (≥17 to <27 g) and heavy (≥27 g) (weight ranged between 6.86 and 37.74 g).

The population of observations on diameter and weight were tested for normality by plotting observed and expected frequency distributions followed by Kolmogorov–Smirnov (K–S) test (StatSoft Inc. 1995). The variability of mean values of seed size and seedling growth parameters is represented as standard deviation (Zar 1984). The differences between group means were detected by one-way analysis of variance (ANOVA) followed by *post hoc* pair wise multiple comparisons called as Fisher's Least-Significant-Difference (LSD) test. Simple or multivariate linear regression models were fitted to seed size (diameter and weight) and seedling growth (height, collar diameter and leaf number) parameters.

Seed germination percentage was calculated. The time required between sowing and emergence of radicle from the soil surface was considered as 'germination time'. The time spent between radicle emergence and sprouting of first pair of leaves was considered as 'leaf emergence time'. Two tailed $z$ statistic (Hoshmand 1998) was used to determine differences in germination percentages between two samples and probabilities calculated following StatSoft Inc. (1995).

## Results

### *Seed population and variation in seed size*

Of 200 hollong seeds collected from the forest floor, 10 'hollow' seeds (devoid of cotyledonary mass) were rejected and 190 'filled' seeds (containing cotyledonary mass) were measured for diameter and weight. The populations of diameter and weight measurements followed normal distribution (Figure 3). Diameter of all 190 sown seeds ranged between 2.53 cm and 4.06 cm and averaged 3.24 ± 0.30 cm. Seed weight ranged between 6.86 and 37.74 g and averaged 18.84 ± 6.63 g.

It is generally assumed that a seed will have an increasingly greater weight with an increase in its diameter. This is expected to result, as in hollong, in a significant positive linear relationship ($n = 190$, $r = 0.687$, Table 1) between diameter and weight (Figure 4a). The relationship gets stronger if only seeds that germinated were considered ($n = 92$, $r = 0.869$, Table 1), and seeds that did not germinate ($n = 98$, $r = 0.564$, Table 1) were discarded (Figure 4b). Often, ungerminated seeds exhibit large diameter but small weight. Mean diameter of 98 ungerminated seeds (3.19 ± 0.28 cm) was lower than that of 92 germinated seeds (3.29 ± 0.31 cm) and the difference in means was statistically significant (df $= 1$, $F = 5.38$, $p < 0.021$). Similarly, mean weight of ungerminated seeds (15.43 ± 5.69 g) was far lower than that of germinated seeds (22.47 ± 5.56 g) and the difference in means was highly significant (df $= 1$, $F = 74.48$, $p < 0.000$).

The scatter plot of seed diameter ($x$-axis) and weight ($y$-axis) was fan-shaped (Figure 4a). Germinated and ungerminated seeds segregated spatially into two distinct populations (Figure 4b). However, edges of two populations were fuzzy, partly overlapping. Ungerminated seeds were mostly distributed toward the lower end of $y$-axis.

Only 69 out of 92 germinated seeds grew into seedlings. If seeds that died after germination are excluded, the positive linear relationship between diameter and weight (Figure 4c) gets further stronger ($n = 69$, $r = 0.930$, Table 1). Seeds that died after germination did not exhibit a significant

