TREE–CROP INTERACTIONS
A Physiological Approach

Edited by

Chin K. Ong

International Centre for Research in Agroforestry
P.O. Box 30677
Nairobi
Kenya

and

Peter Huxley

Oxford, UK

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R. Ranganathan and C.T. de Wit

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Mixed Cropping of Annuals and Woody Perennials: An Analytical Approach to Productivity and Management

R. RANGANATHAN* AND C.T. DE WIT†

Department of Theoretical Production Ecology, Wageningen Agricultural University, PO Box 430, 6700 AK Wageningen, The Netherlands

Introduction

Growing woody perennials with annual crops attempts to provide a strong foundation for conservation oriented farming and meet shortages of fodder and fuelwood. The role of perennials in minimizing leakage of nutrients from the system and recycling them, preventing soil erosion and thereby positively influencing the growth of plants associated with them is the biological premise to agroforestry systems (King, 1979). However, a significant concern is that competition from the perennial to the annual may reduce or possibly override the otherwise positive aspects of such mixed cropping (Verinumbe and Okali, 1985; Singh *et al.*, 1989a, b; Rao *et al.*, 1990; Jama and Getahun, 1991; Yamoah, 1991). This is particularly so in situations where the perennial is of less direct economic value than the annual as farmers seldom consider conservation in itself as a benefit.

This chapter is concerned not so much with the biological premise of agroforestry systems, as with the mathematical and experimental analyses of trade-offs in annual and perennial production. It elaborates on well confirmed theories of competitive interactions between plants and discusses the use of production possibility frontiers, drawn from economics literature.

* *Present address: ICRISAT Asia Center, Patancheru 502 324, Andhra Pradesh, India.*
† *Deceased.*

The production possibility frontier expresses the yield of the annual as a function of the perennial (or vice versa), shows all combinations of maximum yields that can be obtained and allows for the calculation of optimal sowing densities. The trade-off in productivity of one component as a consequence of the other is thereby quantified. With time, the changing morphology and increasing biomass necessitates changes in management to control the dominance of the woody perennial. Management guidelines for maintaining a sustained production of the annual have been derived from studies on crop–weed interactions.

The analytical approaches are supported and illustrated with experimental results from mixed cropping trials of perennial pigeonpea and groundnut in the semi-arid region of India. Some sections of this chapter have already been discussed in other papers and, where this is so, the development of the argument is brief.

Competition and Productivity

The key to increasing productivity in mixed cropping is understanding the nature of interaction between species in the mixture. Plants compete for growth factors such as light, water, nutrients, oxygen and carbon dioxide and the outcome of this competition is, in general, a reduction in plant growth and performance of the species in mixture. An aspect, other than the physiological mechanisms of interaction in mixed crops, is that of population dynamics wherein the effects of competition on productivity are examined without necessarily going into the mechanisms of the interaction. In such studies the effects of interspecific and intraspecific competition are analysed and used to measure yield advantage, if any, achieved through mixed cropping.

Model development

In the analysis of interspecific and intraspecific competition in crop mixtures, de Wit (1960, 1961) used a replacement series design where seed numbers (N_i and N_j) of the two species vary simultaneously in such a way that their sum S remains constant. It was shown that biomass yields (Y_i and Y_j) are often well presented by hyperbolic replacement functions:

$$Y_i = \frac{k_{ij}N_i}{k_{ij}N_i + N_j} M_i \qquad (2.1a)$$

$$Y_j = \frac{k_{ji}N_j}{k_{ji}N_j + N_i} M_j \qquad (2.1b)$$

where M_i and M_j are yields of the sole crops when sown at density S. The parameters k_{ij} and k_{ji} reflect the competitive effect of species j on i and i on j

respectively. De Wit (1960) showed that when the product $k_{ij}k_{ji}$ equals 1, the two species i and j are competing for the same resources at the same time. $k_{ij}k_{ji} > 1$ indicates the species are partly complementary in resource use. The premise of mixed cropping is the spatial and temporal use of resources by crops in the mixture; the crops have different heights and rooting depths, and make their peak demand on resources at different times. Spatial and temporal complementarity is achieved by cropping species with different growth curves.

If species j does not grow at all, its yield is zero and by substituting $(S - N_i)$ for N_j Equation 2.1a can be reduced to the density function:

$$Y_i = \frac{B_i N_i}{B_i N_i - 1} Q_i \tag{2.2}$$

where Q_i is the maximum yield achieved at high densities and $B_i Q_i$ is the yield of a plant when free from competition from other plants. By combining Equations 2.1 and 2.2, de Wit (1960, 1961) and Spitters (1983) derived the following additive functions:

$$Y_i = \frac{B_i}{B_i N_i + B_{ij} N_j + 1} Q_i \tag{2.3a}$$

$$Y_j = \frac{B_j}{B_j N_j + B_{ji} N_i + 1} Q_j \tag{2.3b}$$

where B_{ij} and B_{ji} characterize competitive abilities. It was also shown that for species that are temporally complementary in resource use $0 < B_{ij} < B_j$ and $0 < B_{ji} < B_i$, while $B_{ij} = B_j$ and $B_{ji} = B_i$ in situations where both species compete for the same resources at the same time. From these equations it can be inferred that one plant of species i has the same effect on Y_i as $B_{ij} B_i^{-1}$ plants of species j. Similarly, one plant of species j has the same effect on Y_j as $B_{ji} B_j^{-1}$ plants of species i.

The parameters B_i, B_j, B_{ij} and B_{ji} can take values up to infinity causing some difficulties with the convergence criteria associated with non-linear regression algorithms that may be used in their estimation. Although the yield–density relationship is better visualized in de Wit's notation (as in Equations 2.3a and b), the parameters are more easily estimated using Spitters' (1983) notation. They are:

$$Y_i = \frac{N_i}{b_{i0} + b_{ii} N_i + b_{ij} N_j} \tag{2.4a}$$

$$Y_j = \frac{N_j}{b_{j0} + b_{jj} N_j + b_{ji} N_i} \tag{2.4b}$$

It can be shown that the parameters b_{i0}, b_{ii} and b_{ij} from Equation 2.4a are equal to $(B_i Q_i)^{-1}$, Q_i^{-1} and $B_{ij}(B_i Q_i)^{-1}$ respectively.

Such simple mathematical expressions of complex biological processes necessarily introduce some compromise. Yields reach a maximum at finite rather than infinite densities, and at very low densities there is a linear relationship between plant density and yield rather than a hyperbolic one. However, the hyperbolic relationship has been shown by many researchers to be an acceptable description of the biological process of competition (Shinozaki and Kira, 1956; de Wit, 1960, 1961; Willey and Heath, 1969; Spitters, 1983). Exceptions are when one crop profits from the presence of the other or its growth is inhibited by allelopathic effects.

