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CONSIDERATIONS WHEN EXPERIMENTING WITH CHANGES IN PLANT SPACING

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Considerations when experimenting with changes in plant spacing

General considerations

Crop yields are highly dependent on plant density (plant population per unit area of land) but there are many factors to consider when attempting to assess an "optimum" spacing. The three underlying variables to manipulate are:-

- Plant population per unit area of land (plant "density" = number of plants hectare^{-1}).
- Rectangularity (the ratio of between- to within-row spacing), and
- Plant arrangement. That is whether, within any stated rectangularity, the plants of adjacent rows are opposite one another (i.e. a "square" plant) or are offset ("staggered") in some way.

Rectangularity applies only to row-cropping systems, but the concepts of plant arrangement extend to clumping and other forms of heterogeneous spacing arrangements between species in mixed cropping patterns. Figures 1 to 4 give some row cropping examples.

The highest yields are obtained when a sufficient number of plants occupy an area so as to utilize the environmental resources (light, water, nutrients) maximally, but without plant stature, the distribution of dry matter, or the flowering/fruiting processes being adversely affected, or to a point where pest organisms are encouraged.

Because available environmental resources usually vary between-seasons there is no set "optimum" plant density for seasonal species, although it is usually feasible to establish a mean plant density at which yields are maximal for the "average" season. In places where there are large seasonal differences in rainfall and/or in cloudiness, therefore, a larger number of years of experimental work are required to establish a recommendation than in more constant environments.

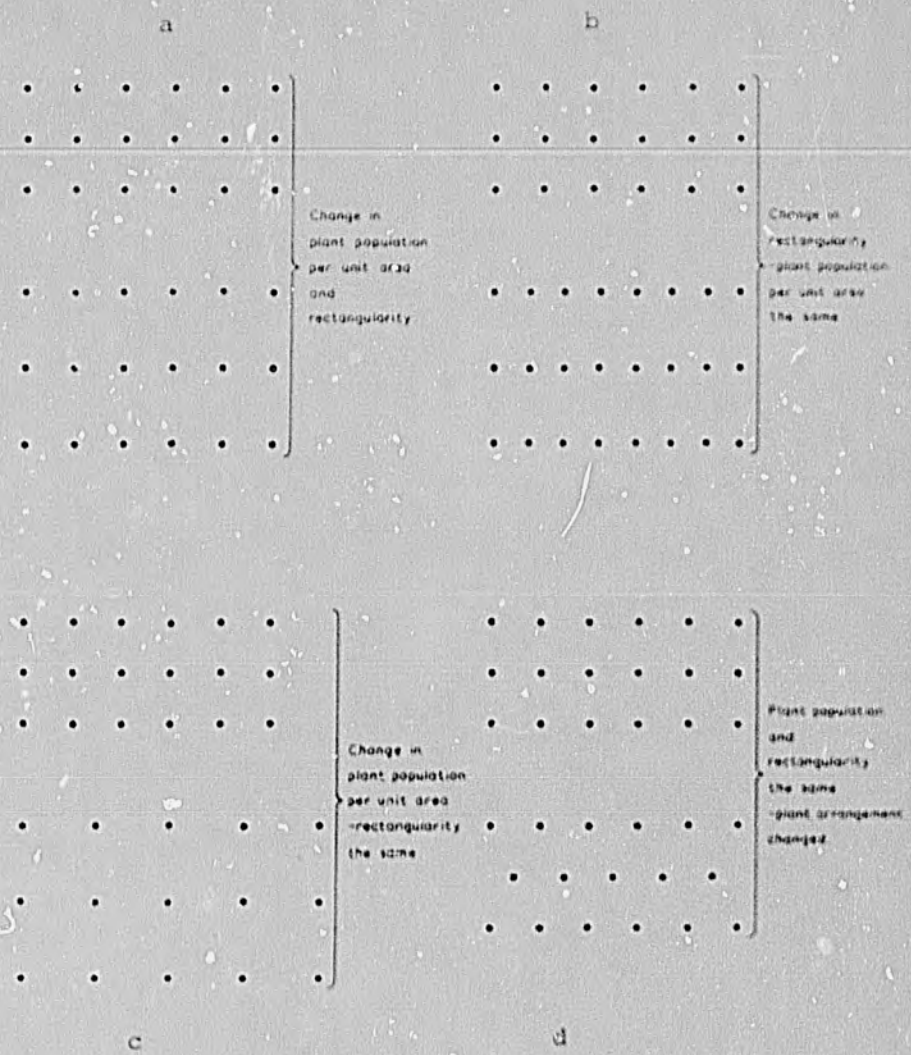


Figure 1. Illustrations of some changes in plant population per unit area (plant density) rectangularity and plant arrangement - see text for explanations.

The resource-sharing capacity of perennials can change markedly within age, and this factor has to be considered in determining original planting distances and subsequent thinning and/ or pruning regimes. With woody perennials we also need to consider not only whether we require total biomass or just a plant part but whether, in the latter case, we are to regularly harvest a renewable part, (e.g. fruits, or vegetative parts such as leafy shoots), or a non-renewable part intermittently (e.g. woody main stem).

Environmental resources, both in spatial and temporal terms, and both above and below ground, can usually be better shared between a mixture of species than by sole cropping, and this is one of the cases for mixed cropping. In sole cropping evenly-spaced plants will be more likely to be sharing environmental resources maximally (but not fully) compared with irregularly-spaced plants, and this is one of the cases for row-cropping. Maximum yields will then, apart from the effects of other management factors, be obtained with a rectangularity of 0.866 (sin 60°) with the plants staggered between rows (that is with all plants spaced equi-distant from one another as in a series of equilateral triangles).Fig.2

In plant mixtures exact species ratios and distances between plants will depend on the growth habits and physiological responses of the species concerned. The manipulation of rectangularity, where this can be easily managed through row-cropping, can be a powerful tool to obtain effective species combinations. Especially if it is combined with manipulation of sowing or harvesting times (with seasonal crops), or with pruning/lopping regimes(with woody perennials). Then individual species can have better access to, particularly, water and light at critical periods of their growth and development. "Alley-cropping" for example, is one form of mixed planting that utilises the benefits of high rectangularity ratios and lends itself to a range of other management manipulations.

Apart from its major influences on yield per unit area, plant density greatly affects the size of individual plant parts. This factor is commonly used to manipulate crops so as to provide suitable-sized products so as to satisfy the particular requirements of the farmer, the fresh market, the sawmill, or the cannery or other processing plant. For example with

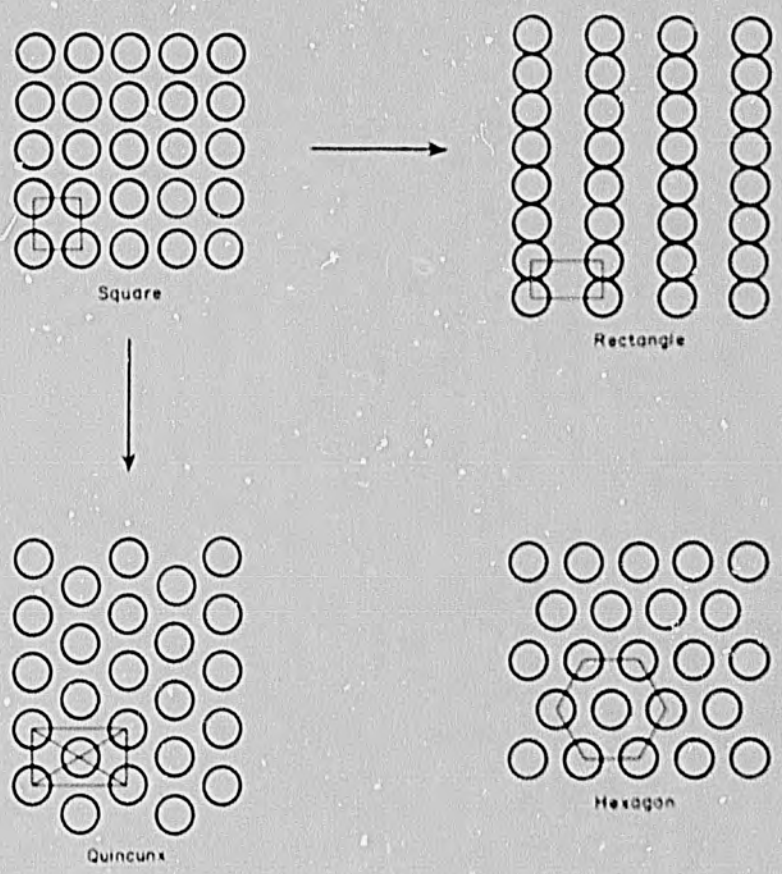


Figure 2. Some alternative planting arrangements. Plants in the hexagonal arrangement are all equidistant from one another (see page 3). The quincunx planting permits successive alternative row thinnings (either diagonally or vertically/horizonally) to leave various regularly-spaced arrangements.

timber or poles; tubers or roots (e.g. carrots); fruits (maize cobs), or even an edible stem and inflorescence such as the pineapple.

Even when plants of the same species are assembled together (sole cropping) plant-to-plant interference effects result in a range of plant sizes. A relatively few specimens become dominant and a greater number suppressed to some degree or another. This results in a positively skewed population distribution for plant size which is more emphasized as plant density is increased and which is accentuated with the age of the crop (Figure 3).

The choice of plant density and arrangement is, of course, only one set of factors to consider in manipulating yield, plant size, or the size of plant parts. The need for access (for example for weeding, crop spraying and harvesting) can impose spacing restraints, particularly on rectangularity, which may not be remedied by concomitant increases in within-row spacing to correct for overall plant population per unit area.

The influence of plant population per unit area of land on yield for a seasonal crop is illustrated in Figure 4a. When the output is measured as total biomass the yield/plant density relationship is asymptotic. On a per plant basis this relationship is described by the commonly-used "reciprocal yield" equation

1. $$\frac{1}{w} = a + bx$$

where: w = the mean weight of an individual plant, and

x = plant population per unit area

- and a and b are a constant and a coefficient respectively.

