MERCHANTABLE TIMBER PRODUCTION IN *DALBERGIA SISSOO* PLANTATIONS ACROSS BANGLADESH: REGIONAL PATTERNS, MANAGEMENT PRACTICES AND EDAPHIC FACTORS

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HOSSAIN SMY & MARTIN AR. 2013. Merchantable timber production in *Dalbergia sissoo* plantations across Bangladesh: regional patterns, management practices and edaphic factors. *Dalbergia sissoo* (sissoo) is an extensively planted tree species in Bangladesh, primarily because of its fast growth rate and multiple economic benefits. However, only a few studies have quantified baseline timber volumes attainable under sissoo cultivation in Bangladesh, and even fewer since large-scale sissoo dieback occurred in the mid- and late 1990s. Using data from 72 plantations across five Bangladeshi regions, we derived region-specific rotation-age volume estimates for sissoo. We also examined how sissoo volumes were correlated with plantation characteristics (plantation age, per cent mortality, per cent sissoo and tree density) and soil characteristics (texture, soil pH and organic matter). Sissoo volume estimates differed significantly across regions, ranging from 52.0–80.0 m^3 ha^{-1} in the Khulna and Chuadanga regions respectively. Our highest estimates were considerably lower than virtually all reported sissoo volume estimates due to high tree mortality in the plantations we surveyed (46.4 ± 11.3% of stems). Sissoo volume was negatively associated with soil clay content whereby the lowest region-specific rotation-age volumes associated with the highest average clay content. Results of this study suggest sissoo plantations in Bangladesh are likely to yield less revenue earnings than they have historically or compared with other commercial plantation species.

Keywords: Dieback, *Fusarium solani*, *Ganoderma lucidum*, tree plantation, standing volume, timber yield

HOSSAIN SMY & MARTIN AR. 2013. Penghasilan kayu boleh niaga di ladang *Dalbergia sissoo* merentasi Bangladesh: corak serantau, amalan pengurusan serta faktor edafik. *Dalbergia sissoo* merupakan pokok yang ditanam luas di Bangladesh kerana kadar pertumbuhannya yang pesat serta faedah ekonomi yang besar. Bagaimanapun, hanya beberapa kajian telah menentukan garis asas isi padu yang dapat dicapai dengan penanaman *D. sissoo* di Bangladesh dan jumlahnya semakin berkurangan sejak serangan mati rosot secara besar-besaran pada awal dan lewat tahun 1990-an. Menggunakan data daripada 72 ladang di lima wilayah di Bangladesh, kami memperoleh anggaran isi padu usia pusingan wilayah tertentu. Kami juga menyelidik bagaimana isi padu *D. sissoo* dikaitkan dengan ciri ladang (usia ladang, peratus kematian, peratus *D. sissoo* dan kepadatan pokok) serta ciri tanah (tekstur, pH tanah dan bahan organik). Anggaran isi padu *D. sissoo* berbeza dengan signifikan merentas wilayah dan berjulat antara 52.0 di Khulna hingga 80.0 m^3 ha^{-1} di Chuadanga. Anggaran tertinggi yang diperoleh dalam kajian ini jauh lebih rendah berbanding isi padu sissoo yang pernah dilaporkan. Ini disebabkan kadar kematian yang tinggi di ladang iaitu sebanyak 46.4 ± 11.3% batang. Isi padu sissoo berkait secara negatif dengan kandungan tanah liat yang mana isi padu usia pusingan wilayah tertentu yang terendah berkait dengan kandungan tanah liat yang tertinggi. Keputusan kajian mencadangkan bahawa ladang di Bangladesh besar kemungkinan memberi hasil yang berkurangan berbanding dengan hasil sebelum ini serta spesies ladang komersial yang lain.

INTRODUCTION

Dalbergia sissoo (Fabaceae) (sissoo) is one of the most widely utilised plantation tree species in the Indian subcontinent, largely due to its fast growth and multiple economic uses including fuelwood, fodder and furniture, and to a lesser extent, medicinal uses. Use of sissoo as a plantation species is particularly appealing as its economic incentives tend to accrue within 15 years of plantation establishment (Haque & Kamaluddin 1995). Research has also shown sissoo trees are drought tolerant nitrogen fixers and when planted in large numbers, they are

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effective in reclaiming sodic lands (Mishra et al. 2002). These ecological benefits are expected to increase in necessity as drought, nutrient depletion and salinisation continue to reduce productivity in South Asian farmland (Mishra et al. 2002, Alauddin & Quiggin 2008). Ultimately, as demands for economic and ecological benefits of this species continue to increase, it is expected that sissoo plantations in the Indian subcontinent will continue to expand commensurately.