Production possibility frontiers

In mixed cropping one crop cannot be considered independently of the other and measures of yield advantage must express the yield of one crop as a function of the other, so as to determine when more production of one crop and less of the other is advantageous. In addition, such measures must recognize the different requirements of the farmer and incorporate factors other than biological ones which influence his decision to intercrop.

Production functions in economics are analogous to growth curves of crops as they respond biologically to available resources. The production possibility frontier (PPF) has been used as a theoretical tool (Filius, 1982; Raintree, 1983; Tisdell, 1985) to illustrate complementarity or competition between the agricultural and tree components in agroforestry. The PPF as developed by Ranganathan (1992) expresses the yield of a crop as a function of the other and shows maximum combinations of products which can be obtained after consideration of all possible plant density combinations, assuming the most efficient use of available resources. Using Spitters' Equations 2.4a and b as a base for its derivation, Ranganathan (1992) evaluated trade-offs in biological productivity in different intercropping systems such as oats–barley, pigeonpea–sorghum and groundnut–maize.

When N_i and N_j are very large, Equations 2.4a and b can be written in the form:

$$Y_i = \frac{1}{b_{ii} + b_{ij}\dfrac{N_j}{N_i}}$$

$$Y_j = \frac{1}{b_{jj} + b_{ji}\dfrac{N_i}{N_j}}$$

Solving these equations for $N_j N_i^{-1}$ and $N_i N_j^{-1}$ and multiplying the outcomes gives:

$$\left(\frac{1}{b_{ii} Y_i} - 1\right)\left(\frac{1}{b_{jj} Y_j} - 1\right) = C \qquad (2.5)$$

where

$$C = \frac{b_{ij}b_{ji}}{b_{ii}b_{jj}}$$

The PPF can be empirically calculated using Equation 2.5 and it represents maximum yield combinations of the two crops obtained after a consideration of all possible plant density combinations.

Field experiments with perennial pigeonpea and groundnut

Pigeonpea, a crop primarily of India, has been successfully intercropped with annuals like sorghum, groundnut and maize. In the southern semi-arid states of India it is extensively intercropped with groundnut and sorghum. Pigeonpea seed is an essential part of the diet while stems, after pod harvest, provide kindling wood. Perennial pigeonpea is a short-lived multipurpose woody species providing grain, fuelwood and green fodder during the dry season. Its deep-rooting and drought-tolerant nature makes it a useful crop in areas of low and uncertain rainfall which characterize much of the semi-arid tropics.

Studies at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) with perennial varieties of pigeonpea have shown that they are much like annual varieties in their first year of growth and possess the same slow initial growth that makes annual varieties so suitable for intercropping. Daniel and Ong (1990) demonstrated the possibility of intercropping perennial pigeonpea with annual crops without any serious adverse effects on annual crop yield in the first year.

Field trials were conducted at ICRISAT in Hyderabad, India where long term average rainfall in the rainy season (July–October) is 610 mm, and 148 mm in the post rainy season. Perennial pigeonpea was intercropped with groundnut in four replacement series where groundnut was sown as a sole crop at 8, 16, 32 and 64 plants m^{-2} and pigeonpea at sole crop densities of 1.5, 3, 6 and 12 plants m^{-2}. Accordingly, one pigeonpea plant replaced 5.33 groundnut plants.

At the start of the rainy season in 1989 (Experiment 1), both pigeonpea and groundnut were sown together. Groundnut was harvested 110 days later. After pigeonpea seed harvest, 240 days after sowing, the stand was lopped to a height of 0.5 m and allowed to regrow through the rest of the dry season. At the start of the following rainy season, when pigeonpea entered its second year of growth, it was pruned once again to a height of 0.5 m and 14 days thereafter groundnut was resown into the year-old pigeonpea alleys. Total biomass and marketable yields of groundnut and pigeonpea were measured at every harvest. The relatively small dry season growth of pigeonpea (harvested at the start of the 1990 rainy season) was not included in the analysis. In 1990 a similar trial (Experiment 2) was initiated but discontinued in the following year.

Experimental results and other details are fully described in Ranganathan (1993) so that here only the outcome is presented in Table 2.1 as parameter values and their standard errors. Pigeonpea and groundnut biomass yields obtained from Experiments 1 (years 1 and 2) and 2 (year 1) were used in the calculation of the parameters of Spitters' Equations 2.4a and b. Calculations for the second year data (Experiment 1 – year 2) have been made using the original plant densities of pigeonpea although actual densities were lower because of plant mortality.

The PPFs in Fig. 2.1 were derived for the three data sets. The relatively low pigeonpea yields in Experiment 1 – year 1 (Fig. 2.1a) and the difference in convexity of the first year curves are explained by the delayed sowing of pigeonpea in Experiment 1. Waterlogging caused pigeonpea seedling mortality and resowing at a later date to achieve the planned plant densities. The extremely convex shape of all three curves indicates a large yield advantage (Ranganathan *et al.*, 1991) in intercropping perennial pigeonpea with groundnut. According to Daniel and Ong (1990), perennial pigeonpea is similar to medium-duration annual varieties except for its longer duration to flowering and maturity, lower harvest index, greater ratoonability and deeper rooting habit. Thus it can be inferred that yield

Table 2.1. Estimated parameters of the Spitters' equations.

	b_{i0} (plants 100 g^{-1})*	b_{ii} (m^2 100 g^{-1})*	b_{ij} (m^2 100 g^{-1})*	Adj. R^2
Experiment 1 – year 1				
Pigeonpea	0.151	0.288	0.042	0.90
	(0.089)	(0.030)	(0.012)	
Groundnut	1.127	0.254	0.133	0.94
	(0.303)	(0.197)	(0.112)	
Experiment 2 – year 1				
Pigeonpea	0.044	0.149	0.00001	0.73
	(0.012)	(0.006)	(0.001)	
Groundnut	2.072	0.191	0.739	0.94
	(0.349)	(0.014)	(0.152)	
Experiment 1 – year 2				
Pigeonpea†	< 0.044	0.150	0.00001	–
	–	–	–	
Groundnut	2.285	0.244	5.718	0.98
	(0.467)	(0.018)	(0.662)	

* Standard errors of means are shown in parentheses; † non-linear algorithm not possible; see Ranganathan (1993) for estimation of parameters.