When the output is a plant part, such as the fruits, seeds, stems or tubers, the relationship is found to be fitted by a parabolic curve of the type:

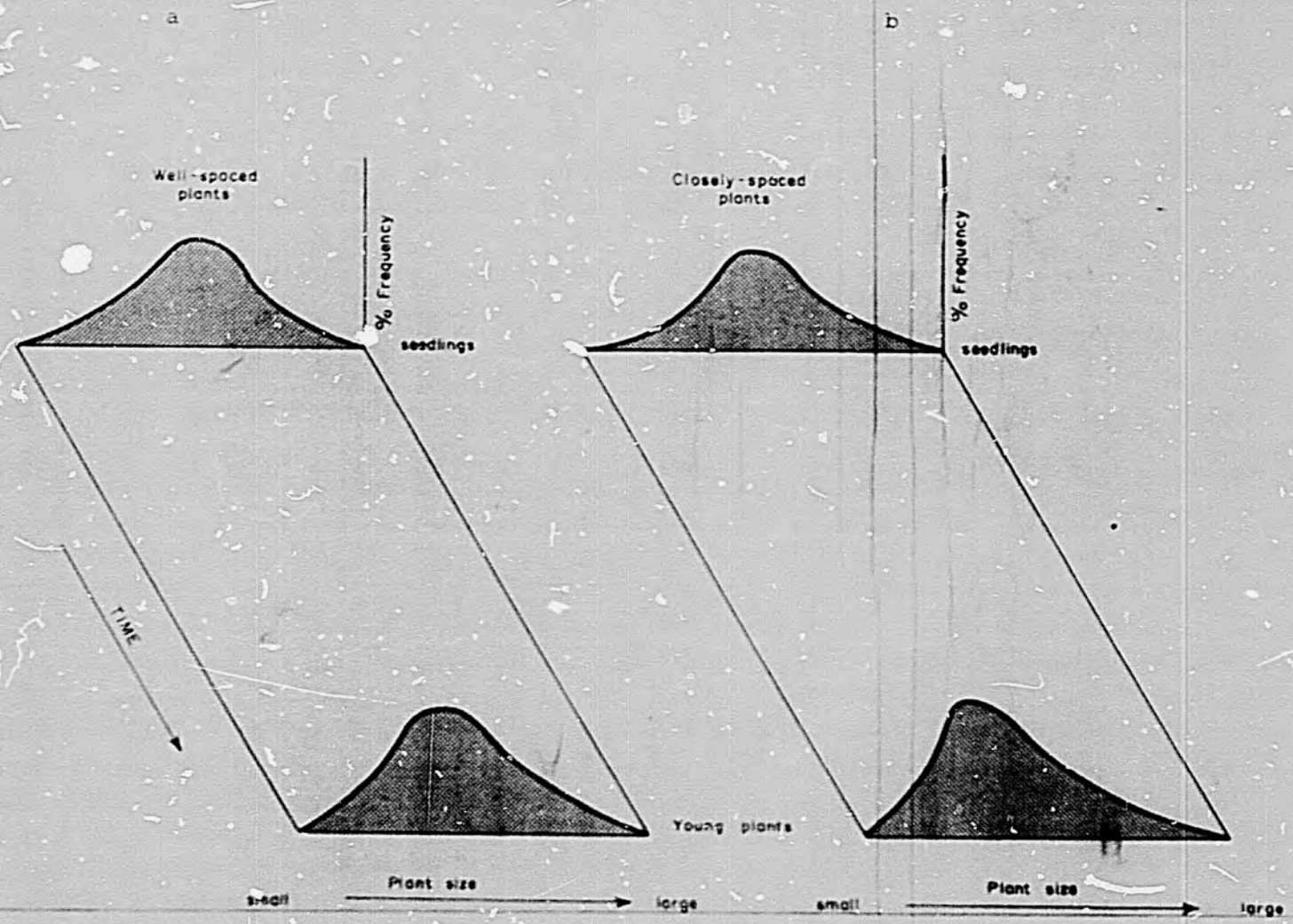


Figure 3. Changes of the frequency distribution of individual plant size with time in a sole cropping situation starting with (a) relatively well-spaced plants and (b) closely-spaced plants. In both cases a few plants become dominant and the frequency distribution for plant size becomes positively skewed - but more so with (b) than (a).

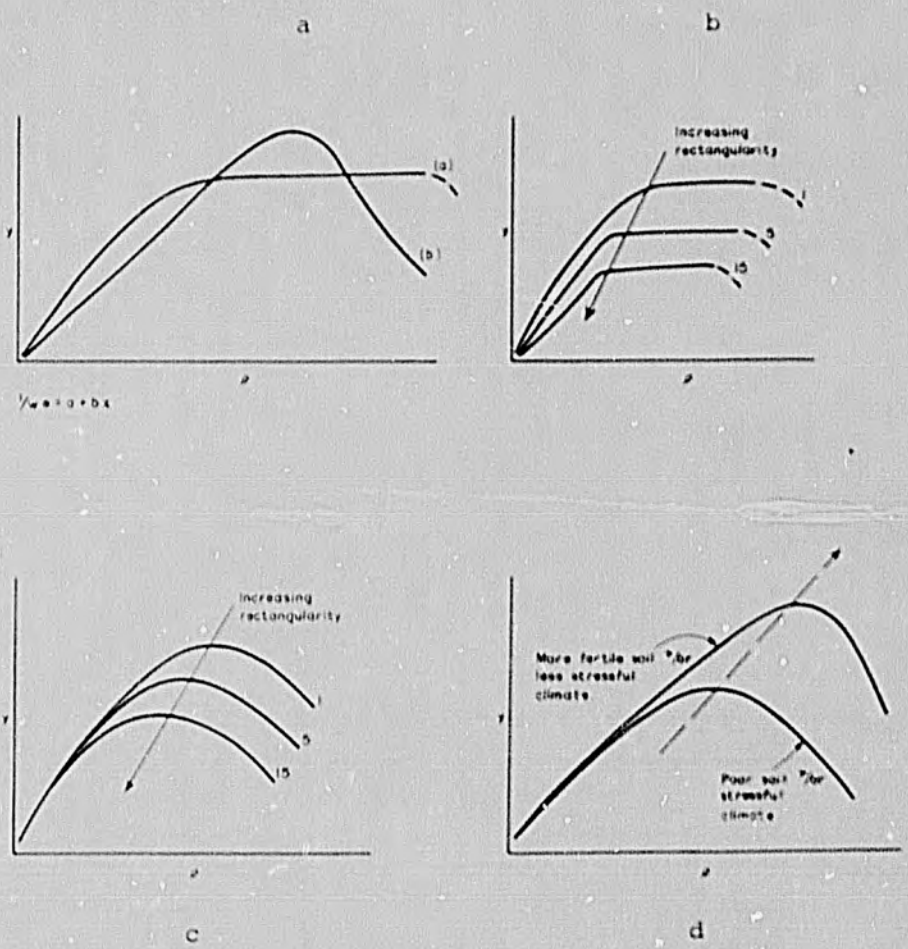


Figure 4. (a) Basic yield per unit area (y) plant density (ρ) relationships
(b) (c) The effects of increasing rectangularity on an asymptotic and parabolic relationship, respectively.
(d) The general trend in a parabolic yield/density relationship brought about by changing soil fertility and climatic stress.

2. $\frac{1}{w} = a + bx + cx^2$

The two relationships can both be expressed by the simple equation:

3. $\frac{1}{w^{\theta}} = a+bx$

and when the yield response is asymptotic $\theta = 1$, and when parabolic $\theta<1$. Also the constant "a" represents an influence of plant genotype and "b", the coefficient, is related to environmental potential (see Willey and Heath, 1969, for the arguements).

Figures 4a and 4c indicate the changes in these basic relationships when rectangularity is increased. Although the general principles are well established individual species will, of course, respond to changes in rectangularity in somewhat different ways. For example, the yields per unit are of some indeterminate species with wide ranging shoot systems (such as Solanum potatoes or spreading forms of cowpea) are less affected by higher rectangularities than plants of more rigid form (such as most trees and shrubs) which cannot exploit wide between- to within-spacing so readily.

The overall effects of environmental improvement (more fertile soils, less water stress, improved light conditions) is not only to raise yield levels per unit area of land but to increase the plant population at which this is acheived (Figure 4d. Thus, although the exact extent of any particular environmental improvement has to be measured experimentally for any species (or species mixture) a knowledge of this trend permits at least some degree of conjectural extrapolation based on known principles and responses.

Appropriate orientation of crop rows, even in tropical latitudes, can contribute to better light interception and distribution over the canopy.

Thus North-South oriented rows may be potentially higher yielding than those aligned East-West. However, this aspect may not be considered as important a contributor to sole crop yield as others discussed above, at least in the early phases of investigation, although its effects on light distribution between upper storey (trees) and lower storey (agricultural crops) associations in agroforestry systems can be considerable.

Dealing with woody perennials

The effects of changes in plant density etc described above for seasonal plants will be modified in species with a woody perennial structure by the various ways that a persistent canopy can influence plant form and development, with consequent effects in the distribution of dry matter within the individual plant. Also by ageing effects. As discussed by Cannell (1983) close-spaced trees forming a dense canopy will be taller (and so possess a higher proportion of stemwood), have fewer lower branches (due to self-pruning) and set less fruit (due to shading of potential fruiting sites). Such factors will influence the shape of the parabolic yield/density relationships but not obviate them. Ageing of individuals will diminish, annual dry matter increment in part because of an overall increase in the respiratory load within the population, and also because of an eventual loss of efficiency in canopy photosynthesis through a number of causes. This too will alter the progressive changes asymptotic and parabolic relationships alike.

Because multipurpose trees species may be grown so as to optimize provision of a range of products: total biomass (for soil restoration/ soil conservation), total woody biomass (for fuelwood), leafy biomass (for fodder), fruits and/or seeds, other plant products (bark, gums, waxes etc), or a combination of these, an understanding of the relevant plant responses to density stress are certainly necessary. Furthermore, harvests may be as a single terminal harvest (but rarely), as irregular harvests during the productive lifespan (e.g. timber or fuelwood thinnings), as regular annual or seasonal harvests once the trees are mature (fruits, seeds) or as intermittent within-season harvests (leafy fodder or browse, sap, gums etc). Sequential or intermittent, harvesting of vegetative materials, or thinning of whole trees will change the level of density stress

so as to set back the trends in plant modification being established, either in so far as these may be reversible on existing parts (e.g. re-establishment of a higher rate of stemwood increment) or, more likely, for the plant parts that are formed anew thereafter (e.g. re-establishment of fruiting points on new branches that can then emerge.

For woody stems and branches foresters consider changes in both the "Current Annual Increment" (CAI) and the average of this with time, the "Mean Annual Increment" (MAI). Figure 5 shows the effects of planting density on MAI for total woody biomass and for merchantable timber, respectively Figures 6 and 7 show hypothetical time-trends for changes in total biomass and a renewable plant part harvested annually, respectively.