This is particularly true in Bangladesh where 60% of private and 90% of public tree plantations are sissoo dominated (Anonymous 2000). More specifically, across Bangladesh it is estimated that 60% of plantations in northern and southern regions and 20% in central and eastern regions are under sissoo cultivation (Baksha & Basak 2000, Webb & Hossain 2005, Huda et al. 2007). This rapid expansion of sissoo-dominated plantations is largely based on the assumptions that vast expanses of land in Bangladesh are suitable for sissoo cultivation.

Yet despite the vast area delineated as suitable for sissoo plantation in Bangladesh, there remain few studies quantifying the amount of timber that can be attained under sissoo cultivation. Virtually all research on the physiology, growth and propagation of sissoo has focused on Indian plantations or sissoo performance in greenhouse and lab settings. Among the studies that do exist from Bangladesh, few have provided sissoo volume estimates across the diverse regions. This lack of data may result in misleading volume estimates for Bangladeshi plantation managers, who are playing a progressively larger role in plantation species selection (Kabir & Webb 2005).

It has been reported that sissoo plantations in Bangladesh yield up to 124.0 $m^3 ha^{-1}$ merchantable timber after 20 years (Haque & Kamaluddin 1995). However, this study was restricted to the Chuadanga district of Bangladesh and might not necessarily be representative of volumes attainable in plantations across the country. Bangladesh maintains pronounced abiotic gradients in temperature, precipitation and soil fertility that likely influence sissoo plantation growth. For instance, the alluvial flood plain of the Ganges River in the south-western region of Bangladesh is expected to provide well-aerated and well-drained substrates that are particularly suitable for sissoo timber production (FAO 1998, Lodhiyal et al. 2002). There is also reason to believe that geography has an important effect on sissoo plantation yield; early research from Pakistan has shown growing conditions are more important in determining sissoo growth compared with sapling provenance (Vidakovic & Siddiqui 1968).

Furthermore, since the majority of sissoo plantation yield estimates were made available, a prolonged period of elevated sissoo mortality had greatly affected the viability of plantations in Bangladesh from 1992 till 2000. During this time about 2 mil sissoo trees were killed due to a large-scale dieback event, ostensibly caused by soil-borne root-rot fungi, namely, *Fusarium solani* and *Ganoderma lucidum* (Baksha & Basak 2000, Webb & Hossain 2005). At the plantation level, effects of this dieback have been severe. In a survey involving 72 sissoo plantations in Bangladesh, 52% of sissoo trees were either dead or dying (Webb & Hossain 2005). Similar rates of mortality in nearby Nepal have already prompted many farmers to establish *Eucalyptus camauldulensis* (Myrtaceae) plantations as an alternative to sissoo (Baksha & Basak 2000, Webb & Hossain 2005). Thus, to comprehensively evaluate potential economic returns from sissoo plantations, contemporary volume estimates must incorporate these observed dieback events.

To address this, we used data from the 72 plantations surveyed by Webb and Hossain (2005) across five districts in Bangladesh to (1) develop and compare region-specific predictive models to estimate timber volume at sissoo rotation-age, i.e. 20 years, (2) identify plantation characteristics correlated with standing timber volume on sissoo plantations in Bangladesh and (3) examine the relationships between plantation soil conditions (soil pH, soil organic matter, and per cent of sand, silt and clay) and standing sissoo plantation volume. In addressing these questions, our study seeks to provide information useful for forest extension workers, farmers, non-governmental organisations, and government officials to evaluate ecological and economic viability of sissoo plantations in Bangladesh.

MATERIALS AND METHODS

Study area

This study was conducted in five districts of Bangladesh: three in the northern area of the country (Rangpur, Dinajpur and Nilphamari) and two in the south-western area of the country (Chuadanga and Khulna). All five districts experience subtropical climate defined by three main seasons, namely, monsoon or wet season (June–October), cold season (November–February) and hot season (March–May). Annual rainfall in Bangladesh averages 1100 mm, 93% of which occurs during the monsoon season (BBS 2000), while average temperature in the country ranges from 21.8 to 34.8 °C. Annual rainfall in the northern and south-western regions ranges from 50 to 400 and 40 to 300 mm respectively, while average temperature ranges from 16.2 to 35.2 and 16.8 to 31.6 °C respectively (BBS 2011). Both regions are characterised by flat topography, with northern regions overlying alluvial flood plains with lateritic soil, and south-west regions considered to be the Ganges River flood plain (BBS 1996).