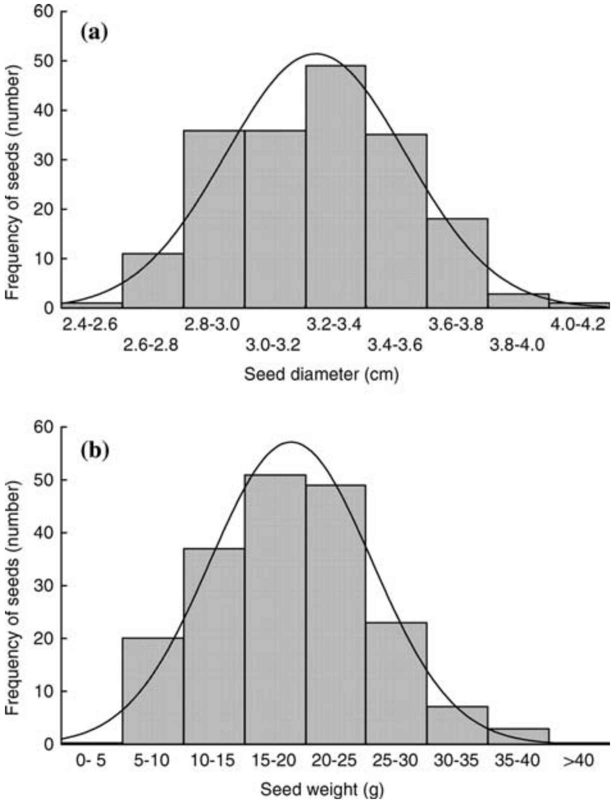

*Figure 3.* Frequency distribution of seeds: (a) diameter. (b) weight measurements of hollong seeds. The observed distribution (bar) was fitted to an expected normal distribution (curve). For seed diameter, skewness was 0.024, kurtosis was –0.457 and K–S test yielded d = 0.057 at $p > 0.20$. For seed weight, skewness was 0.324, kurtosis was –0.363 and K–S test yielded d = 0.050 at $p > 0.20$.

relationship between diameter and weight ($n = 23$, $r = 0.292$, Table 1). However, mean diameter of seeds died-after-germination (3.33 ± 0.29 cm) was comparable with grew-to-seedlings seeds (3.27 ± 0.31 cm) with an insignificant difference between means (df = 1, $F = 0.599$, $p < 0.441$). Similarly, mean weight of seeds died-after-germination (21.27 ± 5.00 g) was also at par with grew-to-seedlings seeds (22.88 ± 5.72 g) with an insignificant difference between means (df = 1, $F = 1.436$, $p < 0.234$).

### *Seed germination*

Germination is hypogeous (Figure 2). The radicle emerges from the crown of the seed (nut) and curves downwards (Figure 2a and b). The cotyledons take

