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Mulch and Shade Model for Optimum Alley-cropping Design Depending on Soil Fertility

M. VAN NOORDWIJK

International Centre for Research in Agroforestry, ICRAF-SE Asia, PO Box 161, Bogor 16001, Indonesia

Agroforestry or Woodlots Plus Cropped Fields

In many popular texts on agroforestry, the simple fact that tree and crop products can both contribute to a viable farming enterprise seems to be sufficient reason to use agroforestry systems. According to the definition used by ICRAF, however, agroforestry systems are not simply farming systems where both trees and crops or animals give useful products to the farmer, but systems where tree and crop (and/or animal) production interact (Lundgren and Raintree, 1982; Nair, 1993). Understanding and predicting such interaction should thus be at the heart of an agroforestry research programme.

Figure 3.1 gives a tentative classification of agroforestry systems, based on the degree of spatial and temporal overlap of the tree and crop components. Systems in the lower left corner do not fall under the definition of agroforestry, as here trees and crops do not interact. Systems in the upper right corner are generally not viable as competition between the tree and crop component will be too severe. In the upper left corner we find (improved) fallow systems, where a crop and a tree phase alternate on the same land. From a biophysical point of view, such systems are fairly simple and can be successful, but farmers will hesitate to put efforts into improving the fallow phase; it is thus understandable that developments in the direction of relay-establishment of the fallow vegetation are sought, which move the system towards the centre of the graph. Alley cropping was

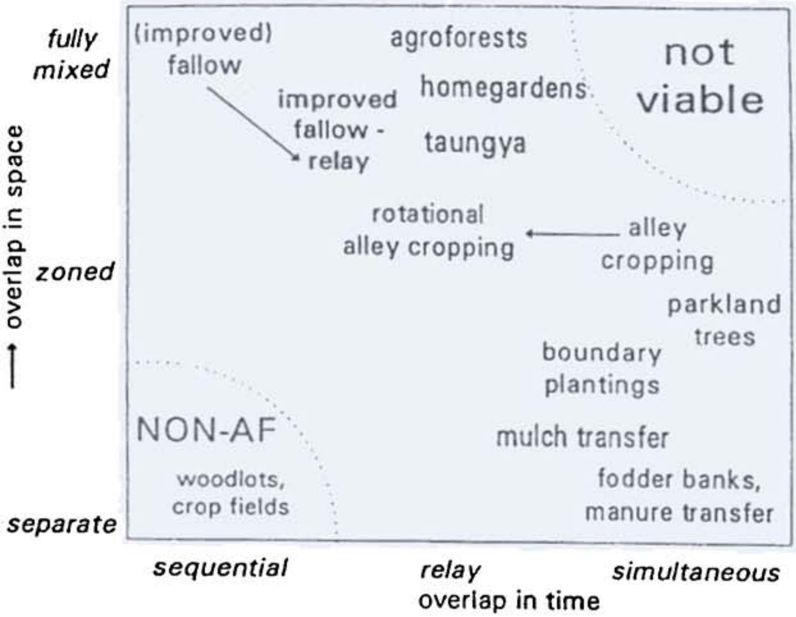

Fig. 3.1. Classification of agricultural systems based on both trees and crops, with regard to the degree of overlap in time (*x*-axis) and space (*y*-axis).

first developed as a fully simultaneous spatially zoned system, but recently interest in 'rotational alley cropping' has also moved the system towards the centre of the graph. Agroforestry systems with full-grown trees are either based on low tree densities (parklands, boundary plantings) or on relay systems, with a short crop and long tree phase (taungya, homegarden, agroforests).

The total yield of an agroforestry system in any given year can be described as the sum of the crop yield, the yield of tree products, the yield of animal products and the change in land quality, which reflects the concerns over the long term sustainability of the system. If we restrict ourselves to agroforestry systems without an animal production component, we obtain:

$$Y_{tot} = E_c Y_c + E_t Y_t + E_L \Delta L \qquad (3.1)$$

where:

Y_{tot} = total yield [\$ ha^{-1}]
E_c = price per unit crop yield [\$ kg^{-1}]
Y_c = crop yield [kg ha^{-1}]
E_t = price per unit yield of tree products [\$ kg^{-1}]

Y_t = yield of tree products (or 'net present value' of future productivity) [kg ha^{-1}]
E_L = price per unit change in land quality [\$ X^{-1}]
ΔL = change in land quality for future production in units X to be further specified [X ha^{-1}].

