Journal of Coastal Conservation 6: 181-190, 2000

Optimizing investment strategies for mangrove plantations by considering biological and economic parameters

Webb, Edward L.[1*] **& Than, Maung Maung**[2]

[1]*School of Environment, Resources and Development, Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathum Thani, 12120 Thailand;* [2]*FREDA, No. 24 Yawmingyi Rd. Dagon Township, Yangon, Myanmar;*
**Corresponding author; Fax +6625246132; E-mail ewebb@ait.ac.th*

Abstract. Coastal deforestation in the Ayeyarwady Delta, Myanmar (formerly Burma) is addressed through the promotion of native-species mangrove plantations on cleared land formerly sustaining natural mangrove forests. To date there are no attempts to determine the optimal mangrove plantation strategy to maximize economic returns for private or communal plantation owners. We integrated empirical biological and economic data to suggest optimal mangrove plantation strategies in the region. We censused 4-yr old *Avicennia officinalis* mangrove plantations in two townships to calculate survival and growth rates of mangroves planted using different techniques across an inundation gradient. We used the calculated rates to forecast the production of fuelwood, poles and posts at 10, 13 and 15 yr after establishment. We calculated the compound rate of growth for the three commodities over a 7-yr period, and then forecast commodity price for the same harvest intervals. Integration of those parameters in our model led us to conclude that both profit and the internal rate of return would be greatest for plantations of seedlings raised in polyethylene bags as opposed to bare-root or direct propagule planting. Therefore, the use of potted seedlings should be promoted, despite higher initial costs. The optimal rotation period varies according to ground level and planting technique. Optimizing economic returns for coastal plantations does not necessarily require a sacrifice of ecological benefits.

Keywords: *Avicennia*; Ayeyarwady; Burma; Coastal zone; Community forestry; Growth model; Myanmar; Projections.

Abbreviations: CRG = Compound rate of growth; IRR = Internal rate of return; MMK* = Local Myanmar currency.

Introduction

Mangroves constitute a valuable coastal ecosystem (Aksornkoae 1993). The necessity of managing these ecosystems for present and future benefits as well as near-shore ecological protection and productivity is well accepted (Cruz 1984). Mangroves are under an ever-increasing threat from growing coastal populations (Cohen 1997). Particularly in developing countries, conservation of mangrove resources must be promoted alongside the appropriate management strategies so people can benefit from the resource base as well as maintain incentives for its protection (Librero 1984). The case of Myanmar exemplifies this situation, as local inhabitants rely heavily on mangrove products for subsistence and commercial products but overexploitation is rapidly degrading coastal ecosystems (Than 1999). There is a pressing need to promote reforestation and conservation efforts in the coastal regions of Myanmar.

In an attempt to recover deforested mangrove habitat and provide a source of wood products outside the receding natural forests, the Myanmar Forest Department began coastal reforestation efforts in 1979. By the late 1990s over 9500 ha of coastal plantations had been established in the Ayeyarwady Delta, designed to meet the fuelwood and minor construction needs of local communities. Nearly 7900 ha were mangrove plantations, with *Eucalyptus* species contributing a minor component. The most important mangrove species for reforestation is the native *Avicennia officinalis* (*Avicenniaceae*), which accounts for ca. 50% of the reforestation area in Ayeyarwady (Than 1999). The harvest schedule for *A. officinalis* plantations is 10 yr after planting, when three timber products are harvested: fuelwood, poles and posts. Poles and posts are used for light and moderate construction activities; all products are consumed locally or sold at local markets.

Plantation establishment techniques are still at an experimental stage to determine optimal planting and harvesting strategies to maximize economic gains for plantation owners. Experimental plantations were initiated in 1995 but there have been no attempts to analyse the short-term differences between the different strategies. The present research was designed to integrate the biological elements of mangrove plantations in Ayeyarwady with economic data on mangrove product price, and to forecast economic gains for plantations using different planting strategies. This project analysed survival and growth of four year old *Avicennia officinalis*

Due to a discrepancy between official conversion quotes and local real value no conversion estimate in USD is given.

plantations as a function of substrate level and planting technique. The results were used to construct a production and revenue model to determine the optimal plantation strategy for small-scale, individual or community-based mangrove plantations in the Ayeyarwady Delta.

Methods

Site overview and plantation strategies

This research was undertaken in the Ayeyarwady Delta (Fig. 1). The deltaic substrate was formed through alluvial deposition by the Ayeyarwady River, resulting in relatively homogeneous soil parent material. The topography of the Ayeyarwady Delta is generally flat except for sand ridges located in some areas. Annual rainfall in Ayeyarwady is ca. 2500 - 3000 mm, with ca. 100 rainy days per year and distinct wet and dry seasons (Fig. 2). Salinity ranges from 2 - 20 ppt depending upon tidal and seasonal conditions (Than unpubl.).

It is well known that the frequencies and levels of inundation (along with other hydrological parameters) affect numerous aspects of mangrove ecosystem ecology (Watson 1928; Lugo & Snedaker 1974; Cintrón-Molero & Schaeffer-Novelli 1991; Rico-Gray & Palacios-Rios 1996; Ellison & Farnsworth 1997; Imbert & Ménard 1997), therefore Burmese forestry professionals classify Ayeyarwady mangrove substrate into three ground level classes based on subtle topographical variations that influence the frequency of tidal inundation: high, medium and low. High ground receives 4 - 22 tidal inundations per month and is usually found adjacent to large tributaries. Medium ground receives 24 - 32 inundations per month and low ground, generally occurring near small drainage tributaries, receives 34 - 44 inundations per month. Discrepancies in inundation class result in large differences in hydrological and salinity conditions, particularly during the dry months. It is common knowledge among Ayeyarwady foresters that highest mangrove seedling mortality occurs on high ground during dry months (Than, pers. obs.), although this phenomenon has not been precisely quantified.