Experimental approaches

The establishment of yield/plant density relationships for sole crops can be achieved either by using conventional (e.g. randomized block) or systematic field layouts (for the latter see separate W. Paper). The former are more robust but, if adequate internal guard rows are to be provided (at least double), which is essential for spacing experiments (see Figure 8), then the effective experimental area can be quite restricted Systematic designs enable a wide range of spacing levels to be tested in a small amount of space without the use of internal guard rows. But a rigorous statistical analysis of the results is usually difficult.

Several authors have suggested that only a limited number of spacing treatments (3 or 4) are needed to establish a mathematical yield/plant density curve as long as certain assumptions are satisfied e.g. that the reciprocal yield relationship (or plant weight plotted against plant population per unit land area) is linear. This relationship can hold good with all types of plants, including trees and shrubs, but until any particular species has been studied under a range of environmental and management conditions some departure from a strictly linear relationship cannot just be assumed. It seems prudent, therefore, especially at the start of an experimental programme with a new species, to accept the need to encompass a reasonable range of plant density and rectangularity treatments in any experimental programme e.g. at least 5 plant densities and 3 rectangularities).

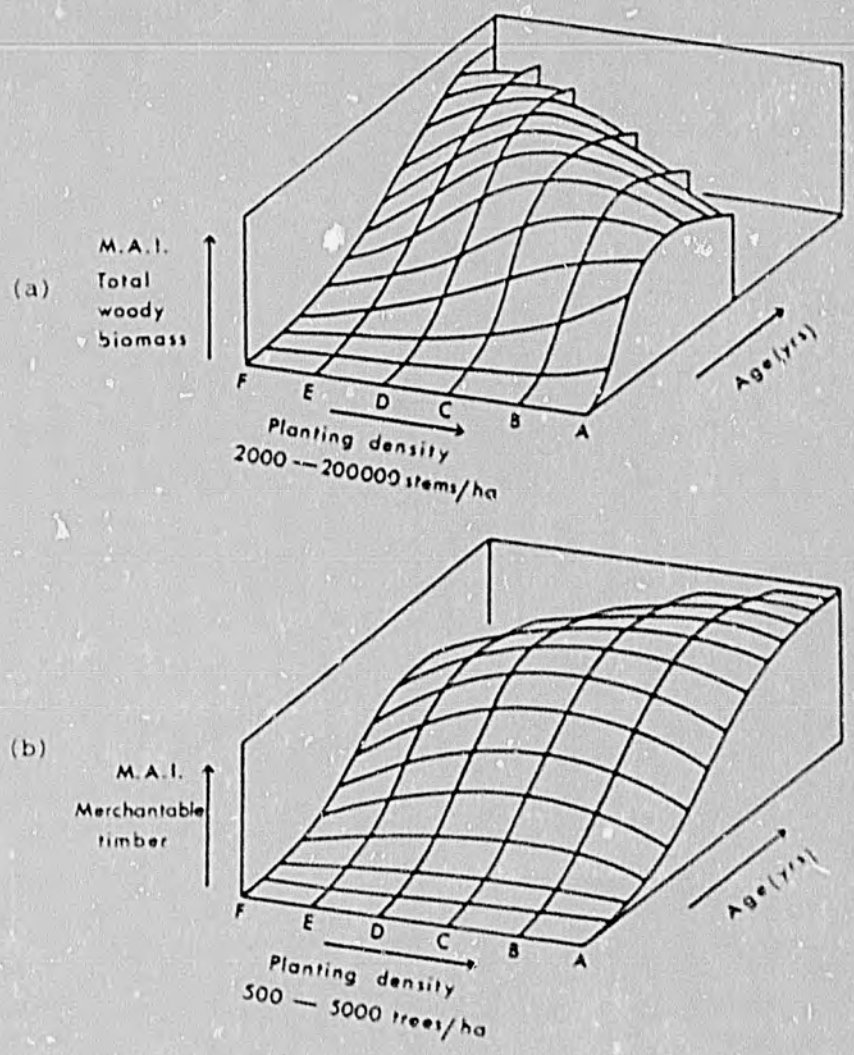


Figure 5. Effects of planting density on the mean annual increment (MAI) of trees grown for woody biomass (a) (branches and stems of any diameter) and merchantable timber (b) stems above a given diameter). Note that there is an optimum density for woody biomass as well as timber production, and that thinning will move the population in the direction A to F. Remember that closely spaced trees will be small in diameter, but not necessarily height, and that, in unthinned stands, the number of trees at harvest will be less than at planting owing to self-thinning. From Cannell, M.G.R. 1983. Plant population and yield of trees and herbaceous crops, pp. 489-502 in P.A. Huxley (Ed) "Plant Research and Agroforestry", ICRAF. Nairobi.

Figure 6. Changes with time of total biomass accumulation per unit area of land for different plant densities of a woody perennial species. Eventually the net annual increment due to carbon fixation and mineral uptake will be exceeded by losses (parts shed, total respiration and this will happen sooner at high plant densities.

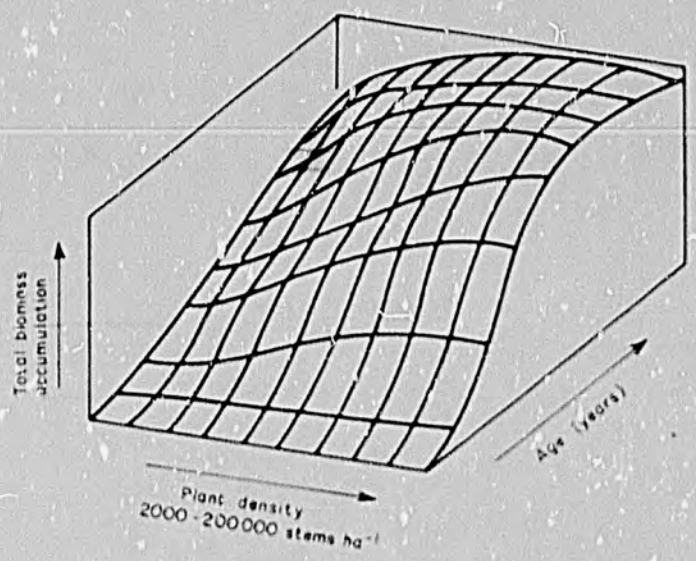
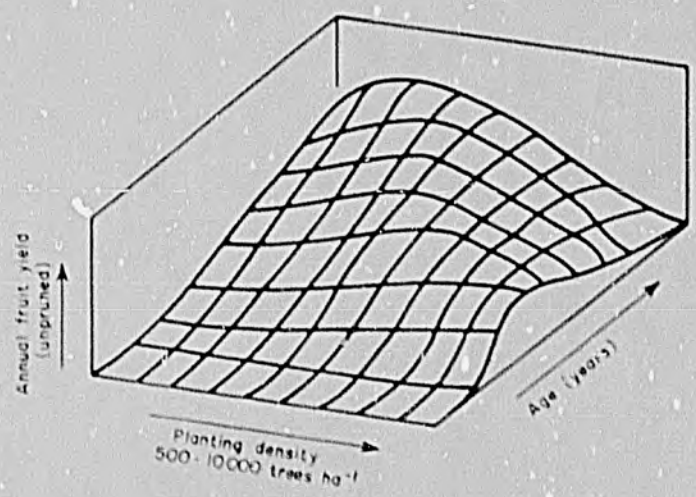


Figure 7. Changes in annual fruit yield with time for a woody perennial species planted at different densities. Small amounts of fruit per plant can give substantial yields per unit area at very high plant populations early on, but increasing densities (and the development of pests and diseases) can make such unpruned stands rapidly unproductive. Mid-level



populations will attain maximum yields per unit area later but possibly become unproductive less quickly. Low levels of plant population will give longer individual tree yields but too wide a spacing will limit yield per unit area (although it may make management easier). Pruning at any time will shift the response to the left.