From this equation we can explore under which conditions a maximization of total yield will lead to a choice for an agroforestry system, with both a tree and a crop component, and under which conditions pure tree or crop production will be preferred.

In the most simple case we may describe all tree–crop interactions as linear functions of the relative tree area f_t. For crop yield Y_c we may formulate:

$$Y_c = (1 - f_t)(Y_{0c} + f_t F - f_t C_{tc})$$

where:

f_t = relative tree area (for an agroforestry system: $0 < f_t < 1$)
Y_{0c} = crop yield in the absence of trees [kg ha^{-1}]
F = positive effect of trees on crop yield, e.g. due to (short term) soil fertility improvement, per unit relative tree density [kg ha^{-1}]
C_{tc} = crop yield decrease due to competition by the tree, per unit relative tree density [kg ha^{-1}].

For the yield of tree products we may consider a negative interaction only:

$$Y_t = f_t(Y_{0t} - (1 - f_t)C_{ct})$$

where:

Y_{0t} = yield of tree products in the absence of crops [kg ha^{-1}]
C_{ct} = decrease in yield of tree products due to competition by the crop, per unit relative crop density [kg ha^{-1}].

The change in land quality for future production, ΔL, may be negative for a pure crop system and may become more positive with increasing relative tree density (unless a substantial part of tree products is exported from the field):

$$\Delta L = (1 - f_t)\Delta L_c + f_t \Delta L_t = \Delta L_c + f_t(\Delta L_t - \Delta L_c) \qquad (3.4)$$

where:

ΔL_c = (normally negative) change in land quality for future production while under monoculture crop [X ha^{-1}]
ΔL_t = (normally positive) change in land quality for future production while under tree cover [X ha^{-1}].

Two contrasting views exist on trees: in agroforestry trees are generally seen as 'soil improvers', especially where fast-growing N_2 fixing trees are used, while in plantation forestry there is serious concern about soil depletion due to short rotation forestry, especially where fast-growing trees are used (Sanchez *et al.*, 1985; Bruijnzeel, 1992). The different perceptions are partly due to different conditions (poor soils used for plantation forestry) and management practices (more damage may be done to the soil while harvesting the timber than by the nutrient export as such).

If sustainability is considered a hard constraint ($\Delta L > 0$), then:

$$f_t \frac{-\Delta L_c}{\Delta L_t - \Delta L_c} \quad (3.5)$$

Alternatively, the costs of land degradation may be considered to be outweighed by direct benefits and be restored later as happens in shifting cultivation or fallow rotation systems.

Agroforestry systems are defined as systems that combine trees and crops (thus $0 < f_t < 1$) and where tree–crop interactions occur. An optimum tree density $f_{t,opt}$ may be found for $dY_{tot}/df_t = 0$, if $d^2Y_{tot}/(df_t)^2 < 0$. Only if this optimum tree density is between 0 and 1, agroforestry practices are the best choice.

$$\frac{dY_{tot}}{df_t} = E_c(F - C_{tc} - Y_{0c}) + E_t(Y_{0t} - C_{ct}) + E_L(\Delta L_t - \Delta L_c) - 2f_t(E_c(F - C_{tc}) - E_t C_{ct})$$

The requirement $d^2Y_{tot}/(df_t)^2 < 0$ leads to:

$$E_c F > E_c C_{tc} + E_t C_{ct} \quad (3.7)$$

which shows that the positive interaction term on the left hand should be larger than the negative one on the right hand; otherwise it is better to have crops and trees on separate plots. Yet, it is possible to compensate a negative interaction term with a larger positive other term. A positive overall interaction can be obtained for systems where neither the crop nor the tree component shows an absolute benefit. For $f_{t,opt}$ we then obtain:

$$f_{t,opt} = \frac{-E_c Y_{0c} + E_t Y_{0t} + E_L(\Delta L_t - \Delta L_c)}{2(E_c(F - C_{tc}) - E_t C_{ct})} + 0.5 \quad (3.8)$$

which can be rewritten as:

$$f_{t,opt} = \frac{X - 1 + L}{2(I_{tc} + X\, I_{ct})} + 0.5$$

where:

$X = (Y_{0t}E_t)/(Y_{0c}E_c)$ is the ratio of financial returns on a pure tree and a pure crop system

$I_{tc} = (F - C_{tc})/Y_{0c}$ is the scaled net tree crop interaction
$I_{ct} = (-C_{ct})/Y_{0t}$ is the scaled net crop tree interaction
$L = E_l(\Delta L_t - \Delta L_c)/(Y_{0c}E_c)$ is the scaled relative importance of changes in land quality.

