Table 3.1. Parameter values for a number of hedgerow trees used in alley-cropping experiments on an acid soil in Sumatra (Hairiah *et al.*, 1992; van Noordwijk *et al.*, 1995); the last two columns give total dry weight of prunings (DW_{tot}) and total N contents (N_{tot}) measured at a 4-m hedgerow spacing and about 5 pruning events per year.

Tree species	w (m)	LAI_p	LWR	SLA ($m^2 kg^{-2}$-1)	D_p (kg m^{-1})	N_p (kg kg^{-1})	f_a	x	DW_{tot} (Mg ha^{-1} $year^{-1}$)	N_{tot} (kg ha^{-1} $year^{-1}$)
Leucaena leucocephala	3.5	2.5	0.7	24	0.53	0.024	0.6	0.7	8	190
Gliricidia sepium	3.0	2.3	0.6	22	0.53	0.029	0.6	0.9	8	230
Calliandra calothyrsus	3.7	3.0	0.7	20	0.86	0.030	0.5	0.7	12	360
Peltophorum dasyrrachis	1.5	3.0	0.6	12	0.53	0.021	0.5	0.4	8	170
Erythrina orientalis	2	1.6	0.7	20	0.27	0.028	0.6	0.5	4	110

Figure 3.8 and Table 3.2 the predicted optimum hedgerow spacing is given, for three levels of inherent soil N supply. The calculations show a three-fold variation in both the M and S parameters between the five tree species, and a two-fold variation in the $M:S$ ratio (50–97 kg N ha^{-1} shaded). The soil N supply above which alley cropping never has an advantage (whatever the tree spacing) only varies from 100 to 123 kg ha^{-1}. The optimum tree spacing at N_s below the critical value depends strongly on the tree species, however. The tree spacing of 4 m used in the experiment from which the tree parameters were derived was approximately optimal at a N_s level of 60 kg ha^{-1} for *Peltophorum* and *Erythrina*, but was too narrow for the three other trees even at $N_s = 30$ kg ha^{-1}. The calculations thus show that a comparison of different tree species at a single hedgerow spacing cannot be extrapolated to other hedgerow spacings, as the spacing used can be below optimum for some of the trees, about right or above optimum for others. The table also shows that in situations where the inherent soil N supply is changing over time, any hedgerow spacing chosen has to be a compromise; a spacing which was good initially will become too narrow if soil fertility is improving and too wide if the soil fertility is declining. Unfortunately, hedgerow spacing cannot be easily adjusted, unless the trees are grown in pots (which would jeopardize any nutrient recycling functions of the trees). The best practical way to modify the effective tree density may be to vary pruning height and switch to ground-level pruning if trees are too competitive while soil fertility is adequate.

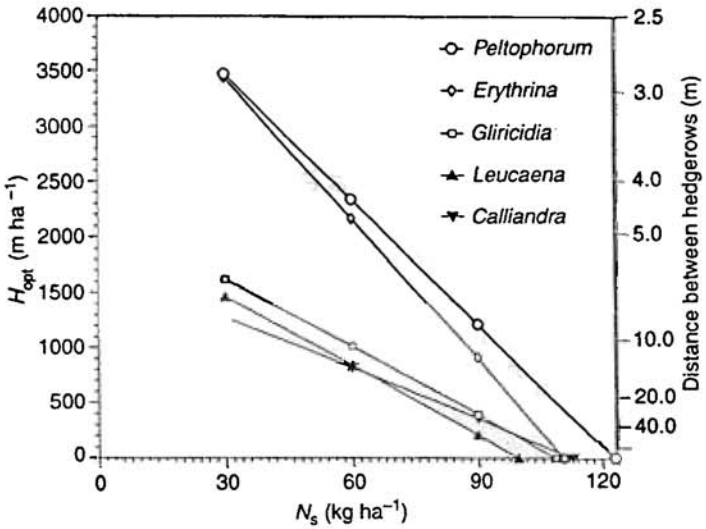


Fig. 3.8. Predicted optimum hedgerow spacing for five tree species, based on the parameters in Table 3.1, as a function of inherent soil fertility.

Table 3.2. Calculated optimum hedgerow spacing for the tree parameters of Table 3.1 for a crop with a maximum N uptake of 200 kg ha^{-1}; $\varepsilon = 0.25$, $P_t = 2$ prunings per crop.