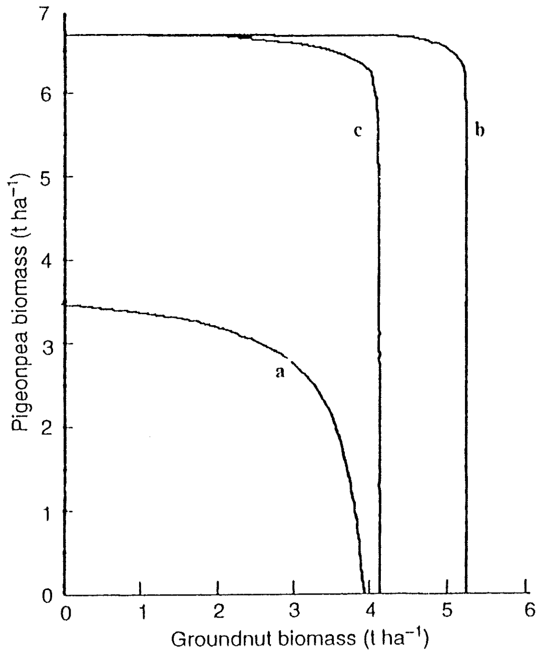

Fig. 2.1. Production possibility frontiers for pigeonpea–groundnut intercrops. a, Experiment 1 – year 1; b, Experiment 2 – year 1 and c, Experiment 1 – year 2.

advantage as shown by the PPFs is due to temporal complementarity of the two species.

The PPF is the envelope of joint production curves, as illustrated in Fig. 2.2. The joint production curves are calculated from Equations 2.4a and b. The curves taking off from the vertical axis show the very gradual decline in pigeonpea yield (Experiment 2 – year 1; pigeonpea density N_p was held constant but at different levels) when groundnut density N_g was increased. Pigeonpea apparently suffered little competition from groundnut. The curves taking off from the groundnut axis (x) represent yields of pigeonpea and groundnut obtained when groundnut density was held constant (at different levels) and pigeonpea density gradually increased. The six curves radiating out from the origin give the yields of pigeonpea and groundnut when densities of the two crops were varied but the ratio ($N_g N_p^{-1}$) kept constant.

Economic evaluation

The importance of an economic evaluation cannot be overestimated because the market value of products provides the farmer with a tool in

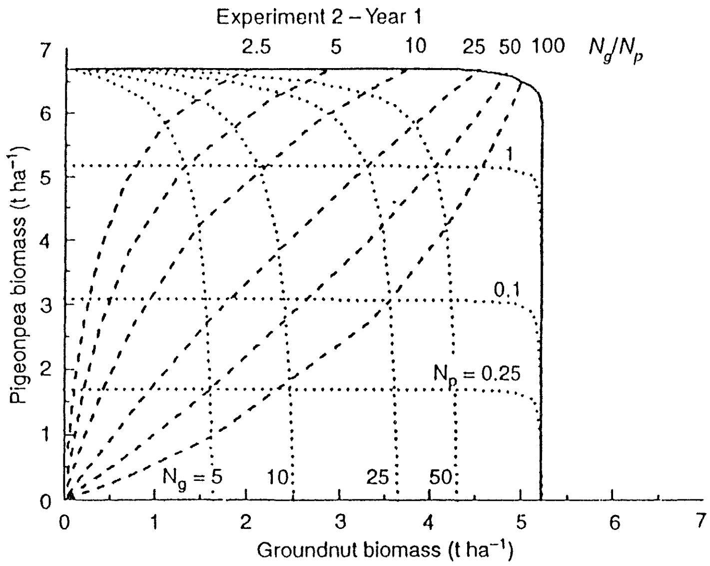

Fig. 2.2. Production possibility frontier for a pigeonpea–groundnut intercrop. Inner curves show yield combinations at different densities, calculated using Spitters' model of competition.

allocating limited resources between competing uses and puts different crops and their products on a comparable basis. The preceding section took total biomass into consideration. In this section on economic analysis, marketable yield rather than total biomass will be considered as it is often the aim of agriculture.

In response to density stress, a plant regulates its allocation of assimilatory products to its various organs thereby affecting the relationship between marketable yield (pods, grain, leaves) and total biomass. This response varies from species to species. When marketable yield and total biomass have a similar response to density, that is, harvest index (HI) remains constant, the PPF for marketable yield can be directly derived from Equation 2.5. But in cases where this is not so, the PPF has to be derived numerically from the relationship between total biomass and marketable yield.

It was shown by Ranganathan (1993) that in mixtures irrespective of whether plants suffer from interspecific or intraspecific competition the relationship between *per-plant* marketable yield and total biomass is well approximated by the same straight line. When the straight line passes through the origin, harvest index remains constant even at high competition stress. However, in many instances the straight line expressing the relationship between per-plant marketable yield and total biomass makes a positive intercept with the *x*-axis. This reflects a diminishing harvest index with decreasing per-plant yield.

The numerical derivation of the PPF for marketable yield thus requires an estimation of the parameters to Equations 2.4a and b and the linear relationship between per-plant marketable yield and total biomass. Dividing biomass yields per hectare, estimated from Equations 2.4a and b, by the density at which it was obtained gives per-plant biomass. From the linear relationship between per-plant biomass and marketable yield, the corresponding per-plant marketable yield is obtained. Multiplication of these per-plant yields with the density gives marketable yield per hectare for both crops. A plot of the yield combinations gives joint production curves for marketable yield (similar to those in Fig. 2.2) and once again the envelope is the production possibility frontier.

The per-plant marketable yield–biomass relationships for pigeonpea and groundnut in Experiment 2 – year 1 are shown in Fig. 2.3 and the joint production curves with their envelope, the PPF, for marketable yields per hectare in Fig. 2.4. Both per-plant marketable yield–total biomass relationships are linear, but in the case of groundnut the line has a large positive intercept with the per plant biomass axis (x), so that the harvest index decreases in the normal density range with decreasing plant size; first slowly and then rapidly. The positive intercepts are reflected in the joint production functions in Fig. 2.4 turning inward; groundnut yields show a greater decline with increasing density of pigeonpea. The harvest index of pigeonpea in this experiment was less dependent on plant size than

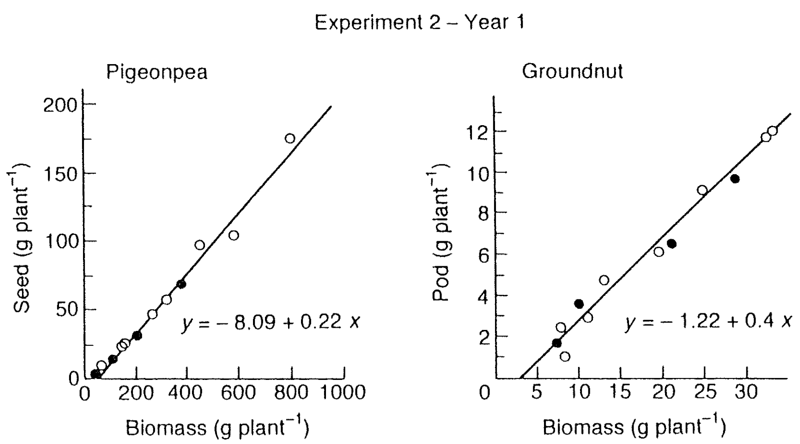

Fig. 2.3. Per-plant marketable yield–biomass relationships for a pigeonpea–groundnut intercrop. Open symbols represent yields in mixture and closed symbols yields in monoculture.