Mangrove foresters in Ayeyarwady are currently experimenting with three different planting techniques for plantation seedlings: bare root (BR), direct seed sowing (DS) and potted (PT). BR- and PT-seedlings are grown in a nursery for one year prior to transplanting into the newly established plantation (Than 1999). PT seedlings are grown in polyethylene bags according to traditional rural nursery propagation methods (Than 1999), which allows for direct transplanting without root damage. Roots of BR seedlings are trimmed prior to transplanting; the benefit of this procedure is lower nursery and transport costs, as well as greater planting efficiency. Seedlings of both these methods are ca. 0.4 m in height when transplanted (Than pers. obs.). Direct seed sowing is the direct planting of propagules at the time of plantation establishment. For all planting techniques, the spacing was 1.8 m × 1.8 m (cf. *Rhizophora* spacing in Thailand of 1 m × 1 m or 1.5 m × 1.5 m; Aksornkoae 1993).

Survey design

Mangrove populations were censused in two plantations totalling ca. 40 ha in the Bogalay and Laputta townships. In Bogalay, the plantation was located near Padecau village, ca. 12 km from the southern coastline; in Laputta the plantation was situated on U Kyun Island, 25 km from the coast (Fig. 1). Within each plantation,

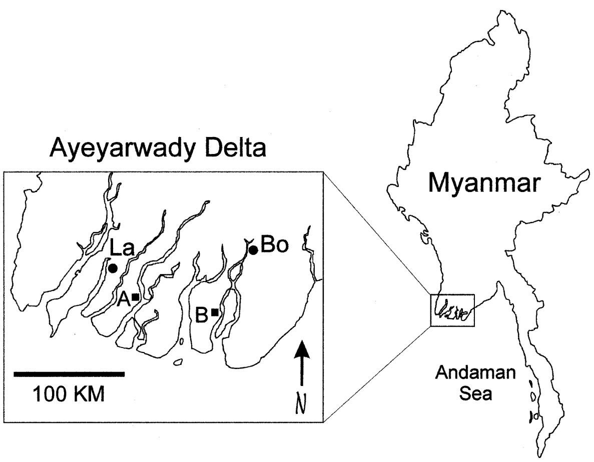

Fig. 1. Map of Myanmar (Burma) and the Ayeyarwady Delta. La = Laputta town, Bo = Bogalay town. The Laputta and Bogalay study sites are indicated by A and B, respectively.

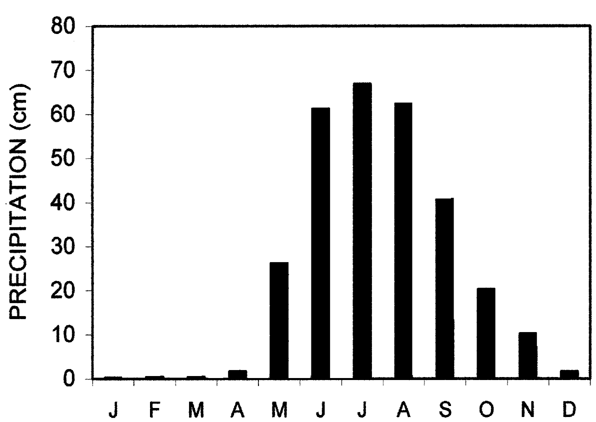

Fig. 2. Rainfall data for Ayeyarwady Delta, Myanmar. Values are 60 year means at Diamond Island and Bassein, both in the Delta region. From Nuttonson (1963).

planting treatments had been established in a block design by the Forest Department. Surveys followed a stratified 3 × 3 block design (3 planting techniques × 3 ground levels), with the census plots randomly placed by overlaying a grid of 18 m × 18 m quadrats on the plantation map containing information on ground level and planting technique. The grid cells in which plots would be established were randomly selected. The minimum criteria for plot establishment was that the selected cell was undisturbed and exhibited > 75% available substrate (i.e. no large drainage canals or unsuitable substrate). Each census plot covered an area equivalent to 100 seedlings planted in 1995. Our analysis presents production and economic return estimates on a per hectare basis.

Eight plots per planting technique/ground level combination (hereafter referred to as treatment) were established, resulting in a total of 72 plots (3 planting techniques × 3 ground levels × 8 plots per group), within which a total of 7200 seedlings had been planted in 1995. We refer to individuals in 1995 as seedlings and those surveyed in 1999 as saplings.

Within each plot, live saplings were counted and height measured using either a calibrated bamboo pole or a clinometer. Dead saplings were recorded and examined but in most cases it was impossible to determine the cause of death; missing saplings were recorded as dead. The girth (at 1.4 m) was also recorded in a randomly selected subset of 160 trees per treatment to allow calculation of timber volume. Girth was recorded to the nearest 2.5 cm which is normal practice in the region.

Plantation production and revenue model

Production

We used growth estimates and survival figures to forecast future plantation production. To construct the production and revenue model we used data from the randomly selected saplings for which both height and girth were recorded. Survival data (number of seedlings alive at year 4) were applied to the projection of each treatment to reflect the number of saplings expected to be harvestable in the model.

We categorized mangrove saplings in each treatment into 2.5 cm girth classes and estimated mean class girth increment over that period as girth/4. We applied the calculated growth increments to predict the girth for stems of those classes at harvest times of 10, 13 and 15 yr. Height increment for each girth class was calculated (height yr 4 - height yr 0)/4 and then used to project heights for that girth class at each projected harvest time. Using both girth and height parameters we projected timber volumes at harvest based on the volume formula used by the Myanmar Forest Department:

$$\text{Volume} = (\text{girth}/4)^2 \times \text{height} \quad (1)$$

Volumes were only necessary for the calculation of revenue from fuelwood sales; for pole and post revenues only the projected number of stems per girth class above the minimum limit was necessary.