Data collection and analysis

Within the five districts, we randomly identified 72 sissoo plantation plots of 0.5–1.0 ha, spaced at least 1 km apart. The plantations selected were actively managed, undergoing regular manual thinning and pruning. Within each plantation, we delineated a 50 × 100 m survey area that was subdivided into 100 m^2 (0.01 ha) grid cells. Of these cells, three were randomly chosen for sampling. A total of 21,600 m^2 sissoo plantation was inventoried. In each inventory plot we located all trees and identified them as either sissoo or non-sissoo. The non-sissoo species mainly included *Acacia auriculiformis*, *Acacia mangium*, *Acacia catechu*, *Albazzia lebbek*, *Albazzia procera*, *Azadirachta indica* and *Leucaena leucocephala*. For all sissoo trees we measured diameter at 1.3 m aboveground (dbh) and merchantable tree height (H) from the base to the lowest branching/forking on the bole. Tree heights were measured using a laser rangefinder and all observations were made by a single observer to ensure consistency.

We used a published allometric equation from 30 destructively-sampled trees in the Khulna region of Bangladesh (Khan & Faruque 2010) to estimate volume for each sissoo tree, such that:

$$V = a + b(dbh^2 \times H) \qquad (1)$$

where V = tree volume (cm^3) and a and b = constants fit through least squares regression (-5209 and 34.9 respectively). This equation provided very strong approximation of sissoo volume, where $r^2 = 0.995$ (Khan & Faruque 2010).

Sissoo volumes within grid cells were then summed and multiplied by 100 to determine standing volume per hectare (expressed in m^3 ha^{-1}). A plantation-level average was then taken as mean standing volume in the three surveyed plantation plots. Data on plantation age (number of years since establishment) and plantation density (number of sissoo trees ha^{-1}) were collected from the selected plantations. Plantation owners provided information on plantation age based on official documentation of the year the plantation was established.

In each inventory plot, all sissoo trees were classified as healthy, dying (clearly affected by disease but alive) or dead. In our survey plantation plots, all dead and decaying trees have been removed and used as fuelwood (SMY Hossain, personal communications with plantation owners). Per cent sissoo was calculated as the proportion of sissoo trees among all species. The per cent of total mortality in the inventory plots was calculated as the percentage of sissoo population classified as dead or dying due to disease. All tree health classifications were made by a single observer, with diagnoses made based on symptoms that had been well documented by plant pathologists, foresters and plantation owners (Bakshi 1974, Webb & Hossain 2005).

To characterise soils at the plantation plots, five soil samples were collected along a diagonal of each 10 m × 10 m inventory plot. Soil samples were taken from 30 cm depth, pooled in the field and stored in plastic polybags. All samples were transported to the Bangladesh Soil Resource Development Institute within 2 days of collection for chemical (soil pH and organic matter) and physical (per cent sand, silt and clay) analyses.

Statistical analysis

All statistical analyses were conducted using R v. 2.10.1. Our first analysis step was to test for non-linear patterns of standing plantation volume with age. This was initially done on the basis of a linear regression that included age and a second-order polynomial age term, with the intercept forced through the origin (plantation of age 0 maintained a volume of 0 m^3 ha^{-1}). The overall predictive power of this model was strong (adjusted $r^2 = 0.8203$, $p < 0.0001$) but the second-order age term was not significant (ß = -0.1002

± 0.077 (standard error), p = 0.199). Therefore, in all subsequent analyses, linear models that did not include a second-order age term were used.

Our first analysis was designed to test for the effect of district on plantation volume. This was done by performing an analysis of covariance (ANCOVA) with district and age, and district-by-age interaction terms included as independent variables. Using multiple regression analysis, we then used predictor variables that were found to be statistically significant in the ANCOVA analysis to develop predictive models for standing sissoo volume.

To identify plantation characteristics correlated to sissoo volume, we employed a three-step process. We first performed a backward stepwise regression analysis on a full model of the form:

$$V = \beta_0 + \beta_1 A + \beta_2 M + \beta_3 S + \beta_4 D + \varepsilon \qquad (2)$$

where V = sissoo volume (m^3 ha^{-1}), β_0 = intercept, β_1, β_2, β_3 and β_4 = coefficients for age (A), sissoo mortality (M), per cent sissoo (S) and sissoo planting density (D) respectively, and ε = model error. We then used multiple regression analysis to assess the significance of plantation characteristics included in the most parsimonious model, which was identified based on the lowest Akaike's information criteria (AIC) score.