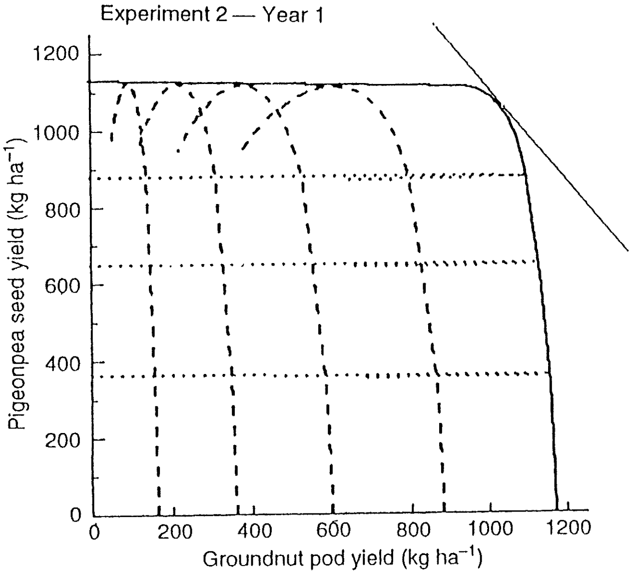

Fig. 2.4. Production possibility frontier for pigeonpea seed and groundnut pod yields. Yields have been calculated from per-plant marketable yield–biomass relationships and Spitters' model of competition.

groundnut, so that the joint production curves obtained with a constant pigeonpea density (dotted lines, Fig. 2.4) show only a slight decrease in seed yield with decreasing biomass (and increasing density).

The economically optimal seed yield combination corresponds to the tangent of the price line to the PPF. A price line reflects a fixed value of production, that is, the total value of the crops expressed as the sum of their constituent prices. The slope of the price line is the negative of the price ratio. For instance, if groundnut pods are priced 20% higher than pigeonpea seeds, the price line would have a slope of -1.2. Assuming this was so, the price line shown in Fig. 2.4 is tangential to the PPF at the point where groundnut pod and pigeonpea seed yields are close to 1050 and 1025 kg ha^{-1} respectively. Substituting these yields in Equation 2.5 and using parameter values for Experiment 2 – year 1 (in Table 2.1), plant densities that would optimize economic returns to the farmer are 32 and 1 plant(s) m^{-2} of groundnut and pigeonpea. Similar calculations for the data of Experiment 1 – year 2 show groundnut pod and pigeonpea seed yield to be approximately 325 and 1260 kg ha^{-1} and the corresponding plant densities are 25 and 1 plant(s) m^{-2}. From a comparison of yields in the 2 years, it is obvious that in the second year of intercropping groundnut yields are severely depressed due to competition from pigeonpea and even in its first year of intercropping, pigeonpea yields were close to their asymptotic value.

Since pigeonpea and other similar perennials are valued for more than their seed yield, an economic analysis must include all such factors, fodder and fuelwood, and those others which influence farmers' decisions to intercrop. Price per kilogram of seed of the annual is often a decisive factor; it sometimes far exceeds the market price of the produce, on other occasions availability of seeds is low. An economic assessment taking a few such factors is described below.

Figure 2.5 shows the frontier for net returns in the first year of intercropping pigeonpea with groundnut. In this economic assessment pigeonpea fodder and groundnut seed costs have been taken into consideration, in addition to the market prices of pigeonpea seed and groundnut pods. Though groundnut fodder is sold in many parts of the tropics it is assumed to have no economic value for the purpose of this discussion. Pigeonpea fodder has been assigned an arbitrary price of $US 5.34 ton^{-1} ($US 1 = IRs 28.00). This is much lower than the price of other green fodders but in the semi-arid regions of India where pigeonpea is grown, perennial varieties are relatively uncommon and no reliable market exists. It is assumed that groundnut pods have a market price 20% higher than that of pigeonpea seeds and the latter have been assigned a price of

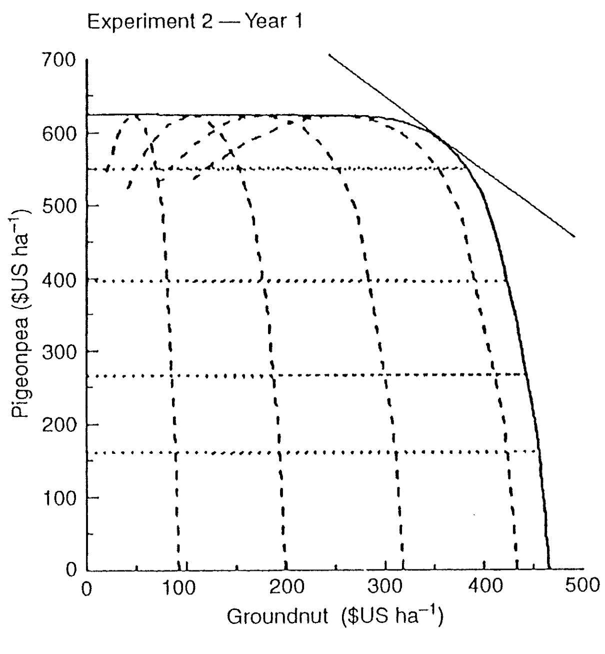

Fig. 2.5. Production possibility frontier for financial returns and price line for a pigeonpea–groundnut intercrop.

\$US 0.54 kg^{-1}. The price of groundnut seed is high relative to the price of the produce and has been taken as \$US 2.68 kg^{-1}.

Optimum production under such market conditions corresponds to the point where a line with slope -1 is tangential to the frontier. The inner curves show that increasing groundnut density is not economical beyond a certain limit as the cost of seed exceeds the incremental pod yield. Optimum net returns from groundnut and pigeonpea are \$US 360 and 600 ha^{-1}, respectively and are achieved at plant densities of 15 and 1 plants m^{-2}. Note that the plant density of pigeonpea is unchanged but reduced, from 32 to 15, in the case of groundnut.