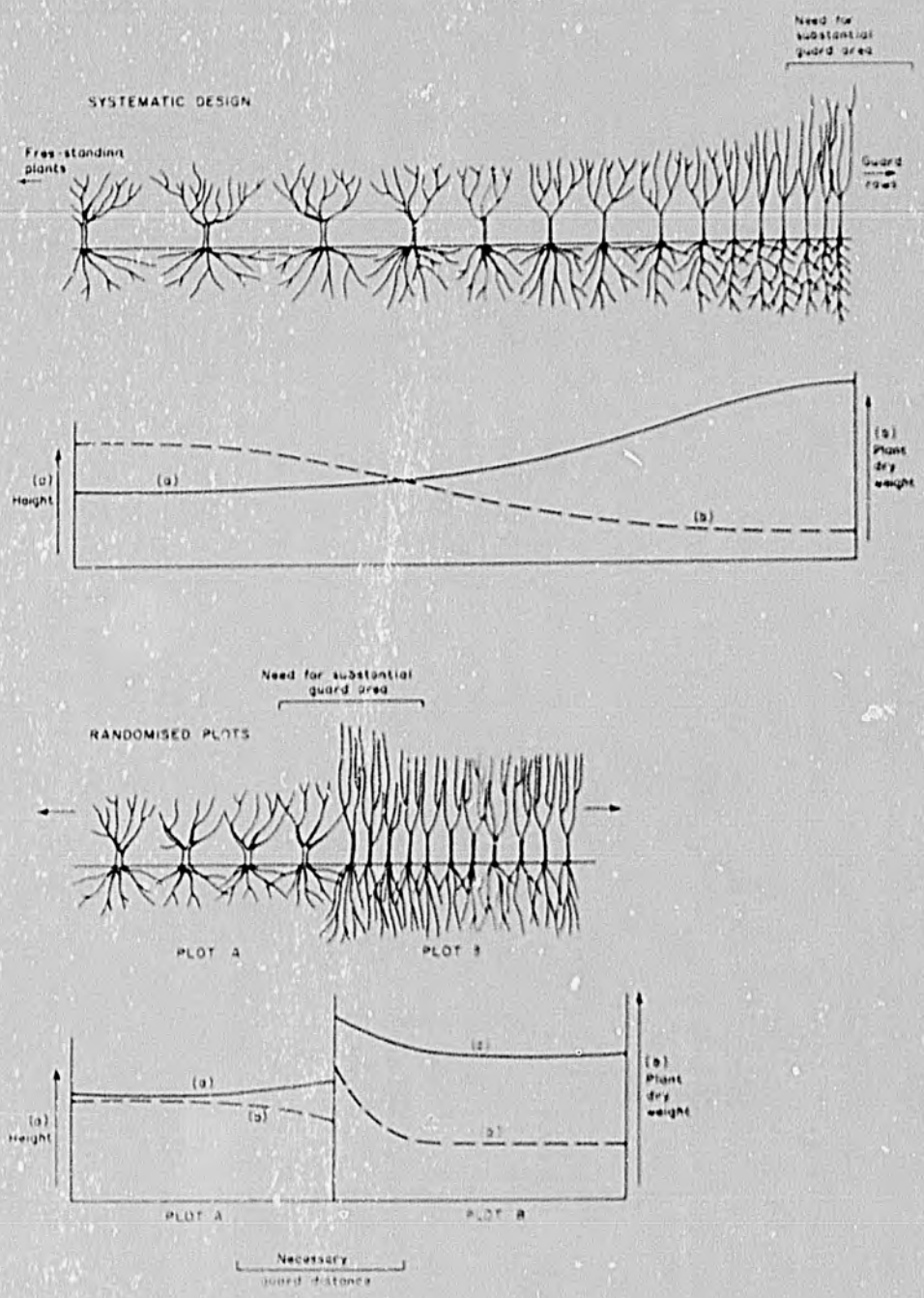


Figure 8 Systematic designs require adequate external guard rows (especially at the close-spaced part) but no internal guard rows. Conventional randomized block layouts involving spacing treatments also require internal (between-plot) guard areas which can often take up a considerable area.

In many mixed cropping situations it is seldom easy to predict the full effects of changes in plant density and arrangement on either the composite or individual yields of the components, or on the size-regulating effects on plant parts. It is, therefore, often necessary to arrange for this to be tested experimentally. This particularly applies to agroforestry plant associations where the species combinations may not have been investigated in this way previously. As the possible combinations of variables and levels of the spacing variables are numerous, and other management factors have also to be included, the space and time taken to obtain reliable results can be considerable. Furthermore, experiments need to be repeated over several seasons and to cover the transformations with age of the woody component(s). We have, therefore, to break the problem down and find quick, cost-effective approaches. This may best be done by formulating a programme in the following manner.

- Evaluate any existing information about the known responses of the individual plant components to changes in plant density and rectangularity.

- Formulate a selected set of treatments that investigates the effects of plant density and rectangularity in an unconfounded way, and also of different levels of intimacy of the components.
  - So that the results can be made much more extrapolatable to further changes in these variables and, to some extent to the effect of changes in environmental conditions as far as these can be predicted from the general body of knowledge.

- Select a basic minimum of other critical management variables (pruning/lopping of woody component(s), time-of-sowing of the seasonal component(s), from what is known or can be postulated as likely to minimize detrimental between-species interface effects.

- Split the investigation into several small, easily-managed experiments if the number of variables and levels that must be studied is still unavoidably large.

Working in the above way is likely to provide a much better understanding of what is happening than by setting up experiments that merely

test "packages" of treatments (for example, a set of "practical" hedge-row comparisons). Such treatments almost invariably confound the effects of plant density and rectangularity and so give results that cannot be extrapolated, or provide any fundamental understanding of plant responses to these overriding variables. The main excuse for undertaking such "package" experiments is when either the problems of species selection and/or management options are so little understood that the main purpose of the experiment is to help define these, or when they are so well known for a particular site or area that simple on-farm trials are all that are needed to test the best of a small set of establishment options.

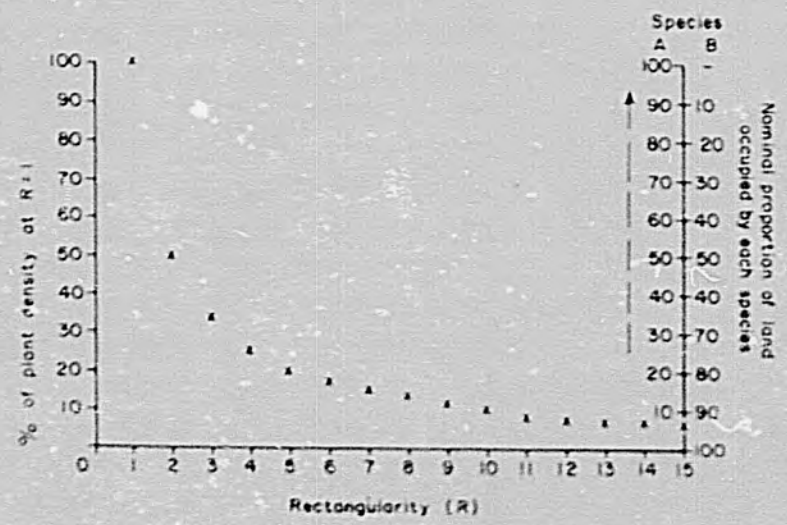
There is now a large body of literature concerning the evaluation of species mixtures in field trials (see selected references). Comparatively little refers to mixtures of woody perennials and herbaceous species, however.

Rectangularity as an important spacing tool in mixed cropping situations.

Manipulating the rectangularity of the tree/bush species in a mixed tree/crop association can be a convenient way to obviate adverse effects of interspecific interference and this is the basis of "alley-cropping". But Figure 9 illustrates some simple points to remember. First, that changes in rectangularity above 5 or 6 have a greatly diminishing effect. Second, that at low rectangularities even a small change will greatly reduced the plant population per unit area and, as Figure 4 shows this is the more influential of the two variables on yield i many situations. Figure 10 illustrates the advantage often to be gained by revising the in-row spacing of the trees when increasing the rectangularity, giving several examples.

In experimental field layouts it may be desirable to keep rectangularity and plant density unconfounded and this can be achieved only if between-row spacing changes (rectangularity changes) are simultaneously accompanied by the necessary in-row spacing changes (see legend Figure 9).

If plants in a 2-component mixture were of approximately the same stature, and each is assumed to occupy an approximately equivalent area of alloted space, then row-cropping with



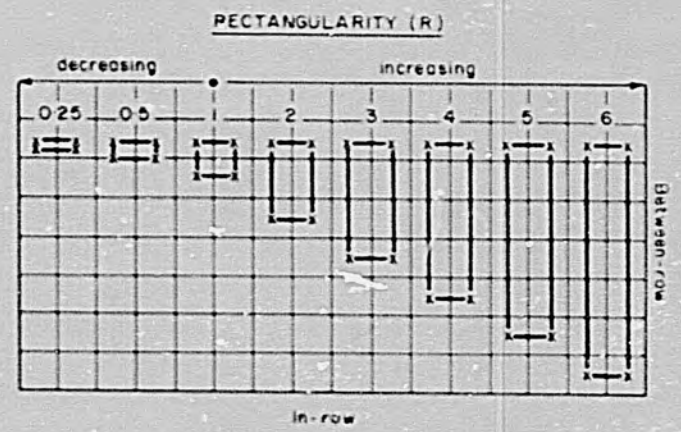


Figure 9. Different rectangularities (right) and the way in which plant population per unit area changes with a change in rectangularity if the in-row spacing remains the same (left). Changes in the nominal allocated area (assuming the species A is a tree and it occupies all the land at its optimum plant density at rectangularity 1) are shown on the right-hand axis, but the actual area utilized by each species will be more in the direction of the dotted arrow as the tree matures and its canopy and roots spread to the between-row space.

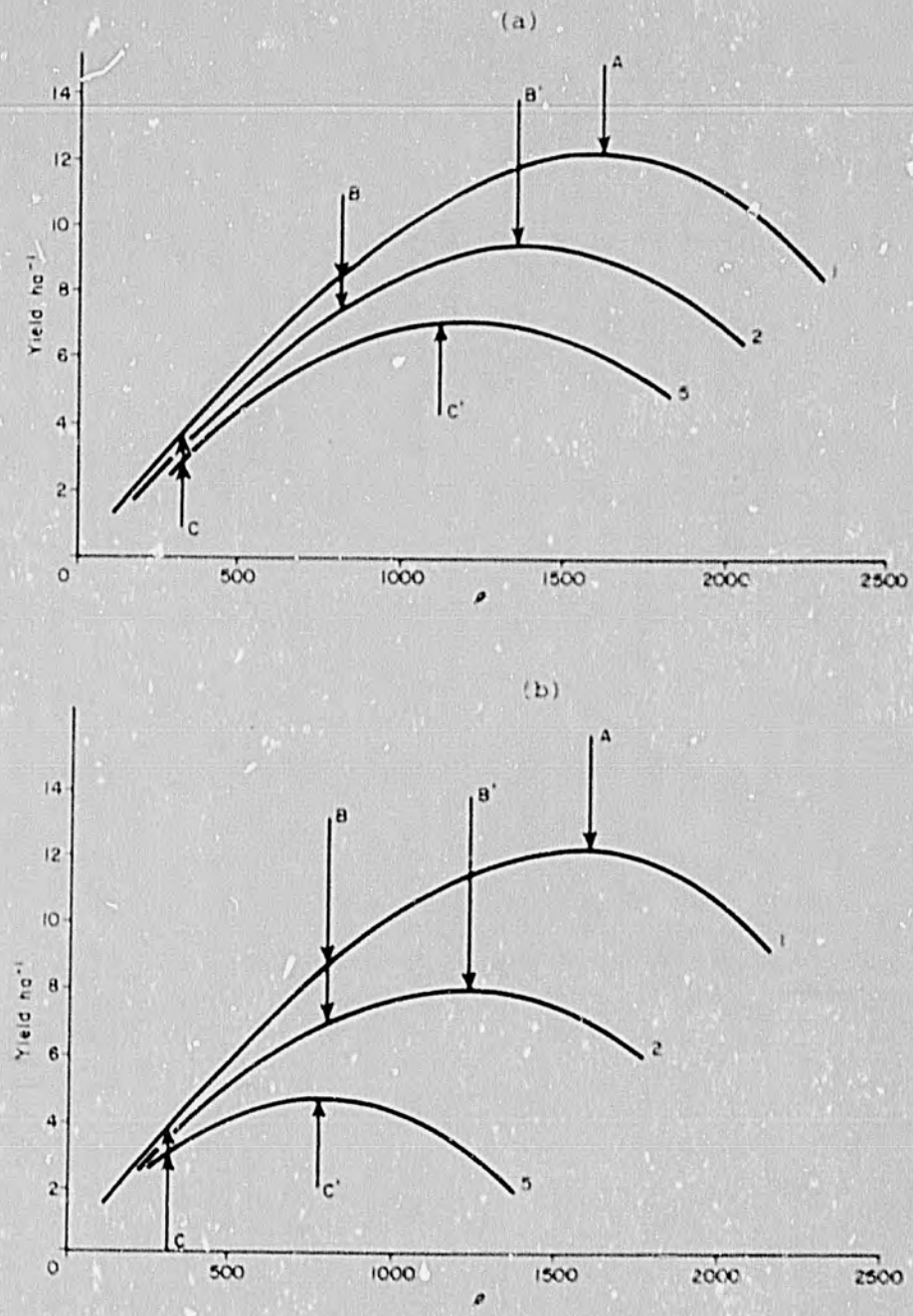
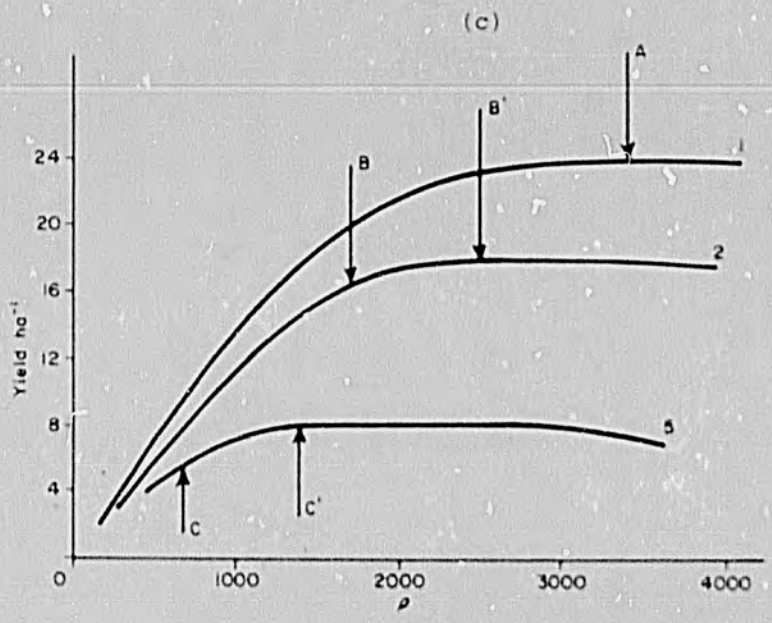