We followed the same analysis steps to evaluate the relationship between plantation soil conditions and sissoo volume. In this analysis, the full model used in the backward stepwise regression analysis was:

$$V = \beta_0 + \beta_1 A + \beta_2 pH + \beta_3 O + \beta_4 Si + \beta_5 Sa + \beta_6 CI + \varepsilon \qquad (3)$$

where V = sissoo volume (m^3 ha^{-1}), β_0 = intercept, β_1, β_2, β_3, β_4, β_5 and β_6 = coefficients for age (A), pH, organic matter (O), per cent silt (Si), per cent sand (Sa) and per cent clay (Cl) respectively, and ε = the model error. Variables included in the most parsimonious model were then used in a multiple regression analysis to test for significance.

RESULTS

Districts

Standing sissoo volume varied significantly as a function of both age ($F_{1, 62}$ = 52.51, p < 0.0001) and district (F4, 62 = 12.3, p < 0.0001). The age-by-district interaction term however was not statistically significant in the ANCOVA analysis ($F_{4, 62}$ = 0.534, p = 0.711) suggesting that in our dataset, the rate of increase in sissoo volume with plantation age did not differ across regions (Figure 1). A multiple regression model including categorical district terms and age was highly significant ($F_{6, 66}$ = 101.2, p < 0.0001), explaining 89.3% of the variation in sissoo volume (Table 1). A simple linear regression only including age was still highly significant but explained 8.3% less variation in sissoo volume (adjusted r^2 = 81.9%, p < 0.0001, Figure 1) compared with a multiple regression model with district-specific model terms. At a given age, plantations in Chuadanga, Dinajpur and Rangpur districts were predicted to maintain 16.2–17.9 m^3 ha^{-1} greater volume compared with plantations in Nilphamari district, and 26.1–27.8 m^3 ha^{-1} greater volume compared with plantations in Khulna district (Figure 1, Table 1).

Table 1 Parameters for multiple regression model predicting sissoo volume as a function of plantation age and district, and estimated 20-year volumes (± 95% confidence intervals) for plantations from five regions in Bangladesh

Coefficient	Model evaluation			Estimated rotation-age volume estimate		
	Estimate	SE	p value	Lower 95%	Estimate	Upper 95%
Age	3.02	0.54	< 0.0001	-	-	-
Chuadanga	19.57	5.41	0.0006	69.42	80.01	90.61
Dinajpur	18.35	5.00	0.0005	68.99	78.79	88.59
Khulna	-8.24	5.20	0.119	42.01	52.20	62.39
Nilphamari	1.72	4.84	0.724	52.68	62.16	71.64
Rangpur	17.89	4.69	0.0003	69.13	78.33	87.53