The constraint $0 < f_{t,opt} < 1$ then leads to:

$$\frac{1 - L - I_{tc}}{1 + I_{ct}} < X < \frac{1 - L + I_{tc}}{1 - I_{ct}} \tag{3.10}$$

Outside the constraints (Equation 3.10) one would prefer either a pure tree system ($f_t = 1$) or a pure crop system ($f_t = 0$), depending on the values of $E_c Y_{0c}$ and $(E_t Y_{0t} + E_l L)$. The equations also show that the choice for an agroforestry or a more simple system not only depends on the biophysically determined parameters, but also on the 'value' assigned to the various possible products (trees, crops and land).

Figure 3.2 shows a general demarcation of the domain for agroforestry based on the economic value of tree and crop production (the tree products should be discounted for the length of the harvest cycle) and the strength of the interaction term. The larger the positive interaction on crop production $(F - C_{tc})$, the larger the scope for agroforestry (i.e. the range of price ratios which lead to $0 < f_{t,opt} < 1$). For realistic estimates of the interaction term, the tree products need to have some direct value to the farmer to justify agroforestry. If trees have no direct value, the interaction term $(F - C_{tc})/Y_{0c}$ has to be 1.0 or more, i.e. the net positive effect of trees on crop yield per unit tree area has to exceed the monocultural crop yield per unit area.

With these equations one can describe approximately stationary systems, as approximated in alley cropping where the normal growth of the tree component is checked by regular pruning. For most other agroforestry systems, however, the tree–crop interactions change from year to year. When the tree component is more valuable than a pure crop, there may still be scope for crops in the first year(s) when the trees are still small. The approximately stationary situations of 'alley cropping', however, may offer good opportunities for further investigation. To get one step further, we will attempt to formulate the tree–crop interaction term based on external resources limiting crop production, such as light and nutrients.

Hedgerow Tree–Crop Interactions

In hedgerow intercropping systems, trees and food crops are interacting in various ways. As both positive and negative interactions occur, site-specific optimization of the system may be required. The most important interactions probably are:

1. Mulch production from the hedgerows, increasing the supply of N and other nutrients to the food crops,

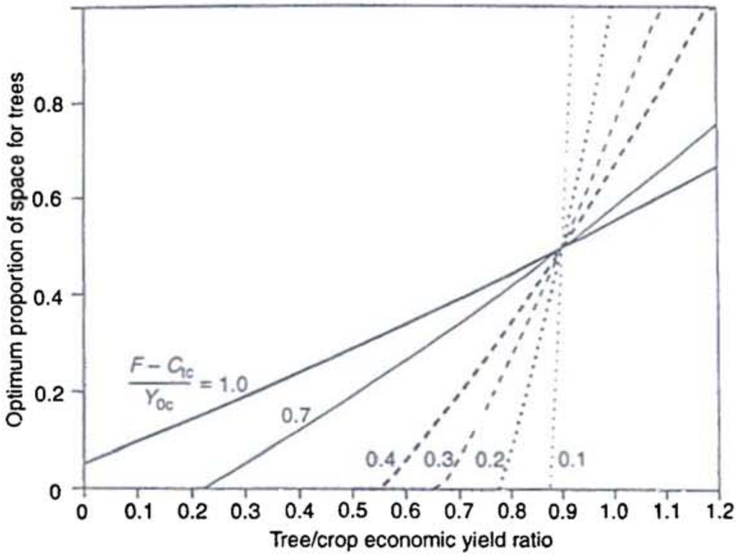

Fig. 3.2. Optimum allocation of land to trees, $f_{t,opt}$, as a function of the economic yield ratio of tree and crop products ($Y_{0t}E_t/(Y_{0c}E_c)$) and the relative interaction term $F - C_{1c}/Y_{0c}$, for $C_{1c}/Y_{0t} = 0.1$ and $E_1(\Delta L_t - \Delta L_c)/(E_c Y_{0c}) = 0.1$ (based on Equation 3.8).

2. Shading by the hedgerows, reducing light intensity at the crop level,
3. Competition between tree and crop roots for water and/or nutrients in the topsoil,
4. Nitrogen supply by tree roots to crop roots, either due to root death following hedgerow pruning or by direct transfer if nodulated roots are in close contact with crop roots,
5. Effects on weeds, pests and diseases,
6. Long term benefits by erosion control and maintenance of soil organic matter.