Other factors that influence decisions to intercrop have not been dealt with. Labour costs, for instance, play an important role in decision making where mechanization exists. Mixed cropping imposes design and operational restrictions on the implements used to mechanize crop production. Costs could potentially be so large that it is economically advantageous to grow sole crops and sacrifice the benefits of complementarity, recycling of nutrients and erosion control. Indeed, harvesting difficulties were a main reason why farmers in Western Europe stopped most mixed cropping despite the agronomic advantages. Even where mechanization does not exist, opportunity costs to a farmer may be high. Family labour that may be used in managing the perennial could be more gainfully employed in other farm activities. Conservation benefits obtained from mixed cropping have also not been included in this discussion.

The woody perennial

Dominance

Berendse (1979) studied the coexistence of species, some with the ability to exploit a refugium (resources not available to the others). He showed that in order to coexist, species without the refugium had to be the stronger competitor for common resources. In mixtures of annuals and perennials, the perennial is able to exploit a refugium because of its longer growth period and extensive root system. In the second and/or subsequent years of intercropping it has, therefore, a competitive edge over the annual.

The dominance of a woody perennial over the intercropped annual is visualized in Fig. 2.6 where biomass yields of pigeonpea and groundnut (grown in a replacement series with monocrop densities approaching optimum at 6 plants m^{-2} of groundnut and 32 plants m^{-2} of pigeonpea) are plotted against relative density. Actual yields as observed in the field and those estimated from the yield–density relationship discussed in the earlier sections are presented. The observed yields may deviate, sometimes systematically, from the estimated yields because observations from all four replacement series were used in the determination of parameters.

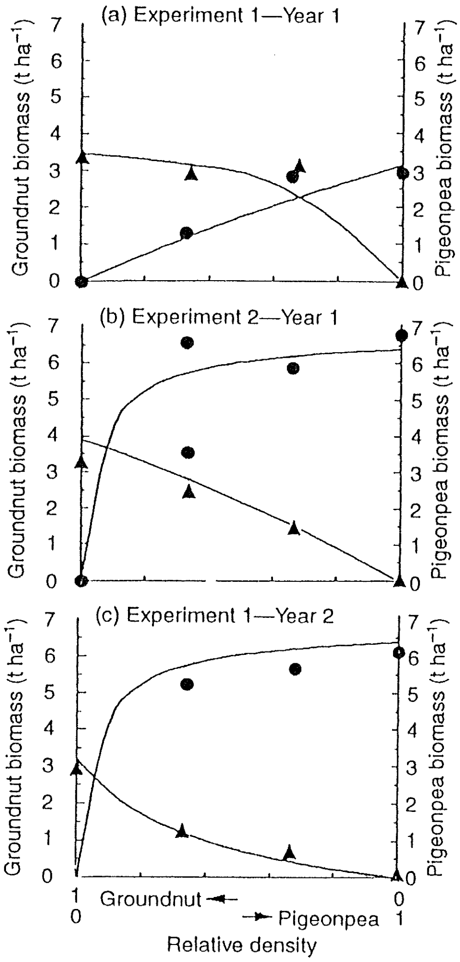

Fig. 2.6. Replacement series diagrams. Curves calculated using Spitters' model of competition, parameters in Table 2.1 (● ▲ actual observations).

In Experiment 1 – year 1, the groundnut crop did not suffer from the presence of pigeonpea, as is reflected by the convexity of yield–density hyperbola. This was due to delayed sowing of much of the pigeonpea. In Experiment 2 – year 1, pigeonpea and groundnut were sown together and groundnut suffered competition from pigeonpea as seen in the near-linear relationship between groundnut relative density and yield. Despite pruning pigeonpea 14 days before and 40 days after planting groundnut, groundnut was dominated by pigeonpea in year 2 of Experiment 1. The value of parameter b_{ij} in Table 2.1, which quantifies the effect of groundnut on pigeonpea yield, confirms these results.

Pigeonpea's dominance in this cropping system may be acceptable because what is lost in annual marketable yield of groundnut is made up by pigeonpea seeds. The direct economic return is, therefore, not very sensitive to the composition of the mixture. However, in many other mixed cropping systems that include woody perennials, the latter do not contribute to food production. In areas where agroforestry is most recommended, food production is the primary objective of subsistence level farming. Thus, a main concern of agroforestry is that competition from the perennial to the annual may override the other benefits obtained from the inclusion of perennials in the system.

Growth

Provided soil fertility is maintained, the yield achieved in time by a pruned woody perennial approaches an equilibrium value that is independent of initial plant density. That this equilibrium yield is directly related to the parameters that govern the density response of the species is demonstrated in this section.

In the case of annuals, seeds that are produced in one year may be resown the following year. When growing conditions are the same, yield in year $n+1$ can be calculated by replacing seed number by yield in year n in Equation 2.2:

$$Y_{n+1} = \frac{BY_n}{BY_n + 1} Q \qquad (2.6)$$

where Y_n and Y_{n+1} are yields (in kg ha^{-1}) in years n and $n+1$ and Q is the maximum yield achieved at high seed densities. The quotient $Y_{n+1} Y_n^{-1}$ approaches the product BQ for low values of Y_n; BQ is accordingly a dimensionless multiplier in this case. If the value of this multiplier is smaller than 1, Y_{n+1} is smaller than Y_n and the yield approaches zero in the course of time. But if BQ is larger than 1, the yield approaches an asymptotic yield Y_a which can be obtained by substituting Y_a for both Y_n and Y_{n+1} in Equation 2.6:

$$Y_a = \frac{BY_a}{BY_a + 1} Q$$

so that

$$Y_a = Q - \frac{1}{B} \qquad (2.7)$$

The asymptotic yield Y_a is always lower than the maximum yield at high plant densities and the more this is so, the smaller the value of B.

For perennials, however, there are no seeds to be resown. But it was shown by van den Bergh (1968) that in grasses the harvested quantity is a good indicator of the quantity of roots and stubble that remain in the field.

This is so because above- and below-ground biomass are positively correlated. For shrubs that are pruned, the amount of stems and leaves that are removed and the amount of stubs and roots that remain on the field for regrowth are likely to be positively related. Although recognizing the need for experimental verification, there is little reason to dispute that Equation 2.6 holds for shrub vegetation that is coppiced every year.