The production projections relied on three primary assumptions: (1) that the distributions of individuals within each size class was not highly skewed, (2) that height and girth increments would remain constant (i.e. linear) within the projection period and (3) that survival would be 100 % during the projection period. Because stem diameters were measured to the nearest cm, we could not test assumption 1. Growth models for young mangrove plantations are few but those available (*Rhizophora* spp.) show constant growth rate across mangrove size and age classes (Putz & Chan 1986; Weechakit 1987; Anon. 1994). This supports the assumption of constant growth rates during the projection interval. The assumption of 100 % survival after yr 4 has not been empirically validated for *Avicennia* plantations, yet is consistent with published data on terrestrial species. It is recognized that most plant populations sustain the highest mortality rates during early life stages (e.g. De Steven 1988; Olmsted & Alvarez-Buylla 1995; Hardwick et al. 1997), leading to low mortality rates for older individuals (e.g. Howard & Valerio 1992; Howard 1993; Vanclay 1994; Howard et al. 1996). Olmsted & Alvarez-Buylla (1995) found almost 100 % survival for > 3-yr old individuals of the palm *Thrinax radiata* in natural forest. Higher light levels generally confer a higher probability of survival for many plant species in natural forest (Denslow et al. 1990; Augsburger 1984a, b; Augsburger & Kelly 1984). The plantations are weeded until the saplings are competitively dominant so it is justifiable to assume a high survival rate for *Avicennia* saplings in plantations following 4 yr of growth.

It is recognized that the assumption of 100 % sapling survival may produce conservative results in a comparison of revenue among plantation strategies. For example, if future sapling survival rates are not 100 % it is logical to assume that the treatment with the highest mortality rate will continue to have that relative rank mortality and that the lowest will remain lowest etc. If this were indeed the case, then assuming a common survival rate of 100 % would underestimate the divergence in future population structures and, therefore, revenues. We acknowledge this interpretation and accept this potential source of error because violation of the assumption will not affect the final rankings of revenue by treatment (although optimal harvest schedules may need to be revised).

Revenue

Table 1. Dimensions, observed and forecast prices (in MMK) for fuelwood, poles and posts of *Avicennia officinalis* in the Ayeyarwady Delta, Myanmar. Prices for poles and posts are per unit; numbers in parentheses refer to the price used to calculate CRG (compound rate of growth) between 1992 and 1999. For justification of using a CRG of 20 % to calculate price projections for posts, see Text.

	Minimum girth[a]	Price range 1992[a]	Price range 1999[a]	CRG (%)	Forecast prices		
					2005	2008	2010
Fuelwood	-	400 /m^3	1800 /m^3	24.0	6 534 /m^3	12 449 /m^3	19 132 /m^3
Pole	20 cm	20-30 (25)	80-100 (90)	20.1	270	467	558
Post	30 cm	80-100 (90)	150-300(200)	14.0	493	731	950
				20	597	1032	1486

[a]From Than (1999).

We used local market data for mangrove plantation products from 1992 and 1999 (Than 1999) to calculate the compound rate of growth (CRG) during that time. In turn, CRG was used to forecast commodity prices.

Interviews by Than (1999) revealed that the three categories of *A. officinalis* timber use were fuelwood (< 20 cm girth), poles (20 - 30 cm) and posts (> 30 cm). Market prices of poles and posts were positively correlated with diameter, so we used the mid-range price to calculate CRG for prices from 1992 to 1999. CRG was then used to forecast prices for each commodity (Table 1), assuming the same CRG as 1992 - 1999.

We used the growth data to forecast the output for each plantation treatment, then combined those results with the projected commodity prices to predict revenue – MMK/ha – for each plantation treatment at 10, 13 and 15 yr after planting. For fuelwood, we calculated revenue as timber volume multiplied by the projected fuelwood price (MMK/m^3). For poles and posts, revenue was calculated as the number of stems multiplied by the projected price per stem.

Expenditures for plantation establishment and maintenance were incorporated into the model in order to calculate profits (Table 2). This information was gathered through interviews (Than 1999) as well as through extensive experience in the study area (MMT). The expenditures reflect those necessary for an individual or community to establish a plantation rather than the government, which offers lower labour rates.

The internal rate of return (IRR) was calculated for the three different harvest schedules (10 yr, 13 yr, 15 yr) for each treatment. IRR takes into account the distribution of expenditures and revenue schedule over the life of the investment and indicates a constant rate of return for each strategy.

Results

Mangrove survival and growth

Survival

Both planting technique and ground level influenced survival and growth characteristics. In terms of planting technique, PT-seedlings consistently had the highest survival at all ground levels (Table 3). In terms of ground level, medium ground conferred the highest survival percentages to BR-seedlings, while PT-seedlings had the highest survival on low ground. Survival differences across ground levels for DS-seedlings were not statistically distinct.

Growth

PT-seedlings grew faster at all ground levels than the other two planting techniques, particularly at medium and low ground levels (Table 4). At high ground level,

Table 2. Expenditures (BUK / ha) associated with establishing, maintaining and harvesting plantations of *A. officinalis* at a planting density of 1.8 m × 1.8 m in Ayeyarwady Delta, Myanmar. Prices are for private or community-based enterprises.

	Yr 0 (pre-planting)			Yr 1				Yr 2	Yr 3	Yr 4 - 9	Yr 10	Total
Planting technique	Site prep.	Seeds	Nursery	Seeds	Staking	Planting	Weeding (× 2)	Weeding (× 2)	Weeding (× 1)		harvest	harvest
Bare Root	2000	100	500		500	1000	1500	1500	750	0	3000	10 850
Direct Seed	2000			100	500	300	1500	1500	750	0	3000	9 650
Potted seedlings	2000	100	1500		500	2000	1500	1500	750	0	3000	12 850

Table 3. Mean survival (percentage ± SD) to 4 yr of *Avicennia officinalis* seedlings in plantation conditions of the Ayeyarwady Delta, Myanmar, categorized by planting technique and ground level. Parametric one-way ANOVA was used, $n = 8$ for each cell because the unit of replication was the plot. A test for heterogeneity of variances (Levene's) was not significant for each case.