Disregarding the long term effects through the soil and the more direct effect (positive or negative) through weeds, pests and diseases, interactions 1 and 4 are positive, 2 and 3 are negative. Little quantitative information about the below-ground interactions 3 and 4 is available as yet, the overall effect may be positive or negative. Wherever water availability is limiting crop growth (roughly in zones with less than 150 mm of rainfall per month in the growing season, based on 4 mm day^{-1} of evapotranspiration and 20% losses by runoff and deep infiltration), however, negative effects will normally predominate.

For some time, tree–crop interactions have been studied primarily by focusing on the tree–crop interface. For below-ground interactions, however, no clear 'interface' exists as tree roots may extend 30 m from the stem or more (see Chapter 7).

As a first step we will here consider only the above-ground interactions 1 and 2 and derive a simple model for *mulch* and *shade*, which can be used for optimization of hedgerow intercropping in conditions where water is not limiting. In hedgerow intercropping the following choices can be made:

1. Tree species,
2. Distance between hedgerows,
3. Pruning regime (height and frequency),
4. Crop, cultivar, crop population density and plant spacing,
5. Additional fertilizer input level.

As these factors are interacting and field experiments involving all factors are too large to be manageable, a simple model describing the interaction may help to predict optimum patterns beforehand so as to test relevant ones in a field experiment. In the following we will use the distance between hedgerows as the parameter to be optimized, given characteristics of the tree, the pruning regime, the crop and soil fertility level. The conventional control for hedgerow intercropping experiments, crops without trees, fits in this scheme as it represents an infinitely large distance between hedgerows. A point of warning is appropriate here, as in practical experiments below-ground interactions may not have been effectively excluded in so called 'control' plots; the control plot may therefore give a lower yield and the positive effects of alley cropping may be overestimated. On most smallholder farms a similar mining of adjacent (or neighbours') plots by trees can be expected (Coe, 1994).

Shade and Mulch Model

Crop growth as influenced by N-uptake and shade

The relationship between dry matter production and N uptake can often be described by the rising branch of a quadratic function. Under severe N limitation dry matter production increases almost linearly with increasing uptake; when the maximum production is approached the N concentration in the crop as a whole is about twice the minimum value. A simple model was formulated by van Noordwijk and Wadman (1992) and van Noordwijk and Scholten (1994):

$$Y_c = f_p U\left(2 - \frac{f_p U}{Y_{m,l}}\right) \tag{3.11}$$

and

$$U = f_u(N_s + f_a N_a) \tag{3.12}$$

where:

Y_c = dry matter yield of crop [Mg ha^{-1}]
f_p = crop efficiency in producing yield per unit N taken up from the soil [kg yield per kg N uptake]. f_p equals the harvest index divided by the required N concentration in biomass (van Noordwijk and Scholten, 1994)
U = amount of N taken up by the crop [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_u = uptake efficiency [kg N uptake per kg N available]
N_a = amount of N added [kg ha^{-1}]
N_s = amount of N available in the soil, without any (organic) fertilizer [kg ha^{-1}]
$Y_{m,l}$ = maximum yield, not limited by N shortage, under current light conditions [Mg ha^{-1}].

The quadratic function reaches a maximum value for:

$$N_a = \frac{Y_{m,l} - N_s f_u f_p}{f_a f_u f_p} \tag{3.13}$$

In the present model we will assume that internal regulation of N uptake is complete, so N uptake will not be more than this value required for maximum crop production, but this assumption is not important as we do not consider supra-optimal N supply.

Under reduced light intensity the crop cannot reach the maximum yield value. In the humid tropics with relatively short days and under overcast sky, we may assume that for light demanding crops any further reduction in light leads to a proportional (linear) decrease in maximum (potential) yield level, Y_{max}:

$$Y_{m,l} = f_j Y_{max} \tag{3.14}$$

with:

Y_{max} = maximum yield potential without shading by trees,

f_j = fraction of light *not* intercepted by trees above the crop canopy.