SE = standard error

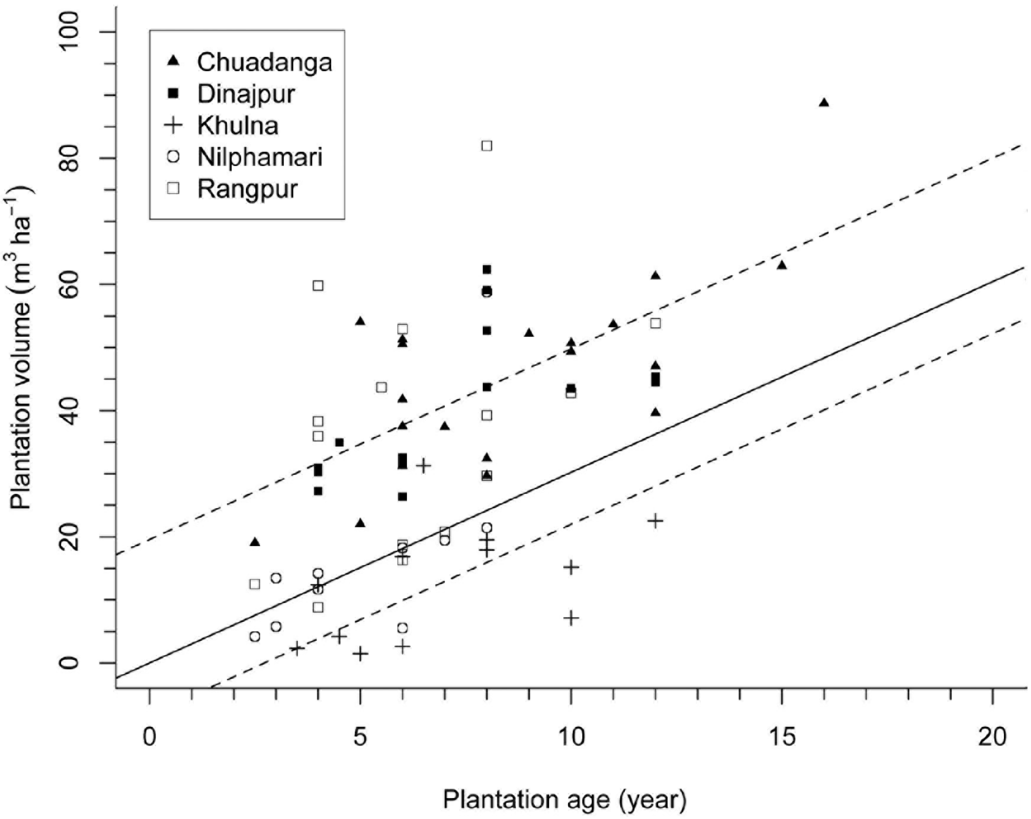

Figure 1 Standing volume as a function of age for 72 sissoo plantations across five districts in Bangladesh; solid trend line represents a linear model fit where plantation volume is a function of plantation age, constrained to have a y-intercept = 0 (n = 72, $F_{1, 71}$ = 325.8, adjusted r^2 = 0.8185), dashed trend lines represent linear model fits where intercepts vary depending on district (see Table 1); for visualisation, only the highest (Chuadanga region) and the lowest (Khulna region) district-specific volume models are shown, all other models (Dinajpur, Nilphamari and Rangpur regions) are parallel and intermediary between these two models (see Table 1 for parameters); a multiple regression model including an age term and district-specific intercepts (Table 1) was significantly related to plantation volume ($F_{6, 66}$ = 101.2, adjusted r^2 = 89.31, p < 0.0001)

At rotation age of 20 years, plantations in the Chuadanga region would be expected to produce the highest sissoo average volumes, i.e. 80.0 m^3 ha^{-1} (95% confidence level = 69.4–90.6 m^3 ha^{-}). Plantations in the Dinajpur (78.8 m^3 ha^{-1}, 95% confidence level = 69.0–88.6 m^3 ha^{-1}) and Rangpur districts (78.3 m^3 ha^{-1}, 95% confidence level = 69.1–87.5 m^3 ha^{-1}) were also predicted to maintain relatively high sissoo volumes at rotation age. Plantations in Khulna and Nilphamari districts, however, were predicted to produce much lower sissoo volumes at plantation age with 52.2 m^3 ha^{-1} (95% confidence level = 42.0–62.4 m^3 ha^{-1}) and 62.2 m^3 ha^{-1} (95% confidence level = 52.7–71.6 m^3 ha^{-1}) respectively (Figure 1, Table 1).

Plantation characteristics

Stepwise regression analysis performed on plantation characteristics found sissoo volume was most parsimoniously explained by a model that included age, per cent tree mortality and planting density (Table 2). Per cent sissoo was the only plantation characteristic not included in the AIC-selected model. A multiple regression model which included age, mortality and planting density significantly predicted standing sissoo volume ($F_{3, 68}$ = 16.84, p < 0.0001), explaining 40.1% of the variation in volume across plantations (Table 3). In this model, however, only age (t = 5.72, p < 0.0001) and per cent sissoo mortality (t = -3.58, p = 0.001) were statistically significant predictor variables, while

Table 2 Akaike's information criteria (AIC) values for five models predicting standing sissoo volume as a function of plantation characteristics for 72 sissoo plantations in Bangladesh

Model	Parameter				Model evaluation	
	Age	Sissoo mortality	Per cent sissoo	Sissoo planting density	AIC	ΔAIC
Model 1*	x	x		x	394.64	
Model 2	x	x			395.65	1.01
Full model	x	x	x	x	396.63	1.99
Model 3	x			x	405.08	10.44
Model 4		x		x	420.88	26.24

Model AIC values were determined through a backward stepwise regression procedure; *most parsimonious model fit; x = parameters included in each model; ΔAIC = difference from the most parsimonious model, i.e. model 1

Table 3 Multiple regression model predicting standing sissoo volume as a function of three plantation characteristics for 72 sissoo plantations in Bangladesh

Model coefficient	Estimate	SE	t value	p value
Intercept	28.312	9.90	2.86	0.006
Age	3.55	0.62	5.72	< 0.0001
Per cent sissoo mortality	-0.62	0.17	-3.58	0.001
Sissoo planting density	0.002	0.001	1.70	0.093

SE = standard error

sissoo planting density was not significant ($t = 1.7$, $p = 0.093$; Table 3).