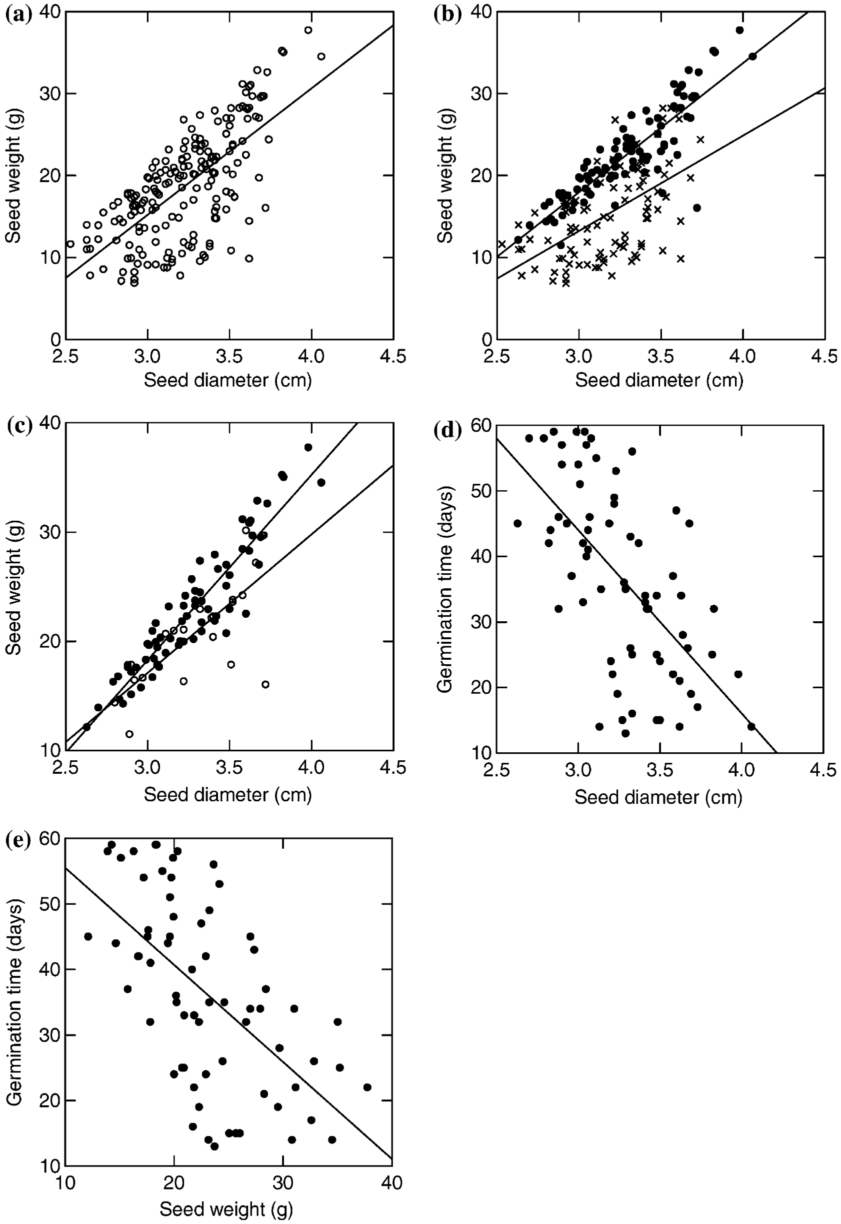

*Figure 4.* Regression models. (a) A fan-shaped scatter of seed diameter and weight measurements with linear regression function. (b) Marked germinated (solid circle) and ungerminated seeds (cross) in scatter with separate regression functions. (c) Marked germinated and grew-to-seedlings (solid circle) and ungerminated seeds (hollow circle) in scatter with separate regression functions. (d) Negative linear relationship between seed diameter and germination time. (e) Negative linear relationship between seed weight and germination time.

*Table 1.* Regression model, correlation coefficient ($r$), $F$-ratio of one-way of analysis of variance (ANOVA), and significance level ($p$) explaining relationships between structural and growth variables of seed and seedlings of hollong.

| Seed/seedling growth stage | Sample size ($n$) | Dependent variable ($Y$) | Independent Variable(s) ($X$) | Regression model | $r$ | $F$-ratio | $p$ level |
|---|---|---|---|---|---|---|---|
| All seeds sown | 190 | seed weight | seed diameter | $Y = -31.127 + 15.447X$ | 0.687 | 168.010 | 0.000 |
| Seeds that did not germinate | 98 | seed weight | seed diameter | $Y = -21.609 + 11.621X$ | 0.564 | 44.725 | 0.000 |
| Seeds that germinated | 92 | seed weight | seed diameter | $Y = -29.217 + 15.735X$ | 0.869 | 278.487 | 0.000 |
| Seeds germinated, but died | 23 | seed weight | seed diameter | $Y = 86.740 - 14.932X$ | 0.292 | 1.960 | 0.176 |
| Seeds germinated and grew | 69 | seed weight | seed diameter | $Y = -32.569 + 16.951X$ | 0.930 | 428.674 | 0.000 |
| Seeds germinated and grew | 69 | germination time | seed diameter | $Y = 127.942 - 27.976X$ | 0.621 | 41.970 | 0.000 |
| Seeds germinated and grew | 69 | germination time | seed weight | $Y = 70.348 - 1.483X$ | 0.599 | 37.581 | 0.000 |
| Seedlings 154 days old | 69 | leaf number | seed diameter | $Y = 1.082 + 0.857X$ | 0.385 | 11.670 | 0.001 |
| Seedlings 154 days old | 69 | collar diameter | seed diameter | $Y = 1.392 + 0.759X$ | 0.342 | 8.902 | 0.004 |
| Seedlings 154 days old | 69 | height | seed diameter | $Y = -0.348 + 2.664X$ | 0.409 | 13.468 | 0.000 |
| Seedlings 154 days old | 69 | leaf number | seed weight | $Y = 2.778 + 0.048X$ | 0.396 | 12.478 | 0.001 |
| Seedlings 154 days old | 69 | collar diameter | seed weight | $Y = 2.848 + 0.045X$ | 0.369 | 10.580 | 0.000 |
| Seedlings 154 days old | 69 | height | seed weight | $Y = 5.048 + 0.145X$ | 0.406 | 13.225 | 0.001 |
| Seedlings 245 days old | 69 | leaf number | seed diameter | $Y = 3.847 + 0.565X$ | 0.194 | 2.626 | 0.110 |
| Seedlings 245 days old | 69 | collar diameter | seed diameter | $Y = 0.970 + 1.280X$ | 0.520 | 24.800 | 0.000 |
| Seedlings 245 days old | 69 | height | seed diameter | $Y = -3.475 + 6.972X$ | 0.485 | 20.575 | 0.000 |
| Seedlings 245 days old | 69 | leaf number | seed weight | $Y = 4.619 + 0.047X$ | 0.295 | 6.383 | 0.014 |
| Seedlings 245 days old | 69 | collar diameter | seed weight | $Y = 3.364 + 0.078X$ | 0.580 | 34.004 | 0.000 |
| Seedlings 245 days old | 69 | height | seed weight | $Y = 9.262 + 0.440X$ | 0.558 | 30.248 | 0.000 |
| Seedlings 154 days old | 69 | seed diameter | collar diameter, height | $Y = 2.585 + 0.072X_1 + 0.049X_2$ | 0.429 | 7.455 | 0.001 |
| Seedlings 154 days old | 69 | seed weight | collar diameter, height | $Y = 9.660 + 1.662X_1 + 0.809X_2$ | 0.438 | 7.847 | 0.001 |

