Analysis of Yield Advantage in Mixed Cropping

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Analysis of Yield Advantage in Mixed Cropping

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The field research reported in this thesis was done at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru (AP) 502 324 India.

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Stellingen

1. The primary objective of most farming is food production and the objectives of agroforestry can only be met through sustained and increased food production.
   This thesis

2. In mixed cropping, the importance of an economic evaluation is important because the opportunity costs of growing produce provides the farmer with a tool in allocating limited resources between competing uses and puts different crops and their products on a comparable basis.
   This thesis

3. Knowledge of spatial and temporal crop combinations is the only prerequisite to successful multiple crop management.

4. An important consequence of multiple cropping research has been to bring ecologists and agronomists together.
   R D Hart 1986 Ecological framework for multiple cropping research. In *Multiple Cropping Systems*, 40-56 (Ed C A Francis). New York: Macmillan Publishing Co.

5. Intensification of agriculture in India has offered women nothing specific yet and so they remain as dependent on men as they ever were.

6. Competition from perennials to annuals may reduce or override the otherwise positive aspects of such mixed cropping, particularly in situations where the perennial is of less direct economic value than the annual.
   This thesis

7. Traditionally agroforestry has been successfully practiced most where rainfall is either limiting to crop production or is distributed bimodally.

8. Environmental degradation in underdeveloped countries is not gender neutral.

9. In poor countries, increased agricultural production and poverty alleviation come at the cost of environmental degradation.

10. Religious differences will no longer be an important issue in India if the economic status of the country improves.

11. A tree's a tree. How many more do you want to look at? If you've seen one, *you've seen them all.*
    Ronald Reagan

12. The difference between a "stelling" and an aphorism is the truth.

Radha Ranganathan
Analysis of Yield Advantage in Mixed Cropping
Wageningen, 13 January 1993

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Abstract

It has long been recognized that mixed cropping can give yield advantages over sole cropping, but methods that can identify such yield benefits are still being developed. This thesis presents a method that combines physiological and economic principles in the evaluation of yield advantage. A production possibility frontier, drawn from economics literature, represents the maximum yield combinations that can be obtained from intercropping. Inter- and intra-specific competition for resources determine yield in mixed cropping. Production possibility frontiers have been derived using such *a priori* knowledge of the processes underlying mixed cropping, thereby facilitating economic and agronomic analyses of yield advantage. The analytical procedure used in such analyses is illustrated for various crop mixtures.

The assumption underlying the derivation of a production possibility frontier is the hyperbolic relationship between yield and plant density. This assumption cannot always be made for marketable yield. Per-plant marketable yield and total dry matter relationships are explored and used to derive production possibility frontiers.

When annuals are cropped with perennials, the strongly competitive perennial often dominates, effecting a significant yield reduction in the annual. Management seeks to alter the competitive relationships of the perennial and annual towards a more equitable distribution of resources. A strategy for managing the perennial, on the basis of its competitive strength, by relating yield loss in the annual to the relative leaf area of the perennial in the mixture is described.

Field experiments with groundnut (*Arachis hypogaea*) intercropped with perennial pigeonpea (*Cajanus cajan*) and the analysis of yield advantage from this cropping system are discussed.

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In the final stages of 'writing up', friends and colleagues at the Department of Theoretical Production Ecology read parts of the manuscript and gave valuable advice and comments as well as moral support. I thank Gon van Laar for her advice on the final presentation of this thesis. Other friends in Wageningen provided succour in moments of stress.

Finally, I sincerely thank my husband Ranjan for his support and patience.

As the twig is bent, the tree inclines.

Virgil, 70-19 BC

Contents

Chapter 1
Introduction

Introduction

A perspective on competition in mixed cropping

Mixed cropping, the growing of two or more crops together on the same piece of land, is a widespread practice in subsistence farming all over the tropics for varied reasons such as increased production with limited land resources, reduced risk through stability of production, spreading labour demand, diversity in diet and better utilization of resources. It is reported that in the Latin American tropics 60% of maize (Francis *et al.*, 1976), 95% of groundnut in Nigeria and 56% in Uganda (Okigbo and Greenland, 1976) is grown in association with other crops, and in India 80 to 90% of all pigeonpea is intercropped (Aiyer, 1949). Although mixed cropping is not a new concept, only lately is there a sustained interest in understanding the underlying processes and seeking ways to increase the productivity of such systems in tropical agriculture (Papendick *et al.*, 1976; ICRISAT, 1981; Francis, 1986).

The key to increasing productivity in mixed cropping is understanding the nature of interaction between crops 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. Yet, in a number of instances greater production from intercropping than when either crop is grown alone has been recorded. Through an examination of biophysical factors and their relationships in intercropping, researchers at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and elsewhere were able to conclude that greater and better exploitation of resources was probably the most common basis for higher yields (Willey *et al.*, 1986). Crops differed in their use of growth resources in such a way that they were able to complement each other. Studies showed an improvement in the amount of dry matter formed per unit radiation intercepted (Marshall and Willey, 1983), greater nutrient uptake (Hall, 1974a, b) and improved water use (Vorasoot, 1982).

These studies have focused on the physiological mechanisms of interaction in mixed crops. Another aspect of the interaction between crops is population dynamics. Gain in mixed cropping has been said to originate because higher total plant populations are possible (Andrews and Kassam, 1976). Studies in population dynamics examine the effects of competition on productivity, without necessarily going into the mechanisms of the interaction. Such studies analyse the effects of inter- and intra-specific competition in the system and measure extra contribution, if any, to production from crop mixtures.

An understanding of the effects of competition began with a study of those reactions of plants to density which determine crop yield in pure stands by Kira *et al.* (1953) and Shinozaki and Kira (1956). Their description of the yield/density effect was extended by de Wit (1960) to analyse competition in mixtures of crops and in the experimental design used by him, mixtures ranged from one monoculture to another in such a way that the proportion of two species varied while overall density remained constant. It was shown by de Wit that in the case when species had similar growth curves and excluded each other, inter-specific competitive relationships could be fully characterized by parameters that were derived from intra-specific experiments, that is, in a replacement series the effects of inter- and intra-specific competition were separated. De Wit's models of competition and the index which expresses the results, the relative yield total (de Wit and van den Bergh, 1965), have found much use in gaining useful insights into the nature of niche differentiation in natural systems (Trenbath, 1974; Hall, 1974a, b; Berendse, 1981) because the effects of total density are separated from proportion (Harper, 1977; Spitters, 1980). 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 and which do not necessarily exclude each other. In such instances, total plant density and species proportion influence competitive relationships in the mixture, and therefore, the interpretation of replacement series experiments.

Studies in crop-weed situations led to the development and use of additive experiments where a species is sown at a standard density and the second is sown with it at a range of densities. Since density and frequency are both free to vary in such experiments, one of the major disadvantages of this design is that density effects are confounded with that of proportional composition (Harper, 1977; Spitters, 1980; Trenbath, 1976). The danger of confounding beneficial interactions between crops with a simple response to changed density can be overcome by using a range of densities to determine the optimum sole crop density, critical in the assessment of any yield advantage from the mixture. Research in crop-weed interactions has led to the development of models that provide farmers and other land managers with a tool to evaluate various management options through manipulating competitive relationships between species.

The complete range of outcomes of competition between two crops form a response surface, and replacement series and additive experiments represent only slices of that surface (Firbank and Watkinson, 1990). The only design which comprehensively explores a range of proportions and densities of two competitors is the replacement series repeated at a range of total densities (Silvertown, 1987). Firbank and Watkinson (1985) analysed such an experiment and quantified the effects of competition over all the densities and frequencies studied. Except in the situation where an increase in the yield of one crop leads to an increase of the other or where the growth of a crop is inhibited by allelopathic effects, Spitters (1983) extended de Wit's competition model by introducing parameters which were measures of inter-specific competitive effects and described a method of analysis which allowed yields of both species in a mixture to be estimated at any combination of frequency and density. It was thus possible to estimate the effects of competition, in situations where crops in a mixture were complementary in resource use and only partly excluded each other.

Crop growth curves are like independent production functions as they respond biologically to available resources. In multiple cropping one crop cannot be considered independently of the other. Thus, measures that quantify yield advantage in intercropping must express the yield of one crop as a function of the other. Further, they must help to determine when more production of one crop and less of the other is advantageous, that is, not just ensure that advantages are validly assessed but recognize the different requirements of a farmer and incorporate factors other than biological ones which influence his decision to intercrop. A production possibility curve, drawn from economics literature (Henderson and Quandt, 1971), expresses the yield of one crop as a function of the other, shows all combinations of two products which can be produced by one or both crops and can be used to calculate optimal sowing densities. The production possibility frontier is the envelope of all yield combinations and represents the maximum yield combinations that can be achieved. They have been used as a theoretical device by Filius (1982) and Tisdell (1985) to illustrate complementarity or competition between agricultural and forestry systems. Pearce and Gilliver (1979) used the underlying principle to graphically evaluate trade-offs in intercropping treatments.

Drawing on the notion of production possibility curves, Ranganathan *et al.* (1991) presented an analytical procedure for evaluating trade-offs in biological productivity in intercropping experiments. Yields were plotted on the two axes and the shape of the curve passing through these points indicated the nature of the relationship between the crops; complementary if the curve was convex and competitive, if concave. They defined the relationship as complementary if there was yield advantage in intercropping. Such bioeconomic relationships allow an economic evaluation of the cropping system at the same time as an agronomic one. The importance of an economic evaluation cannot be overestimated because the market value of products provides the farmer with a tool to allocate limited resources between competing uses, and puts different crops and their products on a comparable basis. But the disadvantage with the method developed by Ranganathan *et al.* (1991) is that it assumes the observed yields are the maximum that can be achieved and that the empirically fitted curve is the production possibility frontier. Production possibility frontiers are best built on some *a priori* information on the processes underlying the 'enterprise', here intercropping. The question is the integration of biological information with the economic principles of production possibility frontiers so that the parameters of such a function are explained in biological terms and justifiable on the basis of experimental evidence. Further, what is the sowing density of the mixture that is optimal, both biologically and economically to a farmer?

Even as research in mixed cropping of annual crops is gaining ground, another aspect of it, mixing annuals with woody perennials is in the state that research in mixing annuals was a decade or so ago, with an evaluation of benefits with respect to biophysical aspects of soil fertility, water and soil conservation and microclimate amelioration. Preliminary research shows that the perennial is strongly competitive in the second and subsequent years (Verinumbe and Okali, 1985; Yamoah, 1991; Jama and Getahun, 1991; Singh *et al.*, 1989a,b; Rao *et al.*, 1990; Rao *et al.*, 1991), and acceptable yield levels of the annual can be maintained only if the perennial is managed in order to reduce its competitive strength (Huxley, 1983; Buck, 1986). Management is inherently equivalent to manipulating the competitive relationship between species in the mixture, but what is the basis to it? How much should the perennial be managed and can a relationship between management of the perennial and yield of the annual be established?

Outline of the thesis

Existing models of competition are extended and modified in this thesis for an evaluation of yield advantage in mixed cropping. In Chapter 2 production possibility frontiers are derived using parameters that characterize inter- and intra-specific competitive stresses in an intercrop. Analysis of yield advantage using this method is illustrated with data from three intercropping experiments, along with a description of some of the possible bioeconomic analyses. The derivation of production possibility frontiers for marketable yield is not always straightforward because marketable-yield/density relationships are not always hyperbolic. But through a consideration of per-plant yields, biomass and marketable yield, it is possible to draw the 'envelope' of all marketable yield combinations in the mixture. The derivation of this envelope and calculation of seed density ratios that need to be sown in order to obtain optimal yields is given in Chapter 3.

Through the production possibility frontier for an annual/perennial mix, trade-offs in production of the annual due to competition from the perennial are quantified in Chapter 4. The application of a crop-weed model to give management options for reducing the competitive strength of the perennial is also discussed in this Chapter. Field experiments on perennial pigeonpea and groundnut were conducted and the data used to illustrate the methods developed and discussed in Chapters 3 and 4. Experimental details and some of the results not pertinent to the previous Chapters are presented in Chapter 5.

Terminology

Mixed cropping is defined as the growing of two or more crops together on the same piece of land (Willey, 1979; Papendick *et al.*, 1976). Crops are not necessarily sown at the same time and neither do their harvest times coincide. Mixed cropping can be achieved through growing crops simultaneously for a significant part of their growing periods, intercropping, or growing individuals crops in sequence, sequential or relay cropping. In this thesis, mixed cropping refers specifically to the situation where crops share a significant part of their growing periods. It is also used in a general sense without implying any special spatial pattern unless so specified. Though the principles of mixed cropping apply to situations with more than two crops, unless specified the terms mixed crop and intercrop refer only to two crops being present in the mixture.

The growth of plants in monoculture or mixture is influenced by biological and physical processes which are generally referred to as competition. Harper (1961) criticised the use of this word because of its lack of an independent scientific meaning. He proposed the use of the term 'plant interference' and by his definition, competition is only one facet of the interference between plants, albeit a very dominating one. Trenbath (1976), following Harper's terminology, uses competition only where there is competition for some specific growth factors such as light, water or nutrients. The term 'competition' is used in its broadest sense in this thesis and represents interactions of all kinds-positive, negative and exclusion.

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Chapter 2

Production possibility frontiers and estimation of competition effects: the use of *a priori* information on biological processes in intercropping

Experimental Agriculture 1992 28(3): 351-368

Production possibility frontiers and estimation of competition effects: the use of *a priori* information on biological processes in intercropping

Abstract

Production possibility frontiers contribute much to an economic evaluation of yield advantages from intercropping. The difficulty with estimating a production frontier empirically from experimental data is one of ascertaining that the fitted curve corresponds with the frontier. This problem has been overcome by deriving the frontier from *a priori* knowledge of the biological processes that determine the outcome in intercropping. The hyperbolic relationship between biomass yield and plant density, and the parameters that characterize the degree of intra- and inter-specific competition in intercropping are used in this paper to derive production possibility frontiers. The method is illustrated with data from three intercropping studies. A brief review of the two main methods used by researchers to evaluate the results of intercropping and their limitations is also presented.

Introduction

Natural plant populations are usually mixtures of species, within which individuals and species are interacting with each other. The description and quantification of these interactions form the subject of a specialized area of study called population ecology (Hart, 1986). Plants growing together influence each other by changing their environment, that is, by affecting conditions such as temperature, availability of sunlight or wind movement. They may also compete for soil nutrients and water.

Plant population dynamics take into account such interactions within the mixture by answering questions such as: how does the presence of species A affect the growth and yield of species B, how does B affect A, and does the effect of B on A and A on B change with changes in proportions and densities of the species?

Mixed cropping, a centuries-old technique of farming, has parallels with basic ecological principles relating to plant interactions. Farmers in the developing world have been growing two or more crops together on the same piece of land for reasons such as better exploitation of the environment, reducing risk, controlling weeds, spreading labour demand and satisfying dietary requirements. Research in mixed cropping has tried to provide an understanding of how to improve the productivity of these systems. The question asked is similar to those in the study of population dynamics in ecology: what is the nature of the interaction between species in a mixed crop?

The outcome of mutual interaction within a mixture is, in general, a reduction in plant growth and performance of both species. Yet, in a number of instances, mixed cropping has been seen to have advantages over sole cropping because total production is greater than either crop grown alone (Willey, 1979a, b; ICRISAT, 1981a). Various methods or indices for quantifying such yield benefits have been described and used extensively, but all have their particular advantages and disadvantages. In this paper, the main methods are reviewed and an alternate method, which overcomes some of the weaknesses of the existing ones, is proposed. This combines a physiological model, which expresses the yield of crops in an intercrop as a function of their population densities, with the concept of production possibility frontiers from economics. The method is illustrated with the help of data from intercropping experiments and some of the economic interpretations that can be made using the method are briefly discussed.

Though some researchers use the term 'interference' to describe the response of an individual plant or plant species to its environment when this is modified by the presence of other individuals or species (Harper, 1961), the term 'competition' is preferred here. The words 'mixture' and 'mixed crop' are used interchangeably though some researchers prefer 'intercrop' and/or 'mixed crop' to describe specific crop mixtures.

Some measures of competition

Two of the earliest attempts at measuring change in interacting populations over time were by Lotka (1925) and Volterra (1928) with application to animal ecology. The Lotka-Volterra differential equations expressed population changes over time in terms of the inhibitory effects of the competing populations and environmental limits. De Wit (1960) successfully applied these equations to interacting plant populations. He illustrated his analysis with experiments on an intercrop of barley and oats grown in a replacement series. In such series, mixtures range from one monoculture to the other in such a way that the sum $z_1 + nz_2$ is always a constant, where z_1 and z_2 are the seed rates of the two species and n is a constant by which one species replaces the other in the series.

De Wit and van den Bergh (1965) characterized the performance of species in a replacement series by the relative yield total (RYT). The RYT is the sum of the relative yields of the species in the mixture. The relative yield is expressed as the ratio r of the yield of a species in the mixture to its yield in monoculture. Then

$$\text{RYT} = r_a + r_b + \ldots\ldots + r_n$$

The value assumed by the RYT indicates whether the species are performing better in mixture than in monoculture, but only for that particular total density. Three situations can be distinguished.

> RYT = 1. In this case, the species exclude each other. Yields of the two crops in a mixture can also be obtained by sowing part of the field with one crop and another part with the other. If it is observed in the range of seed densities normally grown, it represents the situation where there is no yield

advantage in mixed cropping. Depending on the prices, it is economic to grow either one of the two species.

RYT > 1. The two species are, at least, partly complementary in resource use. This can happen when their growth periods are only partly overlapping. The yields obtained in a mixture can only be achieved in monoculture by sowing a larger area partly with one crop and the remainder with the other. In these situations, there is a biological advantage in mixed cropping; whether it translates into economic advantage depends on prices.

RYT < 1. In such instances, allelopathic effects exist to the extent that one species 'poisons' the other. The yields obtained in a mixture can be achieved in monoculture by sowing a smaller area, partly with one crop and partly with the other. This kind of result has been observed when one species carries a virus that is transmitted to the other (de Wit, 1960).

Thus for replacement experiments, an RYT greater than 1 will always represent the case where there is some yield advantage in intercropping. The same cannot be inferred if the condition of fixed density is not met; density responses of the intercropped species are likely to be confounded with the effects of competition. Spitters (1980) discusses in some detail the fallacious conclusions that can be drawn from the RYT if the underlying conditions are not satisfied.

A popular alternative to the RYT, the land equivalent ratio (LER), was first conceptualized by Willey and Osiru (1972) as a basis for assessing yield advantage in situations where yield advantage in a mixture can occur without exceeding the yield of the higher yielding species. A yield advantage occurs, if the mixture produces more yield from a given area of land than can be obtained by dividing that area of land into pure stands of the two species. The LER is defined as the relative land area under sole crops required to produce the yields achieved in intercropping (Willey, 1979a). Unlike the RYT it does not assume that total crop densities are constant. The LER is widely used in assessing yield advantage from additive experiments where a fixed density of one species is grown with a variety of densities of the other. The LER is popular because it has no restrictive conditions for its use and puts different crops, irrespective of their level of yield, on a comparable basis.

Limitations

Some of the limitations with these measures of competition (or yield advantage) lie, not with the indices themselves, but with their application. Some researchers (Jolliffe *et al.*, 1984; Connolly, 1986) observe that the conditions of a replacement experiment are so restrictive that no valid generalizations can be made. This is, however, true in general of mixed cropping experiments and not only of replacement experiments. Replacement experiments repeated at a range of densities are said to be the only kind of design 'which comprehensively explores a range of proportions and densities of two competitors' (Silvertown, 1987), but since fixed density is a precondition for their use, they are not suitable for describing how the yield will behave in a mixture in which density is not held constant (Inouye and Schaffer, 1981). The RYT is thus not an appropriate measure of yield advantage for additive experiments. Additive experiments (Harper, 1977; Silvertown, 1987) are currently in favour because they answer more directly agricultural questions about the extent to which the full yield of one crop is affected by another (Willey, 1979a; Spitters and van den Bergh, 1982). For example, additive designs are used quite extensively in crop-weed experiments because they mimic the real situation of a crop, planted at fixed density but infested with weeds.

A major problem associated with the use of LERs in additive experiments is one of interpretation because the effects of total plant density and a high density of one crop on the other are compounded, that is, the proportional composition and the density of the mixture and their effects are completely confounded (Harper, 1977; Trenbath, 1976; Spitters, 1980). Trenbath (1976) underlines the importance of understanding how values of LER arise in formulating cropping recommendations. The danger of confounding beneficial interactions between components with a simple response to changed density can be overcome by using a range of densities so that it is possible to determine the optimal sole crop density for that site and season. However, most additive experiments are conducted with a single sole crop density which is assumed to be optimum without further proof. The crux of all LER calculations lies, then, in the choice of the standardizing sole crop yield. Although researchers, such as Willey and Osiru (1972) and Mead and Willey (1980), take care in pointing out what the standardizing sole crop yield should be, Francis (1989) points out that calculated and presented LERs ultimately depend on experimental objectives whose interpretation is at the discretion of the researcher.

Spitters' model on competition

Spitters (1983) developed a method of estimating the degree of intra- and inter-specific competition from the total biomass yield of species in a mixture. The model uses total biomass because its production is approximately linearly related to the particular resource that limits growth. The distribution of this resource is reflected in the biomass of each species.

Within a species, intra-specific competition expresses itself in the response of biomass to plant density. The hyperbola has been shown to describe this relationship (de Wit, 1960; Willey and Heath, 1969). The yield of a species is given by

$$Y_j = \frac{B_j N_j}{B_j N_j + 1} Q_j$$

where N_j (plants m^{-2}) is the plant density of crop j, Q_j (g m^{-2}) is the asymptotic yield at high density (Y_j will approach Q_j at this density) and B_j (m^2 plant^{-1}) is the space occupied by a single plant when it stands far apart from others (and is hence free from competition); the yield of this single plant is given by B_jQ_j.