Figure 3.3 shows the assumed relation between N uptake and crop yield for some numerical examples. The circles on the line for $f_j = 0$, $f_j = 0.25$ and $f_j = 0.5$ suggest the possibility of optimizing crop yields by hedgerow intercropping. Decreasing the distance in between hedgerows may lead to increased N uptake as well as increasing shade (f_j). As N

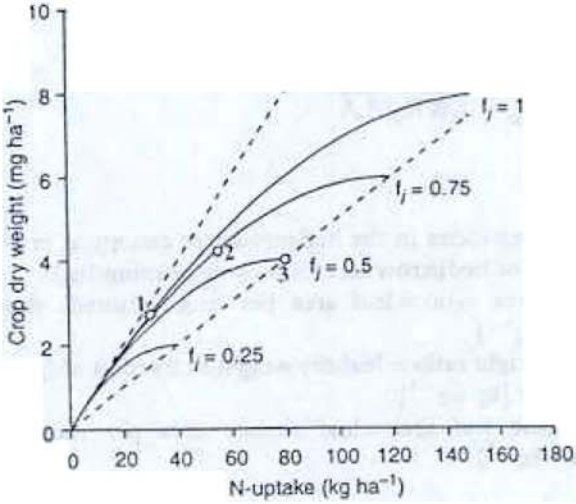

Fig. 3.3. Assumed relation between N uptake and crop yield according to Equations 3.10 and 3.13, for a value of Y_{max} of 8 Mg ha^{-1} and for f_p of 20 kg kg^{-1}. The circles on the line for $f_j=0$, $f_j=0.25$ and $f_j=0.5$ indicate the possibility of optimizing crop yields by hedgerow intercropping.

limitation becomes less severe but shading increases, crop yields may show an optimum response curve to distance between hedgerows.

Mulch production by the hedgerow trees

The amount of N supplied to the soil in prunings per crop is equal to:

$$N_a = HP_fD_pN_p = \frac{10^4 P_f D_p N_p}{D_h} \tag{3.15}$$

with:

H = length of hedgerows per ha [m ha^{-1}] = $10^4/D_h$
D_h = distance between two hedgerows [m]
P_f = frequency of pruning per crop growing season
D_p = dry weight of prunings per cutting cycle per m of hedgerow [kg m^{-1}]
N_p = N concentration in prunings [kg kg^{-1}].

For the biomass production D_p we can formulate:

$$D_p = \frac{LAI_p w}{LAR_p} = \frac{LAI_p w}{LWR_p SLA}$$

with:

LAI_p = leaf area index in the hedgerow tree canopy at pruning [$m^2\ m^{-2}$]
w = width of hedgerow tree canopy at pruning [m]
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 [$kg\ kg^{-1}$]
SLA = specific leaf area = leaf surface area per unit leaf dry weight [$m^2\ kg^{-1}$].

Combining Equations 3.14 and 3.15 gives:

$$f_a N_a = \frac{Hwf_a LAI_p N_p P_f}{LWR_p SLA} = HM \qquad (3.17)$$

where:

$$M = \frac{wf_a LAI_p N_p P_f}{LWR_p SLA}$$

The factor M combines several tree characteristics to obtain the amount of N available to the crop from prunings per metre of hedgerow. It is relatively high for trees with a wide crown, a high leaf area index, a high N content, frequent pruning, thick leaves (low SLA), many twigs and branches (low LWR) and a well-timed N release (high f_a).

Crop shading by hedgerow trees

For the shading by the hedgerows we may simplify the description by distinguishing between the crops directly underneath the canopy of the hedgerow trees (an area wH) and the crops outside the tree canopy (an area $10^4 - wH$). If all light came under an angle of 90° the shade factor would be:

$$f_i = 1 - \frac{Hw(1 - \varepsilon^{xLAI_p})}{10^4} = 1 - SH$$

with:

ε = light interception fraction by foliage at LAI = 1
x = fraction of hedgerow tree canopy above the crop canopy.

If light comes from a different angle, the shade intensity in the zone w may be less and in the remaining zone it will be more. As a first approximation, Equation 3.18 may still hold. The factor S indicates the equivalent space [ha m^{-1}] occupied by the hedgerow canopy at complete light interception, per unit hedgerow length. It is high for wide crown canopies and high values of ε and LAI_p.