Soil characteristics

In analysing soil variables, stepwise regression analysis found sissoo volume was most parsimoniously explained by a model which included age, pH and per cent clay as predictor variables (Table 4). Percentages for silt, sand and organic matter were not retained in the AIC-selected model. When analysed in a multiple regression framework, the AIC-selected model was highly significant ($F_{3, 68} = 14.41$, $p < 0.0001$), explaining 36.2% of the variation in sissoo volume. In this model, age ($t = 5.1$, $p < 0.0001$) and per cent clay ($t = -2.79$, $p = 0.007$) were statistically significant predictors of sissoo volume, while soil pH was only marginally significant ($t = 1.93$, $p = 0.058$, Table 5).

DISCUSSION

Our results indicated that rotation-age volume estimates in Bangladeshi sissoo plantations differed substantially across regions (Figure 1, Table 1). Highest mean estimated rotation-age yields were found in plantations in the Chuadanga (80.0 ± 10.6 $m^3\ ha^{-1}$), Dinajpur (78.8 ± 9.8 $m^3\ ha^{-1}$) and Rangpur (78.3 ± 9.2 $m^3\ ha^{-1}$) regions. These values were about 16–28 $m^3\ ha^{-1}$ greater than those in the Nilphamari (62.2 ± 9.5 $m^3\ ha^{-1}$) and Khulna regions (52.2 ± 10.2 $m^3\ ha^{-1}$) (Figure 1, Table 1). When accounting for plantation age, per cent tree mortality was a significant predictor of sissoo volume (Tables 2 and 3), indicating that contemporary sissoo volume estimates must take into account recent large-scale dieback events (Webb & Hossain 2005). Lastly, we found per cent clay, which was negatively related to sissoo volume, was the most important soil variable related to plantation volume (Tables 4 and 5).

Compared with other reported yields from sissoo plantations of similar ages in Bangladesh and other countries, our results showed much lower sissoo volumes. For example, sissoo yield in Bangladesh was estimated at 124.0 $m^3\ ha^{-1}$ (Haque & Kamaluddin 1995). When compared with our data from all five regions, these values represented substantial overestimates of 44.0–71.8 $m^3\ ha^{-1}$. More drastic differences were found

Table 4 Akaike's information criteria (AIC) values for seven models predicting standing sissoo volume as a function of plantation soil characteristics for 72 sissoo plantations in Bangladesh

Model	Parameter						Model evaluation	
	Age	Organic matter	pH	Per cent sand	Per cent silt	Per cent clay	AIC	ΔAIC
Model 3*	x		x			x	399.20	-
Model 2	x		x	x		x	400.57	1.37
Model 4	x					x	401.03	1.83
Full model	x	x	x	x	x	x	402.50	3.30
Model 1	x	x	x	x		x	402.50	3.30
Model 5	x		x				405.02	5.82
Model 6			x			x	420.54	21.34

Model AIC values were determined through a backward stepwise regression procedure; *the most parsimonious model fit; x = parameters included in each model

Table 5 Multiple regression model predicting standing sissoo volume as a function of age and two plantation soil characteristics for 72 sissoo plantations in Bangladesh

Model coefficient	Estimate	SE	t value	p value
Intercept	-2.3422	9.3762	-0.25	0.8035
Age	3.3111	0.649	5.102	0.00003
pH	3.5841	1.8597	1.927	0.05810
Per cent clay	-0.375	0.1343	-2.792	0.00680

Model was highly significant ($F_{3, 68} = 14.41$, $p < 0.0001$) and explained 36.17% of the variation in plantation volume, parameters included in the model were selected based on a backward stepwise regression procedure (see Table 3); SE = standard error

when comparing our results with those from other countries, such as a study by Tewari (1994) who found sissoo plantations in Panjab, India held an average of 146.6 m^3 ha^{-1} timber. Similarly, 6–8-year-old Indian sissoo plantations yielded average timber volume of 82.8 m^3 ha^{-1}(Jalota & Sangha 2000); this was comparable with the highest 20-year volume estimate obtained from this study (Figure 1). Jalota and Sangha (2000) also reported that 19–21-year-old plantations were expected to produce 538.0 m^3 ha^{-1} of merchantable timber, approximately 6.5 times the largest volume estimate found in our data (80.0 ± 10.6 m^3 ha^{-1} in the Chuadanga region, Table 1). Considering these prior estimates were derived in the midst of large-scale sissoo dieback, our data suggest that extant published volume estimates from sissoo plantations across the Indian subcontinent (including Bangladesh-specific estimates) may overestimate rotation-age merchantable timber yields from sissoo plantations in Bangladesh.