De Wit (1960) extended this equation to account for the effects of other species on the yield of a mixture. He also showed that the two equations can be expressed in terms of the same parameters B_1 and B_2, if the two species have similar growth curves and exclude each other in a replacement series at normal densities (RYT=1). The yield of species 1 and 2 in an intercrop is given by

$$Y_1 = \frac{B_1N_1}{B_1N_1 + B_2N_2 + 1} Q_1 \qquad (2.1a)$$

$$Y_2 = \frac{B_2N_2}{B_1N_1 + B_2N_2 + 1} Q_2 \qquad (2.1b)$$

One of the reasons some crop combinations give a yield advantage is because they are temporally complementary in resource capture (Willey, 1979a). In such cases, the species are only partly excluding each other (Hall, 1974). Spitters (1983) generalized de Wit's equations for such situations by introducing two new parameters into the equations.

$$Y_1 = \frac{B_1N_1}{1 + B_1N_1 + B_{1,2}N_2} Q_1$$

$$Y_2 = \frac{B_2N_2}{1 + B_2N_2 + B_{2,1}N_1} Q_2$$

Unlike de Wit's equations, the above expressions are independent of each other in the parameters and allow for an estimation of competition effects in situations where the species in a mixture are complementary in resource use and the condition of fixed density is not met. From these equations it can now be inferred that one plant of species 1 has the same effect on the yield Y_1 as $B_{1,2}/B_1$ plants of species 2. Similarly, one plant of species 2 has the same effect on Y_2 as $B_{2,1}/B_2$ plants of species 1.

However, there are some problems in estimating the parameters B_1, B_2, $B_{1,2}$ and $B_{2,1}$. Since these parameters can take values up to ∞, it is possible that the convergence criterion associated with the non-linear regression algorithm may not be met. Thus, even though the function is better visualized in de Wit's notation, Spitters' notation is used in this paper. Spitters expresses Y_1 and Y_2 as

$$Y_1 = \frac{N_1}{b_{1,0} + b_{1,1}N_1 + b_{1,2}N_2} \qquad (2.2a)$$

$$Y_2 = \frac{N_2}{b_{2,0} + b_{2,1}N_1 + b_{2,2}N_2} \qquad (2.2b)$$

The parameters $b_{1,0}$ and $b_{2,0}$ (plants g^{-1}) are the reciprocal of the weight per plant of species 1 and 2 when they are free from competition. The parameters $b_{1,1}$ and $b_{2,2}$ are the reciprocals of the maximum biomass per unit area achieved at infinite density. It can be seen that Spitters' Equations 2.2a and b are the same as the generalized de Wit equations. The parameters $b_{1,0}$, $b_{1,1}$ and $b_{1,2}$ from Equation 2a are equal to $1/B_1Q_1$, $1/Q_1$ and $B_{1,2}/B_1Q_1$.

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 quite an acceptable description of the biological process of competition (Willey and Heath, 1969; de Wit, 1960).

Production possibility frontiers

Economic analysis has not contributed much to the evaluation of productivity in intercropping, as evaluation in economic terms is considered inappropriate due to seasonal price fluctuations in inputs and lack of a cash economy in most areas where intercropping is practiced (Beets, 1982, quoted in Ofori and Stern, 1987). The approach to assessing yield advantage developed in this section uses the concept of production possibility frontiers or curves from economics. This approach builds on the biological processes underlying intercropping and lends itself readily to economic interpretation.

A production function gives mathematical expression to the relationship between quantities of inputs employed and the output produced. This functional relationship is based on an examination of the many alternative ways in which inputs can be combined to produce any given output, and a selection of the most efficient way of using inputs. The production frontier is thus the maximum output obtainable from every possible input combination (Henderson and Quandt, 1971).

In a manner analogous to this argument, it is possible to summarize a relationship between two outputs, say yields from an intercrop. As discussed earlier in the paper, the yield of a mixture is dependent on the plant densities of the two crops. Assuming that resources have been used in the most efficient way, the production possibility frontier for the two yields gives the range of maximum yields that can be obtained after considering the yield from all possible plant density combinations. The frontier thus gives the best combination of plant densities. Every other combination is 'technically inefficient'.

A graphical derivation of a production possibility frontier (PPF) for an intercropping situation is shown in Figure 2.1. The yields from crop 1 and crop 2 are plotted on the two axes. The dotted lines show combinations of yield for which the production process is not technically efficient. The curves radiating from the y-axis are obtained by keeping the density of crop 1 fixed at different levels, varying that of crop 2 and then calculating the corresponding yields using Spitters' equations. Similarly, the curves radiating upwards from the x-axis are obtained by keeping the density of crop 2 fixed at different levels, varying that of crop 1 and calculating the corresponding yields. The envelope of all these curves is the production possibility frontier.

Knowledge of the PPF allows further economic analyses. The optimal point of production corresponds to the tangent of the price line (AB in Figure 2.1) to the curve. A price line reflects a fixed value of production, that is, the total value of the crops expressed as the sum of their constituent values. The line gives a locus of points of the same value of production for fixed prices and variable quantities of products. Hence, the value of production at A, C and B are all the same. Assuming input costs are constant, if the price of crop 1 increases, the price line will be steeper and the optimum point closer to E, reflecting the need to produce more of crop 1 in order to maximize gross economic returns. Similarly, a price increase in crop 2 will result in a flatter curve and tip the economic balance towards crop 2.

The shape of the production possibility curve indicates the nature of the relationship between two crops. If the line is bowed outward from the origin, i.e. convex (as in Figure 2.1), the two crops interact positively and are complementary;

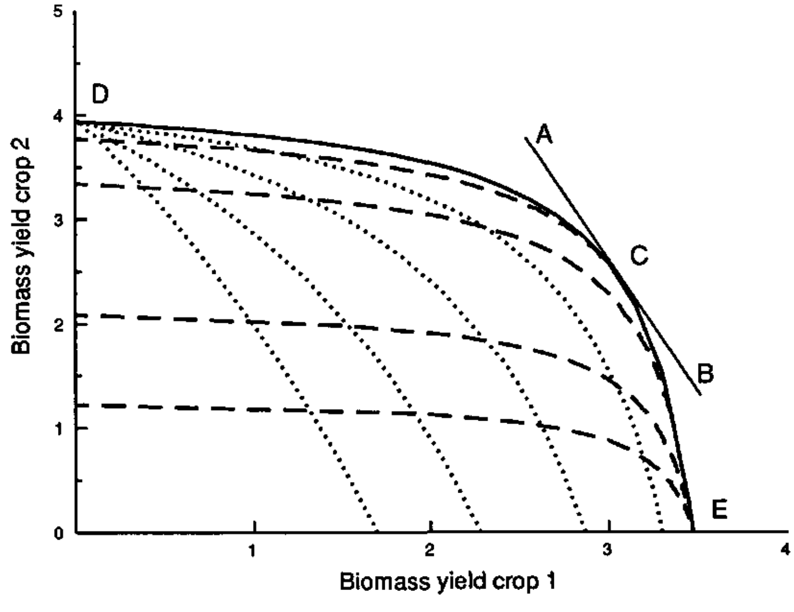

Figure 2.1 The production possibility frontier and price line. The inner curves show yield combinations of the two crops (obtained using Spitters' model of competition) that are technically inefficient.

if bowed inward towards the origin, that is, concave, the crops interact negatively and *are allelopathic.* A *straight line indicates that the crops exclude each other* and in a mixture their yield is no greater than if they had been planted as monocrops. The interpretation of the PPF is thus analogous to the LER or the RYT, except that the interpretation is not restricted to replacement series and not confounded by density effects.

Though similar to the LER or RYT, the PPF uses more information. Mathematically, global and local optima are accepted terms. The LER and RYT can be likened to local optima because they are restricted to some specific mixture combination from a limited range. The PPF makes it possible to examine the whole *range of 'best' mixture combinations from some limited number of* combinations. But the LER and RYT are more easily visualized because they are characterized by single numbers.

An index similar to the LER and RYT, but based on the PPF has been suggested by Ranganathan *et al.* (1991). The yield advantage index (YAI) is the ratio of the area under the production possibility curve to the area under the triangle formed by the two axes and the line joining the sole crop yields on the axes. The line joining the sole crop yields is, in fact, the production possibility curve when the two crops in a mixture exclude each other. The YAI can take values between 0 and 2. The maximum value illustrates the situation where the yields of the crops show no reduction when in a mixture. Since the YAI is based on the PPF, it provides more complete information than the LER or RYT.

Estimation of the production possibility frontier

The difficulty with estimating a frontier empirically from experimental data on yields, as in Ranganathan *et al.* (1991), is in ascertaining that the fitted curve actually corresponds with the production possibility frontier. Some points of the scatter, to which the curve is fitted, may be technically inefficient, while others must fall on the production frontier. A regression approach using least-squares is not at all appropriate for fitting a curve that corresponds to the frontier because of the possibility of inefficient points influencing its location.

It is desirable to derive a production possibility frontier from *a priori* knowledge of the processes that determine the outcome, in this case grain yields or biomass; to build, if possible, on the description of the biological processes underlying intercropping. An explanation of functional form restrictions, if any, should be possible in biological terms and justifiable on the basis of experimental evidence.

Information from Spitters' Equations (2.2a and b) provide a strong base for the derivation of a production possibility frontier. As N_1 and N_2, plant densities of crops 1 and 2 in the intercrop, approach ∞, it follows that the yields of the two crops are given by:

$$Y_1 = \frac{1}{b_{1,1} + b_{1,2}\frac{N_2}{N_1}} \qquad (2.3a)$$

$$Y_2 = \frac{1}{b_{2,2} + b_{2,1}\frac{N_1}{N_2}} \qquad (2.3b)$$

From Equations 2.3a and b it follows that

$$\frac{N_2}{N_1} = \frac{1}{b_{1,2}Y_1}(1 - b_{1,1}Y_1) \qquad (2.4a)$$

$$\frac{N_1}{N_2} = \frac{1}{b_{2,1}Y_2}(1 - b_{2,2}Y_2) \qquad (2.4b)$$

By multiplying Equations 2.4a and b, the following expression is obtained

$$\left(\frac{1}{b_{1,1}Y_1} - 1\right)\left(\frac{1}{b_{2,2}Y_2} - 1\right) = C \qquad (2.5)$$

where

$$C = \frac{b_{1,2}\, b_{2,1}}{b_{1,1}\, b_{2,2}}$$

Equation 2.5 defines a production possibility curve for outputs obtained by intercropping. It can be seen that C can take values between 0 and ∞. When C takes the value 1, the function is a straight line; when C is greater than or less than 1, the function is curved inward and outward, respectively. The function is flexible, requires few parameters to summarize the relationship between the two outputs and is easy to estimate by the use of non-linear regression.

The use of Equation 2.5, however, requires a word of caution. It is a mathematical expression of the interaction between plants in an intercrop and as such is valid only if certain mathematical conditions are satisfied. From the equation it is apparent that the parameters should be greater than 0. The expression no longer holds if any of the parameters, $b_{1,1}$, $b_{1,2}$, $b_{2,2}$ or $b_{2,1}$, approach 0. But this condition in no way devalues the usefulness of the method; if any of the parameters approach 0, it implies little or no interaction between the crops and the expression is no longer an accurate description of the situation. It is, of course, still possible to arrive at the production possibility frontier but only by drawing the envelope as described in the previous section and as shown in Figure 2.1.

Given that the parameters $b_{1,1}$, $b_{1,2}$, $b_{2,2}$ and $b_{2,1}$ are greater than 0, the yield advantage index (YAI) is given by

$$YAI = \frac{\int_0^{\frac{1}{b_{1,1}}} Y_2 \, d(Y_1)}{\frac{1}{2\, b_{1,1}\, b_{2,2}}}$$

where the numerator is the area under the frontier and the denominator, the area under the 'curve' formed when the crops exclude each other. On simplification, YAI can be expressed in terms of the parameters of Spitters' equations.

$$YAI = 2\left[\frac{C \ln (C)}{(C-1)^2} - \frac{1}{C-1}\right]$$

where

$$C = \frac{b_{1,2}\, b_{2,1}}{b_{1,1}\, b_{2,2}}$$

YAI ranges between 0 and 2 depending on the values taken by *C*. *C* can take values between 0 and ∞. Taking limits as *C* approaches 0 and ∞, we have

$$\lim_{C \to 0} YAI = 2$$

$$\lim_{C \to 1} YAI = 1$$

$$\lim_{C \to \infty} YAI = 0$$

Thus, given that the hyperbolic function exists, the YAI is a sufficient statistic for the production possibility frontier.

From the production possibility curve, it is possible to calculate the ratio of seed densities to be sown in order to obtain the optimal yield combination at the prevailing prices. The point at which the price line is tangential to the PPF can be calculated by equating the first differential of the PPF to the slope of the price line. The slope is given by $-p_1/p_2$ where p_1 and p_2 are the existing prices of crops 1 and 2:

$$-\frac{p_1}{p_2} = \frac{-b_{1,2}\, b_{2,1}}{[(b_{1,1}\, b_{2,2} - b_{1,2}\, b_{2,1})Y_1 - b_{2,2}]^2}$$

Two solutions to Y_1 are obtained. The smaller of the two values is the optimal yield of crop 1. By substituting this value in Equation 2.4a, the ratio of seed densities of the species in the intercrop can be calculated.

For crop combinations which result in yield advantage through mixed cropping, there is an economic advantage only when $-p_1/p_2$ is greater than the slope of the price line tangential to the PPF at $Y_1 = 0$ and smaller than the slope of the price line tangential to the PPF when Y_1 is maximum. These limits are expressed by:

$$\left(-\frac{b_{1,2}\ b_{2,1}}{b_{2,2}^2},\ -\frac{b_{1,1}^2}{b_{1,2}\ b_{2,1}}\right)$$

When this condition is not satisfied, it is more economic to plant one or the other crop in monoculture. The seed ratio will accordingly be very large or very small.

The method described here is applicable to situations where the value of the products is proportional to the total biomass alone and costs do not vary much for different plant densities as one moves along the frontier. Neither of the above conditions is excessively restrictive when one is interested in assessing biological productivity over a reasonable range of input use intensity.

The data set

As examples of the use of the method, production possibility curves have been derived for experimental data from three intercropping trials. Along with the production frontier obtained from the function derived above, production possibility curves for plant densities ranging from technically inefficient to those that are efficient have been drawn. The examples demonstrate that the curve derived from Equation 2.5 corresponds to the frontier, and that the method is applicable to data from a wide range of situations.

Data set 1

The first set of data is from experiments conducted in Indonesia on maize (*Zea mays* L.) and groundnut (*Arachis hypogaea* L.) between 1978 and 1980 (van Hoof, 1987). The two crops have different growth durations; the time from sowing to maturity of the maize was 85 days and of the groundnut was 105 days. Replacement series were grown at different total densities in a randomized block design with four replicates. The recommended plant density for groundnut was 16 plants m^{-2} and for maize 8 plants m^{-2}.

Data set 2

This data set is from de Wit's experiment of 1959 (de Wit, 1960) in the Netherlands with oats (*Avena sativa* var. Libertas) and barley (*Hordeum vulgare* var. Herta) and is used as an example of two species with similar growth curves crowding for the same space. The experiment was a replacement type repeated at a high density of 322 plants m^{-2} and at the recommended density of 32 plants

m^{-2}. Both trials were laid out as 5 x 5 lattices with two replicates.

Data set 3

The third data set comes from an experiment conducted in 1979 at the ICRISAT Center, Patancheru, India (ICRISAT, 1981b). The objective of the experiment was to determine the optimal total population of an intercrop of sorghum (*Sorghum bicolor* (L.) Moench) and pigeonpea (*Cajanus cajan* (L.) Millsp.). Pigeonpea populations with a 40% (2, 2.8, 4, 5.6, 7.8, 10.9, 15.3 plants m^{-2}) were systematically arranged at each of the four populations of sorghum (4, 11, 18, 32 plants m^{-2}). Sole pigeonpea was planted at 4 plants m^{-2} and sole sorghum at each of the intercrop populations. The experiment was of the additive type and replicated four times.

Discussion

The parameters estimated from Spitters' equations show close correspondence with observed biomass (Table 2.1 and Figure 2.2). The negative value of $b_{i,0}$ for maize (Table 2.1) implies an increase in biomass per unit area for monocrop maize when the stand gets sparse. This is, of course, not possible. The negative value is caused by random errors arising from the fact that there are no yield observations at very wide spacings. The estimate here for $b_{i,0}$ is not significantly different from 0. In instances like this, it is best to use the value 0 for $b_{i,0}$. The parameter $b_{i,0}$ is the reciprocal of the weight of a plant when it stands far apart from other plants. From the observed yields in an experiment it is possible to calculate the highest yield per plant. The true value of $b_{i,0}$ lies between 0 and the reciprocal of the highest observed yield per plant.

As the density of groundnut increased from 2.5 plants m^{-2} to 350 and more, the yield of sole groundnut increased till the increment was so small as to be insignificant (Figure 2.3a). Similar curves, but radiating upwards, were obtained by keeping the maize density constant at different levels and varying the groundnut density. The concentric nature of these inner curves is a reflection of the underlying asymptotic relationship between biomass and plant density. The solid line-the production frontier-gives the maximum yield that can be achieved.

The shape of the curve shows that there is a yield advantage in mixing maize and groundnut (YAI=1.32). This result is consistent with prior agronomic knowledge about the relationship between the crops. In mixtures of grain crops, such as maize, with legumes a yield advantage is generally the rule. In this experiment, the harvest index for both maize and groundnut is constant over the range of densities considered and the production frontier for grain can be calculated in the same way as the frontier for total biomass.

De Wit *et al.* (1979) found that for oats and barley seed/straw ratios were hardly affected by density. The production frontier has thus been directly derived for seed yield (Figure 2.3b). The shape of the curve shows that there is little yield advantage in mixed cropping (YAI=0.7) and the largest yield, grain or cash, is

Table 2.1 Estimated parameters of the Spitters' equations

	$b_{i,0}$ (plants 100 g^{-1})	$b_{i,i}$ (m^2 100 g^{-1})	$b_{i,j}$ (m^2 100 g^{-1})	Adj.R^2
	Maize/groundnut (van Hoof, 1987)			
Maize	0	0.193	0.027	0.996
	(0.065)	(0.004)	(0.007)	
Groundnut	1.716	0.222	0.597	0.983
	(0.732)	(0.097)	(0.034)	
	Oats/barley (de Wit, 1960)			
Oats	3.07	0.165	0.365	0.993
	(0.480)	(0.034)	(0.007)	
Barley	3.695	0.180	0.071	0.995
	(0.379)	(0.010)	(0.006)	
	Sorghum/pigeonpea (ICRISAT, 1981b)			
Sorghum	0.194	0.072	0.010	0.990
	(0.036)	(0.005)	(0.002)	
Pigeonpea	0.018	0.215	0.021	0.988
	(0.045)	(0.003)	(0.009)	

Standard errors are shown in parentheses

obtained if the whole field is sown with either oats or barley, whichever yields more. However, de Wit also reported that farmers in the Netherlands planted oats and barley together because lodging in barley was found to be less when it was grown with a certain proportion of oats. In addition although barley was preferred, farmers planted both on fields where the pH varied because on patches where the pH is low, oats yielded well and on patches where the pH was higher, barley grew well. In this way, farmers reduced their risks.

Sorghum/pigeonpea is an extremely common combination in many parts of India. Trials conducted at ICRISAT have shown that there are substantial yield advantages from this combination (Rao and Willey, 1983; Natarajan and Willey, 1980a, b). The strong positive interaction between a fast growing, early maturing crop and a slower growing one is quite obvious in the shape of the curve (YAI=1.91) and is reflected in a large benefit (Figure 2.3c). Pigeonpea yields are more or less constant for a very large range of sorghum densities. As in the other cases, the relationship between total dry matter and grain yield is characterized by a constant ratio. A frontier for grain can easily be derived using Equation 2.5.

In each of the examples of intercropping considered here, the relationship between grain and biomass has been characterized by a constant ratio. This need not be the general case but in cases where this is not so, the production frontier

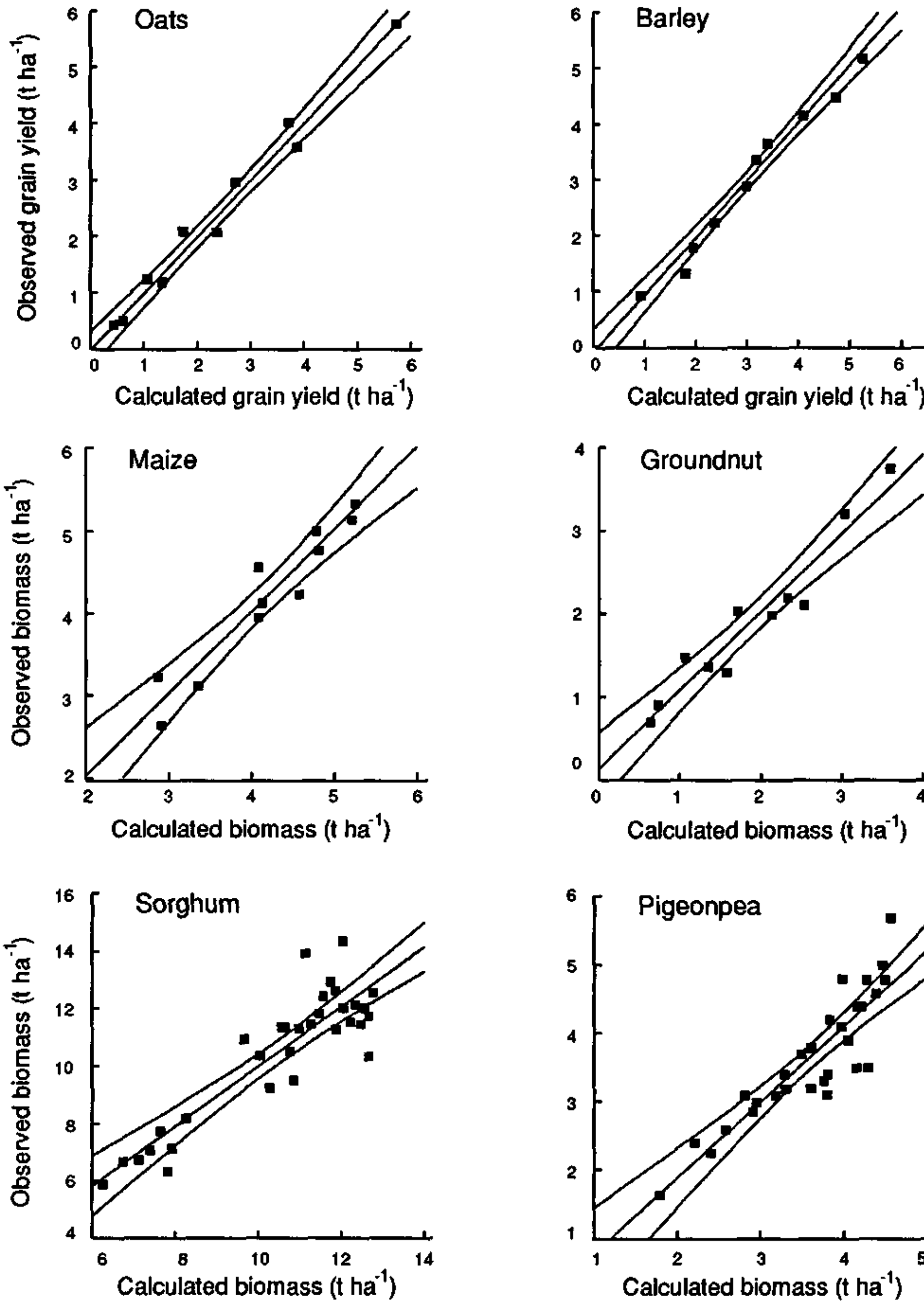

Figure 2.2 Regression fit between observed and calculated (using Spitters' model of competition) biomass and 90% confidence bands.