Figure 10. The sets of curves show some postulated yield responses to changes in plant density at different rectangularities (1,2 and 5). In (a) the effects of increasing rectangularity are less than in (b) but, in both cases B and C indicate the yields obtainable when the plant population is reduced to a half or a fifth, respectively when the in-row spacing is *not* changed to compensate for the increase in rectangularity (continue over).



		Plant density	Rectangularity	Nominal area (%)	Revised optimum plant density	Estimated yield (t ha⁻¹)
						Plant part
①	A	1600 (optimum)	1	100	-	12.2
	B	800	2	50	(B') 1350	9.6
	C	320	5	20	(C') 1100	7.1
②	A	1600 (optimum)	1	100	-	12.2
	B	800	2	50	(B') 1250	8.0
	C	320	5	20	(C') 875	4.75
						Biomass
③	A	3400 (optimum)	1	100	-	24.0
	B	1700	2	50	(B') 2500	17.5
	C	680	5	20	(C') 1400	8.0

Figure 10. (continued)

B' and C' indicate on the appropriate curves what scope there is, in this hypothetical situation, for such compensation.

In (c) the same situation is demonstrated for an asymptotic (total biomass) response curve, with less opportunity for compensation in this case. Unless the relationships such as these shown here are known, the effects of manipulation of rectangularity and plant density can only be conjectured.

the two species (as in situations shown later in Figure 12) between-row space as shown on the right-hand axis in Figure 9. If species A is a tree or bush it will clearly soon occupy a greater proportion of the available space at the expense of a smaller-statured agricultural crop species and continue to increase its share as the canopy develops, unless this is restricted by management. In practice, therefore the space allocation will always be less than shown (i.e. in the direction of the right-hand arrow). It may be useful to consider the "extra" space needed, if this can be approximated, in terms of the number of rectangularity units (in-row spacing) it represents, and this should then be added to the initial rectangularity choice (remembering that after R5 or 6 there is little effect or either plant density or allocated space). This may make a useful "rule-of-the-thumb" approach to alley-cropping dimensions, especially if a further correction is also made for any "interface" effects on the yield of the two components (i.e. any likely successful "encroachment on tree space by the agricultural crop, a positive effect; or conversely, any extended interference by the tree beyond its canopy spread). However, to discover what these effects actually are in practice it is really necessary to examine specific tree/crop interfaces in the field. This can be done either by selecting part of a spacing experiment to work on, or by a prior (and relatively simple) separate field experiment using just a simple geometric design (see Section on "The Tree/Crop Interface".

In an "alley-cropping" situation the rectangularity will usually be such that the tree/bush species exerts virtually no intraspecific interference from row to row other than, perhaps, from a small amount of mutual shelter. Thus the three factors to consider in influencing yield are the within-row effects of the tree/bush species on its own growth and development, the interface effects between the tree and the agricultural crop and the within-crop conditions of the latter. The comments made previously highlight the need to consider carefully the within-row spacings of the tree so as to maintain an effective plant population per unit area. This is particularly important in the early years of establishing hedegrows when within-row tree/bush spacing will have an effect on its growth, form and productivity. Later within-row spacing of the hedgerow species will become less influential (Figure 11). It is also important to have a clear understanding of the interface effects, both for chosing compatible species and in order to

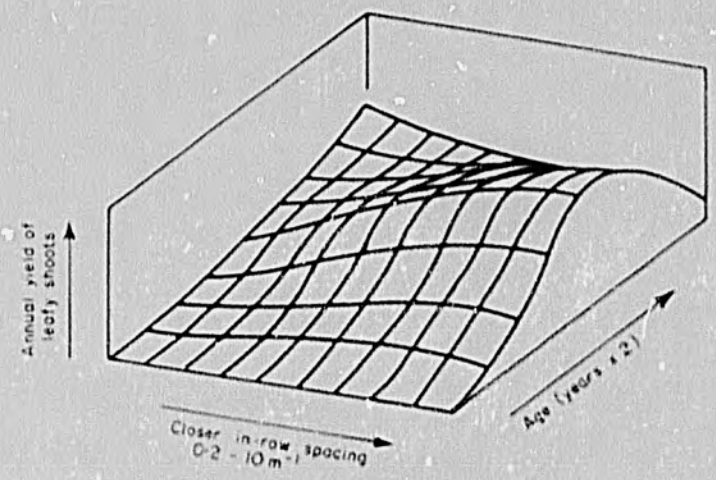


Figure 11. Changes with age in the yield of leafy shoots in hedgerows with different within-row spacing. Assuming no over-browsing or excessive lopping and that hedge height is restricted to that achieved after 4-5 years. A decline in the numbers of active vegetative buds available may sometimes occur with some species (e.g. tea) after continued pruning of leafy shoots.

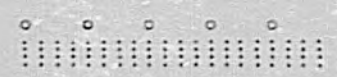
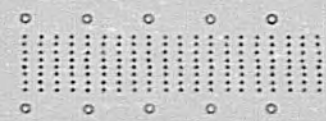
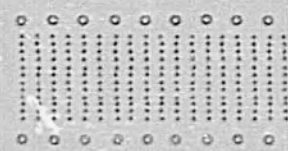
	Species A (O) Plant density (plants ha^{-1}) (a) actual	(b) nominal	Rectangularity	Area ratio	Example	Species B (·) Plant density (plants ha^{-1}) (a) actual	(b) nominal	Rectangularity
(a)	2500	2500	1	1:1		40000	80000	0.5
(b)	1666	1666	1.5	1:2		53333	80000	0.5
(c)	2500	2500	4	1:1		60000	80000	0.5

Figure 12. Various ways of intercropping a tree species (o) and a herbaceous agricultural crop (::): (a) interpolating between the tree rows (shown planted on the square); (b) removal of alternate tree rows to allow more space; (c) increasing the tree rectangularity but re-establishing the original plant density by a closer in-row spacing; (continued).

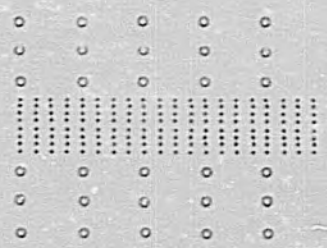
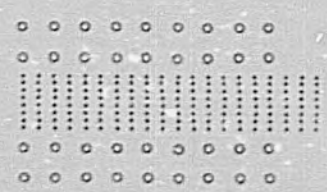
	Species A (O)				Example	Species B (·)			
	Plant density (plants ha⁻¹) (a) actual	(b) nominal	Rectangularity	Area ratio		Plant density (plants ha⁻¹) (a) actual	(b) nominal	Rectangularity	Area ratio
(d)	3000	5000	0.5	3.2		32000	80000	0.5	2.3
(e)	5000	5000	1	[illegible]		40000	80000	0.5	[illegible]

Figure 12 (cont') (d) and (e) show zonal arrangements (using strips). Biologically the option arrangement to maximize yields will depend on the individual yield/plant density relationships and the interface effects.

manipulate the rectangularity to the best effect*. The crop growing in the "alley" will, unless the tree/bush rectangularity is unusually small, be partly growing under "sole crop" conditions and its yield in this central region of the strip can, therefore, be estimated from local knowledge, or from previous sole crop spacing experiments. Effective alley cropping design and management will be brought about by using existing information to estimate the overall outcome of selected species/spacing combinations, and by designing field experiments that provide actual data relating to the underlying issues discussed here.

Design choices

In both mixed and zonal cropping situations the proportions of plant components needed in order to satisfy the particular levels of product required may need to be the modified depending on both the biological requirements to optimize the effect of interactions between components, as well as environmental demands to maintain land sustainability (and thus to keep a high proportion of trees/shrubs in the cropping system). Not only will the individual plant densities for each component require looking into but also the rectangularity options both within and between component species. Figure 12 shows that there are a number of alternative ways of arranging the spacing of the tree component in a mixed tree/crop system depending on what outputs we required and whether the nature of the tree/crop interface indicates better possibilities for either an intimate or separate arrangement. A reduction in adverse interface effects can be achieved by decreasing the size of the individual zonal areas (towards sole cropping) and/or by altering the rectangularity (and in effect, increasing the actual plant density but not the plant population per unit allocated area) of both components so as to leave a bigger gap between them at the interfaces. An example is shown in Figure 13. The effect on within-species yields of increasing the actual plant density has to be compared with any improvement shown by the mixture.