	Ground level			
Planting technique	High	Medium	Low	*p*
Bare-root seedlings	45.8 (9.7)	71.0 (7.4)	59.3 (10.9)	< 0.001
Direct-seed sowing	55.8 (6.5)	65.4 (10.7)	63.3 (6.5)	0.066
Potted seedlings	75.1 (7.4)	80.9 (5.3)	84.1 (6.6)	< 0.05
p	< 0.001	< 0.01	< 0.001	

there was no practical difference between PT- and DS-seedlings even though the overall ANOVA was significant. Within each planting technique, seedlings consistently grew fastest on low ground (Table 4). Thus, potted seedlings had the highest survival and growth rates. Within each planting technique, seedlings on low ground exhibited highest growth rates but survival results were not consistent across all treatments.

The height and diameter results obtained by projecting to 10 and 13 yr (App. 1) are in agreement with the findings of Siddiqi & Khan (1991) who reported mean heights and diameters of 11-14 yr *A. officinalis* individuals to be 4.4 - 9.3 m and 8.8-16.1 cm, respectively. Although the Siddiqi & Khan results showed a large range of sizes at 11-14 yr (as do the results of this study), the similarity does indicate that our growth projections are robust.

Price projections

CRG among the three mangrove wood products from 1992 - 1999 was 24% for fuelwood, 20% for poles and 14% for posts (Table 1). The low calculated CRG for posts was a concern, because long-term projections between poles and posts using the calculated CRGs would have eventually resulted in poles exceeding posts in price, which is untenable. Therefore, to retain consistency with other CRG results, we calculated future price projections for posts using a 20 % CRG.

By integrating the projected plantation production and commodity prices, we forecast commodity output and revenues for each plantation treatment (Table 5). The projected revenues at 10 yr were highly variable, ranging from 55 102 MMK/ha for DS saplings on high ground to 1 196 516 MMK/ha for PT saplings on low ground. For all treatments, the greatest revenue increases occur between 10 and 13 yr, when there is a predicted shift in plantation output from fuelwood to poles, or from poles to posts. Between yr 13 and 15 there is no predicted shift in plantation outputs for any treatment, so the increase in projected revenue is a function of CRG only.

IRR was variable across treatments; nevertheless for all ground levels potted seedlings produced the highest IRR (Table 6). Table 6 also indicates the optimal harvest time to maximize investment returns; this optimum varied across ground levels. On high ground, where growth and survival rates were consistently lowest, the optimal harvest schedule was calculated at 13 years for PT and BR seedlings and15 years for DS. Faster growth rates on low ground decreased optimal harvest time to 10 yr for all planting techniques, whereas medium ground still required 13 yr for optimal maturity for BR and DS treatments. Potted seedlings optimized at 10 yrs on medium ground. Thus, profits and IRR are highest using potted seedlings on all ground levels. A decrease in growth or survival due to planting treatment or ground level generally increases the optimal harvest age for that plantation type.

Table 4. Mean height increments (m/yr ± SD) calculated over 4 yr for seedlings in each planting technique and ground level. $N = 160$ for each cell. K-W ANOVA is a Kruskal-Wallis non-parametric ANOVA. A K-W ANOVA was used because variances were heterogeneous.

	Ground level			
Planting technique	High	Medium	Low	*p*
Bare root seedlings	0.43 (0.09)	0.60 (0.16)	0.78 (0.12)	< 0.001
Direct seed sowing	0.50 (0.05)	0.62 (0.07)	0.78 0.21)	< 0.001
Potted seedlings	0.51 (0.08)	0.80 (0.12)	0.92 (0.15)	< 0.001
p	< 0.001	< 0.001	< 0.001	

Note: a 2-way parametric ANOVA was also run with initial height as a covariate, this was significant at $p < 0.001$.

Table 5. Projected timber uses (commodities) and revenues (MMK/ha) based on growth and price projections for *Avicennia officinalis* plantations of Ayeyarwady Delta, Myanmar. Percent of saplings refers to the percent of the population of seedlings that survived to four years.

Yr 10			Yr 13		Yr 15			
Planting method	Ground level	Commodity	Percent of saplings	Revenue per ha	Percent of saplings	Revenue per ha	Percent of saplings	Revenue per ha
Bare root	High	Fuelwood	97		56		56	
		Pole	3		41		41	
		Post	0	72 966	3	381 981	3	556 800
	Medium	Fuelwood	72		37		37	
		Pole	23		35		35	
		Post	5	287 152	28	106 861	28	1 553 567
	Low	Fuelwood	31		7		7	
		Pole	38		24		24	
		Post	32	567 541	70	1 484 098	70	2 107 396
Direct seed	High	Fuelwood	100		94		94	
		Pole	0		6		6	
		Post	0	55 102	0	237 143	0	508 404
	Medium	Fuelwood	99		42		42	
		Pole	1		56		56	
		Post	0	144 479	1	662 902	1	944 580
	Low	Fuelwood	48		28		28	
		Pole	31		20		20	
		Post	22	457 829	53	1 269 354	53	1 847 895
Potted	High	Fuelwood	92		42		42	
		Pole	8		50		50	
		Post	1	181 658	9	839 302	9	1 191 996
	Medium	Fuelwood	8		0		0	
		Pole	64		8		8	
		Post	29	852 183	92	2 404 789	92	3 441 852
	Low	Fuelwood	2		1		1	
		Pole	34		1		1	
		Post	64	1 196 516	98	2 568 525	98	3 696 603

Table 6. Internal rates of return for the various *Avicennia officinalis* plantation strategies, based on the constructed model and using a 20 % compound rate of growth for posts (see Text). Numbers in bold italics indicate the optimal harvest time for that particular planting technique for each ground level.

	Potted seedlings			Bare-root seedlings			Direct seed sowing		
Year	High	Medium	Low	High	Medium	Low	High	Medium	Low
10	37.1	***62.1***	***68.0***	27.3	48.3	***59.6***	25.8	40.4	***59.5***
13	***43.8***	56.7	57.6	***37.6***	***49.9***	54.0	34.3	***46.5***	54.6
15	40.2	51.0	51.7	35.3	45.5	48.6	***36.3***	42.4	49.3

Table 7. Density (no./plot ± SD) of *Sesarma taeniolatum* burrows and *Panicum repens* clumps across ground levels in *Avicennia officinalis* plantations, Ayeyarwady, Myanmar. From Than (1999).