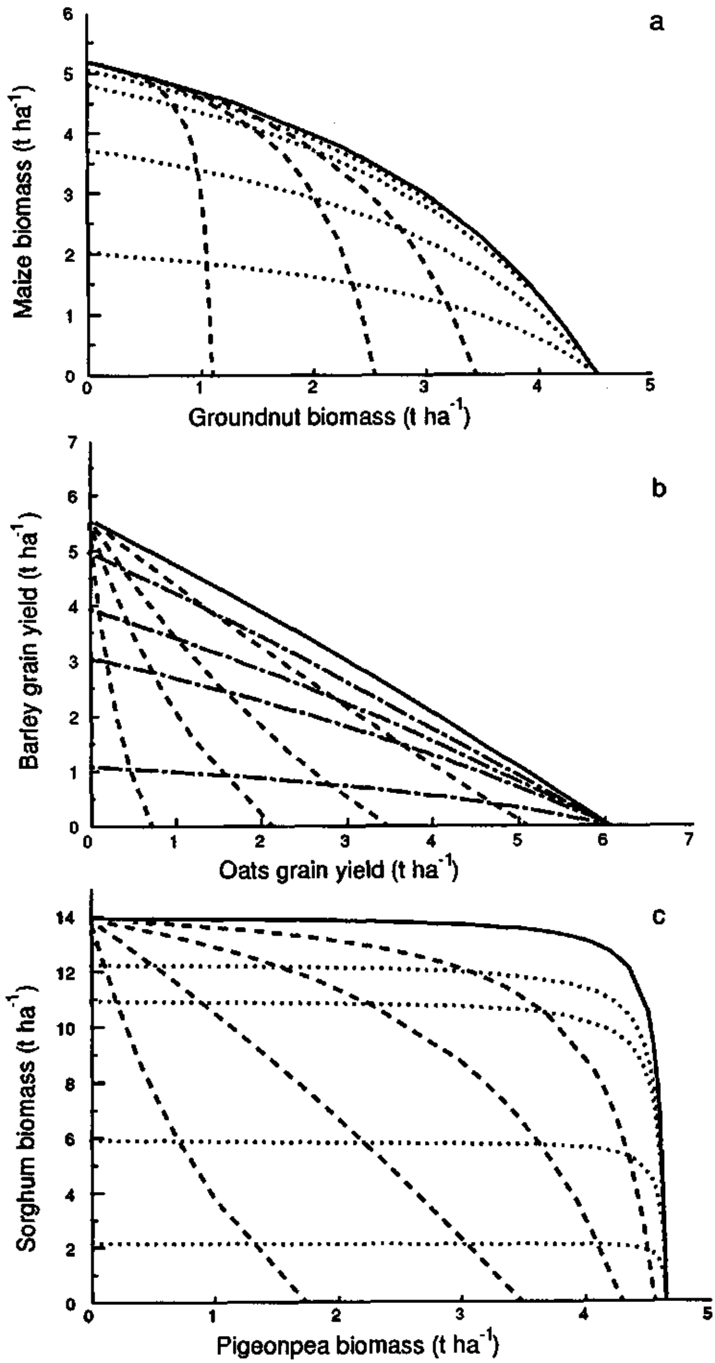

Figure 2.3 Production possibility frontiers for (a) Groundnut/maize biomass (b) Oats/barley grain and (c) Sorghum/pigeonpea biomass.

cannot be calculated using Equation 2.5. The envelope as described in Figure 2.1 must be drawn after calculating the grain yield as in the case of the seed/straw relationship for all points on the production frontier for biomass.

In many instances, input costs change as one moves along the frontier. Seed costs are particularly important and play a major role in a farmers decision making process. For example, in mixed cropping with groundnut, farmers are restricted in the range of sowing densities available to them by the cost of groundnut seed. The cost per kilogram of seed for sowing is often four to five times the market price per kilogram of yield. There exists an optimum density beyond which the cost of seed required to achieve a certain level of yield exceeds the anticipated returns from the produce. Assuming all other input costs are constant, a production frontier where seed costs are taken into account can be numerically calculated as in Figure 2.1 but Equation 2.5 cannot be used. Net yields can be calculated by the expression:

$$Y_i = \frac{N_i}{b_{i,0} + b_{i,i} N_i + b_{i,j} N_j} - f_i N_i$$

where

$$f_i = \frac{P_s}{P_h} \textit{(seed weight)}$$

P_s is the cost of the seed and P_h is the market price for the harvested grain. By drawing the inner curves as in Figure 2.1 and then the envelope, the 'profit frontier' is derived. The frontier for data from van Hoof's experiment (van Hoof, 1987) on the assumption that there is no cost associated with maize seed and the price of groundnut seed is five times the market price of the produce is shown in Figure 2.4.

With fluctuations in prices, farmers should be and often are interested in changes in quantity of outputs produced as a response to changes in prices. This can be illustrated by a sensitivity analysis. Assuming that there is an existing market price for biomass and that input costs are constant along the frontier, changes in the relative production of one crop as a result of changes in price ratios are shown in Figure 2.5. On the x-axis is a range of ratios of the price of oats (or sorghum or maize) to that of barley (or pigeonpea or groundnut). The y-axis gives the optimum yield of oats (or sorghum or maize) relative to the total optimum yield of the intercrop.

The response curve for oats and barley is akin to a step function. For a very small change in the price ratio of oats to barley (0.8 to 1; the economic limits discussed in the previous section), oats, which constituted a very small fraction of the total yield, becomes the major component of the intercrop. When the price ratio of oats to barley is slightly greater than the ratio where the 'step' in Figure 2.5 occurs, it makes economic sense to grow only oats. The intercrop of sorghum and pigeonpea is a contrasting case. Only at very, very low prices of sorghum

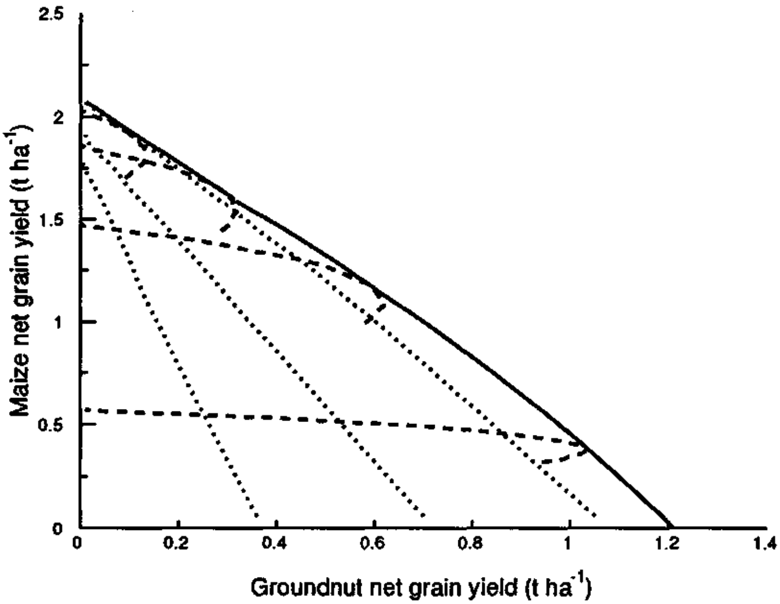

Figure 2.4 'Profit frontier' for maize/groundnut grain yields after groundnut seed costs have been accounted for in the calculation of net grain yield.

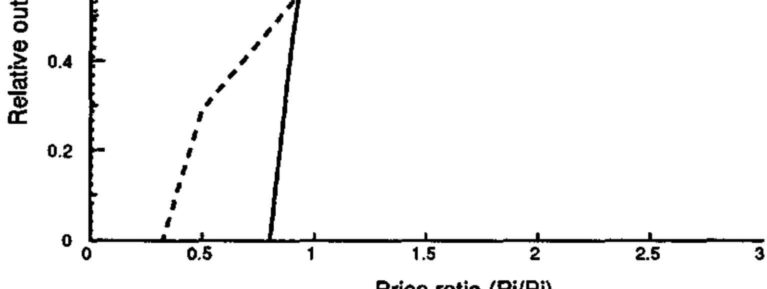

Figure 2.5 Change in relative output as a response to change in prices of species i and j; oats and barley (solid line), sorghum and pigeonpea (dotted line), maize and groundnut (dashed line), respectively.

relative to pigeonpea will farmers plant sole pigeonpea. But as the price ratio increases from close to 0 to 0.5, the proportion of sorghum in the intercrop increases from a very small quantity to 76%. That this proportion stays more or less the same for large values on the x-axis is indicative of the fact that intercropped sorghum and pigeonpea show huge yield advantages.

The third intercrop combination of maize and groundnut shows greater sensitivity to changes in prices. The proportion of maize in the intercrop shows a gradual change with an increase in its price relative to that of groundnut. In order to maximize profits, farmers would need to respond even to slight changes in prices by altering the proportion of the crops in the intercrop.

Conclusions

Production possibility frontiers have long been used as a theoretical device to express the relationship between two outputs. The frontier itself, however, has not always been easy to estimate. The method suggested here to derive a production frontier is built on strong *a priori* knowledge of the underlying biological processes in intercropping. It is flexible, easily adjusted for economic factors affecting production, and imposes few restrictions on the parameters. Several of the problems of estimation normally encountered with empirical models are overcome.

Furthermore, it has several advantages over the existing methods of analyzing data from intercropping trials. It is applicable to the results from different kinds of trials, is a global measure of biological productivity and provides more information than existing methods.

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Chapter 3

Marketable yield/biomass relationships in the analysis of yield advantage in intercropping

Marketable yield/biomass relationships in the analysis of yield advantage in intercropping

Abstract

The production possibility frontier as a tool in the analysis of competition and yield advantage in mixed cropping can be empirically calculated if yield/plant-density relationships can be characterized by hyperbolic functions. Marketable yield, however, does not always have such a relationship with plant density. Marketable-yield/biomass relationships may vary with density because the proportion of a plant's biomass allocated to marketable yield varies with the extent to which the plant is suppressed through competition. It is shown here that irrespective of whether a plant suffers from inter- or intra-specific competition, the effect is a reduction in mean plant size and the association between per-plant biomass and marketable yield is well represented by a straight line. This Chapter presents a method of estimating marketable-yield/biomass relationships by examining the effect of competition on per-plant yields and discusses marketable-yield advantage for some examples of mixed cropping.

Introduction

An important bioeconomic relationship relevant to mixed cropping is that between two (or more) crops or products (Hildebrand, 1976). The production possibility frontier (Ranganathan *et al.*, 1991; Ranganathan, 1992) illustrates how economics affects and is incorporated into intercropping systems. The derivation of a production possibility frontier for a mixed crop requires the estimation of total biomass based on the hyperbolic relationship it has with density. In agriculture, however, the aim of production is often maximum yield of a desired plant part (referred to here as marketable yield) rather than total biomass. The proportion of a plant's biomass that is allocated to various organs varies with the extent to which it is suppressed through competition. But much of the current understanding of how competition affects plant growth, in monocultures and mixtures, is based on total above ground biomass since it is the most direct measure of plant growth and productivity and is a reflection of the distribution of limiting resources among plants. At low densities there is no competition between plants and biomass is directly proportional to density. At higher densities plants compete with each other and biomass production is restricted by the availability of that resource which is most limiting (Kira *et al.*, 1953).

In the analysis of competition within a sole crop or mixed crop planting, the marketable-yield/biomass relationships play an important role. This Chapter explores per-plant marketable-yield/biomass relationships in monocultures and mixtures with a view to assess marketable-yield advantage in mixed cropping systems using production possibility frontiers. Production possibility frontiers for a perennial pigeonpea/groundnut intercrop have been derived and some economic analyses are also presented.

Competition effects on marketable yield and biomass

The effect of density on crops may be such that at high densities an individual plant's weight almost exactly compensates for the increased numbers of plants per unit area by changing the proportional allocation of assimilatory products to its various organs. This plastic development of individual parts in a plant as a result of density stress, regulates the reproductive output of a population. A plant's response to density stress and the effect on dry matter reallocation varies from species to species. The relationship between biomass and marketable yield with varying density is generally of two kinds and is illustrated in Figures 3.1a and b.

The similarity of wheat's grain and biomass response to density (Puckridge and Donald, 1967) in Figure 3.1a describes a situation where at high densities both biomass and grain yield from an individual plant almost exactly compensate for the increased number of plants per unit area. Accordingly, the harvest index or marketable-yield/biomass ratio remains constant and density stressed individuals are miniature versions of their low density counterparts. In Brussels sprouts (Verheij, 1970) (Figure 3.1b) density increases are initially accompanied by an increase in total plant biomass and sprout yield, thereafter the further addition of plants per unit area results in increased biomass but decreased sprout yield. A density stressed plant in Figure 3.1b is not a miniature version of its low density counterpart and dry matter production requires far higher sowing densities than are necessary for maximum seed production (Akinola and Whiteman, 1974).

According to Harper (1977), differences in density responses between species are dependent on the form of repeating units of construction like leaves, stems and flowers and the size and form of these units change only fractionally over widely varying environments. The numbers of such units and thus size of the whole plant varies greatly with age and growing conditions. Variations in the number of parts largely determines the reproductive activity of a species. For species with a density response demonstrated in Figure 3.1a, reduction in the number of reproductive parts is not detrimental to marketable yield, that is, miniaturization of individual plants with increasing plant density does not affect harvest index. The marketable-yield/biomass relationship on a unit area basis is characterized by a straight line through the origin (Figure 3.1c). For species with a density response as Brussels sprouts, increasing density affects partitioning of dry matter to the detriment of marketable yield. At high densities reproductively inefficient plants are developed so that harvest index changes and marketable-yield/biomass relationship on a per hectare basis is bell shaped as in Figure 3.1d.

One of the main effects of competition is a reduction in mean plant size. When per-plant biomass and marketable yield are considered, the situation for wheat is again characterized by a straight line through the origin (Figure 3.1e) reflecting the constant harvest index. In Brussels sprouts this relationship is no longer bell shaped but a curve which can, in the agriculturally relevant density range, be approached by a straight line (Figure 3.1f). The line, however, does not pass through the origin and has a positive intercept with the x-axis. It implies that

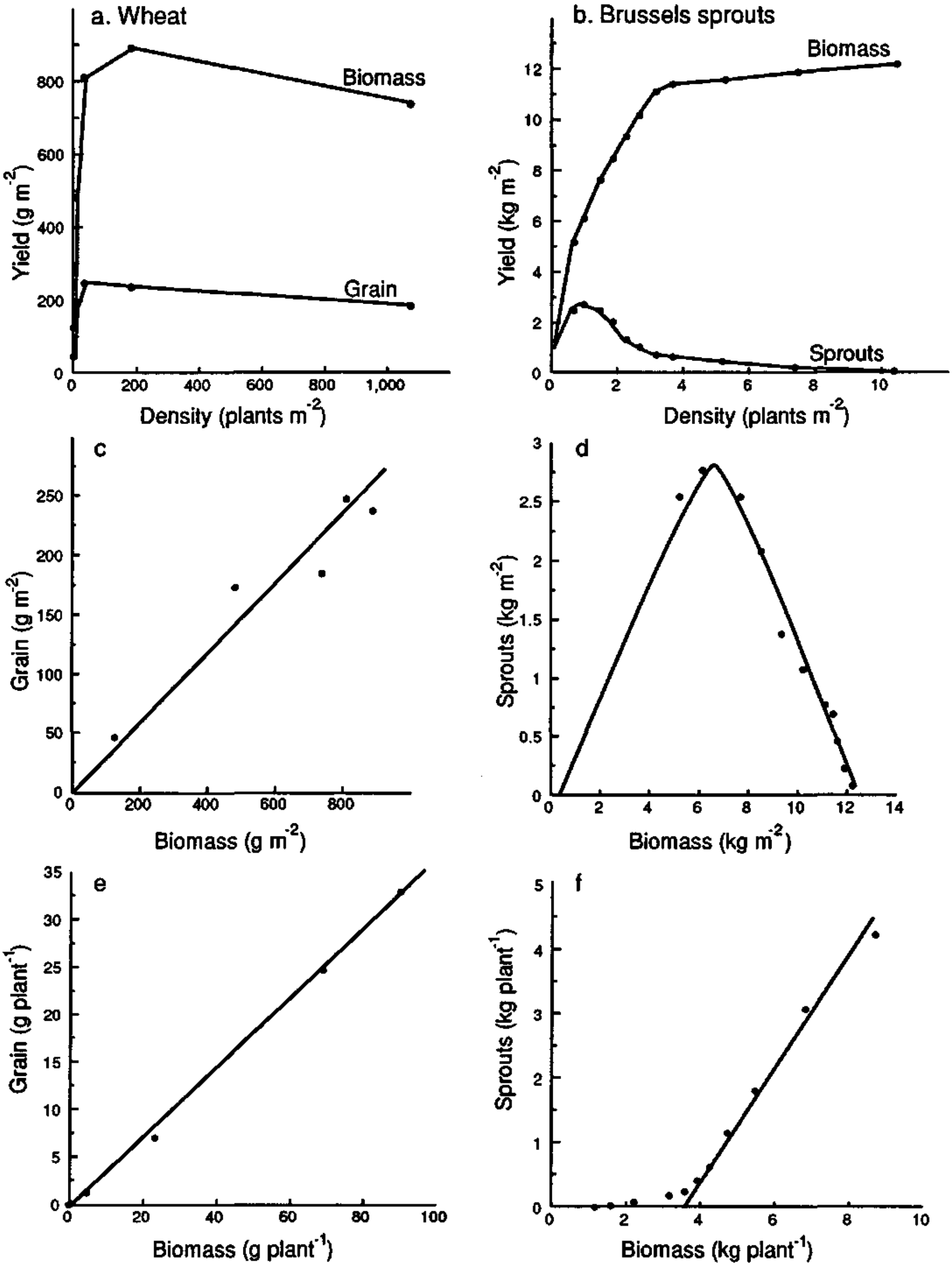


Figure 3.1 Yield/density responses for wheat and Brussels sprouts.

harvest index decreases with decreasing plant size. At the intercept, there is no marketable yield from the plants; in reality, even at high densities there are a few plants with some marketable yield causing the observational points to deviate from the straight line. These points, however, are outside the plant density range relevant to marketable yield production for the crop. The extent of deviation observed at low per-plant yields and the tendency towards a positive intercept depend on the severity of the response of marketable yield to density.

Yield/density responses in mixtures are not always well defined because a certain yield can be achieved by plants at different densities, depending on the inter- and intra-specific competitive stresses they suffer. For instance, the yield of a crop at some fixed density will vary depending on the density of the associated crop. As a result, unit area marketable-yield/biomass ratios are often variable making it difficult to estimate an unambiguous relationship between them. Since per-plant biomass and marketable yield are good indicators of interplant competition in monocultures, it is hypothesized that irrespective of whether a plant in mixture suffers from intra- or inter-specific competition, the effect is a reduction in mean plant size and the association between per-plant biomass and marketable yield will be a straight line.

Yield responses to density and marketable-yield/biomass relationships for perennial pigeonpea intercropped with groundnut in different proportions, both in monoculture and mixture, are presented in Figures 3.2a and b. (A detailed description of the experiments is given in Chapter 5). There is some correlation between per hectare seed and biomass yield, but there is also a considerable scatter in the figures for pigeonpea (Figure 3.2a). Yet in all six instances per-plant yields from monocultures and mixtures fall on the same line. In three cases (Figure 3.2a, Experiment 1-years 1 and 2 and Figure 3.2b, Experiment 2-year 1) the intercept was not significantly different from 0 so that per-plant harvest index was independent of the size of the plants. For the other three there was a positive intercept, implying per-plant harvest index decreased with decreasing plant size.

Figures 3.2a and b provide supportive evidence of the hypothesis that irrespective of the intra- or inter-specific competitions suffered by a plant, the relationship between its marketable yield and biomass is well approximated by a straight line. Further confirmation from other data sets would be desirable but few intercropping experiments cover a sufficiently wide range of densities required for such an analysis.