Where we are dealing with seasonal plants of somewhat similar stature (i.e. herbaceous crop plants in general), and if we are concerned only with maximizing the overall yield per unit area of land, then the choice of total plant population of a two-component mixture will depend on the shape of the individual yield/density response curves and the extent to which these are

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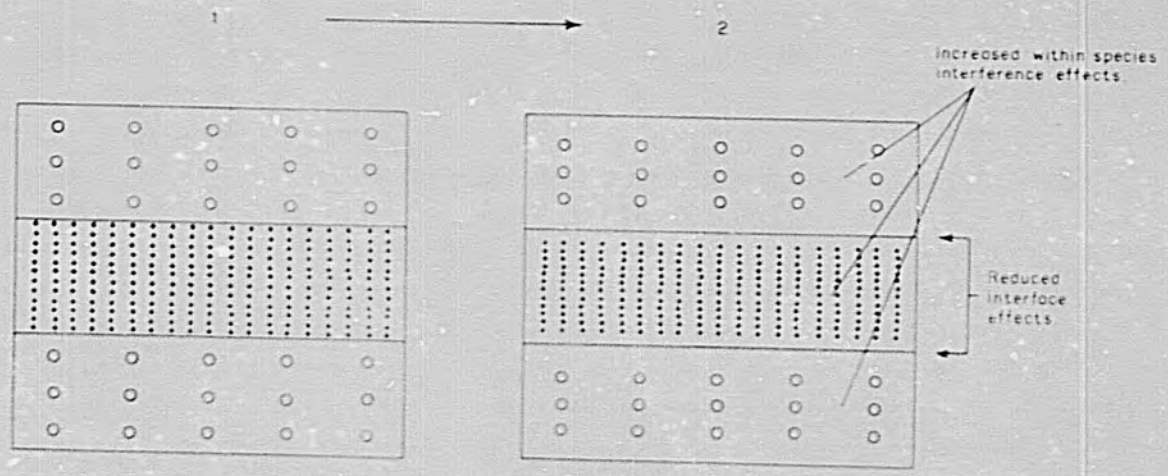
* or the 'intimacy' of other mixed cropping arrangements.



	Species A (O)				Species B (•)			
	Plant density (plants ha^{-1}) (a) actual	(b) nominal	Rectangularity	Area ratio	Plant density (plants ha^{-1}) (a) actual	(b) nominal	Rectangularity	Area ratio
1.	2500	5000	0.5	1:1	40000	80000	0.5	1:1
2.	2500	6250	0.4	1:1	40000	100000	0.4	1:1

Figure 13. If interface effects are particularly detrimental it may pay to separate the zones as far as possible, and this can be done by increasing the nominal plant density of each. The degree to which this effects yield will depend on the actual yield/plant density relationships for each crop (see Figure 4a).

modified in the actual spatial/temporal arrangement in the mixture by between-species interactions.

Figure 14 illustrates some examples of making this choice for 2-component pairs of species that represent a range of different yield/density responses, but without taking any interactions within the mixtures into account (ways of doing this are discussed by Willey and Rao, 1980).

Where one of the components is a tree or shrub then both plant size and the numbers per unit area will be markedly different from those of any herbaceous components (Figure 15). In this case the selection of any appropriate plant density in mixtures may better be made along somewhat different lines (see Huxley, P.A. 1983 The role of trees in agroforestry - some comments), or the space - exploiting possibilities of row-cropping trees at relatively high rectangularities can be utilized. (Figure 10a-c showed the possible advantages that are often still to be gained in compensating the in-row spacing when increasing that between-rows).

In planning spacing experiments it can be useful to know the way in-row and between-row spacings must change in order to maintain a particular plant population per unit area, or some stated fraction of this, and *vice versa*. This is shown in Table 1* as a matrix of factors by which to multiply the plant density chosen as the maximum under consideration (and at a rectangularity of 1.0, initially).

Finally, Figure 16 is an implementation flowchart that indicates the successive stages to be taken when deciding on plant densities and rectangularities. At the same time it indicates some of the more practical questions that need to be answered related to the characteristics of the land use system, as well as showing what type of experimental approach is useful if data still needed for decision-making are not yet available. Appendix 1 displays some suggestions for field layouts involving changes of spacing.

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* A micro-computer programme is available to expand this table and to scan the information contained therein for common (or closely similar) between-row or in-row distances.

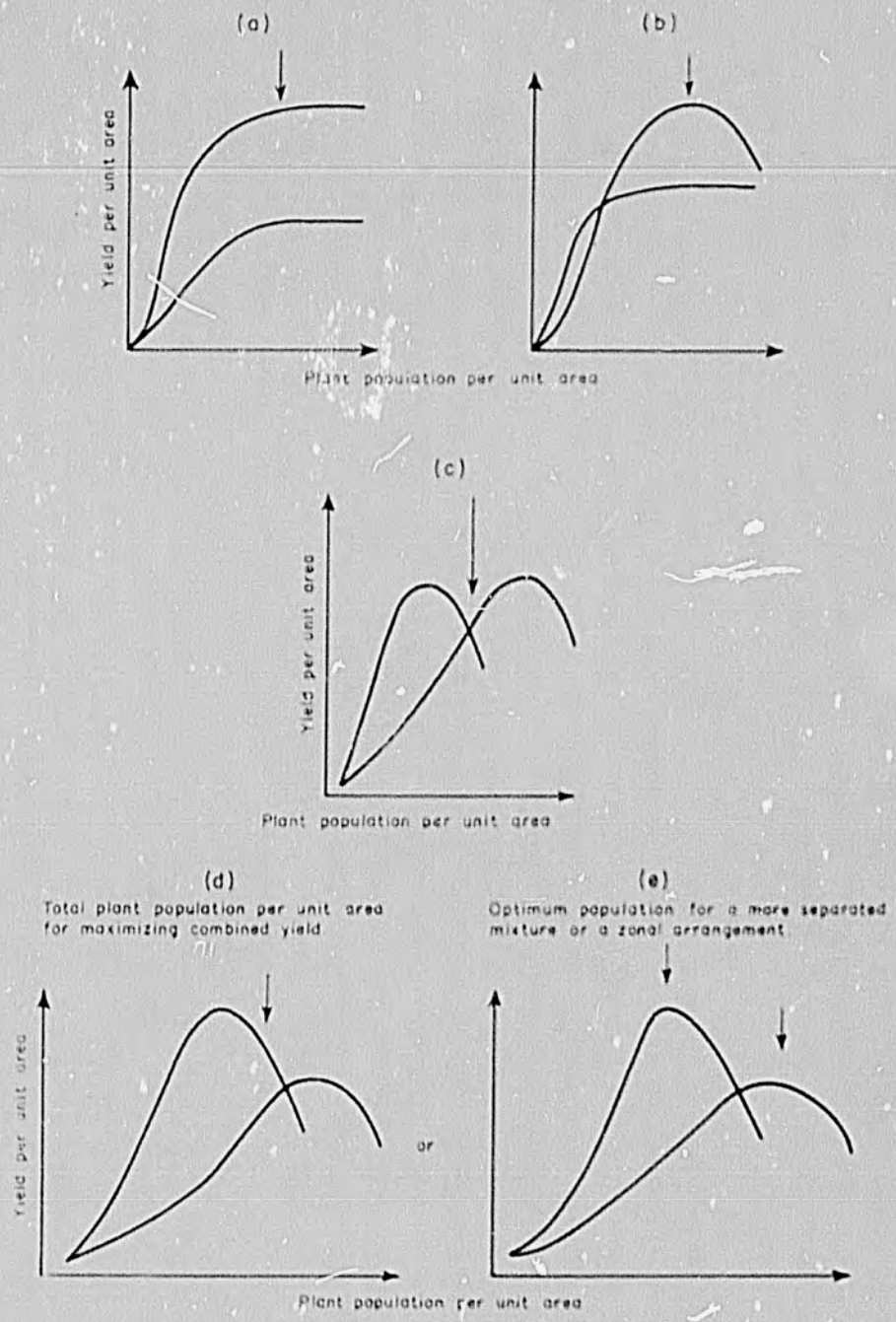

Figure 14. Various yield/plant density relationships of seasonal plant mixtures. The curves show the suggested optimum population of the mixture (a,b & c from Cannell, 1983). (a) two crop species grown for biomass (b) one species grown for biomass and the other for a plant part (c) two species grown for plant parts (and of similar yield potentials)(d) as for (c) but of different yield potentials, (e) as for (d) but to be grown in a zonal system.
Such simplifications do not take into account the farmers requirement to select appropriate yield proportions to suit his needs (see Mead, R. and Willey, R.W. 1980).