Ground level	Number of plots with burrows	Mean number of *S. taeniolatum*	Density of *P. repens* (clumps / plot)
High	5	38 ± 9	27.6 ± 3.2
Medium	5	62 ± 9	47.6 ± 6.2
Low	5	86 ± 5	63.0 ± 8.0
p		< 0.01	< 0 .001

Discussion

Mangrove growth and survival

Ground level was a major factor affecting seedling growth and survival and we argue that the results reflect both the biotic and abiotic parameters of the system. For all planting techniques, seedling growth was slowest on high ground and fastest on low ground (Table 4). On high ground, hydrological stress is probably the primary reason for slowest growth and highest mortality, regardless of planting technique. This argument is supported by other studies in mangrove ecosystems that report a decrease in mangrove growth rates in the dry season (Imbert & Menard 1997), which corresponds with a lower water level (Rico-Gray & Palacios-Rios 1996).

One would expect to see similarly ranked results for survivorship, therefore it is noteworthy that while survival was consistently lowest on high ground, in only one case was survival highest on low ground (PT). Biotic factors, including predation and competition, may have contributed to the mixed survival results. Than (1999) collected data on two biological parameters he considered important for mangrove growth and survival: burrows of the crab *Sesarma taeniolatum* and density of the grass *Panicum repens*. *P. repens* acts as a competitor with other species establishing in open areas, *S. taeniolatum* is an important mangrove predator. Both the density of *P. repens* and the number of crab burrows increased from high to low ground in *A. officinalis* plantations (Table 7), suggesting an increased importance of those factors with a decrease in ground level. Over the first four years of the plantation, the likely result of competition between *A. officinalis* and *P. repens* would be a reduction in growth rather than death. On the other hand, crabs will probably affect short-term survival due to direct seedling predation (Aksornkoae 1993; Anon. 1994). Without a control group we cannot make any definitive conclusions about the influence of either factor on growth or survival. Nevertheless, the consistent pattern of biological factors potentially leading to important ecological effects suggests that further research should determine the relative importance of hydrology, predation and competition in shaping plantation production.

Planting technique also affected the growth and survival of seedlings. Because root systems are well developed in polyethylene bags and remain intact during transplanting, the likelihood of success increases (Pancel 1993; Jackson 1994). This will be especially important during the dry months (Fig. 2), when water levels are lower and well developed root systems will confer an advantage. Moreover, polyethylene bags serve to protect the roots from predators, contributing to high survival rates. Interestingly, bare root seedlings did not consistently perform better than directly-sown propagules in either growth or survival. In this instance it is possible that the trimming of small roots prior to transplanting may have produced a substantial cost to BR-seedlings, but this requires further study.

Therefore, surviving seedlings on low ground can be expected to exhibit higher growth rates than on other ground levels, resulting in the most productive zone of a plantation. For a plantation system that utilizes DS- or BR-techniques, it would be worthwhile considering decreasing planting space to compensate for increased mortality, thereby increasing sapling density at yr 10. This method could result in predator satiation (see Janzen 1974), but would also increase labour costs through thinning treatments if necessary, which would decrease net profits and lower the IRR. Moreover, the negative effect of increased intraspecific competition would need to be considered.

Revenue implications

Variation in projected revenues resulted from the difference in treatment output distribution, which was a function of mangrove survival and growth rates. For example, at 10 yr DS-High produced 100 % fuelwood, whereas BR-Low products were evenly distributed among the three types, resulting in large differences in projected revenues (Table 5). Understanding how growth and survival of species translates into different outputs is crucial to maximize benefits for rural communities. Therefore, these results underscore the importance of integrating both biological and economic factors in the forecasting of investment returns of reforestation efforts.

Despite the intuitive attractiveness of growing large posts for local markets, the optimal plantation strategy is not always waiting for saplings to achieve post size. For example, products expected from PT-saplings at the projected harvest optima are poles and posts, but for DS-seedlings fuelwood is well represented at all optima (Tables 5 and 6). Therefore, using our forecasting model can reveal counterintuitive patterns leading to maximum economic returns for local communities and individuals. It should be reiterated that our conclusions are based on 4-yr data and with underlying assumptions and should be reviewed as the plantation ages to test the accuracy of our predicitons.

Our results suggest that seedlings planted with polyethylene bags will result in the highest revenues and IRRs, regardless of ground level. The higher long-term returns justify the higher setup costs on economic grounds. However, the reality of the situation is that the increased nursery and labour costs are significant, and can represent a substantial portion of an individual's or family's income. The importance of considering all possible plantation options leading to Table 6 is that alternative plantation strategies can be planned when initial costs exceed available capital. This will provide maximum revenues in a suboptimal situation.

Moreover, development agencies with a fixed amount of capital for projects can use this study as a prototype for calculations of optimal allocation of initial expenditures across plantation options, if plantations are a potential investment strategy. On a larger scale, the array of plantation strategies can be compared with potential benefits from other capital investments, to increase decision-making confidence regarding program design.

The fact that the optimal harvest period varies according to planting technique and ground level leads to the conclusion that mangrove plantation management can promote multi-year harvests, even when only one planting treatment is applied across ground levels. Most small-scale plantation owners strive for a one-time harvest regardless of ground level or planting technique, which provides income only during one year. However, by following the optimal harvesting schedule, profits will be maximized and will be generated across years. If a plantation owner establishes the plantation over the course of a number of years, the harvest scheduling may become quite complicated as both the year of establishment and ground level must be taken into account to optimize harvesting, even if only one planting technique is used. A secondary benefit reaped through the utilization of multi-year harvests is ecosystem protection and amelioration of negative environmental impacts associated with large clearcuts. Thus, the results of this study suggest that optimization of economic returns for coastal plantations in Ayeyarwady does not necessarily require a sacrifice of the ecological benefits derived from mangrove plantations.