Under the assumption that soil fertility does not change, yield increase of the perennial in subsequent years can be calculated once Q and BQ are estimated from a density experiment that links yields in two successive years. Using Equations 2.2 and 2.6 hypothetical perennial yields in time are calculated assuming Q equals 10 t ha^{-1} and BQ equals 10, 2.5 and 1.5. The resulting curves in Fig. 2.7 show that the asymptotic yield(s) Y_a decreases with decreasing BQ (as in Equation 2.7). The curves also have the familiar S-shape which was shown by de Wit (1960, 1961) to conform to the well-known logistic growth curves of Lotka (1925) and Volterra (1928).

Woody perennials with a low BQ are less competitive to the annual because their regrowth is slow, but to be a good producer of biomass Q should be high. Such perennials may be hard to find because BQ and Q are likely to be positively correlated. This was implicitly shown by van den

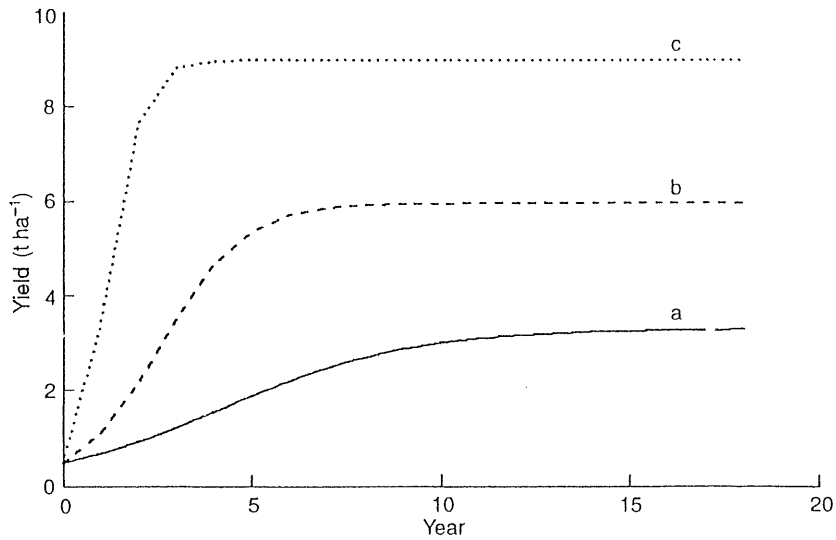

Fig. 2.7. Growth curves for woody perennials that are coppiced every year, calculated with Q=10 t ha^{-1} and a: BQ=1.5; b: BQ=2.5 and c: BQ=10.

Bergh (1968) for perennial grasses and explicitly proven by Spitters (1979) for barley.

Figure 2.8 relates the yield of perennial pigeonpea (in Experiment 1) in the second year with the yield measured in the first year of its growth. The value of Y_a appears to be around 5.5 t ha^{-1} although the scatter is large. Even at the lowest density of planting, yields in the second year were already at the asymptotic value (Y_a). Plant densities in the experiment were unfortunately too high to determine the value of BQ. However, from the steepest observed slope of 7 it can be concluded that the value of BQ approaches 10 and the value of Q according to Equation 2.7 is about 6.7 t ha^{-1}. From a simple density experiment of 2 years it is thus possible to estimate the asymptotic yield of a coppiced perennial.

Management

Suggestions have been made on how to overcome the problem of a strongly competitive woody perennial. Daniel and Ong (1990) and Odongo *et al.* (1996) recommend a low perennial plant density. However, in situations where initial planting densities are so small that asymptotic yields as defined by Equation 2.7 are never reached, part of the field would remain fully outside the influence of the woody perennial. This would leave some of the

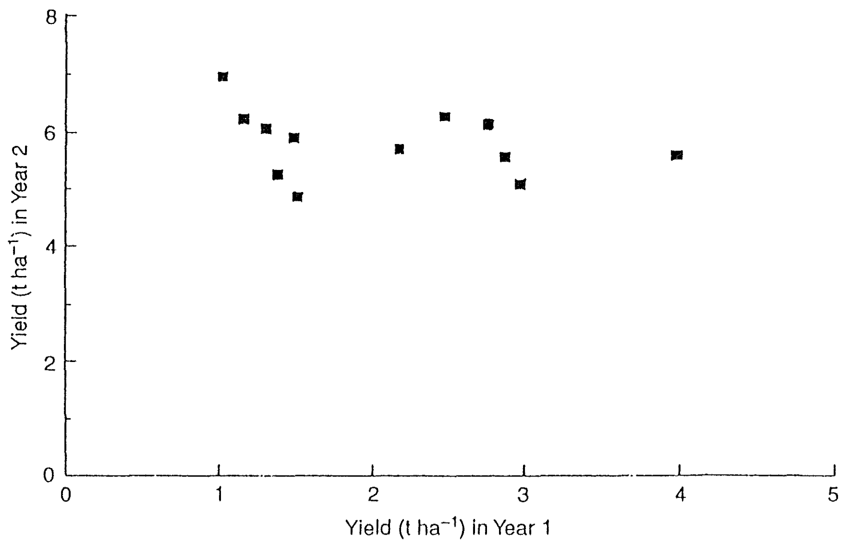

Fig. 2.8. Relationship between pigeonpea yields in the first and second years of growth.

annual as a sole crop and the purpose of the agroforestry system is not fully realized.

Ong (1990) suggests forms of perennial vegetative growth regulation so that there is more complementarity between species in their time dependence for resource sharing. *Faidherbia albida* is an example of a species where resource sharing with the annual is extremely complementary (Miehe, 1986; Poschen, 1986). Mixed cropping systems with *Faidherbia albida* show a unique form of complementarity in that the tree sheds its leaves naturally during the onset of the rainy season and begins leaf production once the understorey crop is well established. This 'competition free' period allows the crop to extend its root system well into the soil profile and to establish a complete crop canopy to capture radiation and water resources (Ong *et al.*, 1992).

One could also experiment with the use of growth retardants on the woody perennial but pruning or coppicing are the alternatives discussed here. Then in the words of Huxley (1983) 'the question is not only what to remove, and how much, but when'.