Combined effects

Combining Equations 3.10, 3.12, 3.16 and 3.18 we obtain crop yield Y as a function of hedgerow length H:

$$Y = f_p f_u \left[(2N_s + MH) + \frac{f_p f_u (N_s + MH)^2}{Y_m (SH - 1)} \right] \tag{3.20}$$

By differentiating Equation 3.19 with respect to H, we can derive that yield Y is maximum when $H = H_{opt}$:

$$H_{opt} = \frac{1}{S}\left(1 - \sqrt{1 - \frac{N_m - N_s - 0.5SN_s^2/M}{N_m + 0.5S/M}}\right) \tag{3.21}$$

where N_m is the available N level required for obtaining maximum yield:

$$N_m = \frac{Y_{max}}{f_p f_u} \tag{3.22}$$

The optimum hedgerow length is inversely proportional to the S parameter, increases less than proportionally with increasing nitrogen production per unit hedgerow length, M, and decreases with increasing soil N supply, N_s. For high values of N_s the best solution is one without hedgerow trees ($H_{opt} = 0$). The critical value for $N_{s,crit}$ where H_{opt} becomes 0 is:

$$N_{s,crit} = \frac{M}{S}\left(\sqrt{\frac{2SN_m}{M} + 1} - 1\right) \tag{3.23}$$

$N_{s,crit}$ is approximately proportional to the $M:S$ ratio.

The yield advantage due to alley cropping at optimum tree spacing, compared with a situation without trees is:

$$Y_{opt} - Y_0 = f_p H_{opt}\left(2M - \frac{SN_s^2 + 2Mf_pN_s + M^2H_{opt}}{N_m(1 - SH_{opt})}\right) \tag{3.24}$$

The yield advantage apparently decreases with increasing N_s.

Results

Figure 3.4 shows some examples of calculations. With increasing N_s, i.e., N available in the soil for the crop from other sources than the prunings, the crop yields obviously increase. For values of N_s which are insufficient for obtaining the maximum yield, crop yields show an optimum response curve to the distance between hedgerows. With decreasing N_s the optimum becomes more pronounced and occurs at smaller distances between the hedgerows.

From curves as shown in Fig. 3.4 we can establish an optimum length of hedgerows per hectare, as a function of N_s. Figure 3.5 gives some

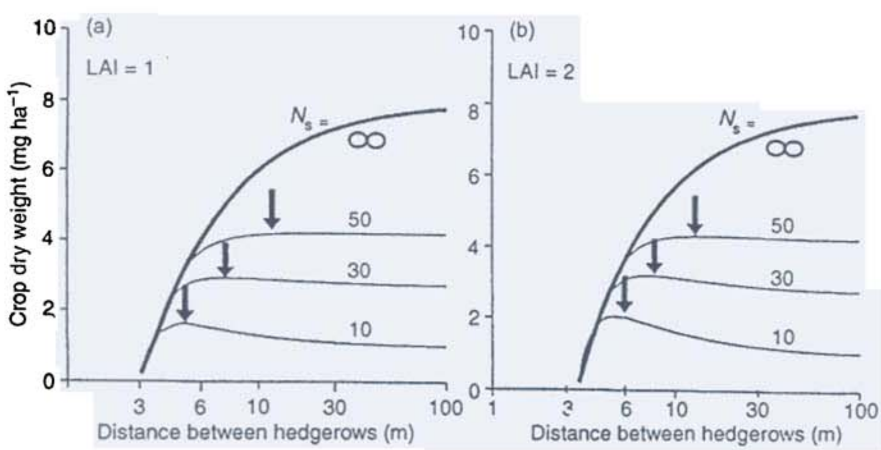

Fig. 3.4. Calculated crop yields as a function of distance between hedgerows and N_s, for a set of data representing maize production; N_s represents background soil fertility; (a) gives results for a rather open hedgerow canopy (LAI = 1); (b) results for a more dense canopy (LAI = 2). Arrows indicate optimal hedgerow spacing for each level of N_s (kg ha^{-1}).

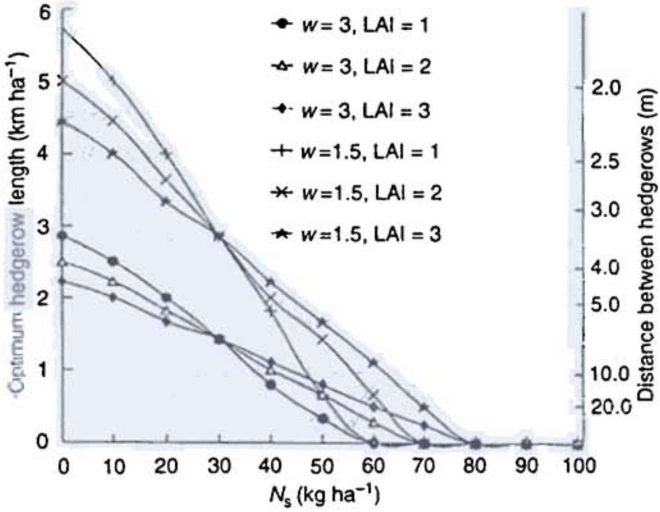

Fig. 3.5. Optimal length of hedgerow per hectare as influenced by N_s and characteristics of the hedgerow tree canopy.

numerical examples, for hedgerow canopies of different width and density (LAI_p).