*Table 1.* Continued

| Seed/seedling growth stage | Sample size ($n$) | Dependent variable ($Y$) | Independent Variable(s) ($X$) | Regression model | $r$ | $F$-ratio | $p$ level |
|---|---|---|---|---|---|---|---|
| Seedlings 154 days old | 69 | seed diameter | leaf number, collar diameter, height | $Y = 2.378 + 0.110X_1 + 0.029X_2 + 0.042X_3$ | 0.193 | 6.424 | 0.001 |
| Seedlings 154 days old | 69 | seed weight | leaf number, collar diameter, height | $Y = 5.866 + 2.018X_1 + 0.875X_2 + 0.691X_3$ | 0.202 | 6.734 | 0.001 |
| Seedlings 245 days old | 69 | seed diameter | collar diameter, height | $Y = 2.196 + 0.144X_1 + 0.017X_2$ | 0.552 | 14.433 | 0.000 |
| Seedlings 245 days old | 69 | seed weight | collar diameter, height | $Y = 1.039 + 2.775X_1 + 0.389X_2$ | 0.624 | 21.001 | 0.000 |
| Seedlings 245 days old | 69 | seed diameter | leaf number, collar diameter, height | $Y = 2.191 + 0.001X_1 + 0.144X_2 + 0.017X_3$ | 0.272 | 9.477 | 0.000 |
| Seedlings 245 days old | 69 | seed weight | leaf number, collar diameter, height | $Y = -1.203 + 0.557X_1 + 2.730X_2 + 0.353X_3$ | 0.368 | 14.188 | 0.000 |
| Seedling height growth | 69 | height 245 days | height 154 days | $Y = 4.904 + 1.724X$ | 0.781 | 104.540 | 0.000 |
| Seedling collar diameter growth | 69 | collar diameter 245 days | collar diameter 154 days | $Y = 2.011 + 0.812X$ | 0.731 | 76.833 | 0.000 |

up moisture, expand and push the plumule upward (Figure 2c and d). The fleshy cotyledons dwell underground within the pericarp and testa to nourish the seedling. After the seedling grows upright with the first pair of leaves conducting photosynthesis, cotyledons detach from the seedling.

Germination started on day-13 and ceased by day-66. Thus, viability of hollong seeds in soil lasted longer than is often assumed, i.e., as much as 9 weeks. Mean germination time was 36.6 days and median 35 days. Germination time declined with increase in seed diameter (Figure 4d) and weight (Figure 4e). Germination time declined from 48.3 days for small to 35.4 days for intermediate to 30.6 days for large seeds (Table 2). Similarly, germination time decreased from 46.1 for light to 37.4 days for intermediate to 27.6 days for heavy seeds (Table 2).

Overall, germination was 48.4%. Germination increased from 39.1% for small to 46.6% to intermediate to 63.4% for large seeds (Table 2). Similarly, germination increased from 19.7% for light to 62.9% for intermediate to 84.0% for heavy seeds (Table 2).

### *Seedling survival and growth*

Survival of germinated seeds was 75%. Survival increased from 60% for light to 76.8% for intermediate to 80.9% for heavy seeds (Table 2). Survival increased significantly from 72.2% for small to 81.3% for intermediate, but did not differ with 65.4% for large seeds (Table 2).

Seedlings resulting from large diameter seeds achieved significantly more vigour than seedlings from intermediate and small diameter seeds (Table 2). Similarly, seedlings resulting from heavy-weight seeds achieved significantly more vigour than seedlings from intermediate and light-weight seeds (Table 2). The difference in seedling vigour between small and intermediate diameter classes and light and intermediate weight classes was insignificant. Seed diameter and seed weight were positively correlated with leaf number, collar diameter and seedling height when measured 154 and 245 days after sowing (Table 1). Also, seed diameter and seed weight showed positive correlations with a combination of leaf number, collar diameter and seedling height (Table 1). The differences in seedling vigour within 3 classes of seed diameter or weight were more pronounced after autumn growth than after wet summer growth, as indicated by greater $F$ values obtained from ANOVA (Table 2).