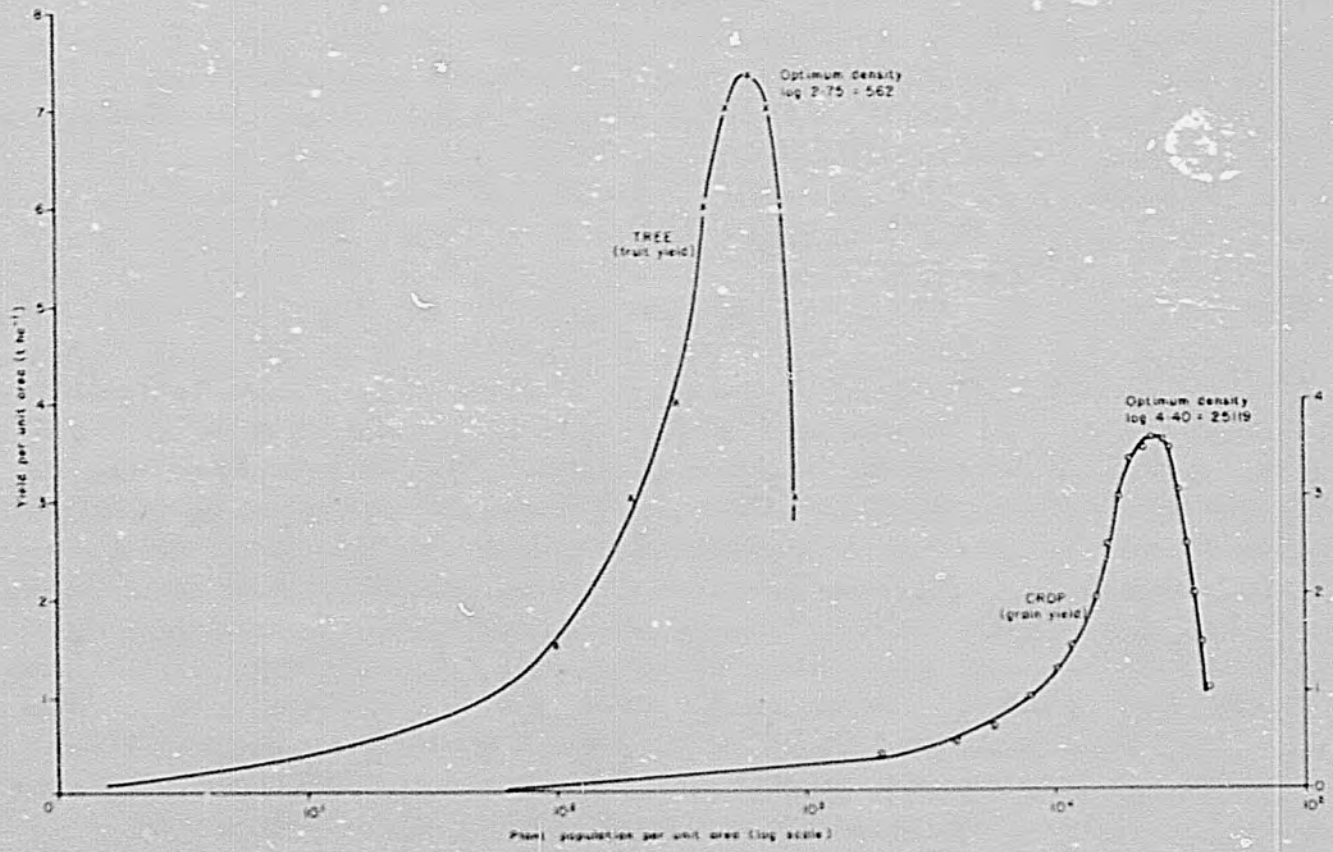

Figure 15. Parabolic yield/density relationships for fresh fruit from a tree species and grain from a cereal. Even when plant density is plotted on a logarithmic scale these two curves barely overlap. Hence "percentage ground cover" is a more practical unit to use with tree/herbaceous crop mixtures.

Plant population (ρ) - plant ha^{-1}		RECTANGULARITY (R) 1	1.5	2.0	3.0	4.0	6.0	8.0	12.0	16.0	24.0	32.0
1.0	a)	1.0	0.6667	0.5	0.3333	0.25	0.1667	0.1250	0.0833	0.0625	0.0417	0.0313
	b)	1.0	1.5	2.0	3.0	4.0	6.0	8.0	12.0	16.0	24.0	32.0
0.75	a)	1.1547	0.7698	0.5774	0.3849	0.2887	0.1925	0.1443	0.0962	0.0722	0.0481	0.0361
	b)	1.1547	1.7321	2.3094	3.4641	4.6188	6.9282	9.2376	13.8564	18.4752	27.7128	36.9504
0.66	a)	1.2247	0.8165	0.6124	0.4082	0.3062	0.2041	0.1531	0.1021	0.0765	0.0510	0.0383
	b)	1.2247	1.8371	2.4495	3.6742	4.8990	7.3485	9.7980	14.6969	19.5959	29.3939	39.1918
0.5	a)	1.4142	0.9428	0.7071	0.4714	0.3536	0.2357	0.1768	0.1179	0.0884	0.0589	0.0442
	b)	1.4142	2.1213	2.8284	4.2426	5.6569	8.4853	11.3137	16.9706	22.6274	33.9411	45.2548
0.33	a)	1.7321	1.1547	0.8660	0.5774	0.4330	0.2887	0.2165	0.1443	0.1083	0.0722	0.0541
	b)	1.7321	2.5981	3.4641	5.1962	6.9282	10.3923	13.8564	20.7846	27.7128	41.5692	55.4256
0.25	a)	2.0	1.3333	1.0	0.6667	0.5	0.3333	0.25	0.1667	0.1250	0.0833	0.0625
	b)	2.0	3.0	4.0	6.0	8.0	12.0	16.0	24.0	32.0	48.0	64.0
0.1667	a)	2.4495	1.6330	1.2247	0.8165	0.6124	0.4082	0.3062	0.2041	0.1531	0.1021	0.0765
	b)	2.4495	3.6742	4.8990	7.3485	9.7980	14.6969	19.5959	29.3939	39.1918	58.7878	78.3837
0.125	a)	2.8284	1.8856	1.4142	0.9428	0.7071	0.4714	0.3536	0.2357	0.1768	0.1179	0.0884
	b)	2.8284	4.2426	5.6569	8.4853	11.3137	16.9706	22.6274	33.9411	45.2548	67.8823	90.5097
0.0833	a)	3.4641	2.3094	1.7321	1.1547	0.8660	0.5774	0.4330	0.2887	0.2165	0.1443	0.1083
	b)	3.4641	5.1962	6.9282	10.3923	13.8564	20.7846	27.7128	41.5692	55.4256	83.1384	110.851
0.0625	a)	4.0	2.6667	2.0	1.3333	1.0	0.6667	0.5	0.3333	0.25	0.1667	0.125
	b)	4.0	6.0	8.0	12.0	16.0	24.0	32.0	48.0	64.0	96.0	128.0

(in most cases rounding the above figures to 3 significant digits will be sufficient)

Table: 1 Factors for multiplying (a) in-row distance and (b) between-row distance of plants in order to achieve selected plant densities and rectangularities. Procede by chosing the maximum plant population required per unit area then calculate the in-row/between-row spacing (x) in metres, for a square plant for that plant density (i.e. R = 1, ρ = 1). For other arrangements multiply x by the appropriate factors given in the table. Note that the between-row factors for alternate columns (R) for any one plant population level (ρ) are multiples of 2; this can be useful in selecting combinations of ρ and R so as to give a more regular layout having multiples of a common unit for between-row dimensions.

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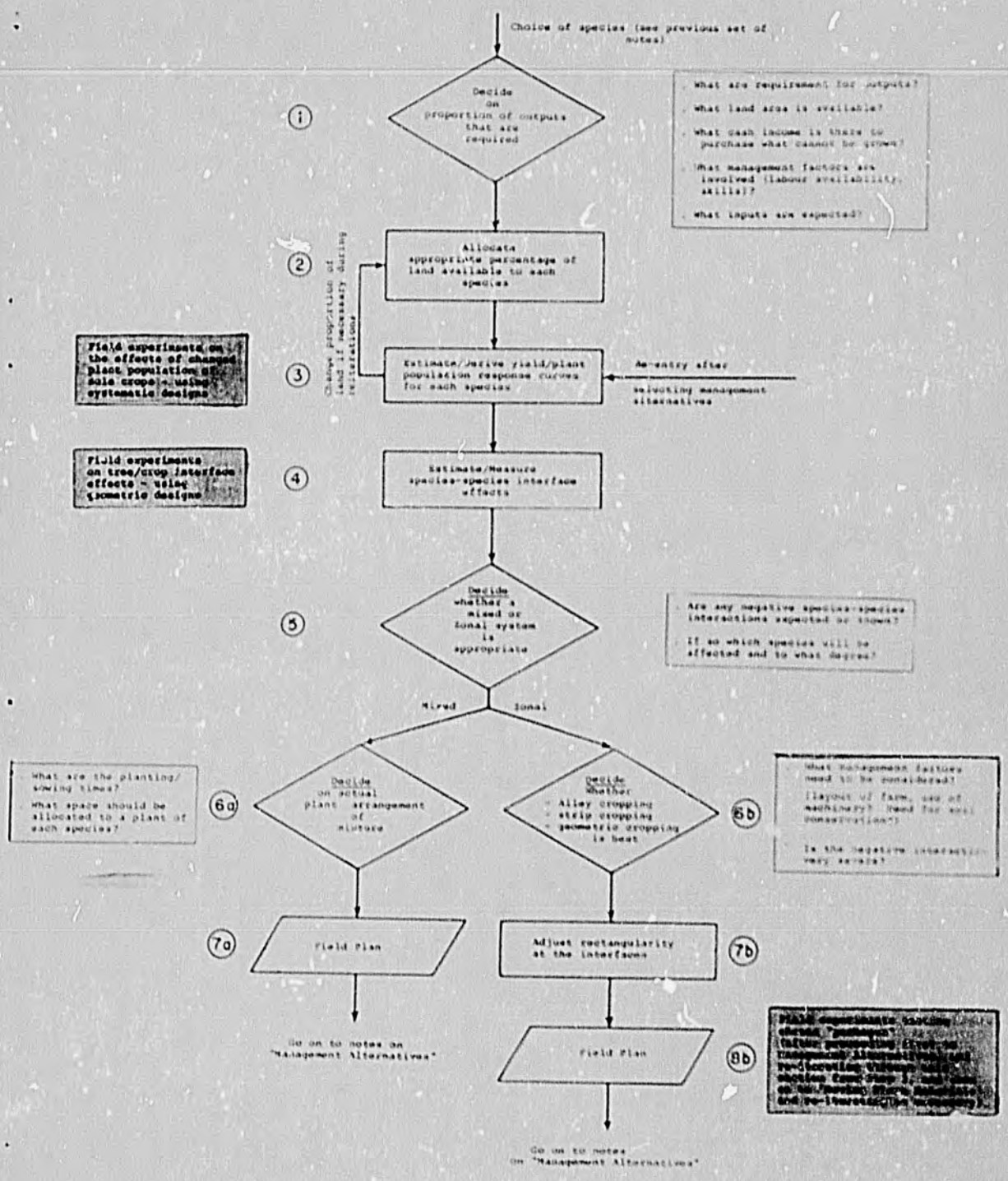
- useful field design and also discusses concepts.

FIGURE 16.

IMPLEMENTATION FLOWCHART FOR DECIDING ON PLANT POPULATION, RECTANGULARITY AND ARRANGEMENT
(Follows "Choice of species flowchart" and continues on to "Management Alternatives"



Appendix 1.

Some examples of experimental designs for spacing experiments

SEE ALSO

Wright, H.L. and Andrew, I.A. Principles of Experimental Design. (pp 67-82) and Andrew, I.A. and Wright, H.L. Evaluation (pp 108-130). Burley, J. and Wood, P.J. 1976. A manual on species and provenance research with particular reference to the tropics. Commonwealth Forestry Institute, Tropical Forestry Papers No. 10. Oxford.