Production possibility frontiers and yield advantage

The production possibility frontier (PPF) as a tool in the analysis of yield advantage in mixed cropping has been discussed by Ranganathan (1992). It was shown that the PPF can be empirically calculated if biomass (Y_i) is estimated by the reciprocal equation

$$Y_I = \frac{N_I}{b_{I,0} + b_{I,I} N_I + b_{I,J} N_J} \qquad (3.1)$$

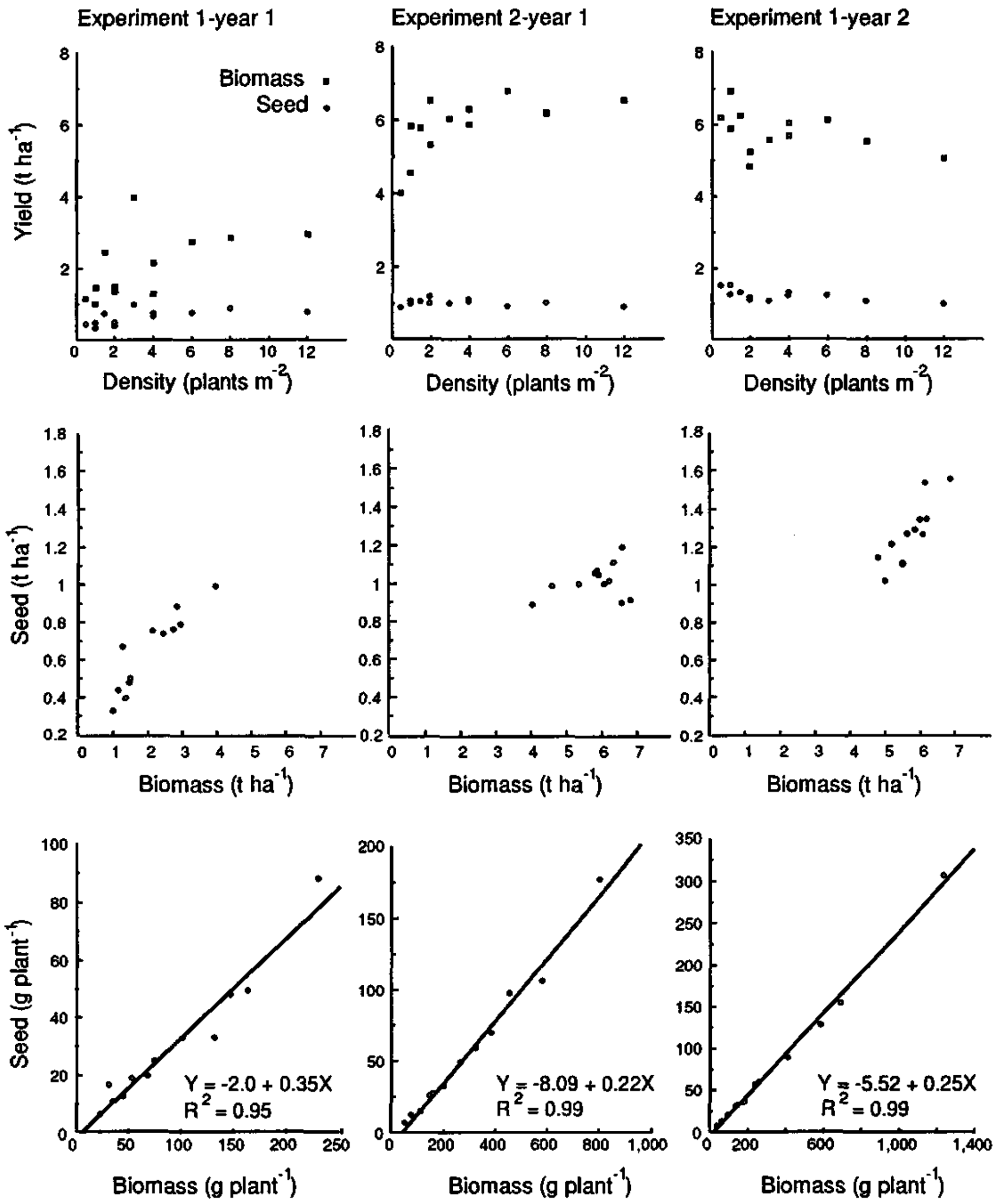


Figure 3.2a Yield/density responses for pigeonpea in an intercrop with groundnut. Open symbols represent yields in mixture and closed symbols yields in monoculture.

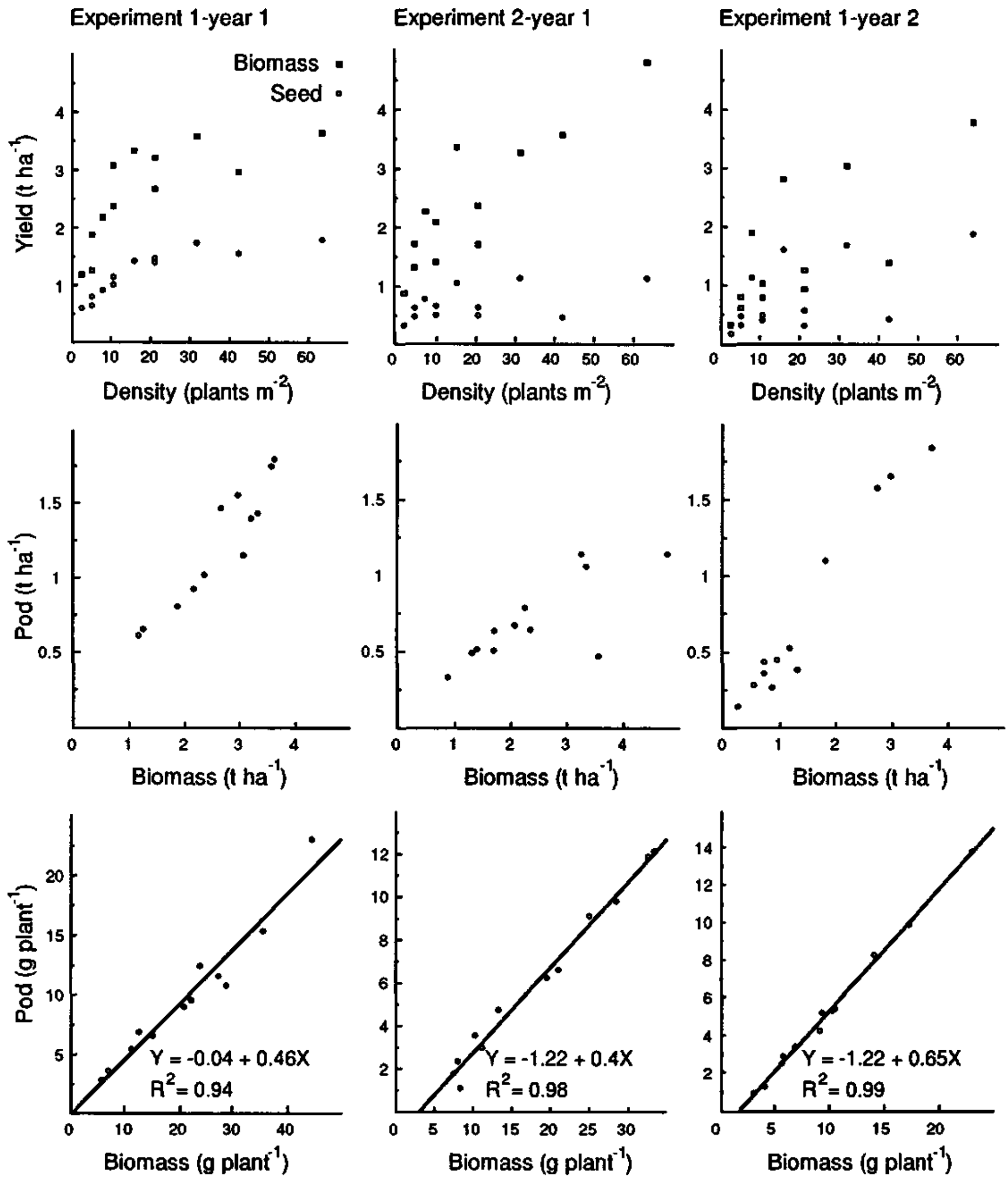


Figure 3.2b Yield/density responses for groundnut in an intercrop with pigeonpea. Open symbols represent yields in mixture and closed symbols yields in monoculture.

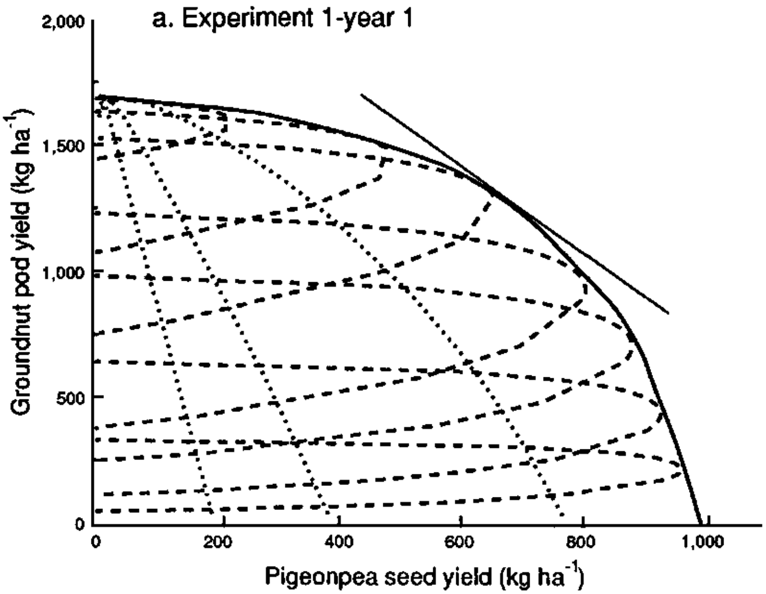
The yield of each component in the mixture depends on crop densities (N_i) and the model parameters are measures of inter- and intra-specific competition in the mixture.

The aim of production in agriculture is generally some marketable yield rather than biomass. When marketable yield and biomass have a similar response to density, that is, harvest index remains constant and the relationship between per unit area biomass and marketable yield is a straight line going through the origin (as in Figure 3.1a), the derivation of a PPF for marketable yield poses few problems. Marketable yield can also be estimated from Equation 3.1. However, if the density response is such that unit area marketable yield/biomass relationship is not characterized by a straight line through the origin, the PPF has to be numerically derived. A numerical derivation requires an estimation of the parameters to the competition model in Equation 3.1 and the linear relationship between per-plant marketable yield and biomass.

From Equation 3.1 unit-area biomass yields of the two crops at different plant density combinations are calculated. For each yield combination so obtained, per-plant biomass yields are calculated by dividing unit-area biomass by the density at which it was obtained. From the linear relationship between per-plant marketable yield and biomass, the corresponding per-plant marketable yield is derived. A reconversion to unit-area scales gives all possible marketable-yield combinations. The maximum marketable-yield combinations constitute the production possibility frontier.

Production possibility frontiers in Figure 3.3a and b have been derived for pigeonpea seed and groundnut pod yields in Experiment 1-year 1 and Experiment 1-year 2 (in Figures 3.2a and b). The parameters to Equation 3.1 for pigeonpea and groundnut are presented in Chapter 5. The dotted and dashed lines give different yield combinations of the two crops, also known as joint production curves. A curve radiating out from the y-axis shows the reduction in groundnut pod yield (when sown at some fixed density) as pigeonpea yield increases in response to its increasing density. Similarly, a curve radiating out from the x-axis shows pigeonpea seed-yield response to increasing competition from groundnut. The solid line enveloping the joint production curves is the production possibility frontier and represents the maximum marketable-yield combinations achieved by pigeonpea and groundnut. The two extremities of the frontier (on the axes) are maximum monoculture yields achieved by the two crops.

The joint production curves radiating out from the groundnut pod-yield axis in Figure 3.3a show that groundnut is only marginally affected by competition from pigeonpea. Even at densities of pigeonpea where intra-specific competition reduced pigeonpea seed yield to 0, there was some groundnut pod yield. This is illustrated by the curves turning inward towards the groundnut yield-axis (y). The 'turning' points of the joint production curves represent maximum yield combinations. The joint production curves radiating out from the pigeonpea axis reveal pigeonpea's greater sensitivity to competition from groundnut. At high groundnut densities pigeonpea produced an insignificant amount of seed.



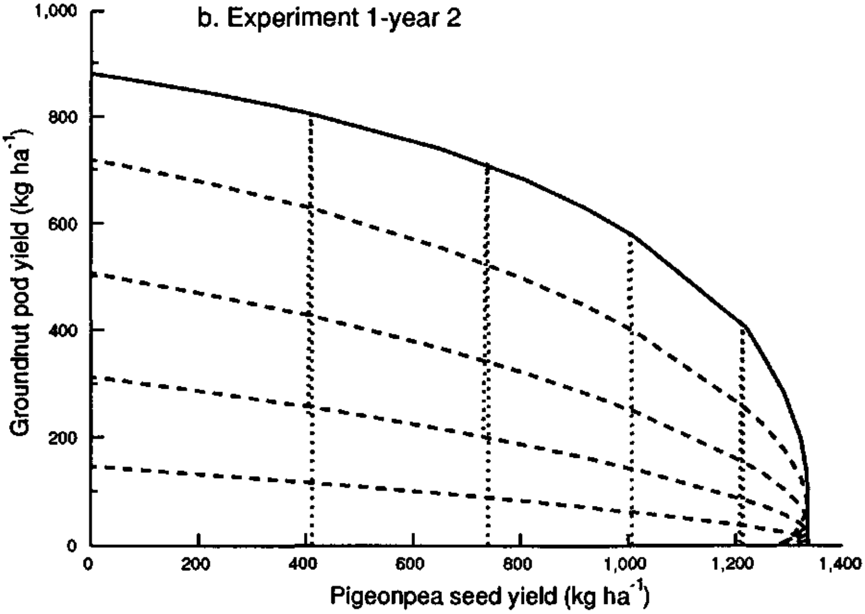


Figure 3.3 Production possibility frontiers for pigeonpea seed and groundnut pod yields. Yields have been calculated from per-plant marketable yield/biomass relationships and Spitters' model of competition.

The PPF in Figure 3.3b is the envelope of joint production curves for groundnut intercropped with year-old pigeonpea. The intercrop was in the second year of the two year rotation. Even at very low plant densities, the year-old pigeonpea plants were almost completely insensitive to competition from groundnut and this is seen in the near vertical joint production curves originating from the y-axis. Groundnut pod yield, on the other hand, was significantly reduced when pigeonpea density was increased. Unlike the first year of intercropping (Figure 3.3a) where groundnut always yielded some pods, in the second year of intercropping groundnut suffered severe competition from pigeonpea.

The economically optimal yield combination corresponds to the tangency of a price line to the production possibility frontier. A price line reflects a fixed value of production, that is, total crop value expressed as a sum of their constituent values (Ranganathan *et al.*, 1991). The slope of this line is the negative of the output price ratio. For instance, when the market value of groundnut pods is 20% higher than that of pigeonpea seeds, the price line has a slope of -1.2. In Figure 3.3a, a price line of slope -1.2 is tangential to the PPF at the point where groundnut pod and pigeonpea seed yields are approximately 1278 and 658 kg ha^{-1} and the corresponding sowing densities of groundnut and pigeonpea are 17 and 5.2 plants m^{-2}, respectively. If the price of groundnut, relative to that of pigeonpea, was to increase, the price-line slope would increase making the line flatter and therefore economically more favourable to groundnut. The proportion of groundnut in the mixture would increase. Conversely, an increase in the price of pigeonpea would give a steeper price line and the optimal point of production would shift in favour of more pigeonpea in the mixture.

In any economic evaluation of mixed cropping with perennials and annuals, multiple outputs like fodder and fuelwood from the perennial and other associated costs can also be considered. Ranganathan (1992) has shown how input costs can be incorporated into an economic assessment of joint production. When seed cost far exceeds the market price of the produce or the availability of planting material is low, productivity per kilogram of seed must be maximized rather than productivity per unit area.

A production possibility frontier for monetary returns from the pigeonpea/groundnut intercrop discussed above (Experiment 1-year 1) is presented in Figure 3.4. In this economic assessment, in addition to pigeonpea seed and groundnut pods, pigeonpea fodder and groundnut seed cost have been taken into consideration. Though groundnut fodder may an economic value, it is assumed to have none for the purpose of this discussion. Pigeonpea fodder has been assigned an arbitrary price of $US 5.34 t^{-1} ($US 1=IRs 28.00). This is much lower than the price of other green fodder 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 and pigeonpea seeds have been assigned a price of $US 0.54 kg^{-1}. Groundnut seed cost is high relative to the price of the produce and has been taken at $US 2.68 kg^{-1}. The envelope is derived the same way described earlier in the paper.

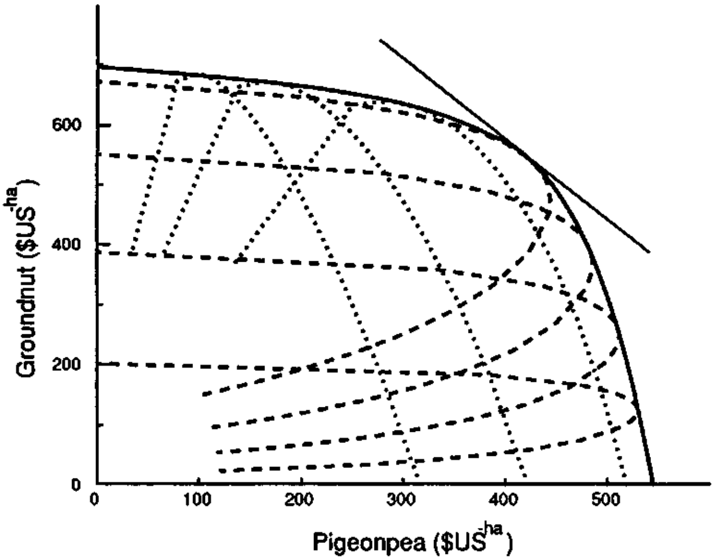


Figure 3.4 Production possibility frontier for financial returns and price line for a groundnut/pigeonpea intercrop.

The optimum financial return corresponds to the point of tangency of a line with slope equal to -1. Optimum returns from the two crops is approximately $US 415 from groundnut and $US 560 from pigeonpea. Inclusion of seed cost is equivalent to decreasing the price of groundnut relative to that of pigeonpea and therefore the point of optimality has shifted away from groundnut. Groundnut sowing density at the economically optimal point of production is 11 plants m^{-2} compared with the 17 obtained when seed cost was not included in the analysis. Increasing the value of pigeonpea by including fodder did not result in increasing the sowing density of pigeonpea which remains at 5.2 plants m^{-2}. This may be so for two reasons, the value assigned to fodder is marginal compared to seed value and pigeonpea seed yield has begun to plateau and increasing densities do not result in increased seed yield.

Discussion

The calculation of production possibility frontiers requires only that Equation 3.1 and the marketable yield/biomass relationship be reliably estimated. Parameters of Equation 3.1 hold only for the situation studied and in another field or another year may vary. In the same field, factors like emergence time of the crops in the mixture can affect competition coefficients; the first seedlings to emerge are likely to be the highest yielding simply because they preempt access to resources (Ross and Harper, 1972). These parameters only show the relative efficiencies of resource capture of two populations in the mixture (Firbank and Watkinson, 1985). For the cropping system under study, the PPF allows an estimation of the optimal yield combination and corresponding sowing density.

The sensitivity of the optimal yield composition, and thereby, optimal sowing density, to changing external conditions, like fluctuating prices, depends only on the curvature of the PPF. For PPFs with slight convexity, small changes in the price ratio result in relatively large changes in the yield composition and sowing density. As the curvature increases, changes are smaller till the change in yield composition is marginal over a wide range of price ratios. This has also been demonstrated for PPFs of different curvatures in Ranganathan (1992).

Much of the above analysis depends on a good estimate of marketable yield. Spitters (1983) suggested the use of harvest index, but he found the relationship between harvest index and per-plant biomass an unreliable one. As an alternative, Spitters also estimated seed yield directly from a quadratic equation where depending on the form of the expression the model had 4 to 6 parameters. Besides being unnecessarily complex for most purposes, its use is limited to trials with a wide range of densities and as mentioned earlier such experiments are rare. Firbank and Watkinson (1985) have directly expressed per-plant seed yield as a function of density. But since the expression does not account for the density of the associated species, it is of limited use in the derivation of the PPF.

The method of measuring yield advantage in intercropping presented here provides the opportunity to include the multitude of factors influencing decision making in the assessment. Mixed cropping with perennials seeks to provide a conservation oriented approach to farming but some benefits like soil conservation or shade may not have a direct economic value. Depending on the level of detail required in the economic evaluation and its purpose, opportunity costs of such benefits can be derived and included in the evaluation.

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Chapter 4

Analysis of competition in mixed cropping of annuals and perennials: agronomic sustainability

Analysis of competition in mixed cropping of annuals and perennials: agronomic sustainability

Abstract

Growing perennials with annuals attempts to provide a foundation for conservation oriented farming. In many cases, however, there exists a trade-off between continued annual production and sustainability of the system. Competition from the perennial may override the otherwise positive aspects of such mixed cropping. The answer lies in making the perennial weakly competitive. This paper details a method of analysis which quantifies potential trade-offs in production through the use of production possibility frontiers and by relating the relative leaf area of the perennial in the mixture to yield loss in the annual, provides a scientific basis for managing the perennial.

Introduction

Growing perennials - crops or trees - with annual crops attempts to provide a strong foundation for conservation oriented farming (Garrity, in press). For instance, in tropical regions where shifting or rotational cultivation and fallows are practiced, declining soil fertility is associated with shorter fallow periods. Intercropping with perennial species which can restore soil fertility has attractive possibilities.

A significant concern in agroforestry research is that competition from perennials to annuals may reduce or possibly override the otherwise positive aspects of such mixed cropping, particularly in situations where the perennial is of less direct economic value than the annual. Where sustainability of the resource base is important, the mixture, even when inhibitory to crop production may have to be encouraged because of long-term beneficial environmental effects from the perennial.