Figure 3.6 shows crop yields at optimum hedgerow spacing as a function of background nitrogen supply, reflected in N_s. This graph shows that on poor soils, with low N_s, hedgerow cropping at optimum hedgerow spacing can give a considerable yield increase. At yield levels more than about 50% of non-N limited yields, however, no benefit from hedgerow intercropping may be expected from our simple model.

Figure 3.7 identifies the domain where at least some forms of alley cropping, with a near-optimum tree spacing, may increase crop production. Based on Equation 3.20 the upper limit of the soil N supply divided by crop N demand N_m can be related to the $M:S$ ratio of the tree, which gives the N supply per unit fully shaded area. The higher the $M:S$ ratio of a tree, the better are its prospects for alley cropping. If one wants alley cropping to work in a range where the control plots allow a crop N uptake near 50% of the maximum, the $M:S$ ratio has to be 50–125 kg N ha^{-1} shaded, for N_m in the range 200–500 kg ha^{-1}.

Table 3.1 gives the required parameter values for several tree species used in alley-cropping trials on an acid soil in Sumatra, Indonesia. The values are based on Hairiah *et al.* (1992) and some new observations. In

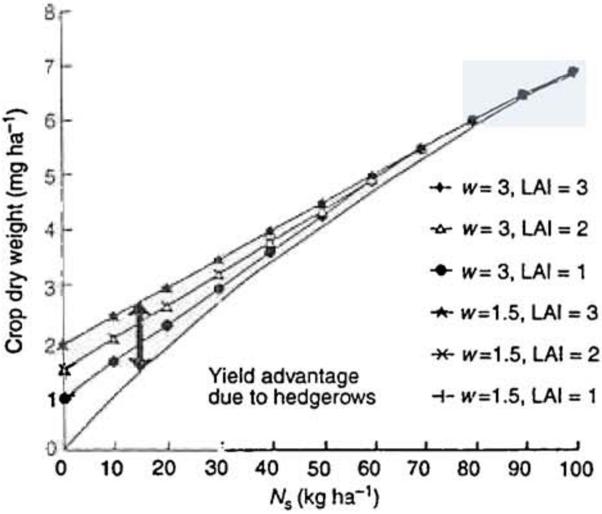

Fig. 3.6. Crop yields at optimum hedgerow spacing as a function of background nitrogen supply, reflected in N_s. A reference line for crop yields without hedgerows is given as well.

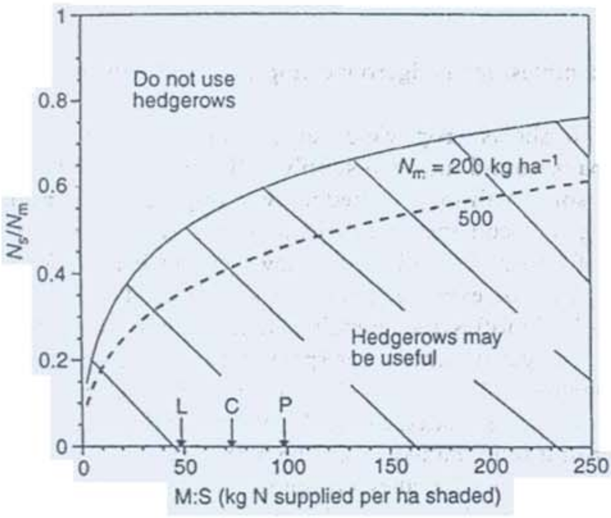

Fig. 3.7. Domain where at least some versions of hedgerow intercropping will give a yield advantage, as determined by the $M:S$ ratio of the tree and the relative fertility of the site (N_s/N_m), based on Equation 3.20. The letters L, C and P indicate the approximate $M:S$ ratio of *Leucaena leucocephala*, *Calliandra calothyrsus* and *Peltophorum dasyrrachis*.