It is tempting to argue that direct seed sowing might result in increased benefits if seed sowing takes place in year 0, i.e. during the time bare root and potted seedlings mature in the alternative plantation scenarios. Following that strategy, a direct seed plantation would have 11 yr to mature instead of 10, assuming a similar target year for harvest. This argument fails because site preparation takes at least 6 months (Than 1999) allowing seedlings to be raised in a nursery during site preparation. It would not be possible to directly plant seeds and thereby achieve a longer growth period for that plantation strategy. In only one case does the IRR of DS seedlings at 13 yr exceed that of another planting technique at 10 yr on the same ground level (Table 6), so the argument also fails on economic grounds.

Finally, it would be worthwhile investigating the possibility of including other species in the *A. officinalis* plantations, because mixed plantation species could provide greater benefits than a monoculture. *Rhizophora* spp. and other genera are valuable in local markets in Asia (Hong & San 1993; Anon. 1994), and could be excellent additions to *Avicennia* plantations where local conditions are favourable. The use of other species would serve to protect against environmental factors such as species-specific pathogens. Moreover, mixed-species plantations can be harvested at different times, providing a more consistent income generation than a one-time harvest of a single species.

Acknowledgements. Support for MMT was provided by His Majesty King Bhumibol Adulyadej of Thailand, through the Asian Institute of Technology. Modelling assistance was provided by C.R. Webb, Jr. Helpful comments on the manuscript were provided by S.T. Kassouf.

References

Anon. 1994. *Mangrove forest management guidelines*. Food and Agriculture Organization of the United Nations, Rome.

Aksornkoae, S. 1993. *Ecology and management of mangroves.* IUCN, Bangkok.

Augsburger, C.K. 1984a. Light requirements of neotropical tree seedlings: a comparative study of growth and survival. *J. Ecol.* 72: 777-795.

Augsburger, C.K. 1984b. Seedling survival of tropical tree species: interactions of dispersal distance, light-gaps, and pathogens. *Ecology* 65: 1705-1712.

Augsburger, C.K. & Kelly, C.K. 1984. Pathogen mortality of tropical tree seedlings: experimental studies of the effects of dispersal distance, seedling density, and light conditions. *Oecologia* (*Berl.*) 61: 211-217.

Cintrón-Molero, G. & Schaeffer-Novelli, Y. 1991. Ecology and management of New World mangroves. In: Seelinger, E. (ed.) *Coastal plant communities of Latin America*, pp. 233-258. Academic Press.

Cohen, J.E. 1997. Estimates of coastal populations. *Science* 278: 1211-1212.

de la Cruz, A.A. 1984. A realistic approach to the use and management of mangrove areas in Southeast Asia. In: Teas, H.J. (ed.) *Physiology and management of mangroves*, pp. 65-68. Dr. W. Junk Publishers, The Hague.

De Steven, D. 1988. Light gaps and long-term seedling performance of a Neotropical canopy tree (*Dipteryx panamensis*, Leguminosae). *J. Trop. Ecol.* 4: 407-411.

Denslow, J.S., Schultz, J.C., Vitousek, P.M. & Strain, B.R. 1990. Growth responses of tropical shrubs to treefall gap environments. *Ecology* 71: 155-179.

Ellison, A.M. & Farnsworth, E.J. 1997. Simulated sea level change alters anatomy, physiology, growth, and reproduction of red mangrove (*Rhizophora mangle* L.). *Oecologia* (*Berl.*) 112: 435-446.

Hardwick, K., Healey, J., Elliott, S., Garwood, N. & Anusarnsunthorn, V., 1997. Understanding and assisting natural

regeneration processes in degraded seasonal evergreen forests in northern Thailand. *For. Ecol. Manage.* 99: 203-214.
Hong, P.N. & San, H.T. 1993. *Mangroves of Vietnam*. IUCN, Bangkok.
Howard, A.F. 1993. A linear programming model for predicting the sustainable yield of timber from a community forest on the Osa Peninsula of Costa Rica. *For. Ecol. Manage.* 61: 29-43.
Howard, A.F. & Valerio, J. 1992. A diameter class growth model for assessing the sustainability of silvicultural prescriptions in natural tropical forests. *Commonw. For. Rev.* 71: 171-177.
Howard, A.F., Rice, R.E. & Gullison, R.E. 1996. Simulated financial returns and selected environmental impacts from four alternative silvicultural prescriptions applied in the neotropics: a case study of the Chiamanes Forest, Bolivia. *For. Ecol. Manage.* 89: 43-57.
Imbert, D. & Ménard, S. 1997. Structure de la végétation et production primaire dans la mangrove de la baie de Fort-de-France, Martinique (F.W.I.). *Biotropica* 29: 413-426.
Jackson, J.K. 1994. *Manual of afforestation in Nepal*. 2nd ed. Forest Research and Survey Centre, Kathmandu.
Janzen, D.H. 1974. Tropical blackwater rivers, animals, and mast fruiting by Dipterocarpaceae. *Biotropica* 6: 69-103.
Librero, A.R. 1984. Mangrove management in the Philippines. In: Teas, H.J. (ed.) *Physiology and management of mangroves*, pp. 79-87. Dr. W. Junk Publishers, The Hague.
Lugo, A.E. & Snedaker, S.C. 1974. The ecology of mangroves. *Annu. Rev. Ecol. Syst.* 5: 39-64.
Nuttonson, M.Y. 1963. The *physical environment and agriculture of Burma*. American Institute of Crop Ecology, Washington D.C.
Olmsted, I. & Alvarez-Buylla, E.R. 1995. Sustainable harvesting of tropical trees: demography and matrix models of two palm species in Mexico. *Ecol. Appl.* 5: 484-500.
Pancel, L. 1993. Nursery management. In: Pancel, L. (ed.) *Tropical forestry handbook*, pp. 463-514. Springer-Verlag, Berlin.
Putz, F.E. & Chan, H.T. 1986. Tree growth, dynamics, and productivity in a mature mangrove forest in Malaysia. *For. Ecol. Manage.* 17: 211-230.
Rico-Gray, V. & Palacios-Rios, M. 1996. Salinidad y el nivel del agua como factores en la distribucion de la vegetacion en la cienaga del NW de Campeche, Mexico. *Acta Bot. Mex.* 34: 53-61.
Siddiqi, N.A. & Khan, M.A.S. 1991. *Growth performance of mangrove trees along the coastal belt of Bangladesh*. UNDP/UNESCO Mangrove Ecosystems Occasional Paper.
Than, M.M. 1999. *Establishment of mangrove plantations in the Ayeyarwady delta, Myanmar*. M. Sc. Thesis, Asian Institute of Technology, Bangkok.
Vanclay, J.K. 1994. Sustainable timber harvesting: simulation studies in the tropical rainforests of north Queensland. *For. Ecol. Manage.* 69: 299-320.
Watson, J.G. 1928. *Mangrove forests of the Malay peninsula*. Malayan Forest Rec. No. 6. Fraser and Newe, Ltd., Singapore.
Weechakit, D. 1987. *Growth and survival of private mangrove plantations (Rhizophora apiculata) at Amphoe Bay, Samut Provinc*e. M. Sc. Thesis, Kasetsart University Graduate School.