The lower observed volume estimates in this study were most likely attributable to high sissoo mortality rates in plantations (Tables 2 and 3). Across the 72 plantations inventoried, sissoo mortality was extremely high averaging 46.4 ± 1.3% of individual stems. Mortality was also the plantation characteristic that was most strongly (and negatively) related to sissoo volume (Tables 2 and 3, Appendix). Mortality was not age dependent (linear regression: $p = 0.137$, adjusted $r^2 = 0.016$), nor did mortality differ significantly across districts (analysis of variance: $F_{4, 67} = 0.8731$, $p = 0.485$). This suggests that high sissoo mortality rates are not necessarily more likely to occur in either young or older plantations and are not restricted to plantations in only certain districts. We, therefore, suggest that the monetary impacts of widespread sissoo dieback must be anticipated across all districts, and that the economic implications of widespread sissoo dieback need to be considered when choosing tree species for all plantations in Bangladesh.

Neither planting density nor per cent sissoo on a plantation was retained in stepwise regression as important predictors of standing volume (Table 2). This result contradicted previous research reporting greater sissoo timber production in plantations with mixed species assemblages compared with monospecific stands (Joshi et al. 1997). Elucidating the mechanisms by which planting density and species assemblages influence sissoo volumes is complex and requires more attention. Using the same dataset as the current study, Webb and Hossain (2005) found planting density and per cent sissoo were positively correlated with plantation mortality rates. Although mortality rate was the only plantation characteristic significantly predicting sissoo volume in the current study, it may in fact only be a proximate cause of low sissoo timber volumes. Identifying the ultimate cause of high mortality (and hence low volume estimates) requires explicit studies. For example, it has been hypothesised that high sissoo planting density and low-diversity plantation assemblages will facilitate spread of root-rot fungi (*F. solani* and *G. lucidum*). However, direct quantification of the rates of pathogenic spread under different planting arrangements remains lacking (Webb & Hossain 2005).

With respect to soil characteristics, our results indicated that lower merchantable timber volumes were negatively associated with higher clay content (Tables 4 and 5). For example, plantations in the Khulna district yielded lowest rotation-age volume estimates and the highest clay content (mean clay content = 46.7 ± 3.5%), while Dinajpur and Rangpur districts maintained very low clay contents (13.2 ± 1.5% and 14.9 ± 2.0% respectively) but high rotation-age volume estimates (Table 2). For Chuadanga, however, the relationship appeared to be positive—Chuadanga yielded the highest volume estimates and maintained high mean clay content (31.3 ± 3.4%). Nonetheless, the overall negative clay–volume relationship observed in this study was consistent with that of previous research (Tewari 1994, Sheikh 1988). Sissoo did not perform well on clay soils due to poor drainage and aeration associated with this soil type (Lodhiyal et al. 2002). Instead sissoo grew best on sandy soils, largely due to improved drainage and aeration.

From our results, sissoo may not be the most economically optimal option for rural plantation farmers in Bangladesh. Additionally, sissoo timber is known to be of lesser value for fuelwood. It also has lower timber value compared with other plantation species such as *Acacia* or *Eucalyptus* (Jalota & Sangha 2000, Kumar et al. 2011). Taking into account the generally poor wood quality, high mortality rates and low rotation-age volume estimates (Figure 1), planting sissoo as a primary tree crop in Bangladesh appears rather risky (Webb & Hossain 2005). Therefore, farmers need to critically reassess whether or not sissoo remains a viable plantation species.

Three immediate actions are needed to build on our research findings. Firstly, studies estimating timber volumes from alternative commercial species on plantations across all five districts should be a research priority. Secondly, an economic analysis of both sissoo and non-sissoo species is needed to facilitate decision making on whether sissoo remains a viable livelihood strategy for farmers in Bangladesh. Finally, research efforts to explicitly identify mechanisms and pathways of sissoo dieback across Bangladesh (and across the Indian subcontinent) are critical to devising plantation management strategies for both sissoo and non-sissoo species.