The question, however, is how to quantify the trade-off in production and assess the sustainability of an agroforestry system. Practical definitions of sustainability are hard to find making it difficult to suggest empirical data needed to test assumptions of sustainability. The hierarchical approach suggested by Blaschke *et al.* (1992) is a useful one in defining sustainability in terms of different objectives *viz.*, agronomic, microeconomic, ecological and macroeconomic sustainability. Of immediate concern to a farmer is agronomic sustainability which has been defined as the ability of a tract of land to maintain production over a long period. In areas where agroforestry is most recommended, the primary concern of subsistence farming is food production. An analytical method which quantifies the trade-off in annual production to that of the perennial in the short term is essential as is a scientific basis for perennial plant management against which agronomic sustainability may be measured.

This paper describes a method of analysing data from mixed cropping experiments. It attempts to draw upon research in natural ecosystems and crop-weed interactions to aid in better understanding agroforestry systems and develop management guidelines for sustainable systems. The method and its underlying principles of resource use and plant interactions are illustrated through data from experiments where perennial pigeonpea was intercropped with groundnut.

Production and sustainability

Except in the perennial's early establishment phase, it physically dominates the annual and hence reduces its growth potential. The perennial's competitive intensity would seem to be related to biomass production suggesting low biomass species or weakly competitive perennials may have distinct advantages in mixed cropping. Alternatively, the perennial can be made weakly competitive by appropriate management. Inter- and intra-specific plant competition, a major factor in determining final biomass, have been quantified by Spitters (1983) who has expressed the yield of intercropped species as

$$Y_i = \frac{N_i}{b_{i,0} + b_{i,i} N_i + b_{i,j} N_j} \tag{4.1}$$

where Y_i is the above ground biomass (vegetative plus reproductive growth) yielded by the intercrop. $b_{i,i}$ and $b_{i,j}$ are measures of inter- and intra-specific competition and N_i and N_j the plant densities of each crop. $b_{i,0}$ is the reciprocal of the weight of a single plant when it is free from competition.

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. Traditionally groundnut is the primary crop with pigeonpea rows spaced up to 5 m apart. Research station trials show that with higher pigeonpea plant populations yield advantages up to 60% are obtained, illustrating the yield flexibility that exists by adjusting the proportion of the two crops (Willey *et al.*, 1982).

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 make it an especially 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 feature that makes annual varieties so suitable for intercropping - a slow initial growth. Daniel and Ong (1990) demonstrated the possibility of intercropping perennial pigeonpea with annual crops without any serious adverse effects on the companion crop in the first year.

Field experiments with perennial pigeonpea and groundnut

Field trials were conducted at ICRISAT in the rainy seasons of 1989 (Experiment 1) and 1990 (Experiment 2) where perennial pigeonpea was intercropped with groundnut in a replacement series repeated at a range of densities. Experimental details are fully described in Chapter 5 so that here only the results that are relevant for the discussion are presented. After grain and biomass harvest, pigeonpea was cut back to a height of 0.5 m from the ground and allowed to grow through the dry season (January-July). At the start of the following rainy season (1990) when pigeonpea in Experiment 1 entered its second year of growth, it was pruned to a height of 0.5 m. Fourteen days after pruning, groundnut was resown into the year-old pigeonpea alleys. Yields of groundnut and pigeonpea were measured at harvest.

The three data sets (Experiment 1-years 1 and 2 and Experiment 2-year 1), are analyzed using production possibility frontiers (Ranganathan, 1992). Assuming the most efficient use of available resources, the production possibility frontier (PPF) gives combinations of maximum yield obtained after a consideration of all possible plant density combinations. The PPF uses *a priori* information on biological processes in intercropping and is expressed by the function

$$\left(\frac{1}{b_{g,g}\, Y_g} - 1\right) \left(\frac{1}{b_{p,p}\, Y_p} - 1\right) = C \tag{4.2}$$

where

$$C = \frac{b_{g,p}\, b_{p,g}}{b_{g,g}\, b_{p,p}} \tag{4.3}$$

Table 4.1 gives the estimated parameters to Spitters' model. The assumption underlying this model is a hyperbolic relationship between plant density and biomass: this relationship could not be fully established for pigeonpea in the second year of its growth as dry matter yields of the year-old pigeonpea varied only marginally between the low and high densities. The value of parameter $b_{i,0}$, the reciprocal yield estimate of a pigeonpea plant standing alone, could not be estimated because the plants in the second year were too close together, even at their widest spacing. However, as this parameter does not appear in Equations 4.2 and 4.3 its value is immaterial to this paper. The production possibility frontier has, however, been derived by estimating only those parameters required for the derivation.

Since observed dry matter yields lie around the asymptote, the parameter $b_{i,i}$, the inverse of which is the maximum yield achieved by the crop, can be estimated by averaging these yields. The parameter $b_{i,j}$ is a measure of the inter-specific competitive stress that one species exerts on the other. It is possible to hypothesize that this parameter should be very small, if not 0, because pigeonpea suffered no competition from groundnut. The dry matter yields of pigeonpea bear this out. The value taken by the parameter in Experiment 2-year 1 shows that groundnut exerted minimal stress on pigeonpea. The long growth period of

Table 4.1 Estimated parameters of the Spitters' equations

	$b_{i,0}$ (plants 100 g^{-1})	$b_{i,i}$ (m^2 100 g^{-1})	$b_{i,j}$ (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[1]	-	0.150	0.00001	-
	-	-	-	
Groundnut	2.285	0.244	5.718	0.98
	(0.467)	(0.018)	(0.662)	

Standard errors are shown in parentheses

[1] Non-linear algorithm not possible; see text for estimation of parameters

pigeonpea after groundnut harvest allows it to recover from any effects of groundnut competition. Stress to year-old pigeonpea (in Experiment 1-year 2) from groundnut can only be less than that suffered by pigeonpea seedlings. The estimated value for $b_{i,j}$ in the first year of intercropping is thus a conservative estimate of inter-specific competition between groundnut and pigeonpea in the second year. A value close to 0 has been assumed to facilitate the estimation of the PPF (see Ranganathan (1992) for details).

Production possibility frontiers estimated for the three intercrops is in Figures 4.1a, b and c. The relatively low pigeonpea yields in Experiment 1-year 1 (Figure 4.1a) and the difference in convexity of the two curves for the first year of growth (Figures 4.1a and b) are explained by the delayed sowing of pigeonpea in Experiment 1-year 1. Mortality in pigeonpea seedlings caused by waterlogging necessitated sowing at a later date to achieve the planned plant densities. Pigeonpea is highly sensitive to daylight at later sowing (J. C. W. Odongo, pers. comm.).

The extremely convex shape of the curve in all three figures indicates a large yield advantage (Ranganathan *et al.*, 1991) in intercropping perennial pigeonpea with groundnut. According to Daniel and Ong (1990), perennial

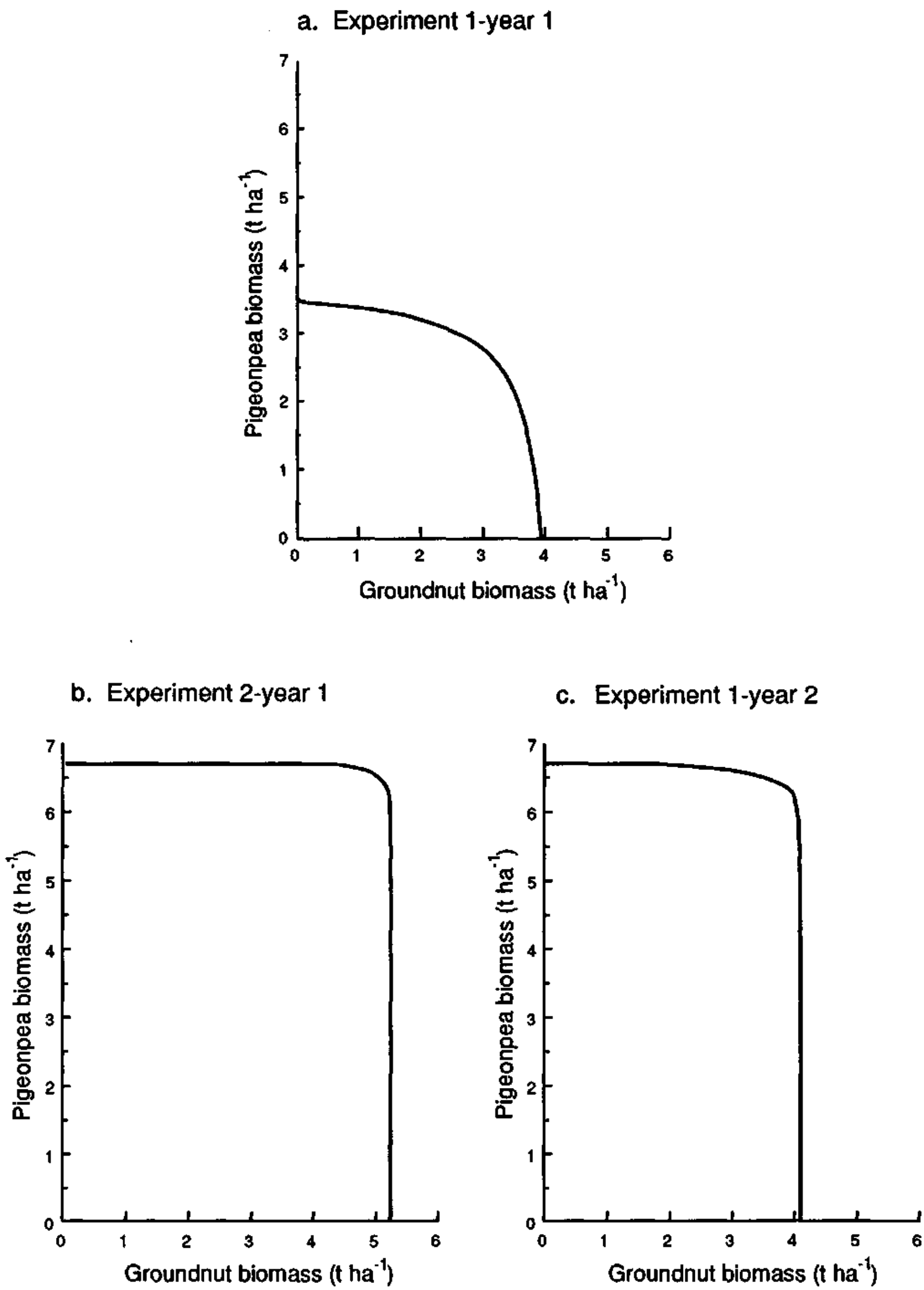


Figure 4.1 Production possibility frontiers for groundnut/pigeonpea intercrops.

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 advantage as shown by the PPFs is due to the temporal complementarity of the two species. Resource use, which is exemplified for annual pigeonpea/groundnut intercrop by light interception and dry matter accumulation in Willey *et al.* (1986), is also exhibited in this system.

Temporal complementarity occurs when component crops make strong demands on resources at different times during the season. De Wit and van den Bergh (1965) suggested that in cases where relative yield total (RYT) values in replacement series were greater than 1 there was complementarity in resource use between the intercropped species. Berendse (1979), in his study on coexistence between species in grassland communities, showed that for plant mixtures, one with the ability to exploit a refugium (resources unavailable to the other) would produce relative yield total values exceeding 1. In demonstrating this, Berendse also showed that in order to coexist, the species without refugium had to have a competitive ability sufficient to balance the extra resources exploited by the species with the refugium.

Berendse's condition for equilibrium has important implications for the sustainability of mixed cropping where crops are of different durations and the longer duration crop can be said to be exploiting a refugium. Competitive interactions within and between these crops determines their proportion of total yield. Competitive stress, inter- and intra-specific and their effect on yield is best visualised through the replacement diagrams of de Wit (1960). Figures 4.2a, b and c give the replacement diagrams for the data from one replacement series. In conjunction with the parameters to Spitters' equations, the effects of competition on yields are now explained. In the first year of intercropping in Experiment 2 (Figure 4.2b), groundnut experienced more inter-specific than intra-specific competition ($b_{i,j}$ greater than $b_{i,i}$, Table 4.1), however competition was not sufficient to cause high yield reductions. The reason for this is slow initial growth of pigeonpea (Willey *et al.*, 1983). In contrast, in its second year of growth (Figure 4.2c), pigeonpea needed to invest little in establishment and despite pruning, dry matter accumulation was fast. As a result it exerted a very high competitive stress on groundnut, causing considerable yield reduction. The estimated parameters for groundnut in Table 4.1 provide evidence of this.

Results from other trials with perennial pigeonpea show considerable yield reductions in the companion crop in the second year of pigeonpea growth (Daniel *et al.*, 1991; Odongo *et al.*, in press). Odongo (unpublished) measured light intercepted by intercropped perennial pigeonpea and groundnut in the second year. Although pigeonpea was pruned before groundnut was sown, its regrowth was so vigorous that intercropped groundnut intercepted less than 20% of incoming radiation throughout its growing period. In addition to utilising resources available after the harvest of groundnut and thereby still displaying temporal complementarity, pigeonpea was making a stronger demand on resources at the same time as groundnut requirements were high. Pigeonpea was more successful in utilising these resources because of its greater biomass. Yield advantage as

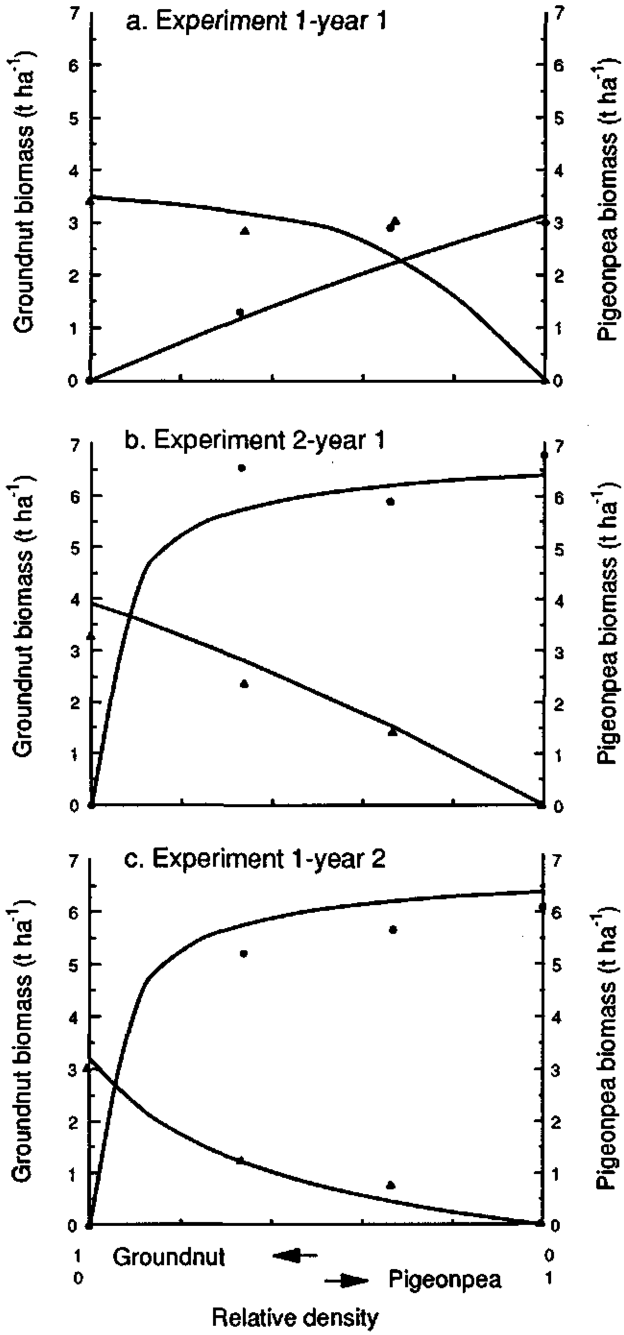


Figure 4.2 Replacement series diagrams. Curves calculated using Spitters' model of competition, parameters in Table 4.1. (• ▲ actual observations).

shown by the PPF (Figure 4.1c) and RYT (Figure 4.2c), despite a substantial drop in groundnut production, is reflective of the continued temporal use of resources.

The issue at hand, however, is not just continued temporal use of resources, but the effect of the strong competition on the annual and the trade-off in production between the two species. Though marketable yields are not being discussed here, a reference to them is made only to make the point that pigeonpea, unlike many other woody perennials, provides an early economic return through its grain yield which is equal to that of groundnut. What is lost in groundnut pod production may be recovered as pigeonpea grain yield. In other mixed cropping systems this may not be the case and the compromise between annual and perennial production may be much greater. Notwithstanding economic compensation, there is still a trade-off between continued groundnut production and the environmental or other benefits of the perennial in the second year. This can be illustrated through the PPF. The production possibility frontier is an 'envelope' of all possible yield combinations with any point on the frontier representing a maximum combined yield. For every point on the frontier, the ratio of plant densities of the two crops can be calculated. Lines radiating out from the origin in Figures 4.3a and b are groundnut and pigeonpea yields when their individual densities are varied but the ratio is fixed. Lines radiating out from the axes show yield combinations lower than the maximum that can be obtained at varied ratios. These lines are derived from Spitters' model on competition (Equation 4.1) by keeping one crop density constant and varying the other. The envelope of all these lines is the PPF.

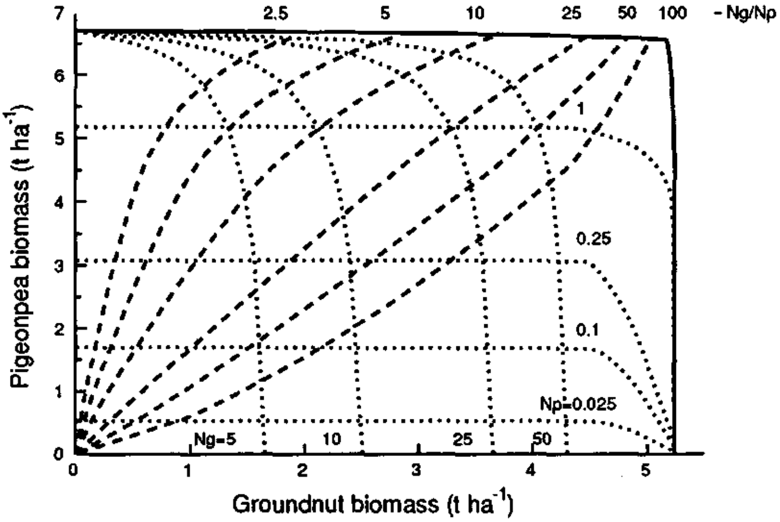
The inner curves can be used as a rough guide to expected yields at densities other than those on the production frontier. For example, at 25 plants m^{-2} (the density at which farmers generally sow groundnut in semi-arid India), Figure 4.3a shows that groundnut biomass yield is about 70% of the maximum achievable yield. Intercropping with pigeonpea reduces the yield further. At the point of intersection of the ratio line (N_g/N_p=25) and the yield curve at N_g=25, the yield of groundnut is only 63% of maximum. Introduction of one pigeonpea plant into a unit area of one m^2 containing 25 groundnut plants has the effect of reducing groundnut yield by 10%.

The slope of the inner lines at the point of take off from the axis is an indicator of yield reduction in that crop with the introduction of the second. Increasing the absolute slope value, increases yield reduction. The slope of the inner lines as they take off from the x-axis is given by differentiating the yield/density equation of groundnut (Y_g in Equation 4.1) with respect to pigeonpea density (N_p) and is given by the expression

$$\frac{dY_g}{dN_p} = \frac{-b_{g,p}N_g}{(b_{g,0} + b_{g,g}N_g + b_{g,p}N_p)^2} \qquad (4.4)$$

at N_p=0. When the competitive stress exerted by pigeonpea is small, dY_g/dN_p takes a value close to zero. As competitive stress increases, the reduction in groundnut

a. Experiment 2-year 1



b. Experiment 1-year 2

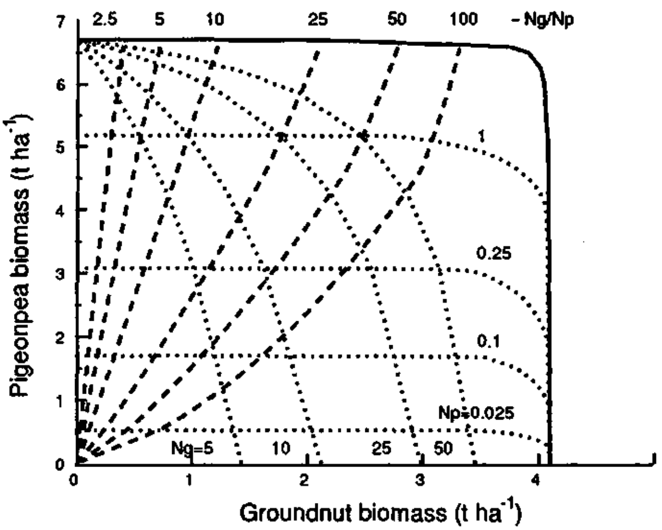


Figure 4.3 Production possibility frontier for pigeonpea/groundnut intercrops. Inner curves show yield combinations at different densities, calculated using Spitters' model of competition.

yield increases which represents an equivalent increase in the absolute slope value at the point of take off.

By comparing inner line slopes for the PPFs of the first and second years of cropping, the trade-off in groundnut production with increasing pigeonpea age can be seen. At a groundnut density of 25 plants m^{-2}, the slope of the inner line in the first year (Figure 4.3a) is -0.39 compared with -2.03 in the second year (Figure 4.3b). Differences in slopes between year 1 and 2 are due to a much larger leaf area per pigeonpea plant in year 2.

This point can be further illustrated by assuming that a loss of 15% of expected annual groundnut production from monocropped fields with populations of 25 plants m^{-2} is acceptable to farmers. In the first year of intercropping at 85% of monoculture yield (3.1 t ha^{-1}) the inner line intersects a density ratio (N_g/N_p) line at value 15. This implies that about 2 plants m^{-2} of pigeonpea can be intercropped with groundnut. In the second year, however, the density ratio needed to achieve the same 85% groundnut yield is greater than 100. At densities of groundnut normally sown by farmers, this would mean pigeonpea would be widely scattered over the field. Pigeonpea yields change only marginally over a wide range of densities reflecting the morphological plasticity of the species (Lawn and Troedson, 1990). Other perennials may not exhibit such a plasticity in yield response and at very wide spacings may not be effective at stabilizing erosion or providing sufficient green manure.