The effect of management on the annual

The same question was posed in weed research and Cousens (1985) and Kropff and Spitters (1991) dealt with the problem by considering the competitive relationship between weeds and crops. They defined relative yield loss (YL) in the crop (c) due to the presence of the weed (w) as:

$$YL = 1 - \frac{Y_{cw}}{Y_c} \tag{2.9}$$

where Y_{cw} and Y_c are yields of the crop at the same density but with and without weeds. By substituting Equation 2.3 for Y_{cw} and Equation 2.2 for Y_c, YL can be written as:

$$YL = \frac{B_{cw}N_w + 1}{B_cN_c + B_{cw}N_w + 1}$$

Under normal sowing densities this expression simplifies to the hyperbolic expression:

$$YL = \frac{c\dfrac{N_w}{N_c}}{1 + c\dfrac{N_w}{N_c}}$$

where

$$c = \frac{B_{cw}}{B_c}$$

This expression relates the relative yield loss of the crop with the seed densities of the crop and weed. The damage coefficient c depends on the competitive abilities of the crop and weed species. However, because of the inherent difficulty of conducting density experiments with weeds and emergence of weeds in flushes, expressions with weed density are not useful for predictive purposes. Kropff and Spitters (1991) characterized the presence of crops and weeds in a mixture by their leaf areas measured at an early stage of growth. Relative yield loss was expressed by:

$$YL = \frac{q\dfrac{LAI_w}{LAI_c}}{1 + q\dfrac{LAI_w}{LAI_c}}$$

or

$$YL = \frac{qL_w}{1 + (q-1)L_w} \quad (2.10)$$

where

$$L_w = \frac{LAI_w}{LAI_w + LAI_c}$$

LAI_w and LAI_c are the leaf area indices of the weed and crop at an early stage of growth and q a damage coefficient that differs from c and has to be determined experimentally.

If the perennial is considered to be like a weed in depressing crop yield, establishing q for the mixed crop allows for an estimation of the amount the perennial must be pruned in order to keep crop yield at acceptable levels. The relationship between crop yield loss and relative leaf area of the weed (perennial) for various values of the damage coefficient q is shown in Fig. 2.9. For $q \gg 1$, severe pruning of the perennial is necessary to keep yield loss of the annual down to an acceptable level, whereas light pruning suffices for $q \ll 1$. Experiments with different crop–weed combinations have proved the usefulness of the approach. It was shown that the value of q is large in situations where weed leaf area ratio (leaf area/above-ground weight) is large compared with that of the crop and the weeds overgrow the crops. Relative early emergence of weeds is not reflected in a high value of q, but in a large relative leaf area (L_w) of the weed.

To show the same approach is equally valid for woody perennials, Ranganathan (1993) determined a damage coefficient q for perennial pigeonpea intercropped with groundnut. A 1-year-old stand of perennial pigeonpea was pruned and groundnut was sown within the alleys. Groundnut was also sown as a sole crop to calculate yield loss in intercropped groundnut due to the presence of pigeonpea. At regular intervals both pigeonpea and groundnut were harvested, leaf area indices and biomass determined. Twenty-five days after sowing, groundnut had a leaf area index of 0.23 while that of pigeonpea was 0.6, so that the relative

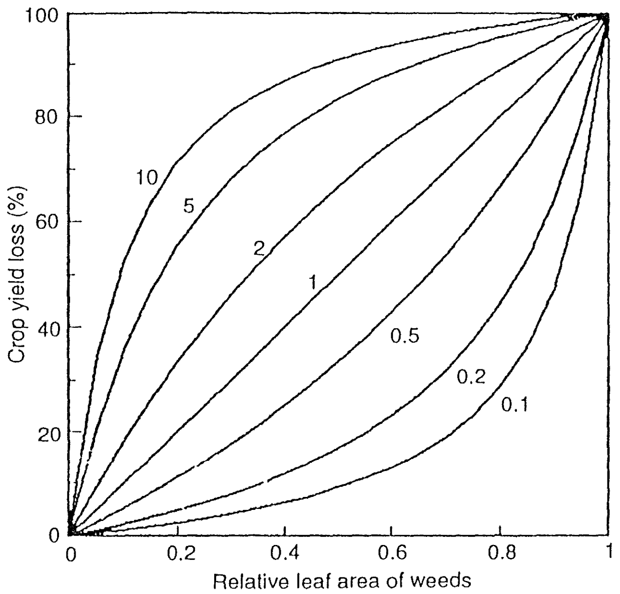

Fig. 2.9. Yield loss functions for different values of *q*, the damage coefficient (source: Kropff and Spitters, 1991).

leaf area of pigeonpea in the mixture was 0.72. After 60 days, relative leaf area increased marginally to 0.83. Within the period when the crop is established and the onset of competition from the perennial, relative leaf area of the perennial is conservative. Groundnut yield loss was measured at 56% and q was estimated from Equation 2.10 to be 0.37.

The yield loss function for perennial pigeonpea and groundnut is given in Fig. 2.10. The value of the damage coefficient is surprisingly low, when pigeonpea's greater height and similarity in leaf area ratios of pigeonpea and groundnut in the early stages of growth are considered. One explanation may be that pigeonpea was not distributed evenly over the field, but confined to rows that were 1.5 m apart. The alley width appears to be wide enough to prevent early shading of groundnut; and groundnut reached maturity before the greater fraction of pigeonpea biomass was formed. This important aspect of the problem was not further pursued.

To compare predicted yield (from Equation 2.10) with that observed in the field, the relative leaf area of pigeonpea in the mixture was varied in an experiment. Although pigeonpea has been known to recover from pruning and produce yields comparable to unpruned pigeonpea, to reduce the uncertainty of it not surviving corrective pruning, pigeonpea plants were covered with muslin bags for 30 and 60 days. Approximately 50% of the

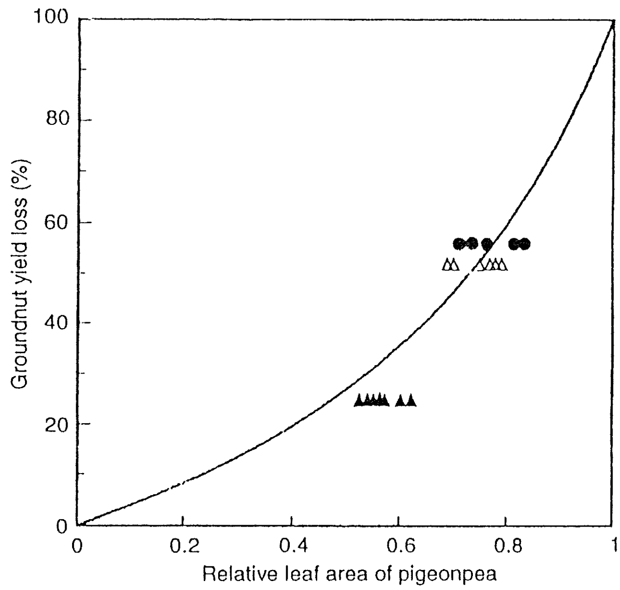

Fig. 2.10. Yield loss function for groundnut–pigeonpea intercrop, $q=0.37$ estimated from an unmanaged stand of pigeonpea (●). Observations from 30-day (△) and 60-day (▲) bag treatments.

incoming light was intercepted by the bags so that the plants continued to grow but at a slower rate.