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Appendix Basic data of sissoo per plantation plot across five districts in Bangladesh

District/plot no.	Mean dbh (cm)	Mean height (m)	No. of sissoo	Mortality (%)	Per cent of sissoo	Plantation age (year)	Density (no. ha^{-1})
Rangpur							
1	16.12	10.13	1086	20	42	8	2586
2	14.65	9.66	834	39	30	12	2780
3	10.03	6.7	5288	55	63	4	8394
4	7.27	4.83	3315	57	72	4	4604
5	11.84	6.16	3124	33	57	4	5480
6	7.21	4.35	4890	53	80	2.5	6112
7	13.02	5.37	3710	52	77	10	4818
8	7.09	3.69	5844	43	61	5.5	9580
9	11.02	4.94	4970	49	53	4	9378
10	9.67	4.21	3387	53	65	6	5210
11	9.31	4.32	4693	53	79	7	5940
12	12.72	5.94	2837	52	82	8	3460
13	8.36	4.28	952	36	29	6	3284
14	11.29	7.16	882	29	35	8	2520
15	10.62	6.28	836	22	26	6	3214
Nilphamari							
16	8.14	3.2	2084	55	54	2.5	3860
17	7.71	3.51	2680	51	66	3	4060
18	8.01	4.32	3677	53	58	3	6340
19	10.23	5.34	1077	44	21	6	5130
20	7.32	3.1	5349	59	87	4	6148
21	12.98	5.64	780	44	20	8	3900
22	7.31	3.98	1950	43	30	4	6500
23	7.45	3.92	3230	65	85	6	3800
24	10.6	6.34	5308	53	55	8	9650
25	8.2	3.41	738	35	18	7	4100
Dinajpur							
26	16.03	5.12	3008	56	64	12	4700
27	11.27	4.92	4500	57	90	6	5000
28	9.82	4.57	2235	43	41	4	5450
29	10.31	5.72	1067	37	27	8	3950
30	14.35	6.83	2688	54	64	6	4200
31	9.88	4.26	1680	43	28	4	6000
32	14.74	6.59	2576	54	56	12	4600
33	9.84	4.47	4307	54	73	4.5	5900
34	10.26	4.77	1955	34	46	6	4250
35	9.37	4.52	2262	54	58	4	3900
36	13.82	6.21	3082	54	67	6	4600
37	16.51	6.01	333	23	19	8	1750
38	15.48	6.81	2975	24	70	8	4250
39	14.28	6.6	6141	62	69	10	8900
40	10.55	4.29	1291	43	29	8	4450
Chuadanga							
41	19.14	7.16	1320	45	44	12	3000
42	16.57	6.4	4200	53	75	10	5600
43	11.57	5.49	1122	43	33	6	3400
44	19.38	7.75	1092	38	26	15	4200

(continued)

Appendix (continued)

45	21.83	8.01	1180	21	40	16	2950
46	8.42	4.48	1887	41	37	2.5	5100
47	15.2	5.76	3038	58	62	12	4900
48	18.84	6.26	3154	59	83	12	3800
49	16.09	6.54	2280	61	60	10	3800
50	12.06	5.15	2730	36	70	6	3900
51	13.44	5.72	2716	54	56	5	4850
52	13.34	5.42	4271	59	73	6	5850
53	10.28	4.04	3605	56	81	5	4450
54	11.9	4.66	2356	58	62	8	3800
55	13.15	5.49	1404	41	36	6	3900
56	9.4	4.71	4458	59	56	6	7960
57	17.37	5.53	667	41	23	9	2900
58	12.07	5.14	4197	58	77	7	5450
59	13.38	5.72	561	39	19	11	2950
60	14.32	6.84	4760	59	68	8	7000
Khulna							
61	6.99	3.56	824	34	27	6	3050
62	5.98	3.22	940	44	20	3.5	4700
63	6.27	3.33	3332	40	85	5	3920
64	8.24	4.12	2670	38	89	8	3000
65	14.11	5.44	1764	40	44	10	4010
66	9.44	4.57	1940	55	40	4	4850
67	10.32	5.21	1584	39	60	12	2640
68	10.72	4.67	1463	36	38	6.5	3850
69	6.35	3.45	1841	39	59	8	3120
70	9.23	4.19	3689	57	66	10	5590
71	11.83	6.47	1039	34	24	4.5	4330
72	6.68	3.28	3018	54	71	6	4250