Received 17 January 2000;
Revision received 20 September 2000;
Accepted 11 October 2000.

For App. 1, see p. 190.

App. 1. Empirical biological results, and production / revenue projections for three mangrove planting treatments in Ayeyarwady Delta, Myanmar. If a girth class is not represented in a row, it indicates that there were no seedlings measured (yr 4) or predicted to achieve (yr 10-15) that size class. 'Girth class' is the categorization of stems into 2.54 cm girth classes (see Text).
a. Census results at 4 yr and projection results to year 10. **b.** Projection results to years 13 and 15.

a.

		YEAR 4						YEAR 10 Projections					
Treatment	Girth class	% in girth class	# in class/ha	Girth (cm)	Height (m)	Volume (m^3/ha)	Mean height increment	Height (m)	Girth (cm)	Timber use	Volume (m^3/ha)	Revenue (BUK/ha)	Total revenue
BR High	1.0	10%	138	2.5	2.0	0.011	0.376	4.3	6.4	FW	0.15	968	
	2.0	46%	638	5.1	2.1	0.215	0.397	4.5	12.7	FW	2.87	18 784	
	3.0	41%	569	7.6	2.4	0.492	0.470	5.2	19.1	FW	6.72	43 899	
	4.0	3%	35	10.2	2.9	0.063	0.588	6.4	25.4	POLE		9 315	72 966
BR Med	1.0	3%	67	2.5	2.3	0.006	0.450	5.0	6.4	FW	0.08	548	
	2.0	34%	732	5.1	2.6	0.303	0.516	5.7	12.7	FW	4.18	27 308	
	3.0	35%	746	7.6	2.7	0.731	0.550	6.0	19.1	FW	10.15	66 318	
	4.0	23%	479	10.2	3.3	1.020	0.700	7.5	25.4	POLE		129 398	
	5.0	4%	93	12.7	4.1	0.385	0.900	9.5	31.8	POST		55 633	
	6.0	1%	13	15.2	4.6	0.088	1.018	10.7	38.1	POST		7 948	287 152
BR Low	2.0	7%	122	5.1	2.8	0.055	0.574	6.2	12.7	FW	0.77	5 002	
	3.0	24%	420	7.6	3.3	0.501	0.696	7.5	19.1	FW	7.12	46 506	
	4.0	38%	664	10.2	3.6	1.542	0.775	8.3	25.4	POLE		179 213	
	5.0	21%	376	12.7	3.9	1.492	0.859	9.1	31.8	POST		224 547	
	6.0	11%	188	15.2	4.3	1.172	0.949	10.0	38.1	POST		112 273	567 541
DS High	1.0	16%	263	2.5	1.8	0.019	0.442	4.4	6.4	FW	0.29	1 913	
	2.0	79%	1323	5.1	2.0	0.433	0.507	5.1	12.7	FW	6.76	44 198	
	3.0	6%	95	7.6	2.6	0.088	0.642	6.4	19.1	FW	1.38	8992	55 102
DS Med	1.0	1%	24	2.5	1.7	0.002	0.432	4.3	6.4	FW	0.03	173	
	2.0	41%	804	5.1	2.3	0.292	0.563	5.6	12.7	FW	4.56	29 810	
	3.0	56%	1097	7.6	2.7	1.057	0.664	6.6	19.1	FW	16.52	107 915	
	4.0	1%	24	10.2	3.1	0.049	0.772	7.7	25.4	POLE		6 581	144 479
DS Low	1.0	4%	71	2.5	1.7	0.005	0.423	4.2	6.4	FW	0.08	494	
	2.0	24%	449	5.1	2.2	0.156	0.539	5.4	12.7	FW	2.44	15 948	
	3.0	20%	378	7.6	2.7	0.375	0.683	6.8	19.1	FW	5.86	38 285	
	4.0	31%	579	10.2	3.5	1.310	0.877	8.8	25.4	POLE		156 279	
	5.0	19%	354	12.7	4.3	1.536	1.075	10.8	31.8	POST		211 562	
	6.0	3%	59	15.2	4.7	0.403	1.175	11.8	38.1	POST		35 260	457 829
PS High	2.0	42%	942	5.1	2.3	0.346	0.444	4.9	12.7	FW	4.69	30 642	
	3.0	50%	1125	7.6	2.6	1.073	0.532	5.8	19.1	FW	14.85	97 058	
	4.0	8%	169	10.2	3.2	0.353	0.685	7.4	25.4	POLE		45 563	
	6.0	1%	14	15.2	4.6	0.093	1.018	10.7	38.1	POST		8 395	181 658
PS Med	3.0	8%	182	7.6	2.8	0.185	0.574	6.2	19.1	FW	2.58	16 840	
	4.0	64%	1549	10.2	3.5	3.524	0.757	8.1	25.4	POLE		418 264	
	5.0	25%	608	12.7	4.2	2.548	0.915	9.7	31.8	POST		362 678	
	6.0	4%	91	15.2	4.9	0.647	1.098	11.5	38.1	POST		54 402	852 183
PS Low	2.0	1%	16	5.1	2.1	0.005	0.408	4.6	12.7	FW	0.07	475	
	3.0	1%	32	7.6	2.9	0.034	0.608	6.6	19.1	FW	0.47	3 074	
	4.0	34%	866	10.2	3.7	2.042	0.789	8.4	25.4	POLE		233 888	
	5.0	39%	992	12.7	4.2	4.219	0.929	9.8	31.8	POST		592 373	
	6.0	18%	441	15.2	4.8	3.102	1.086	11.4	38.1	POST		263 277	
	7.0	7%	173	17.8	5.4	1.862	1.235	12.9	44.5	POST		103 430	1196516

b.