For the 30-day bag treatment, observed groundnut yield loss was 14% and the relative leaf area of pigeonpea was measured at 0.69 and 0.78 after 25 and 60 days. For the 60-day bag treatment, observed yield loss was only 33% and relative leaf areas were 0.53 and 0.63. It is shown in Fig. 2.10 that these observations and the predicted yield loss were not dissimilar, providing supportive evidence of the applicability of this method to managing perennials. The timing of this pruning is not very critical as long as it is done in the exponential phase of growth of the perennial, and before the annual is unable to recover from the competition that it may briefly suffer before the perennial is pruned.

Effect of management on the perennial

In the previous section the leaf area of the perennial was reduced through corrective pruning in the more or less exponential phase of growth. The deferment time D that it takes pruned shrubs to restore leaf area to its pre-pruning level can be calculated from the expression:

$$L_n = L_m \exp(RD) \tag{2.11}$$

where R is the relative growth rate of the shrub in its exponential phase, L_n and L_m are leaf area indices directly before and after corrective pruning. Accordingly the deferment time D is:

$$D = \frac{\ln L_n - \ln L_m}{R} \tag{2.12}$$

If M is the biomass produced over the entire period of growth of the perennial and P the length of this period, the linear growth rate G is MP^{-1}. The loss in weight of the woody perennial W_p due to pruning is:

$$W_p = DG \tag{2.13}$$

Yield loss here depends mainly on the severity of pruning, i.e. ($\ln L_n - \ln L_m$) because G and R themselves are in general proportional.

For pigeonpea yield loss is not compensated for by the extended growth period, because it is governed by daylength (J.C.W. Odongo, Hyderabad, 1991, personal communication). However, some of this loss is saved as the harvest H during the pruning. H can be calculated from:

$$H = \frac{L_n - L_m}{LAR} \tag{2.14}$$

where LAR is the leaf area ratio calculated as the leaf area of newly formed leaves divided by the weight of these leaves and newly formed twigs. The difference $W_p - H$ is the actual yield foregone due to corrective pruning. If a corrective pruning is applied in the linear phase of growth Equation 2.14 can be generalized by using the expolinear growth function introduced by Goudriaan and Monteith (1990), but not discussed in this chapter.

From the result of the periodic harvest experiment discussed in the previous section it was estimated that pigeonpea's relative growth rate (R) was 0.03 day^{-1}, linear growth rate (G) 0.007 kg m^{-2} day^{-1}, LAR 4 m^2 kg^{-1} and leaf area 0.6 m^2 m^{-2} at 25 days after sowing groundnut. Leaf area of groundnut was 0.3 m^2 m^{-2}. According to Fig. 2.10, leaf area of pigeonpea in the mixture has to be reduced to 0.2 to keep groundnut yield loss at 20%. Using the above information in Equations 2.11, 2.12 and 2.14, deferment time D is 37 days, yield loss of the perennial W_p due to pruning was 2600 kg ha^{-1} and the biomass yielded from pruning (H) is 1000 kg ha^{-1}. These amounts are small compared with the maximum biomass of 12,500 kg ha^{-1} achieved in the season.

Some thoughts on experimental design

It is often the practice in many agroforestry systems to use all or part of the harvested perennial as mulch, which may result in soil fertility and structure changes. Such changes complicate the analysis especially if the perennial is a nitrogen fixer; one crop profits from the presence of the other and the yield–density response is no longer hyperbolic (de Wit *et al.*, 1966). The effect of mulch can be determined by a comparison of unmulched and mulched sole crops of the annual and perennial. This implies that all treatments in the experiment be uniformly mulched, if necessary with clippings of the perennial grown outside the experiment. The combined effects of mulching and mixed cropping can be studied only from such experiments. But experiments of this nature easily expand beyond manageable sizes. However, once the existence of hyperbolic relationships is established or taken for granted, to analyse the effect of mulching only requires five treatments that will allow for the estimation of the six parameters B_i, B_j, B_{ij}, B_{ji}, Q_i and Q_j (from Equations 2.3a and b). The five treatments comprise two monocultures each for the annual and the woody perennial, and one mixture preferably at densities that form part of a replacement series with the high plant density monocrops. Some prior information about the species may be needed to select plant densities such that there are sufficiently large differences in the monocrop yields obtained at high and low plant densities. Likewise, the plant densities in the mixture should be such that the annual has a chance to withstand competition from the perennial. With the establishment of the production possibility frontier and other bioeconomic factors, the experiment can then be used to estimate damage coefficients and develop regulatory pruning strategies.

Concluding Remarks

Uncertain weather, pests and diseases that could not be adequately controlled were sometimes the cause of less than satisfactory experimental results, especially so for trials where pigeonpea and groundnut were periodically harvested. Nevertheless a comprehensive analysis of competitive interference between annuals and woody perennials could be made because well-confirmed theories on competition were available and the use of the production possibility frontier proved a valuable analytical tool for evaluating trade-offs in productivity. Sustained food production of the annual is a keystone to successful agroforestry systems and the chapter gives a scientific background to develop guidelines for agronomic management of the woody perennial so that annual production is maintained at acceptable levels in spite of the dominant nature of the perennial.

It may well be argued that agroforestry has many other objectives besides sustaining yield of the annual. But it should be pointed out that in marginal environments where agroforestry is often recommended, the primary concern of the farmer is food production. The perceived benefits of mixed cropping with a perennial, increased production from a unit of land, nutrient recycling, soil conservation, risk alleviation, weed control, integrated pest management, provision of shade to livestock, to name but a few, will be more valued if food production is at least maintained.

Annual pigeonpea in semi-arid environments has proved a very useful companion crop because of its slow initial growth allowing for complementary use of resources. It has been successfully intercropped with not only groundnut but sorghum and maize. The advantage of such intercrops is that there is no significant yield loss in either of the crops due to competition (Willey *et al.*, 1981, 1986) but the disadvantage is, possibly, the recurrent cost of sowing the crop. In intercropping with perennial pigeonpea the cost of regular pruning may be offset by the recurring costs of annual planting and crop establishment but more important are the benefits of additional biomass and utilization of residual moisture in the dry season. It appears that current varieties of perennial pigeonpea are short-lived and not only because of their susceptibility to disease when pruned regularly. This 'self-thinning' nature may be in itself an advantage because it reduces the need for corrective pruning.

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