## **Discussion**

Seeds, after dispersal from the parent tree, deposit on the forest floor to constitute a seed bank. A large number of seedlings can carpet the ground of rain forests shortly after seed dispersal (Barnard 1956; Richards 1957; Whitmore 1975). Seed size is an important life history trait influencing regeneration

*Table 2.* Seed germination, germination time and seedling growth in hollong during wet summer and autumn.

| Seed size estimator classes | Seeds sown on March 11, 2002 | Per cent of sown seeds germinated by June 16, 2002 | Per cent of germinated seeds grew to seedlings | Mean germination time (days) of seeds grew to seedlings | Mean diameter (cm) of seeds grew to seedlings | Mean weight (g) of seeds grew to seedlings | Seedling growth during wet summer (March 11, 2002 to August 12, 2002) | | | Seedling growth during autumn (August 12, 2002 to November 11, 2002) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Seedling height (cm) | Collar diameter (mm) | Leaf number ($plant^{-1}$) | Seedling height (cm) | Collar diameter (mm) | Leaf number ($plant^{-1}$) |
| *Seed diameter (cm)* | | | | | | | | | | | | |
| Small (< 3) | 46 | $39.1^{a}$ | $72.2^{a}$ | $48.3 \pm 9.1^{a}$ | $2.85 \pm 0.10^{a}$ | $15.96 \pm 1.85^{a}$ | $7.07 \pm 2.11^{a}$ | $3.45 \pm 0.59^{a}$ | $3.39 \pm 0.51^{a}$ | $16.53 \pm 4.52^{a}$ | $4.72 \pm 0.54^{a}$ | $5.62 \pm 0.77^{a}$ |
| Intermediate | 103 | $46.6^{a}$ | $81.3^{a}$ | $35.4 \pm 13.5^{b}$ | $3.23 \pm 0.15^{b}$ | $21.94 \pm 2.80^{b}$ | $8.12 \pm 1.81^{a}$ | $3.86 \pm 0.65^{ab}$ | $3.87 \pm 0.57^{b}$ | $18.47 \pm 3.36^{a}$ | $4.97 \pm 0.67^{a}$ | $5.56 \pm 0.91^{a}$ |
| Large (≥3.5) | 41 | $63.4^{b}$ | $65.4^{a}$ | $30.6 \pm 14.2^{bc}$ | $3.69 \pm 0.15^{c}$ | $30.32 \pm 4.22^{c}$ | $9.84 \pm 1.69^{b}$ | $4.24 \pm 0.71^{b}$ | $4.29 \pm 0.85^{c}$ | $23.45 \pm 4.27^{b}$ | $5.92 \pm 0.63^{b}$ | $6.06 \pm 0.97^{a}$ |
| *F* value | | | | 10.343 | 132.441 | 84.552 | 8.964 | 5.376 | 7.474 | 14.347 | 16.775 | 1.847 |
| *p*level | | | | 0.000 | 0.000 | 0.000 | 0.000 | 0.007 | 0.001 | 0.000 | 0.000 | 0.166 |
| df | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| *Seed weight (g)* | | | | | | | | | | | | |
| Light (< 17) | 76 | $19.7^{a}$ | $60.0^{a}$ | $46.1 \pm 10.5^{a}$ | $2.83 \pm 0.12^{a}$ | $15.07 \pm 1.51^{a}$ | $7.28 \pm 2.56^{a}$ | $3.66 \pm 0.56^{a}$ | $3.56 \pm 0.53^{a}$ | $16.08 \pm 5.06^{a}$ | $4.82 \pm 0.50^{a}$ | $5.67 \pm 0.87^{a}$ |
| Intermediate | 89 | $62.9^{b}$ | $76.8^{a}$ | $37.4 \pm 14.6^{b}$ | $3.21 \pm 0.19^{b}$ | $21.32 \pm 2.54^{b}$ | $8.01 \pm 1.86^{a}$ | $3.77 \pm 0.65^{a}$ | $3.79 \pm 0.64^{a}$ | $18.37 \pm 3.30^{a}$ | $4.94 \pm 0.67^{a}$ | $5.51 \pm 0.86^{ab}$ |
| Heavy (≥27) | 25 | $84.0^{c}$ | $80.9^{a}$ | $27.6 \pm 10.1^{c}$ | $3.67 \pm 0.19^{c}$ | $30.95 \pm 3.26^{c}$ | $9.85 \pm 1.65^{b}$ | $4.25 \pm 0.77^{b}$ | $4.29 \pm 0.77^{b}$ | $23.48 \pm 4.28^{b}$ | $5.89 \pm 0.69^{b}$ | $6.18 \pm 0.95^{ac}$ |
| *F* value | | | | 9.038 | 71.10 | 126.593 | 7.660 | 3.704 | 4.806 | 14.745 | 14.397 | 3.476 |
| *p* level | | | | 0.000 | 0.000 | 0.000 | 0.001 | 0.030 | 0.011 | 0.000 | 0.000 | 0.037 |
| df | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| *All seeds* | 190 | 48.4 | 75.0 | 36.6 ± 14.2 | 3.27 ± 0.31 | 22.88 ± 5.72 | 8.37 ± 2.04 | 3.87 ± 0.70 | 3.88 ± 0.70 | 19.33 ± 4.51 | 5.16 ± 0.77 | 5.70 ± 0.91 |