Management

Suggestions have been made on how to overcome the problem of a strongly competitive perennial. Ong (1991) suggests some degree of perennial vegetative growth regulation so that there is more complementarity between species in their time dependence for resource sharing. With the objective of making the perennial weakly competitive, either through pruning, pollarding, lopping or some other means of growth regulation, management seeks to alter the relationship between crops in the horizontal, vertical and temporal dimensions so that different crops share environmental resources of light, water and nutrients (Trenbath, 1976). But as expressed by Huxley (1983) 'the question is not only what to remove, and how much, but when'. Some literature on management exists in herbage research but presupposes a knowledge of the accumulation and use of reserve carbohydrates by perennial legumes as being fundamental to an understanding of management practices (Leach, 1968).

Studies in crop-weed interactions have shown that the most important parameters influencing crop yield loss are weed density (Cousens, 1985) and relative time of weed emergence with respect to the crop (Cousens *et al.*, 1987). Kropff and Spitters (1991) expressed yield loss in a crop due to weeds as

$$YL = 1 - \frac{Y_{cw}}{Y_{cm}} \qquad (4.5)$$

where Y_{cw} and Y_{cm} are estimated from Spitters' (1983) yield/density equations (Equation 4.1) and represent crop yields of the crop with and without weeds respectively. Considering the weed to be a perennial species in order to make the discussion relevant to mixed cropping of annuals and perennials and assuming the annual was sown at an optimum density which was kept constant, yield loss can be expressed as a function of the relative perennial density (N_p/N_a). c characterizes the competitive effect of the perennial on the crop and is expressed at normal densities by b_{cp}/b_{cc}.

$$YL = \frac{c\dfrac{N_p}{N_a}}{1 + c\dfrac{N_p}{N_a}} \qquad (4.6)$$

In practice, however, the above expression for yield loss is not useful for predictive purposes because the sowing density of the annual (N_c) and the plant density of the perennial (N_p) do not reflect factors of early growth such as stand establishment of the annual, severity of pruning for the perennial, differential availability of water and disease effects. Accordingly the value of c may vary greatly over years and locations.

Problems of early growth are better taken into account if the presence of species in a mixture is characterised by their leaf area measured at a suitable time during early growth. In analogy with Equation 4.6, annual yield loss was expressed by Kropff and Spitters (1991) as

$$YL = \frac{q\dfrac{LAI_p}{LAI_a}}{1 + q\dfrac{LAI_p}{LAI_a}} \qquad (4.7)$$

where LAI_p and LAI_a are the leaf area indices of the perennial and annual and q is a damage coefficient. The expression can be more conveniently reformulated as

$$YL = \frac{q\,L_p}{1 + (q-1)\,L_p} \qquad (4.8)$$

where L_p is the share of perennial leaf area in the total leaf area, that is

$$L_p = \frac{LAI_p}{LAI_p + LAI_a} \qquad (4.9)$$

Once q is known the amount of perennial pruning that is necessary at early growth to obtain an acceptable yield loss in the annual can be calculated. It is shown in Figure 4.4 that for $q >> 1$ very severe pruning is necessary to achieve an acceptable yield loss, whereas the pruning can be light for $q << 1$.

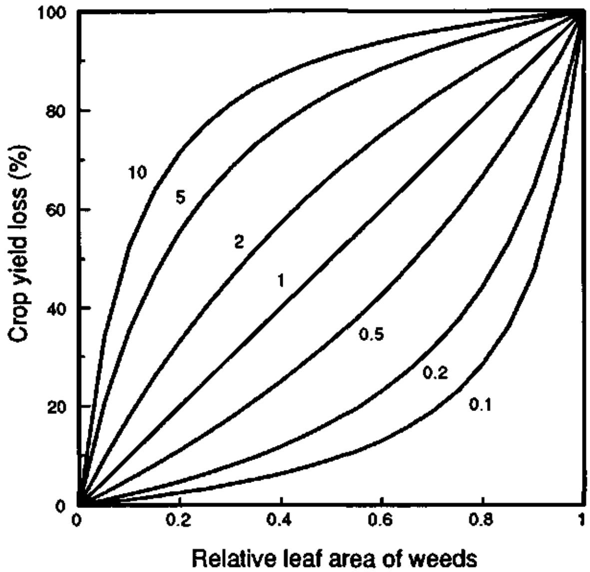


Figure 4.4 Yield loss functions for different values of *q*, the damage coefficient (Source: Kropff and Spitters, 1991).

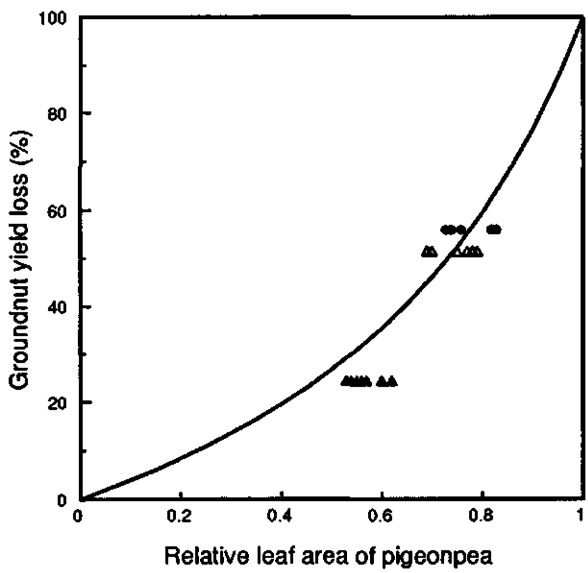


Figure 4.5 Yield loss function for groundnut/pigeonpea intercrop, q=0.37 estimated from an unmanaged stand of pigeonpea (●). Observations from 30-day (△) and 60-day (▲) bag treatments.

The value of *q* can be determined from a measurement of final yield loss of the annual and the share of perennial leaf area early in the season for one mixture of annual and perennial. This latter measurement has to be done after the annual is sufficiently established to enable leaf area measurements but before it suffers appreciably from the competitiveness of the perennial. Within that period, the value of *q* does not change appreciably because both LAI_a and LAI_p increase with time, so that the value of L_p is conservative. This has the advantage that within the above specified period, the time of corrective pruning is not critical.

The relative damage coefficient *q* for a mixed crop of perennial pigeonpea and groundnut was estimated from an experiment that was laid out in the rainy season of 1991 where 14 days after a stand of year-old pigeonpea was pruned, groundnut was sown into the alleys. Yield loss in groundnut as a result of competition from pigeonpea was measured by comparing the intercropped yield with a sole crop yield. Leaf areas of the two crops were measured at regular intervals. Details of the experiment are described in Chapter 5.

A first measure of the relative leaf area of pigeonpea was made 25 days after sowing groundnut. Leaf area index of pigeonpea was 0.6 whilst that of groundnut measured 0.23, so that pigeonpea relative leaf area was 0.72. Although pigeonpea leaf area increased about four and a half times while that of groundnut more than doubled during the next 35 days, the relative leaf area of pigeonpea varied only from 0.72 to 0.83 in this period. This confirms of the fact that even after the onset of competition, the *q* value remains conservative. With a yield loss of 56%, the value of *q* for this period is estimated at 0.37. This gives the yield loss function of Figure 4.5.

This illustrates that in a system where pigeonpea is pruned before sowing groundnut, loss in groundnut yield is relatively low (approx. 20%) for relative leaf areas of pigeonpea up to 50%. For relative leaf areas of pigeonpea higher than 50% in the mixture, yield loss rapidly increases. A small *q* reflects the weakly competitive nature of a per unit leaf area of pigeonpea compared with groundnut. The reason for this may lie in the considerable investment that pigeonpea in its vegetative phase makes in stems and roots, which do not contribute directly to photosynthetic production. Groundnut, on the other hand, invests mostly in leaves and roots which contribute directly to production.

A comparison of predicted yield loss for different relative leaf areas of pigeonpea in the mixture and that observed in the field was made by conducting an experiment where the relative leaf areas of pigeonpea was varied through management. Experimental work in ICRISAT has shown that the regrowth of pigeonpea after successive pruning can be fairly uniform, but there is a risk that some plants do not recover and others die. For reasons of expediency, restricted vegetative regrowth in pigeonpea was simulated by covering individual plants with white muslin bags. Pigeonpea growth was suppressed by maintaining plant cover for 30 and 60 after groundnut was sown in order to expose groundnut to two different relative leaf areas of pigeonpea. Pigeonpea plants were covered when groundnut entered the reproductive stage of its development (30 days after sowing). Yield loss in groundnut was measured for both 'management' treatments.

Figure 4.5 shows the relationship between predicted and observed relative leaf areas for the two bagging treatments. For the 30 day treatment, predicted L_p was 0.74. Observed values vary between 0.69 and 0.78. Predicted L_p was 0.46 for the 60 day treatment and the observed values vary between 0.53 and 0.62.

The question posed by Huxley (1983) about how much and when the perennial should be managed is answered by *q*, the relative damage coefficient. The yield loss function gives an indication of what perennial relative leaf area should be at an early growth stage of the annual, so that yield loss of the annual remains within acceptable limits. The question of when the perennial should be managed depends on perennial regrowth and the onset of severe competition to the annual.

One question relating to productivity of mixed cropping remains. That is, to what extent is perennial production affected by management? For short lived perennials like pigeonpea the answer lies in estimating a damage coefficient which predicts perennial yield loss *not due to the presence of the annual*, but as a result of the pruning that is necessary to benefit the annual. In the manner already described earlier in this paper, the relationship between perennial yield loss and its relative leaf area in the mixture can be established. An optimal decision of how much the perennial should be pruned can be taken after a consideration of both, the yield loss function of both crops.

For pigeonpea, final harvest results show that pigeonpea in the 60-day bag treatment suffered some ill effects with a total dry matter yield 67% of unmanaged pigeonpea. Pigeonpea bagged for 30 days achieved 86% of the yield of unmanaged pigeonpea. Research on the effect of pruning pigeonpea has shown that perennial varieties when pruned have a higher total dry weight and dry weights of various parts than the intact plants. Vigorous new branches that develop on the stumps bear new leaves that are possibly photosynthetically more active than older leaves on plants left intact (Tayo, 1985). Ratooning or pruning in fact stimulates a quicker regeneration of vegetative regrowth. Sheldrake and Narayanan (1977) found that in annual but long duration pigeonpeas up to 75% defoliation resulted in less than 25% yield and that half or more of all leaves could be removed throughout even the reproductive phase with only a slight insignificant effect on yield and yield components.

Conclusions

This paper presents new approaches to examining critical issues in agroforestry or mixed cropping between annuals and perennials. Use of the production possibility frontier has been extended from assessing biological productivity of intercropping systems to illustrate the trade off that occurs between productivity in the annual and perennial. Sustained production is the keystone to successful agroforestry and the paper suggests a scientific basis to managing the perennial so that annual production is sustained. The methods presented here permit an evaluation of whether a given system is sustainable and why.

It may well be argued that agroforestry has many other objectives besides that of maximizing yield from the annual. But it should be pointed out that in marginal environments where agroforestry is most recommended, the primary objective of subsistence level farming is food production and the objectives of mixed cropping with a perennial - increased production from a unit of land, soil conservation, risk alleviation, weed control, integrated pest management, provision of shade to livestock -can be better met if food production is maintained.

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Chapter 5

Measurement and management of competition in mixed cropping: field experiments

Measurement and management of competition in mixed cropping: field experiments

Introduction

A study of mixed cropping includes both the physiological mechanisms of competition, that is, the causes of competition, and their effects on yield. An emphasis on effects involves an analysis of intra- and inter-specific competition without necessarily exploring the underlying mechanisms. Because of its relevance to agriculture, the response of yield per unit area to density in two-species mixtures has been widely studied, pioneered by the work of de Wit (1960).

De Wit's replacement series have been extensively used in the investigation of competition in two-species mixtures where the species are in varying proportions, but overall cropping density is constant. Replacement series use has extended to examining competition in perennial species (van den Bergh, 1968), niche differentiation (Trenbath, 1974), competition for specific nutrients (Hall, 1974a, b) and equilibrium in grasslands (Berendse, 1981). However, the effects of competition vary with total plant density (Firbank and Watkinson, 1985; Jolliffe *et al.*, 1984) and this limits the use of replacement series experiments. Additive experiments where one species invades the space occupied by another have been widely used in crop-weed studies of field situations. But this design has been criticized (Harper, 1977; Trenbath, 1976; Spitters, 1980) because the effects of total density and proportion are confounded thus making the interpretation of results difficult. Neither of the two often-used designs describe all the possible outcomes of competition in mixed cropping.

Replacement series replicated over a wide range of densities allow for systematic variations in total plant density and species proportion, and a separation of inter- and intra-specific competition effects that provides a better quantification of competition in agricultural systems (Radosevich and Roush, 1990). The wide range of outcomes from such a design form a response surface, as opposed to the slices of that surface made by replacement series and additive designs (Firbank and Watkinson, 1990). Spitters' competition model (Spitters, 1983) analyses the competition effects generated by such experiments, and in the absence of allelopathic effects or situations where an increase in the yield of one crop is accompanied by an increased yield of the other, allows the yield of both species in the mixture to be estimated for any combination of frequency and density.

Field Experiments

Data to evaluate yield advantage in mixed cropping (Ranganathan, 1992; Chapters 3 and 4) by integrating the parameters of Spitters' competition model with economic principles were generated using a replacement series repeated at different total plant densities. Yield advantage in cropping annuals with perennials is often only achieved by manipulating competitive relationships in the mixture. Since the relative leaf areas of the crops in a mixture are, in addition to sowing density, determinants of the competitive relationships, the relationship of relative leaf areas to competition was experimentally evaluated. This Chapter describes the details of these experiments together with additional results that have not been previously discussed. Since data from these experiments were used to illustrate new methods of analysis, the reader is referred to earlier chapters for a more complete description and interpretation of the results.

Competition between pigeonpea and groundnut

Objectives

The study aimed to provide information that could be used to evaluate the yield advantage in cropping an annual with a perennial. The evaluation procedure required, within the confines of one experiment, a full description of intra- and inter-specific competition effects.

Methods

Field experiments were conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India (latitude 18° N; longitude 78° E; altitude 550 m) where the long-term average rainfall is 610 mm during the rainy season (July-October), and 148 mm in the postrainy season. The experiments were sited on an Alfisol with poor water-holding capacity. Perennial pigeonpea (*Cajanus cajan* cv. ICP 8094) and groundnut (*Arachis hypogaea* cv. Robut 33-1) were sown as an intercrop in a two-year rotation. In the first of the two years (Experiment 1-year 1), the two crops were simultaneously sown on July 3, 1989 on flat beds and thinned to the required density two weeks after emergence. Heavy rain following emergence caused short-term waterlogging that resulted in pigeonpea being killed by phytophthora blight caused by *Phytophthora drechsleri* Tucker f. sp. *cajani* (Pal *et al.*, 1970). Pigeonpea was resown on 19 July and 7 August to meet the planned density requirements of the study. At sowing 100 kg of di-ammonium phosphate ha^{-1} was applied. The field was manually weeded twice before both pigeonpea and groundnut closed their canopies. Depending on the severity of infection groundnut was sprayed with monocrotophos to control leaf miner (*Aproaerema modicella*) in groundnut. The incidence of *Helicoverpa armigera* in pigeonpea was controlled by frequent sprays of endosulphan, quinalphos and methromyl.

Pigeonpea was sown in rows 1.2 m apart with three rows of groundnut (inter-row spacing 30 cm) sown between. The intra-row spacings of the two crops were varied to achieve different plant densities. Mechanised tillage and spraying of the field imposed some design restrictions and only row intercropping was possible. Local farmers follow a similar practice, sowing a single row of pigeonpea after every 20 to 22 rows of groundnut. Four replacement series each with a

Table 5.1 Plant densities (plants m^{-2}) of pigeonpea and groundnut

	Plant density			
		Replacement series 1		
Pigeonpea	0	4	8	12
	-	(20.8)	(10.4)	(6.9)
Groundnut	64	42.7	21.3	0
	(5.2)	(5.8)	(11.7)	-
		Replacement series 2		
Pigeonpea	0	2	4	6
	-	(41.6)	(20.8)	(13.8)
Groundnut	32	21.3	10.7	0
	(10.4)	(11.7)	(23.4)	-
		Replacement series 3		
Pigeonpea	0	1	2	3
	-	(83.3)	(41.6)	(27.7)
Groundnut	16	10.7	5.3	0
	(20.8)	(23.4)	(47.2)	-
		Replacement series 4		
Pigeonpea	0	0.5	1	1.5
	-	(166.6)	(83.3)	(55.5)
Groundnut	8	5.3	2.7	0
	(41.6)	(47.2)	(93.6)	-

Intra-row spacings (cm) are shown in parentheses

different total density were replicated three times and arranged in a completely randomized design. The design gave four sole-crop treatments each of groundnut and perennial pigeonpea and eight mixtures wherein the proportion of the two crops varied. Since the interpretation of results is based on the yield/density curve being by a rectangular hyperbola, densities included in the experiment had to be within the range that would allow for the estimation of the hyperbolic yield/density function. From experiments previously conducted at ICRISAT Center, 64 groundnut plants m^{-2} and 12 pigeonpea plants m^{-2} were selected as the highest densities. In the three subsequent series, sole groundnut and pigeonpea densities were a half, a quarter and an eighth of the highest plant density selected. The densities covered by the four replacement series are presented in Table 5.1.

Groundnut was harvested on 23 October 1989 after a crop duration of 110 days and total dry matter and pod weights were measured for all treatments. Pigeonpea pods were harvested on 12 February 1990, 240 days after the first sowing. During harvest, pigeonpea was pruned to a height of 0.5 m from the ground. Total dry matter and grain weights were recorded for all treatments.

Pigeonpea was allowed to regrow during the dry season, and at the start of the following rainy season (June 1990) was pruned again to a height of 0.5 m above the ground. Some of the pigeonpea plants died after the first pruning particularly in the high-density treatments. Pigeonpea is known to be susceptible to fusarium wilt (*Fusarium udum* Butler) and sterility mosaic but neither of these diseases was found to be the cause of death in this experiment. A preliminary analysis of the yield data showed that pigeonpea yields increased with density to around 3 plants m^{-2} and thereafter stayed constant. Since dead plants were confined to one or two replicates of the high-density treatments, the reduction in plant numbers was not considered a constraint to continuing the experiment.

Fourteen days after pigeonpea was pruned for the second time, groundnut was sown into the year-old pigeonpea alleys on July 4, 1990 (Experiment 1-year 2). Pigeonpea was vigorous in its regrowth and had to be pruned for the third time 40 days after groundnut was sown, when light measured above the groundnut canopy was less than 50% of all incoming light. Yields from both crops were measured at harvest.

Another trial similar to Experiment 1 (year 1) was sown on an adjacent field on 20 June 1990 (Experiment 2-year 1). To prevent the possibility of waterlogging the experiment was sown on broadbeds and furrows. There is evidence to show that crop biomass does not benefit from raised land configurations on Alfisols (Kanwar, 1986; Sarin and Ryan, 1983). Okada *et al.* (1991) present evidence to the contrary but only in very wet conditions. As the rainfall pattern in the 1990 rainy season did not result in waterlogging, the difference in land management is not considered to affect the analysis of these experiments.

Results

Yield results are presented in Table 5.2. The data were analysed using Spitters' model of competition where dry matter yield is expressed as a function of the densities of the two crops in the mixture.

$$Y_i = \frac{N_i}{b_{i,0} + b_{i,i} N_i + b_{i,j} N_j} \qquad (5.1)$$

The parameters are measures of intra- and inter-specific competition and are estimated through a non-linear regression method available in such statistical software packages as GENSTAT and STATGRAPH. Table 5.3 shows the estimated parameters for the three data sets, and Figure 5.1 confidence bands for the estimation.