				YEAR 13 Projections						YEAR 15 Projections					
Treatment	Girth class	% in girth class	# /ha	Height (m)	Girth (cm)	Timber use	Volume (m^3/ha)	Revenue (BUK/ha)	Total revenue	Height (m)	Girth (cm)	Timber use	Volume (m^3/ha)	Revenue (BUK/ha)	Total revenue
BR High	1.0	10%	138	5.4	8.3	FW	0.32	3 941		6.1	9.5	FW	0.48	9 189	
	2.0	46%	638	5.7	16.5	FW	6.15	76 596		6.5	19.1	FW	9.34	178 703	
	3.0	41%	569	6.6	24.8	POLE		265 840		7.6	28.6	POLE		317 642	
	4.0	3%	35	8.1	33.0	POST		35 604	381 981	9.3	38.1	POST		51 267	556 800
BR Med	1.0	3%	67	6.4	8.3	FW	0.18	2 241		7.3	9.5	FW	0.27	5 235	
	2.0	34%	732	7.2	16.5	FW	8.99	111 977		8.2	19.1	FW	13.69	261 918	
	3.0	35%	746	7.7	24.8	POLE		348 149		8.8	28.6	POLE		415 989	
	4.0	23%	479	9.6	33.0	POST		494 586		11.0	38.1	POST		712 166	
	5.0	4%	93	12.2	41.3	POST		96 170		14.0	47.6	POST		138 477	
	6.0	1%	13	13.7	49.5	POST		13 739	1 066 861	15.8	57.2	POST		19 782	1 553 567
BR Low	2.0	7%	122	8.0	16.5	FW	1.65	20 551		9.1	19.1	FW	2.51	48 112	
	3.0	24%	420	9.6	24.8	POLE		196 315		10.9	28.6	POLE		234 569	
	4.0	38%	664	10.6	33.0	POST		684 990		12.1	38.1	POST		986 333	
	5.0	21%	376	11.7	41.3	POST		388 161		13.4	47.6	POST		558 922	
	6.0	11%	188	12.8	49.5	POST		194 081	1 484 098	14.7	57.2	POST		279 461	2 107 396
DS High	1.0	16%	263	5.8	8.3	FW	0.64	8 006		6.6	9.5	FW	0.99	18 900	
	2.0	79%	1323	6.6	16.5	FW	14.86	185 006		7.6	19.1	FW	22.83	436 772	
	3.0	6%	95	8.3	24.8	POLE		44 132	237 143	9.6	28.6	POLE		52 731	508 404
DS Med	1.0	1%	24	5.6	8.3	FW	0.06	725		6.5	9.5	FW	0.09	1 713	
	2.0	41%	804	7.3	16.5	FW	10.02	124 781		8.4	19.1	FW	15.40	294 590	
	3.0	56%	1097	8.6	24.8	POLE		512 241		10.0	28.6	POLE		612 056	
	4.0	1%	24	10.0	33.0	POST		25 155	662 902	11.6	38.1	POST		36 221	944 580
DS Low	1.0	4%	71	5.5	8.3	FW	0.17	2 068		6.4	9.5	FW	0.26	4 882	
	2.0	24%	449	7.0	16.5	FW	5.36	66 758		8.1	19.1	FW	8.24	157 605	
	3.0	20%	378	8.9	24.8	POLE		176 526		10.3	28.6	POLE		210 924	
	4.0	31%	579	11.4	33.0	POST		597 335		13.2	38.1	POST		860 115	
	5.0	19%	354	14.0	41.3	POST		365 715		16.1	47.6	POST		526 601	
	6.0	3%	59	15.3	49.5	POST		60 953	1 269 354	17.6	57.2	POST		87 767	1 847 895
PS High	2.0	42%	942	6.3	16.5	FW	10.06	125 265		7.2	19.1	FW	15.29	292 587	
	3.0	50%	1125	7.4	24.8	POLE		525 375		8.5	28.6	POLE		627 750	
	4.0	8%	169	9.4	33.0	POST		174 150		10.8	38.1	POST		250 763	
	6.0	1%	14	13.7	49.5	POST		14 513	839 302	15.8	57.2	POST		20 897	1 191 996
PS Med	3.0	8%	182	8.0	24.8	POLE		85 111		9.1	28.6	POLE		101 696	
	4.0	64%	1549	10.3	33.0	POST		1 598 697		11.8	38.1	POST		2 302 000	
	5.0	25%	608	12.4	41.3	POST		626 940		14.2	47.6	POST		902 745	
	6.0	4%	91	14.8	49.5	POST		94 041	2 404 789	17.0	57.2	POST		135 412	3441852
PS Low	2.0	1%	16	5.8	16.5	FW	0.16	1 937		6.6	19.1	FW	0.24	4 519	
	3.0	1%	32	8.4	24.8	POLE		14 711		9.6	28.6	POLE		17 577	
	4.0	34%	866	10.8	33.0	POST		893 970		12.3	38.1	POST		1 287 248	
	5.0	39%	992	12.6	41.3	POST		1 024 002		14.4	47.6	POST		1 474 484	
	6.0	18%	441	14.6	49.5	POST		455 112		16.8	57.2	POST		655 326	
	7.0	7%	173	16.6	57.8	POST		178 794	2 568 525	19.0	66.7	POST		257 450	3 696 603