Mean values are accompanied by standard deviation. Differences within group means were *F*-tested using one-way of analysis of variance (ANOVA). *Post hoc* Fisher's Least-Significant-Difference Test (LSD) was used to determine if any two means within a group were significantly different (designated with different superscripts). Differences in percentages of seeds germinated and seedlings survived were tested using a two-tailed *z* statistic.

success (Gross 1984; Howe et al. 1985; Tripathi and Khan 1990; Paz et al. 1999; Turnbull et al. 1999). Seed size varies many-fold within a species necessitating segregation of seeds that would and would not germinate and establish seedlings. In this study, hollong seeds varied more than five fold in weight and less than two fold in diameter. Nahor (*M. ferrea*), a large-seeded species and canopy associate of hollong also varies seed weight by six and diameter by less than two fold (Khan et al. 1999). A plausible explanation for variation in seed weight is the ability of the species to establish in a mosaic of microsites with different physical and biotic conditions, thus broadening its regeneration niche (Grubb 1977; McGinley et al. 1987). Variation in seed size is also known to help seeds escape predation (Garrison and Augspurger 1983; Uma Shaanker et al. 1988).

Assumption that seed weight increases with its diameter was true in hollong as seed weight showed a positive linear relationship with diameter. The populations of seed diameter and weight measurements were normally distributed and made a good case for statistical analyses (Figure 3). If a threshold of seed weight for germination were to be deduced, all seeds <11 g did not germinate. Nonetheless, this as a threshold lies at far lower end of the weight range of 6.8 and 37.7 g and allows rejection of only a few seeds and acceptance of many seeds that will not germinate. Determining a threshold for seed diameter was difficult since seeds in entire range of diameter did not germinate. However, *x–y* scatter plot showed an interesting fan-like shape of diameter-weight relationship of 190 seed measurements (Figure 4a). Seeds developing the lower blade of the fan failed to germinate and if germinated, failed to establish seedlings. Seeds that followed the handle of the fan germinated and established seedlings (Figure 4b). The non-random, fan-shaped scatter of seeds resulted in abundance of seeds in the lower-left quarter of the *x–y* plot. Such a fan-shaped scatter may be a common feature in tropical species, and needs examination.

Germinated and ungerminated seeds can be distinguished in separate clumps in *x–y* scatter plot. However, edges are fuzzy, partly overlapping. The scatter plot does not suggest a precise threshold of seed diameter or weight required for successful germination and seedling establishment. Seeds that had a relatively smaller weight compared to their diameter and were in the lower-left quarter of *x–y* plot were largely unsuccessful.

Although the relationship between diameter and weight was significant for all seeds sown, it became stronger for seeds that germinated and further stronger for seeds that germinated and established seedlings. This means the seeds that lay close to regression line make potential candidates for raising seedlings. Such seeds can be predicted before sowing from *x–y* scatter of diameter and weight measurements. Seeds that died after germination did not show a significant relationship between diameter and weight. If seeds were selected based on either diameter or weight deciding an arbitrary threshold (cut-off) line, percentage of successful seeds will be lower than if seeds were selected based on a confidence interval of the regression line between diameter and weight. A risk of potential seeds being rejected and unlikely seeds being picked declines if selection was derived from both diameter or weight.

Seed germination in hollong was ‘rapid’, i.e., within 12 weeks, as per the definition of Ng (1978). The minimum time required for commencement of germination was 13 days after sowing, well in conformity with that suggested earlier (Sen Gupta 1939; De 1940). However, germination lasted 66 days and this was far longer than assumed. Mean germination time was 36.6 days and very close to the median value of 35 days, signifying that seeds do not concentrate around a preferred germination time. Large diameter or heavy seeds germinated faster than small diameter or light seeds. Hollong by shedding fruits in spring when temperature has risen and pre-monsoon showers afforded adequate moisture in soil seems to take advantage of large amounts of food reserves to produce vigorous seedlings. This is contradictory to an associate species, nahor wherein seeds disperse in autumn and heavy seeds germinate after elapse of winter though light seeds may germinate early (Khan et al. 1999).