The assumption underlying this model is a hyperbolic relationship between plant density and biomass. As Table 5.2 shows, dry matter yields of pigeonpea in Experiment 1-year 2 varied only marginally between low and high densities. Consequently, the non-linear algorithm in the software packages used had difficulty in establishing a hyperbolic relationship. However, since observed dry matter yields are all scattered around the asymptote, parameter $b_{i,i}$, the inverse of the maximum

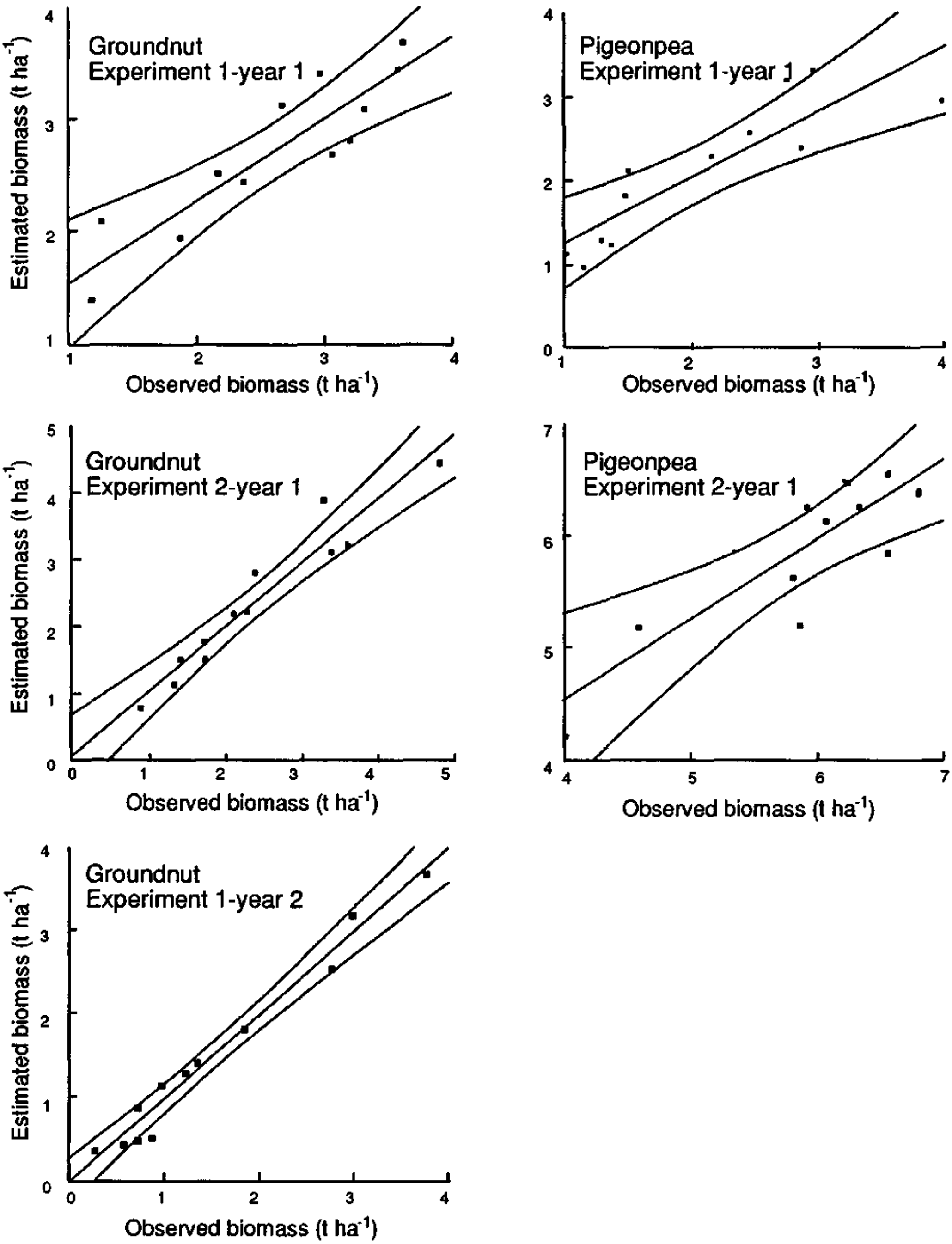

Figure 5.1 Regression fit between observed and estimated (using Spitters' model of competition) biomass and 95% confidence bands.

Table 5.2 Pigeonpea and groundnut yields and their associated densities (plants m^{-2})

Density p'pea	Density g'nut	Expt 1-year 1 p'pea	Expt 1-year 1 g'nut	Expt 2-year 1 p'pea	Expt 2-year 1 g'nut	Expt 1-year 2 p'pea	Expt 1-year 2 g'nut
		Total dry matter (t ha^{-1})					
12	0	2.97	-	6.56	-	5.06	-
6	0	2.76	-	6.80	-	6.12	-
3	0	3.98	-	6.06	-	5.57	-
1.5	0	2.47	-	5.80	-	6.25	-
0	64	-	3.6	-	4.8	-	3.7
0	32	-	3.6	-	3.3	-	3.0
0	16	-	3.3	-	3.4	-	2.8
0	8	-	2.2	-	2.3	-	1.8
8	21.3	2.87	3.2	6.21	1.7	5.54	0.9
4	42.3	1.30	3.0	6.32	3.6	6.04	1.3
4	10.7	2.17	2.4	5.90	1.4	5.69	0.7
2	21.3	1.38	2.7	6.55	2.4	5.24	1.2
2	5.3	1.51	1.9	5.34	1.3	4.84	0.6
1	10.7	1.02	3.1	4.59	2.1	6.93	1.0
1	2.7	1.48	1.2	5.86	0.9	5.89	0.3
0.5	5.3	1.16	1.3	4.03	1.7	6.20	0.7
		(0.798)	(0.640)	(1.087)	(0.475)	(0.910)	(0.436)
		Groundnut pod/pigeonpea seed (t ha^{-1})					
12	0	0.79	-	0.90	-	1.02	-
6	0	0.77	-	0.91	-	1.26	-
3	0	1.00	-	0.99	-	1.11	-
1.5	0	0.74	-	1.05	-	1.34	-
0	64	-	1.80	-	1.14	-	1.84
0	32	-	1.75	-	1.14	-	1.66
0	16	-	1.44	-	1.06	-	1.58
0	8	-	0.93	-	0.78	-	1.10
8	21.3	0.89	1.40	1.01	0.50	1.12	0.27
4	42.3	0.67	1.56	1.11	0.46	1.34	0.38
4	10.7	0.76	1.02	1.04	0.51	1.27	0.36
2	21.3	0.40	1.47	1.19	0.64	1.21	0.53
2	5.3	0.51	0.81	0.99	0.48	1.14	0.28
1	10.7	0.33	1.15	0.98	0.67	1.55	0.45
1	2.7	0.48	0.61	1.07	0.32	1.29	0.14
0.5	5.3	0.44	0.66	0.89	0.63	1.54	0.44
		(0.232)	(0.145)	(0.268)	(0.139)	(0.278)	(0.231)

Standard errors are shown in parentheses

Table 5.3 Estimated parameters of the Spitters' equations

	$b_{i,0}$ (plants 100 g^{-1})	$b_{i,i}$ (m^2 100 g^{-1})	$b_{i,j}$ (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[1]	-	0.150	-	
	-	-	-	
Groundnut	2.285	0.244	5.718	0.98
	(0.467)	(0.018)	(0.662)	

Standard errors are shown in parentheses

[1] Non-linear algorithm not possible; see text for estimation of parameters

yield achieved by a crop, can be estimated by averaging dry matter yields over all treatments. Although it is possible to hypothesize that $b_{i,0}$, the reciprocal of the weight of a single plant achieved when it is free from competition, should take a value larger than that obtained for the other two data sets, it is not possible to estimate this value because even at the lowest density pigeonpea plants were not sufficiently far apart to avoid intra-specific competition. Similarly, the value taken by $b_{i,j}$ should be very small, if not 0, because pigeonpea apparently suffered no competition from groundnut. In Experiment 2-year 1 pigeonpea suffered little competition from groundnut, although it is possible that pigeonpea had sufficient time after the groundnut harvest to compensate for any inter-specific competition it suffered during its initial growing stage.

In Experiment 1-year 1, pigeonpea with its characteristically slow initial growth did not offer groundnut much competition. Two pigeonpea plants had the same effect as one groundnut plant on groundnut's per-plant biomass. Groundnut yields were affected more by intra-specific competition than by pigeonpea. Pigeonpea also suffered more from intra-specific competition than from groundnut; seven groundnut plants effected the same reduction in pigeonpea per-plant biomass as one pigeonpea plant. In Experiment 2-year 1, competition from groundnut had almost no effect on pigeonpea's per-plant biomass whilst groundnut

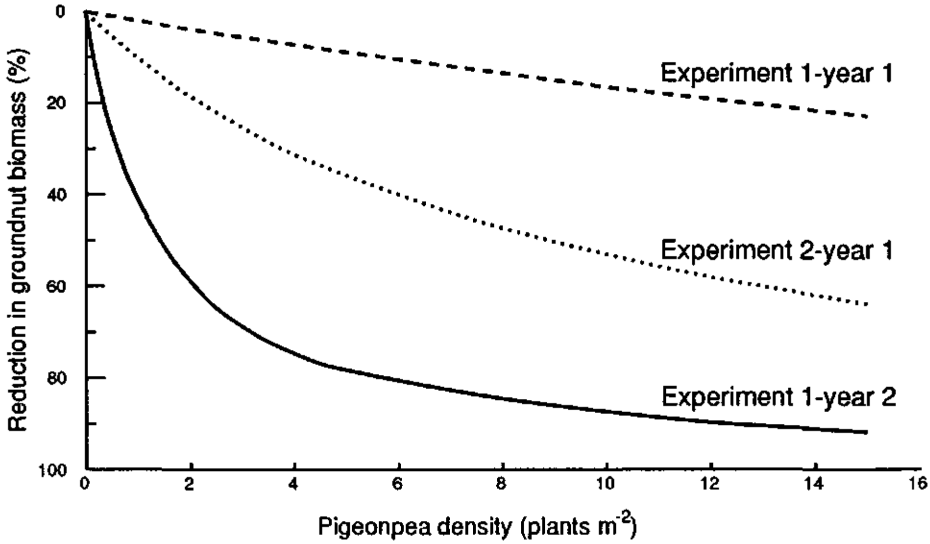

Figure 5.2 Percentage reduction in groundnut biomass with increasing pigeonpea density.

suffered more from inter-specific than intra-specific competition; approximately four groundnut plants were equivalent to one pigeonpea plant in their effect on the per-plant biomass of groundnut.

Groundnut in the second year of the two-year rotation suffered considerable yield loss from the competitive stress exerted by pigeonpea. About 25 groundnut plants had the same effect as one pigeonpea plant on per-plant groundnut biomass. Inter-specific competition increased fifty-fold from the first to the second years of intercropping. Percentage reduction in groundnut biomass with increasing pigeonpea density is illustrated in Figure 5.2. Groundnut yield has been calculated at a fixed groundnut density of 22 plant m^{-2}. Groundnut is the major crop in traditional pigeonpea/groundnut intercrops and farmers are unwilling to accept large yield losses in groundnut. Assuming that a yield loss of up to 20% reduction is acceptable to farmers, two plants m^{-2} of pigeonpea intercropped with groundnut in the first year of the two-year rotation effect a 20% reduction compared to as low as 0.5 plants m^{-2} in the second year.

Prediction of yield loss and management

Objectives

The study aimed to provide data that would relate the relative leaf area of pigeonpea in the mixture to yield loss in groundnut. After estimating the yield loss function for groundnut, the model was used to predict yield loss in groundnut at different leaf areas of pigeonpea in the mixture.

Methods

Initiated in the rainy season of 1991 at ICRISAT Center, the study required groundnut to be intercropped with year-old pigeonpea. An experimental site used in the previous year to compare the performance of three pigeonpea genotypes intercropped with groundnut, was adapted to suit current experimental objectives. Fourteen days after a year-old stand of pigeonpea was pruned, groundnut was sown in the alleys on 1 July 1991. Groundnut was also sown as a monocrop for yield comparisons. Per plant leaf area expansion of groundnut was measured at 10-day intervals starting four days after emergence. A growth analysis of pigeonpea was also done at 15 day intervals starting 4 days after sowing groundnut, to enable the calculation of the relative leaf area of pigeonpea in the mixture. Groundnut and pigeonpea dry matter and grain yields were calculated at harvest.

The yield loss function relates yield loss in the weaker competitor, here groundnut, to the relative leaf area of the stronger competitor (pigeonpea) in the mixture. By an early measurement of the relative leaf area of the stronger competitor, yield loss in the weaker crop can be predicted. Validation of this model requires a comparison of predicted and observed groundnut yield loss for different relative leaf areas of pigeonpea in a specified mixture. The relative leaf area of the stronger competitor is generally varied by using pruning or management regimes. However, in this experiment given the uncertainty of pigeonpea's surviving several prunings it was considered expedient to simulate the effect of pruning by suppressing the pigeonpea's growth. In the experiment the simplest and most effective way of suppressing growth was to cover each pigeonpea plant in the mixture with a muslin bag, and vary the length of time the plants remained bagged.

A light sensor was placed inside the bag to monitor the light intercepted by a covered plant was monitored throughout the period it was covered. Measurements were made every minute, and hourly averages recorded. The daily total was calculated and compared with light measured above the canopy. Measurements showed that 48 to 50% of the incoming light was blocked by the bag. Individual pigeonpea plants were bagged immediately after groundnut was sown. Leaf area measurements of groundnut in the bagged alleys, and pigeonpea in the bags were made at the same intervals in the 'unmanaged' pigeonpea treatment. Thirty days later plants in one treatment were uncovered. The remaining plants were uncovered 60 days after they were bagged to give two 'management' regimes, 30-day and 60-day bag treatments. Dry matter and grain yields of groundnut and pigeonpea in the two treatments were measured at harvest.

Results

As mentioned earlier three genotypes of pigeonpea were previously grown on the experimental site. This Chapter does not discuss varietal differences because the differences, if any, are confounded by such factors as pigeonpea mortality and foliar diseases in groundnut. Unlike the previous experiment pigeonpea started dying in the last two to three weeks before harvest. Further, death was not confined to any one genotype, even though the 60-day bag treatment suffered less than the other treatments. Groundnut was affected by late leaf spot (*Phaeoisariopsis personata*) and the disease was not uniform in its spread among genotypes and treatments, further confounding the effects of any varietal differences. The results of the previous trial on genotypic differences were not conclusive, and further study was recommended before conclusions could be drawn (Odongo, unpublished; C. K. Ong, pers. comm.).

Examination of the field after groundnut and pigeonpea harvests revealed that leaf spot damage to groundnut intercropped with pigeonpea (cv ICP 8860) was relatively consistent across the three treatments. Pigeonpea death in these treatments was also relatively uniform. The results from this genotype (cv ICP 8860) were used to estimate and validate the yield loss function.

Leaf area indexes (LAI) of groundnut in the three (unmanaged, 30- and 60-day bag) treatments were compared with that of sole groundnut in Figure 5.3a, that shows the leaf area index of sole groundnut to be higher than that of intercropped groundnut LAI of groundnut was lowest when intercropped with unbagged pigeonpea. The same trend is observed in Figure 5.3b that shows dry matter accumulation (g m^{-2}) by intercropped groundnut in the three management treatments. The course of leaf area expansion follows the same trend as in pigeonpea and groundnut. In the managed treatments LAI is lower than that observed in unmanaged pigeonpea (Figure 5.4a). An interesting feature of pigeonpea's per-plant dry matter accumulation shown in Figure 5.4b, is that the rate of increase is the same for all treatments, but with a time lag of approximately 15 days. This is half the time the plants were bagged, and corresponds to the difference in treatments in terms of the amount of light intercepted by the plant.

Yields at harvest are presented in Table 5.4. Pigeonpea recovered to record 86% for 30-day bag and 67% for the 60-day bag treatments of dry matter yielded by unmanaged pigeonpea. Harvest index (HI) is a function of the relative durations

Table 5.4 Dry matter and seed yields of pigeonpea and groundnut (t ha^{-1})

Treatment	Dry matter	Seed yield	Harvest index
		Pigeonpea	
Unmanaged	9.53	1.26	0.13
30-day bags	8.23	1.02	0.12
60-day bags	6.42	1.04	0.16
		Groundnut	
Unmanaged	0.87	0.25	0.28
30-day bags	0.98	0.29	0.29
60-day bags	1.51	0.52	0.34
Sole	2.00	0.80	0.40

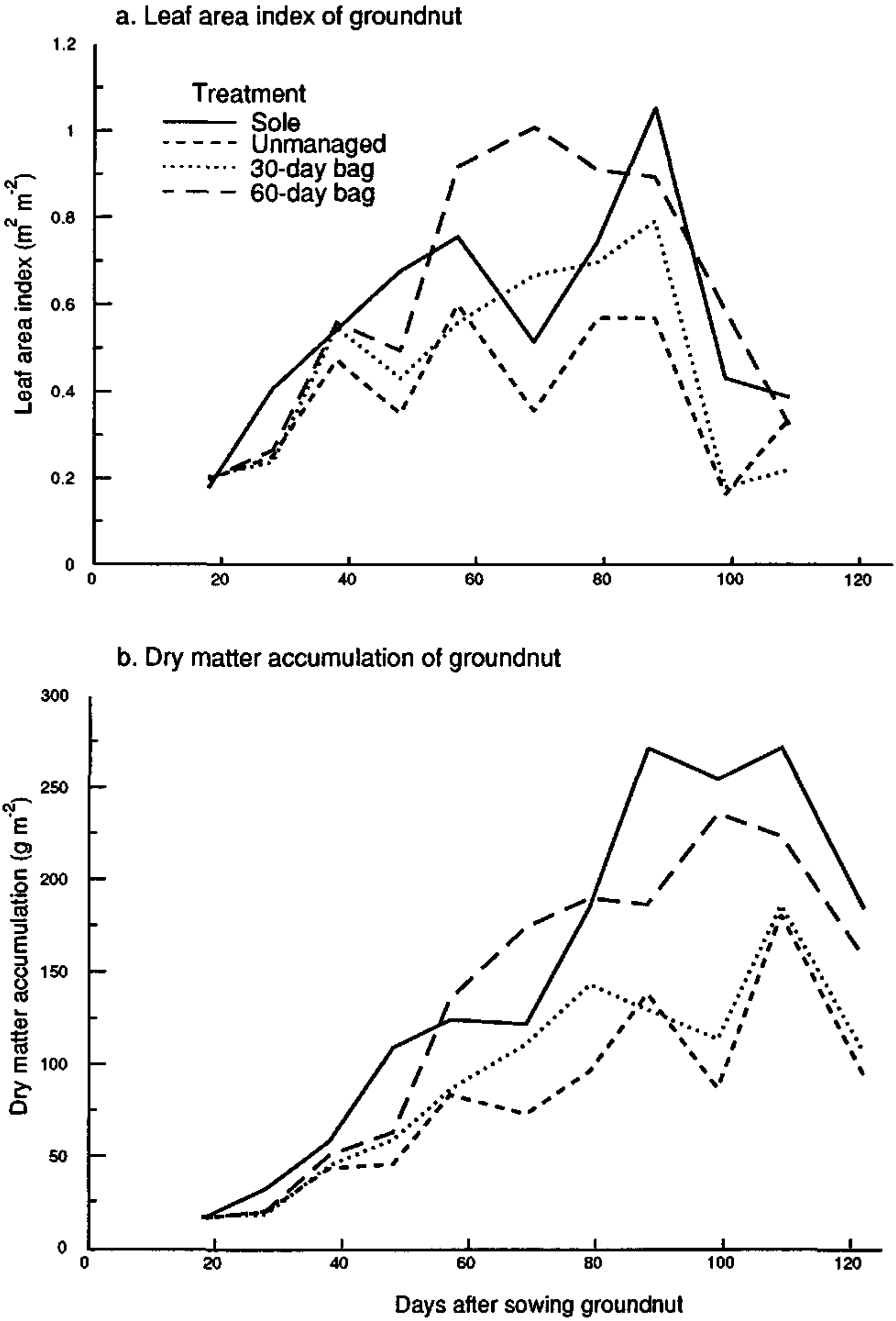

Figure 5.3 Leaf area index (a) and dry matter accumulation (b) of groundnut.

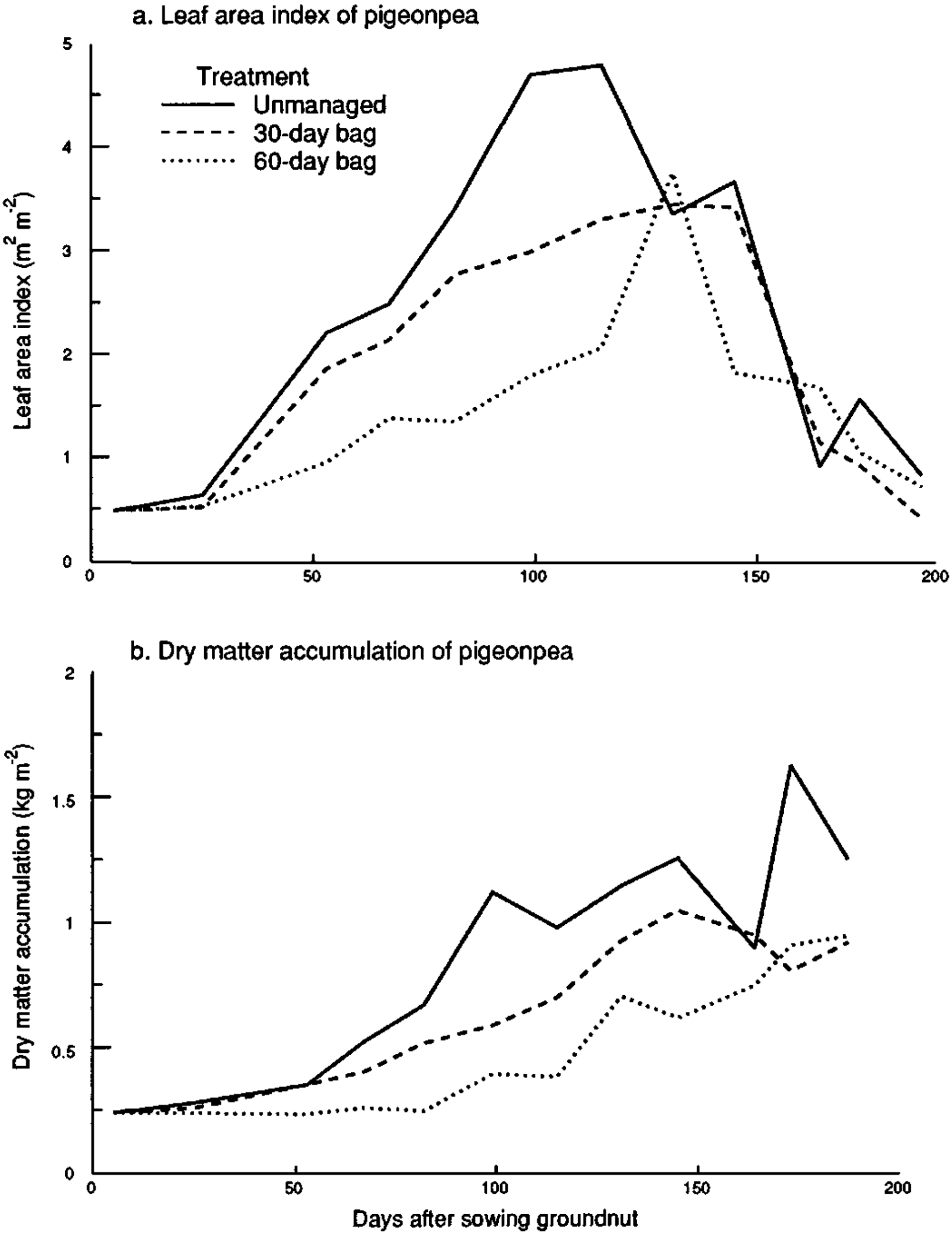

Figure 5.4 Leaf area index (a) and dry matter accumulation (b) of pigeonpea.

of the vegetative and reproductive phases and during the reproductive phase, the relative partitioning of current assimilates and the degree of remobilization of stored assimilates to seeds (Lawn and Troedson, 1990). In this experiment HI was similar in all treatments, but slightly higher in the 60-day bag treatment. In the 60-day bag treatment, HI is marginally higher, perhaps because the duration of reproductive growth represents a slightly larger proportion of the total growth period compared to the other treatments. Pigeonpea in this treatment reached 50% flowering only 50 days after the bags were removed while harvest took place 105 days after the bags were removed. There was no observable difference between the treatments in the time taken to 50% flowering.