					$N_s = 30$ kg ha^{-1}		$N_s = 60$ kg ha^{-1}		$N_s = 90$ kg ha^{-1}	
Tree	M (kg m^{-1})	S (ha m^{-1})	M/S (kg ha^{-1})	$N_{s,crit}$ (kg ha^{-1})	H_{opt} (m ha^{-1})	D_h (m)	H_{opt} (m ha^{-1})	D_h (m)	H_{opt} (m ha^{-1})	D_h (m)
Leucaena	0.0159	3.2	50	100	1460	6.8	833	12	208	48
Gliricidia	0.0184	2.8	66	109	1616	6.2	1005	9.9	395	25
Calliandra	0.0258	3.5	74	113	1271	7.9	813	12	355	28
Peltophorum	0.0117	1.2	97	123	3484	2.9	2355	4.3	1226	8.2
Erythrina	0.0091	1.3	70	111	3451	2.9	2179	4.6	907	11

Discussion

Apparently, hedgerow intercropping, where trees have to be a source of N to the crop, is restricted to situations with a low soil N supply from other sources and crops that can respond to considerably higher N supply than is available. At the economic level, the labour costs for obtaining N this way have to be evaluated against the costs of obtaining N from other sources.

The description given by this model assumes that the prunings are spread equally over the land available, including the area reserved for hedgerow trees. In practice the prunings will be concentrated in the crop zone, but the trees will partly compete with the crops for the N mineralized; as a first approximation the current description therefore may be acceptable. As the crops in the middle of the alley will receive more light, it would make sense to concentrate the pruning only in this middle strip, and accept that the crops closer to the hedgerows have a limiting level of both N and light. The equations given are rather pessimistic on the possibilities of hedgerow intercropping, as they do not consider this possibility of strategic mulch placement (neither do most of the experiments reported in the literature...). Although the model suggests a limited 'niche' for hedgerow intercropping, considerable scope remains for selecting hedgerow trees which are most suitable.

For the situation described, the best hedgerow tree is one with a high $M:S$ ratio, which can be based on a combination of a narrow but compact hedgerow canopy, thick leaves, the major part of the tree canopy not exceeding that of the crop, a high N content and a suitable N release pattern from the prunings, coinciding with crop demand. The need for fine tuning of the N release pattern increases with decreasing residence time for mineral N in the crop root zone, because of shallow rooting and/or high rainfall infiltration surplus over evapotranspiration (van Noordwijk *et al.*, 1992).

The evaluation given may be too pessimistic on the scope for alley cropping for several situations:

1. *Other litter inputs*: Spontaneous litterfall from the trees (turnover of leaf biomass) will add to the mulch supply, without causing further shade. With the intensive pruning regimes required to check the tree growth during the cropping period, however, litterfall will be low for most trees.
2. *Temporal segregation*: If part of the growing season can be reserved for tree growth, litterfall and an increased pruned biomass can be obtained without shading a crop. Off-season biomass production by the tree is probably the major way for agroforestry to increase total resource capture.
3. *Shade-tolerant crops*: The prospects for alley cropping greatly improve if the crop is light-saturated under full sunlight. This opens the option of 'free light interception' by an upper tree canopy, resulting in mulch supply to the

crop without shade costs. In that case sparse open canopies are better than dense hedgerows. This situation is more likely to exist under the clear skies of the semi-arid tropics than under the usually overcast skies of the humid tropics, and more so for C3 than for C4 crops.

Essentially, the approach can also be used for evaluating the optimum tree density for sparse upper storey trees with little or no pruning. The example of tea gardens in Java shows, however, that shade costs of *in situ* N production are considerable. Tea gardens used to have a complete tree cover of trees such as *Paraserianthes falcataria* as a source of N and organic matter, before inorganic fertilizer became abundantly available, but now nearly all trees are removed. Cheaper fertilizer combined with less shade-tolerant new tea varieties induced the change from an agroforestry to a pure crop system. Data on the N response of tea in NE India in the presence or absence of shade trees (Fig. 3.9) are in line with the shade and mulch model presented here: without N fertilizer the presence of *P. falcataria* trees could induce a 50% yield increase. That same yield increase, however, can be obtained with 45 kg ha^{-1} of N in the absence of trees. At a fertilizer rate of 90 kg ha^{-1} trees have no effect on tea yield, but they reduce the maximum attainable tea yield by 250 kg ha^{-1}. If the direct value of the shade trees (e.g. by timber production) plus the saving of about 90 kg N fertilizer per year would offset this yield loss of 250 kg tea per year, it would become worthwhile to reintroduce the trees.

The scope for systems with simultaneous trees and crops has clear limitations. A partial temporal separation may be needed. If we uncouple

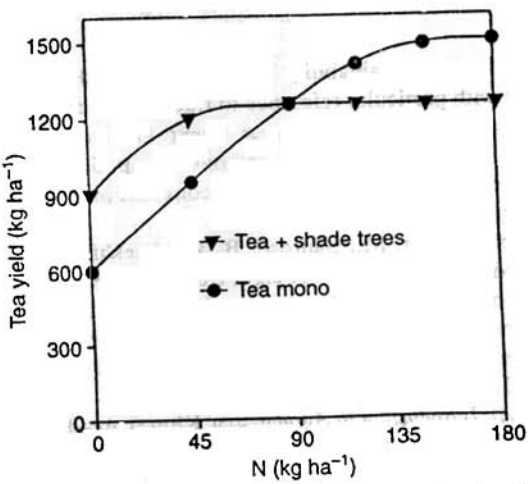


Fig. 3.9. Response of tea yield to N fertilizer application in the presence or absence of *Paraserianthes falcataria* as N_2 fixing tree in NE India (B.C. Barbora, personal communication).