Seed germination success was 48%, but only 37% of seeds could establish seedlings. Large diameter and heavy seeds showed greater germination percentage than small diameter and light seeds. A similar trend has been observed in large-seeded species such as *Quercus* spp. (Tripathi and Khan 1990), *Quercus semiserrata* (Khan and Uma Shankar 2001) and *M. ferrea* (Khan et al. 1999). Large seeds of shade-tolerant species are of adaptive value because they contain relatively large amounts of food reserves that can be used for seedling establishment in dim light on the forest floor (Foster 1986). Sen Gupta (1939) found hollong germination between 28% and 50% and accredited ungerminated seeds as unsound. Sen Gupta (1939) also found germination better under shade than in open.

Survival after germination was as good as 75% and did not vary significantly among three seed diameter and weight classes. Sen Gupta (1939) emphasized that survival of hollong is very high if seedlings do not suffer physical damage and pest attack. Rajkhowa (1961) concluded that mortality of hollong seedlings and saplings is very low and practically negligible once they attain a height of 2 m. The high percentage of survival in hollong is in tune with about 95% survival in nahor (Uma Shankar, personal observation). Seed size, both in terms of diameter and weight, did influence seedling vigour that was significantly greater for seedlings from large diameter and heavy seeds than for those from intermediate and small classes. As seedlings grew, these differences amplified. Nine months after seed sowing, mean seedling height was 19 cm, collar diameter 5.2 mm and leaf number 5.7 seedling$^{-1}$. Sen Gupta (1939) from Lakhimpur reported hollong’s seedling height as 37 cm after 1-year and 100–120 cm after 2-year growth in a managed plantation. In Jeypore division, mean height respectively, was 30 and 105 cm. The present study was conducted at a relatively higher elevation (1400 m) and cooler climate of NEHU Campus, Shillong (about 3 °C lesser mean temperature) in comparison to lower elevation (<1000 m) and warmer climate of Proposed Deomali Elephant Reserve (PDER) wherefrom seeds were collected. Hence, a caveat must be exercised in interpreting results of this study, especially in making comparisons of seedling vigour with other sites.

## Conclusions

Prediction of seeds that would germinate and establish vigorous seedlings is traditionally based on a threshold value of diameter or weight. This study unravels a risk of errors when seeds are separated only by weight or diameter. An *x–y* plot of diameter and weight yielded a fan-shaped scatter that may be a general feature in tropical species and needs examination. The viable seeds cropped up along handle of the fan (regression line). Seeds that were in the lower blade of the fan (or lying away from regression line, especially in lower-left quarter) did not germinate. The populations of viable and non-viable seed were distinguishable, but with a fuzzy edge.

## Acknowledgements

The facilities for experimental work were afforded at the Department of Botany, North-Eastern Hill University, Shillong. Partial funding came from the BOYSCAST Fellowship awarded by the Department of Science and Technology, Government of India, New Delhi. I thank Mr. Panna Deb to facilitate seed collection, Mr. B.D. Rathore for supervision in greenhouse, Mr. H.R. Choudhury for drawing Figure 1 and Shilpi Agrawal for support.

## References

Barnard R.C. 1956. Recruitment, survival and growth of timber tree seedlings in natural tropical rain forest. Malay. For. 19: 156–161.

De R.N. 1940. Nursery and Plantation Notes for Assam. Assam Government Press, Shillong, India.

Foster S.A. 1986. On the adaptive value of large seeds for tropical moist forest trees: a review and synthesis. Bot. Rev. 52: 260–299.

Garrison W.J. and Augspurger C.K. 1983. Double- and single-seeded acorns of bur oak (*Quercus macrocarpa*): frequency and some ecological consequences. Bull. Torrey Bot. Club 110: 151–160.

Gross K.L. 1984. Effect of seed and growth from a seedling establishment of six monocarpic parental plants. J. Ecol. 72: 369–387.

Grubb P.J. 1977. The maintenance of species richness in plant communities: the importance of the regeneration niche. Biol. Rev. 52: 107–145.

Hoshmand A.R. 1998. Statistical Methods for Environmental and Agricultural Sciences. 2nd ed. CRC Press, New York.