Dry matter yields and HI of intercropped groundnut are much lower than its sole crop yield. Many factors could contribute to such a result. Firstly, although groundnut can purportedly withstand a certain degree of shading without a significant loss in pod yield, and shading in the later stages of crop growth does not reduce yields so much as shade in the initial stages (Stirling *et al.*, 1990), little is known about the effect of shading combined with different availabilities of water. Between 50 and 90 days after sowing, when groundnut was at the sensitive phase of pod generation and filling, only 55 mm of rainfall were recorded. Studies on the effect of shade on the yield potential of groundnut were made using bamboo or metal screens that do not take up water as do pigeonpea plants. Secondly, the yield data obtained in this experiment cannot be entirely relied upon for such an analysis because of the leaf loss suffered by the plants towards maturity.

Conclusions

The importance of covering a wide range of total densities and proportions of the two crops in competition experiments has already been discussed. In selecting a wide but practical range of densities and frequencies to be studied, the very low densities of pigeonpea necessary for an accurate estimation of the yield/density function were not included in this study. Consequently, the evaluation of yield advantage was incomplete.

Competition studies on multiple cropping impose design and operational restrictions on the implements used to mechanize crop production. Row spacings need to be uniform such that operations as tilling, spraying, and weeding can be performed consistently over the entire field. And to ensure that one crop is not damaged whilst the other is being harvested. In making the compromise between experimental detail, available time, and resources; the flexibility of the experimental design is lost. In this competition study, only row intercropping was possible, and information on the competitive effects of sowing patterns on yield could not be studied.

The vagaries of the weather, and pest and disease attacks that are beyond the control of the researcher are sometimes the cause of less than satisfactory results. The availability of the resources required to successfully carry out detailed experiments is yet another a problem with researchers must contend. Theoretical studies of the nature discussed in this Chapter require environments relatively free from endemic problems of pests and diseases, and conditions where effects of temperature and moisture are better controlled.

The author would like to acknowledge the contribution of ICRISAT and its field staff to the successful conduct of these experiments.

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Summary

Summary

A perspective

A study of the literature in mixed cropping shows that it has long been practiced in the tropics for a variety of reasons. A view held until recently was that mixed cropping would give way to sole cropping as an inevitable consequence of agricultural development. But the uncertainty of the potential for increasing productivity in sole cropping through new technology and a realisation that intercropping continues to remain a widespread practice has raised interest in mixed cropping. Research in mixed cropping has been fuelled by the fact that mixed cropping can provide yield advantages compared to sole cropping. Recent research into the biophysical aspects of intercropping shows that yield advantage can be substantial and not from the addition of extra inputs, but just by sowing crops together resulting in a better exploitation of resources. The complexity of such cropping systems, however, makes it difficult to quantify this advantage.

Yield advantage depends on the competitive relations between crops in the mixture. Replacement series and additive experiments have commonly been used in intercropping research to assess the relative competitive strengths of the species. A limitation of both these experimental designs is that they do not describe all the possible outcomes of competition in mixed cropping. Replacement series which contain pure stands of each species and mixtures formed by replacing given proportions of one species with equivalent proportions of the other, are best suited for studying competitive relationships in mixtures of species with similar growth curves, but which exclude each other. The effects of inter- and intra-specific competition are separated and inter-specific competition itself is fully characterized by parameters that are derived from experiments measuring intra-specific competition. Additive experiments where one species is grown at a fixed density and the other at a range of densities answer more directly questions about the extent to which the full yield of a crop is affected by another. Unless used with caution this design confounds the effects of inter- and intra-specific competition. The limitations of both these designs are overcome by replacement series repeated at a range of total densities.

Production possibility frontiers

An effective analysis of productivity permits yield from both species in a mixture to be estimated at any combination of frequency and density. In mixed cropping one crop cannot be considered independently of the other and as such, any index which measures yield advantage must determine when more production of one crop and less of the other is advantageous. Production possibility curves, drawn from economics literature, express the yield of a crop as a function of the other and can be used as a tool in the calculation of optimal sowing densities. Since it integrates agronomic and economic principles it facilitates an economic analysis at the same time as an agronomic one. The importance of an economic evaluation cannot be overestimated because the market value of products provides the farmer with a tool in allocating limited resources between competing uses and puts different crops and their products on a comparable basis.

The production possibility curve or frontier represents the maximum combined yield that can be achieved by the two crops and is derived using *a priori* information on processes underlying intercropping, as a result of which parameters of the function are described in biologically meaningful terms. The biological information has been generated using a competition model which expresses dry matter yield as a function of the population densities of the two crops. The parameters of this model quantify the inter- and intra-specific stresses operative in the system. Knowledge of the production possibility function makes it possible to assess productivity in economic terms. The optimal point of production corresponds to the tangent of the price line to the production frontier. A price line reflects a fixed value of production of the two crops and is represented by a line with a slope equal to negative of the market price ratio. The point at which the price line is tangential to the frontier is determined mathematically as are the limits to the price ratio within which intercropping is economically advantageous. The sensitivity of output proportions to changes in price ratios is demonstrated for different cropping systems. From the production frontier seed density ratios that need to be sown in order to obtain an economically optimal yield combination are also calculated.

The aim of agriculture is often the maximum yield of a desired plant part and a production frontier for this marketable yield is important in the evaluation of intercropping. Its derivation, however, is not always straightforward as the basis to the estimation of a production possibility frontier is a hyperbolic relationship between yield and density. A hyperbolic relationship between marketable yield and density is often not observed. The reaction of crops to density is such that the weight of an individual plant at high densities almost exactly compensates for the increased number of plants per unit area, by changing the proportional allocation of assimilatory products to various organs of the plant, and marketable yield often suffers in this reallocation. Further, in crop mixtures marketable-yield/density relationships are difficult to identify because the same yield can be achieved at different densities depending on the competitive stresses at play. However, one of the main effects of competition, inter- and intra-specific, is a reduction in the mean size of individual plants. In situations where seed yield declines with increasing density, per-plant marketable-yield/biomass relationships are well approximated by a straight line that does not pass through the origin. From an estimation of biomass using a hyperbolic function and per-plant marketable-yield/biomass relationships for the crops in the mixture, a production possibility frontier for marketable yield is derived.

The derivation of production possibility frontiers for marketable yield and biomass, and an illustration of its use in an agronomic and economic evaluation of some intercropping systems are described in Chapters 2 and 3.

Agronomic sustainability and management

Growing woody perennials with annuals attempts to provide a strong foundation for conservation oriented farming. But a significant concern is that competition from the perennial to the annual in the second and subsequent years of intercropping may override the otherwise positive aspects of such mixed cropping, particularly in situations where the perennial is of less direct economic value than the annual. In the example of intercropping a perennial with an annual discussed in Chapter 4, the shape of the production possibility frontier, an indicator of the nature of the relationship between crops in the mixture, demonstrated large advantages in intercropping even when competition from the perennial to the annual was large enough to be detrimental to production of the annual. That this is a reflection of temporal complementarity in resource use is confirmed from research in natural systems. Temporal complementarity comes at the cost of annual production so that there exists a trade off in production of the two species. In areas where mixed cropping of perennials with annuals is recommended, the immediate concern of the farmer is food production, but sustainability of the resource base is essential to continued production. Acceptable production levels of the annual may mean very low density levels of the perennial; so low that the environmental benefits accruing from the perennial are negligible.

The successful integration of woody species and their long term environmental benefits into a farming system requires management. Through pollarding, pruning, lopping or other means of growth regulation, management seeks to alter the competitive relationship between the annual and perennial towards a more equitable distribution of environmental resources such as light, water and nutrients. The question that is considered in Chapter 4 is, however, not only what to remove but how much and when. While sowing densities are useful measures of expected yield, they do not reflect factors of early growth and stand establishment that play an equally important role in determining the final outcome. Leaf area measured before crop canopy closes is a better measure of expected yield as factors of early growth and sowing density are contained in it. By replacing parameters of the competition model used in the derivation of the production possibility frontier by leaf area indices, yield loss in the annual is related to relative leaf area of the intercropped perennial giving a strategy for managing the perennial on the basis of its competitive strength.

Field experiments

Illustration of the models developed needs data from experiments which provide for a full description of inter- and intra-specific competition suffered by plants in a mixture and a measurement of leaf area expansion over time. Annual pigeonpea and groundnut are traditionally intercropped in many parts of India. Perennial pigeonpea is a short-lived perennial providing grain, fuelwood and green fodder with potential as a companion crop to groundnut. Its deep-rooting and drought-tolerant nature make it an especially useful crop in areas of low and uncertain rainfall which characterize much of the semi-arid tropics. Perennial pigeonpea and groundnut were intercropped on a two-year rotation and their competitive strengths estimated in the first and second years of the rotation in relation to their sowing densities. The relative leaf area of pigeonpea in the mixture was measured in another experiment where groundnut was sown into year-old pigeonpea alleys. A full description of the experiments is given in Chapter 5. Aspects of importance related to the analysis are also presented and discussed in Chapters 3 and 4.

Samenvatting

Samenvatting

Een perspectief

Uit de literatuur blijkt dat mengteelt van gewassen om uiteenlopende redenen al heel lang wordt toegepast in de tropen. Tot voor kort werd verondersteld dat deze teelt plaats zou maken voor de teelt van monocultures, als een onvermijdelijk gevolg van de landbouwkundige ontwikkeling. Maar de onzekerheden die er bestaan ten aanzien van de toenemende produktiviteit door de toepassing van nieuwe technologie in monoculturen en het besef dat mengteelt nog steeds veel voorkomt, heeft de belangstelling hiervoor doen toenemen. Onderzoek van mengteelten wordt daarbij ook gestimuleerd door het feit dat mengteelt tot grotere opbrengsten kan leiden dan teelt van de afzonderlijke gewassen. Uit recent onderzoek naar de bio-fysische aspecten van mengteelt blijkt dat deze toename aanzienlijk kan zijn en dan niet als een gevolg van extra inzet van produktiemiddelen maar als gevolg van het feit dat het gemengd zaaien tot een betere exploitatie van hulpbronnen leidt. De complexiteit van dergelijke mengteelten maakt echter dat deze voordelen moeilijk hard te maken zijn.

Opbrengstvoordelen hangen af van de concurrentieverhoudingen tussen de gewassen in het mengsel. Bij het onderzoek van het relatief concurrerend vermogen van gewassen is gebruik gemaakt van vervangingsreeksen en additieve proeven. Een beperking van beide proefopzetten is dat zij niet alle mogelijke uitkomsten van concurrentie in mengteelt beschrijven. Vervangingsreeksen omvatten monocultures van de gewassen en mengsels die worden gevormd door vervanging van een bepaalde fractie van het ene gewas door een overeenkomstige fractie van het andere. Onder omstandigheden dat de twee gewassen gelijkvormige groeicurven hebben en elkaar uitsluiten, blijken vervangingsreeksen uitstekend te voldoen. De effecten van intra- en inter-specifieke concurrentie worden dan gescheiden en interspecifieke concurrentie kan volledig worden beschreven met parameters die kunnen worden afgeleid van experimenten die alleen intra-competitie meten. Additieve proeven waarbij het ene gewas bij een bepaalde dichtheid wordt verbouwd en het andere gewas bij uiteenlopende dichtheden, geven een meer direct antwoord op de vraag in welke mate een normaal gewas wordt beinvloed door een andere soort, zoals bijvoorbeeld onkruid. Tenzij met grote voorzichtigheid gebruikt, verstrengelt deze proef-opzet de effecten van intra- en inter-specifieke concurrentie. Proeven waarbij vervangingsreeksen worden herhaald bij een spectrum van totale dichtheden, blijken de beperkingen van beide proefopzetten te niet te doen.

Het front van produktiemogelijkheden

Een doeltreffende analyse dient het mogelijk te maken de opbrengst van beide soorten in een mengsel aan te geven voor elke combinatie van mengverhouding en dichtheid. In het geval van mengteelt is het onmogelijk het ene gewas onafhankelijk te zien van het andere en daarom zal iedere bruikbare index die het opbrengstvoordeel karakteriseert, ook moeten aangeven wanneer het produceren van meer van het ene gewas en minder van het andere voordelen biedt. Het front van produktiemogelijkheden, een begrip ontleend aan de economische literatuur, drukt de opbrengst van het ene gewas uit als een functie van het andere en kan worden gebruikt als een instrument bij de berekening van optimale zaaidichtheden. Omdat het front agronomische en economische principes integreert, vergemakkelijkt het zowel de economische als de agronomische analyse. Het belang van een economische evaluatie kan hierbij niet worden overschat omdat de marktwaarde van de produkten voor de boer richtinggevend is bij de toedeling van beperkte middelen aan concurrerende toepassingen en de verschillende gewassen en hun produkten vergelijkbaar maakt.

Het front van produktiemogelijkheden drukt de opbrengst van het ene gewas uit als een functie van de opbrengst van het andere. Dit front wordt afgeleid uit a priori informatie over de processen die mengteelt beheersen en op basis waarvan de functionele vorm kan worden beschreven in termen een biologische betekenis. De biologische informatie wordt verkregen met behulp van een hyperbolisch concurrentie model waarmee opbrengsten worden geanalyseerd uit vervangingsreeksen, herhaald bij verschillende dichtheden. De parameters van dit model karakteriseren de inter- en intraspecifieke invloeden die zich in het systeem voordoen en geven uitkomsten weer, gemeten als droge stof ha^{-1} van de afzonderlijke gewassen.

Uitgaande van het front van produktiemogelijkheden, kan een economische analyse worden gemaakt. Het optimale punt van produktie correspondeert met de raaklijn van de prijslijn aan het front. Een prijslijn weerspiegelt een bepaalde verhouding van produktie voor de twee gewassen en wordt weergegeven door een lijn met een helling die gelijk is aan de negatieve waarde van de verhouding van de martkprijzen van de twee gewassen. Het punt waar de prijslijn raakt aan het front kan mathematisch worden afgeleid, evenals de grenzen van de prijsverhoudingen waarbinnen gemengde teelt voordelen biedt. De gevoeligheid van de uitkomsten voor veranderingen in prijsverhoudingen kan ook worden nagegaan. Ook kan de verhouding waarin de gewassen moeten worden gezaaid voor het bereiken van de, economisch gezien, optimale opbrengst combinatie worden berekend.

Het gaat in de landbouw vaak om de opbrengst van reproduktie-organen van een gewas, zodat het vaststellen van het produktiefront voor de zaadopbrengst van groot belang is. De afleiding hiervan is niet altijd even gemakkelijk omdat bij de berekening voor het front van produktiemogelijkheden wordt uitgegaan van een hyperbolische relatie tussen opbrengst en dichtheid, en dit is niet altijd zo in het geval van zaad. De reactie van planten op toenemende dichtheid is zo dat het gewicht van individuele planten bij hoge dichtheden vrijwel geheel compenseert voor het toenemend aantal planten per hectare door verandering van de allocatie van assimilatie-produkten naar de verschillende organen. Hierbij komt de zaadopbrengst vaak onder druk te staan. In mengsels van gewassen is er dan vaak geen eenduidig verband tussen opbrengst en dichtheid van zaaien omdat dezelfde opbrengst kan worden verkregen bij verschillende dichtheden, afhankelijk van de concurrentie verhoudingen. Echter, een van de belangrijkste effecten van zowel intra- als inter-specifieke concurrentie is een teruglopen van de grootte van de individuele planten. Het blijkt nu dat het verband tussen zaad en totale droge-stof gewicht per plant, ook in gevallen waarbij de fractie zaad verandert met de plantgrootte, goed kan worden benaderd door een rechte lijn die dan niet door de oorsprong gaat. Deze maakt het mogelijk het front voor de produktiemogelijkheden van zaad op een eenvoudige manier af te leiden van gegevens voor de totale droge-stof.

De afleiding van de produktiefronten voor totale droge-stof en zaad, en een illustratie van hun gebruik voor agronomische en economische evaluatie van enkele mengteelten zijn beschreven in de Hoofdstukken 2 en 3.

Landbouwkundige duurzaamheid en teeltmaatregelen

Het samen verbouwen van houtachtige meerjarigen en eenjarige gewassen poogt de op duurzaamheid gerichte landbouw te versterken. Een belangrijk probleem is hierbij dat de concurrentie die de eenjarige van de meerjarige ondervindt, in het tweede en de daaropvolgende seizoenen, zo groot kan worden dat de voordelen van een dergelijke mengteelt grotendeels wegvallen. Dit is in het bijzonder zo onder omstandigheden waar de meerjarige van gering direct economisch belang is. In het voorbeeld van mengteelten van meerjarigen en eenjarigen, dat in Hoofdstuk 4 wordt besproken, volgt uit de vorm van het front van produktiemogelijkheden (die de aard van de relatie tussen de gewassen in het mengsel aangeeft) dat er grote voordelen zijn verbonden aan mengteelt, zelfs onder omstandigheden waar de concurrentie van de meerjarige zo groot is dat de produktie van de eenjarige werd beperkt. Dat het hier om temporele complementariteit gaat, wordt bevestigd door onderzoek in natuurlijke ecosystemen. Temporele complementariteit gaat ten koste van de produktie van de eenjarige en er bestaat zodoende een uitruil tussen de produktie van de twee gewassen. In gebieden waar gemengde teelt van meerjarigen en eenjarigen wordt aanbevolen, is voedselproduktie door eenjarigen van direct belang voor de boer, terwijl het instandhouden van de produktiemogelijkheden van belang is voor de continuiteit van de produktie op langere termijn. Produktie van het eenjarige voedselgewas op een acceptabel niveau kan zo'n lage dichtheid voor de meerjarige betekenen, dat de gunstige invloed op het instandhouden van de produktie verwaarloosbaar klein is.

Daarom vraagt het instandhouden van de voordelen van meerjarigen voor de produktiemogelijkheden op lange termijn, daarop gerichte teeltmaatregelen. Door knotten, snoeien of andere manieren van regulatie van de groei van de meerjarige, wordt getracht de concurrentieverhoudingen tussen eenjarigen en meerjarigen zo te wijzigen dat licht, water en voedingsstoffen meer aan de eenjarigen toekomen. De vraag die wordt gesteld in Hoofdstuk 4 betreft echter niet alleen wat verwijderd moet worden, maar ook hoeveel en wanneer. Zaai- en plantdichtheden zijn bruikbare maten voor het voorspellen van de opbrengst, maar weerspiegelen niet de invloed van kieming en de snelheid van groei in de beginfase op de uiteindelijke uitkomst. Bladoppervlak gemeten voor de tijd dat het gewas zich sluit, is daarom een betere voorspeller voor de opbrengst. Door het vervangen van de dichtheidsmaten in de concurrentie-modellen door bladoppervakte-indices, werd het mogelijk het opbrengstverlies van de eenjarige te relateren aan het relatieve bladoppervlak van de twee soorten en op basis hiervan een strategie te ontwikkelen voor het terugdringen van de concurrentie van de meerjarige.

Veldproeven

Voor het illustreren van de modellen die zijn ontwikkeld zijn gegevens nodig van experimenten die een volledige beschrijving geven van de intra- en interspecifieke concurrentie waaraan planten in een mengsel bloot staan en van metingen van het bladoppervlak in de loop van het seizoen. Meerjarige duivenerwt (*Cajanus cajan*) en eenjarige aardnoten (*Arachis hypogaea*) werden daarom verbouwd in een tweejarig experiment met vervangingsreeksen bij verschillende dichtheden. Totale opbrengsten en zaadopbrengsten van zowel duivenerwt als aardnoot werden bepaald in het eerste en tweede jaar. De bladoppervlakken van beide gewassen gedurende het seizoen werden gemeten in een ander experiment onder dezelfde omstandigheden, waar aardnoot werd gezaaid in een gewas van duivenerwten dat een jaar oud was. Duivenerwt is, een kortlevende, meerjarige plant die raad, brandhout en groenvoer levert. De diepe beworteling en droogte-tolerantie maken dat dit gewas van bijzonder belang is in streken met de lage en wisselende regenval, die kenmerkend zijn voor de semi-aride tropen. Een volledige beschrijving van de experimenten is te vinden in Hoofdstuk 5, terwijl aspecten die van belang zijn voor de analyse te vinden zijn in Hoofdstuk 3 en 4.

Curriculum vitae

Radha Ranganathan was born on 13 January 1957 in Hyderabad, India. She finished her high school education in 1972 after which she did a bachelor's degree in Mathematics, Physics and Chemistry from Madras University. In 1978 she took a master's degree in Statistics from Bangalore University. After a break of eight years, in 1987 she took another master's degree in Forestry and its Relation to Land Use from the University of Oxford.

In the period between 1978 and 1982, she worked as a researcher in the Indian Institute of Management, Bangalore and Administrative Staff College of India, Hyderabad. From 1982 till 1986 she worked with a non-governmental organisation on projects dealing with land use such as Sericulture and Forestry. In 1988 she joined the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) as a researcher working on the analysis of yield advantage in intercropping systems. She worked as a consultant to Winrock International, Forestry/Fuelwood Research and Development (F/FRED) Project, Bangkok and coordinated a study on farmers' perspectives on multipurpose tree species.

Since July 1989 she has worked on her doctoral thesis at the Department of Theoretical Production Ecology while field research has been done at ICRISAT. She has been financially supported through the period by the Agricultural University, Wageningen and ICRISAT as part of the 'Sandwich Programme'.