the mulch production from the amount of shade cast, e.g. by having a period of the year devoted to tree growth and thus mulch production and a period in which the trees are set back severely and the crops are growing, the potential for *in situ* mulch production will increase. For such a system, however, we need either trees that have the right phenology, such as the famous *Faidherbia albida*, or trees which survive a heavy pruning, e.g. at a low height, take 2 or 3 months to recover, but can still have a good biomass production rate afterwards. If the terms B and BQ in the models of Ranganathan and de Wit (Chapter 2, this volume) are correlated as they suggest, it will be difficult to find such trees. Yet it will be worthwhile to look for the exceptions, i.e. trees which recover slowly from a setback by pruning but have a high biomass production rate once recovered, and solve the shade and mulch dilemma by partly temporal separation of tree and crop growth.

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Appendix: Parameters and Symbols Used

C_{ct} = decrease in yield of tree products due to competition by the tree, per unit relative crop density [kg ha^{-1}]

C_{tc} = crop yield decrease due to competition by the tree, per unit relative tree density [kg ha^{-1}]

D_h = distance between two hedgerows [m]

D_p = dry weight of prunings per cutting cycle per m of hedgerow [kg m^{-1}]

ΔL = change in land quality for future production, units X to be specified [X ha^{-1}]

ΔL_c = (normally negative) change in land quality under monoculture crop [X ha^{-1}]

ΔL_t = (normally positive) change in land quality under tree cover [X ha^{-1}]

E_c = price per unit crop yield [\$ kg^{-1}]

E_t = price per unit yield of tree products [\$ kg^{-1}]

E_L = price per unit change in land quality [\$ X^{-1}]

ε = light interception fraction by foliage at LAI = 1

F = positive effect on crop yield due to soil fertility improvement, per unit relative tree density [kg ha^{-1}]

f_a = application efficiency of added nutrient sources, e.g. prunings; increase in available soil N per unit applied N [kg kg^{-1}]

f_i = fraction of light not intercepted by trees available to the crop

f_p = crop efficiency in producing yield per unit N taken up from the soil [kg yield per kg N uptake]

f_t = relative tree area (for an agroforestry system: $0 < f_t < 1$)

$f_{t,opt}$ = f_t which maximizes crop yield
f_u = uptake efficiency [kg uptake per kg N available]
H = length of hedgerows per ha [m ha^{-1}] = $10^4/D_h$
H_{opt} = H which maximizes yield
I_{ct} = scaled net crop–tree interaction
I_{tc} = scaled net tree–crop interaction
L = scaled relative importance of changes in land quality
LAI_p = leaf area index in the hedgerow tree canopy at pruning [m^2 m^{-2}]
LAR_p = leaf area ratio = leaf area per unit (pruned) shoot dry weight [m^2 kg^{-1}]
LWR_p = leaf weight ratio = leaf dry weight as fraction of (pruned) shoot dry weight [kg kg^{-1}]
M = effective N supplied to crop via mulch, per m of hedgerow [kg m^{-1}]
N_a = amount of N added [kg ha^{-1}]
N_m = amount of available N required for obtaining maximum yield Y_{max} [kg ha^{-1}]
N_p = N concentration in prunings [kg kg^{-1}]
$N_{s,crit}$ = critical soil N level above which alley cropping gives no yield benefit [kg ha^{-1}]
N_s = amount of N available in the soil, without any (organic) fertilizer [kg ha^{-1}]
P_f = frequency of pruning per crop growing season
S = effective crop area shaded by per m hedgerow [ha m^{-1}]
SLA = specific leaf area = leaf surface area per unit leaf dry weight [m^2 kg^{-1}]
U = N uptake by crop [kg ha^{-1}]
w = width of hedgerow tree canopy at pruning [m]
x = fraction of hedgerow tree canopy above the crop canopy
Y_c = dry matter yield of crop [Mg ha^{-1}]
Y_{0c} = crop yield in the absence of trees [kg ha^{-1}]
Y_{0t} = yield of tree products in the absence of crops [kg ha^{-1}]
$Y_{m,l}$ = maximum yield, not limited by N shortage, under current light conditions [Mg ha^{-1}]
Y_{max} = maximum yield without shading by trees [Mg ha^{-1}]
Y_{tot} = total yield of agroforestry system [$ ha^{-1}]
Y_t = yield of tree products (or 'net present value' of future productivity) [kg ha^{-1}]