Howe H.F., Schupp E.W. and Westley L.C. 1985. Early consequences of seed dispersal for a neotropical tree (*Virola surinamensis*). Ecology 66: 781–789.

Khan M.L. and Uma Shankar 2001. Effect of seed weight, light regime, and substratum microsite on seed germination, and seedling growth of *Quercus semiserrata* Roxb. Trop. Ecol. 42: 117–125.

Khan M.L., Bhuyan P. Uma Shankar and Todaria N.P. 1999. Seed germination and seedling fitness in *Mesua ferrea* L. in relation to fruit size and seed number per fruit. Acta Oecol. 20: 599–606.

McGinley M.A., Temme D.H. and Geber M.A. 1987. Parental investment in offspring in variable environments: theoretical and empirical considerations. Am. Nat. 130: 370–398.

Mohan Lal K.B. 1960. Manipulation of undergrowth for aiding natural regeneration of evergreen and semi-evergreen forests. Proceedings of the All-India Tropical Moist Evergreen Forest Study Tour and Symposium, Forest Research Institute, Dehra Dun.

Ng F.S.P. 1978. Strategies of establishment in Malayan forest trees. In: Tomlinson P.B. and Zimmermann M.H. (eds), Tropical Trees as Living Systems. Cambridge University Press, Cambridge, UK, pp. 129–162.

Paz H., Mazer S.J. and Martinez-Ramos M. 1999. Seed mass, seedling emergence, and environmental factors in seven rainforest *Psychotria* (Rubiaceae). Ecology 80: 1594–1606.

Rajkhowa S. 1960a. Assam valley semi-evergreen forests and their regeneration. Proceedings of the All-India Tropical Moist Evergreen Forest Study Tour and Symposium, F.R.I, Dehra Dun.

Rajkhowa S. 1960b. Forest types of Assam with special reference to the evergreen and semi-evergreen forests. Proceedings of the All-India Tropical Moist Evergreen Forest Study Tour and Symposium, F.R.I, Dehra Dun.

Rajkhowa S. 1961. The Upper Assam *Dipterocarpus-Mesua* forests and their regeneration. Indian For. 87(7): 406–425.

Richards P.W. 1957. The tropical rainforest: an ecological study. University Press, Cambridge, UK.

Roy S.B. and Kalyan Naha 1967. Hollong – its past and present. Proc. X Silva. Conf., Dehra Dun, Manager of Publications, Delhi.

Sen Gupta J.N. 1939. *Dipterocarpus* (gurjan) forests in India and their regeneration. Indian Forest Records 3(4), N.S., Silviculture, Manager of Publications, Delhi.

Seth S.K. and Dabral S.N. 1960a. Characteristic features of natural regeneration under various tending schedules in Hollong-Nahor (*Dipterocarpus-Mesua*) forest of Assam. Indian For. 86(6): 355–373.

Seth S.K. and Dabral S.N. 1960b. Standard volume tables for *Dipterocarpus macrocarpus* Vesque. Indian Forest Records 10(9), N.S., Silviculture, Manager of Publications, Delhi.

Srinivasan M.M. 1956. Working plan for the Lakhimpur Forest Division, Assam (1st October, 1949 to 30th September, 1959). Department of Forests, Assam.

StatSoft Inc. 1995. STATISTICA for Windows (Computer Program Manual). Tulsa, OK, StatSoft, Inc, USA.

Tripathi R.S. and Khan M.L. 1990. Effect of seed weight and microsite characteristics on germination and seedling fitness in two species of *Quercus* in a subtropical wet hill forest. Oikos 57: 287–296.

Troup R.S. 1980. The Silviculture of Indian Trees. Forest Research Institute, Dehra Dun.

Turnbull L.A., Rees M. and Crawley M.J. 1999. Seed mass and the competition/colonization trade-off: a sowing experiment. J. Ecol. 87: 899–912.

Uma Shaanker R., Ganeshaiah K.N. and Bawa K.S. 1988. Parent-offspring conflict, sibling rivalry and brood size pattern in plants. Ann. Rev. Ecol. Syst. 19: 177–205.

Vincent A.J. 1961. A note on the growth of eleven individual species of the genus *Dipterocarpus* (Keruing) in naturally and artificially regenerated forest, Malaya. Research Pamphlet No. 28, F.R.I. Federation of Malaya.

Whitmore T.C. 1975. Tropical Rain Forests of the Far East. Clarendon Press, Oxford.

Zar J.H. 1984. Biostatistical Analysis. Prentice-Hall, Inc., New Jersey.