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- From Mead, R. and Stern, R.D. 1980. Designing experiments for intercropping research. Expl. Agric. 16, 329-342.

A relatively small scale example of the use of factorial treatment structure is provided by an ICRISAT experiment. This involved two sorghum population densities (S_1 = 180,000 and S_2 = 120,000 plants/ha), three pigeonpea population densities (P_1 = 40,000, P_2 = 80,000 and P_3 = 120,000 plants/ha) and two row proportions (A_1 = 2 sorghum to 1 pigeonpea and A_2 = 1 sorghum to 1 pigeon-

$S_1P_3A_1$	$S_2P_1A_1$
$S_2P_3A_1$	S
P	$S_1P_1A_1$
$S_1P_2A_2$	$S_1P_2A_1$

$S_2P_1A_1$	$S_1P_2A_1$
P	$S_1P_1A_1$
$S_1P_3A_2$	$S_2P_2A_1$
$S_1P_3A_1$	S

Fig. 2. One replicate of a 3 × 2 × 2 factorial experiment with 2 sole crop treatments, arranged in two blocks of 8 plots.

pea). Large plots were needed for the collection of both growth and yield data, and hence the A X S interaction was confounded with blocks, giving six treatment combinations plus two sole crop plots (S = 180,000 plants/ha, and P = 40,000 plants/ha) in each block of 8 plots. Four blocks were used, comprising two complete replicates of the twelve factorial combinations, and the arrangements of one replicate (two blocks) is shown in Fig. 2. The original plan for this experiment included three complete replicates of a subset of the treatments shown in Fig. 2, which would have reduced the efficiency for many of the major treatment comparisons by factors of 3/2 or even 2.

Consider again the two principal advantages of factorial experiments with at least three factors. One is that the experimenter is able to examine the extent to which the response to one factor is affected by different levels of a second factor (interaction). In the sorghum/pigeonpea experiment the yield response for the three pigeonpea densities can be assessed (and compared) for the two sorghum densities, and also for the two row arrangements, whereas neither of these interactions could have been assessed from the original non-factorial experiment. The second advantage is the greater economy of the factorial experiment because of its hidden replication. In the sorghum/pigeonpea experiment the average comparison of two pigeonpea densities is based on a total of 8 plots per density whereas, with the original non-factorial design, a comparison between two pigeonpea densities would have been based on only 6 plots (two from each replicate). The advantages of hidden replication apply not only to tables of mean yields, but also to graphs of growth against time.

To illustrate these advantages, consider a theoretical intercropping experiment with 6 replicates of all twelve combinations of three densities of crop A

with four densities of crop B. A comparison of the average yields for two different densities of crop A is based on 24 experimental plots per density; and the comparison of any two particular combinations of densities of the two crops is based on 6 plots per combination. Suppose we now introduce three levels of nitrogen application and two genotypes of crop A, and instead of 6 replicates have no explicit replication, giving 72 plots (3 X 4 X 3 X 2) as before. We now have the same precision as before for the original comparisons, but also have comparisons of approximately the same precision between the nitrogen levels, between varieties and between combinations of any two of the four factors. To argue that the comparison between average yields for different densities of crop A may give different estimates from those for the original experiment only emphasizes the need to consider interactions between factors. The requirement to have the experiment arranged in relatively small blocks may reduce some of the advantages of the four factor experiments, but most can be retained through the device of confounding, which was used very simply in the sorghum/pigeonpea example.

Cochran and Cox (1957) is still the best reference book to help choose an appropriate design if no statistician is available for advice, though the designs have to be adapted slightly if sole crop treatments are to be included. If there are only a few sole crop treatments it may be sensible to include them in each block, as in the sorghum/pigeonpea experiment. It is important to realize that in a factorial experiment with a large number of combinations of different factor levels it is not necessary to have any replication in the sense of plots treated identically. Indeed for a large number of factors it is perfectly possible to draw sensible conclusions from an experiment having only a proportion of all the possible combinations of factor levels. These ideas (all of which appear in Cochran and Cox) are very well-established and are in no sense new or radical. The crucial point, which seems not to have been widely appreciated by researchers, is that the usual practice of having 3, 4 or even more replicates is only sensible if the number of treatment combinations is small. To use 3 or 4 replicates as a reason for avoiding large factorials is to misunderstand the purpose of replication.

A question which is related to the idea of factorial structure is the number of levels of a quantitative factor that should be used. There is a substantial body of statistical theory which points to the advantages of using a small number of levels with large replication rather than many levels with less replication (the replication may be hidden). Statistical results show specifically that the number of levels required should be the same as the number of parameters needed to describe the form of response. Thus only three levels are needed if a quadratic polynomial is used to summarize the yield response. If it is required to detect departures from a quadratic polynomial then a fourth level is needed, but it seems unlikely that more than four levels should be used for any one factor in a randomized experiment, and three will frequently be adequate, particularly if they are well spaced.

Augmented Block Design

The leucaena-spacing experiments on which the model is being based are in the augmented block design of Federer and Raghavarao (1975). The design allows one to ask questions of both a fairly advanced nature, with replications, and a preliminary nature for which replication is unnecessary. For example, one planting utilizing the augmented block design consists of four replications of six plots each (Fig. 1). Each replication has four replicated treatments and two unreplicated, or augmented, treatments. The replicated treatments are 5000, 10 000, 20 000, and 40 000 plants/ha. Augmented treatments range from 2500 plants/ha (preferred by foresters) to 80 000/ha, about the population density of a cornfield.

Analysis of variance is performed only on the replicated treatments, and experimental variations thus derived are used in tests of the augmented treatments. Augmented treatments are adjusted, according to the replication in which they are located, by the formula:

$$T_{adj} = T_{unadj} - X_{.} + X_{..}$$

where T_{adj} = adjusted treatment mean; T_{unadj}

From Rick H. Van Dan Beldt. 1983. Effect of spacing on growth of leucaena pp.103-108 in "Leucaena research in the Asia-Pacific region. Proceedings of IDRC/NFTA Workshop held in Singapore, 23-26 November, 1982. IDRC, Ottawa.

(see also Annexure to Manual Section 3C for further information on augmented designs).

Spacing (m)	Plot number	Spacing	Plot number
1 × 0.25*	101	1 × 0.25*	406
1 × 2*	102	1 × 2.5	405
1 × 1.5	103	1 × 2*	404
1 × 1*	104	1 × 0.75	403
1 × 0.5*	105	1 × 0.5*	402
1 × 3	106	1 × 1*	401
1 × 1*	201	1 × 1*	306
1 × 2*	202	1 × 0.375	305
1 × 0.25*	203	1 × 0.25*	304
0.5 × 0.25	204	0.5 × 0.33	303
1 × 4	205	1 × 2*	302
1 × 0.5*	206	1 × 0.5*	301

48 m

12 m

Fig. 1. Augmented block design of University of Hawaii leucaena spacing studies; plots consist of four rows spaced 1 m apart, with variable spacing within rows. Data are taken from centre rows at regular intervals. Means of augmented (nonreplicated) treatments are adjusted according to the replication in which they occur (= replicated treatment).*

= unadjusted treatment mean; X_r = mean of replicated treatments incorporating augmented treatment; and $X_{..}$ = overall mean of replicated treatments.

The augmented block design has the distinct advantage of incorporating far more treatments than the randomized block design used widely in forestry and agriculture. In all, 12 spacings at each site are examined for parameters of growth — height and diameter — over 4 years.

From Willey, R.W. and Rao, M.R. 1980.
A systematic design to examine effects of plant population and spatial arrangement in intercropping, illustrated by an experiment on chickpea/safflower. Expl. Agric. 17, 63-73.

Treatments and design

Four within-row spacings of chickpea were factorially combined with fifteen within-row spacings of safflower at two row arrangements; sole plots of each crop were included at four plant populations, as follows:

Intercrops

Chickpea: 25.0, 12.5, 8.3 and 6.3 cm within-row (C_1-C_4)

Safflower: 75.0 to 19.8 cm within-row in fifteen steps equivalent to 10% increases in population (S_1-S_{15})

Sole crops

Chickpea: 25.0, 12.5, 8.3 and 6.3 cm within-row (C_1-C_4, equal to 13.3, 26.7, 40.0 and 53.3 plants/m^2)

Safflower: 75.0, 38.5, 26.3 and 19.8 cm within-row (S_1, S_8, S_{12}, S_{15}, equal to 4.4, 8.7, 12.7 and 16.7 plants/m^2)

Row arrangements

1 chickpea: 1 safflower in 30 cm rows (1:1)

2 chickpea: 1 safflower in 30 cm rows (2:1)

The basic layout was a strip-plot design with strips of chickpea spacing treatments crossed with the intercrop row arrangement and sole plot treatments (Fig. 1). Safflower spacings were systematically changed, within each row arrangement, with the closest spacing towards the middle of the chickpea strip

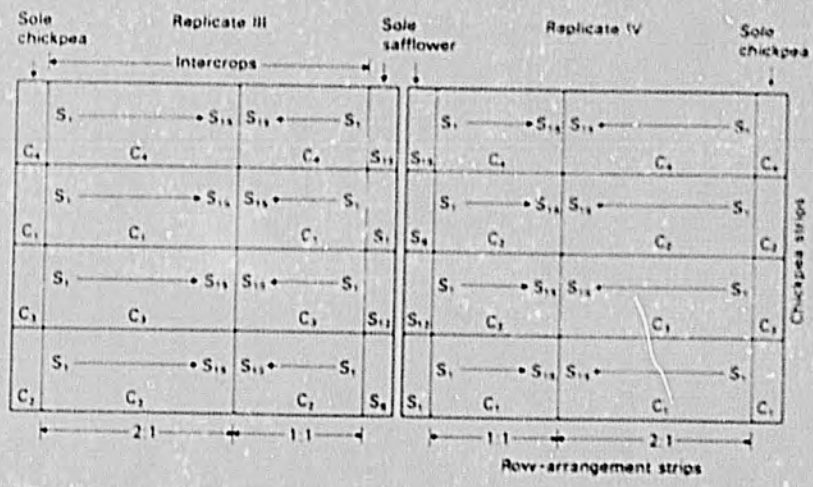


Fig. 1. Lay-out of two replicates showing chickpea and row-arrangement strips, position of sole plots, and direction of systematic change in safflower population.

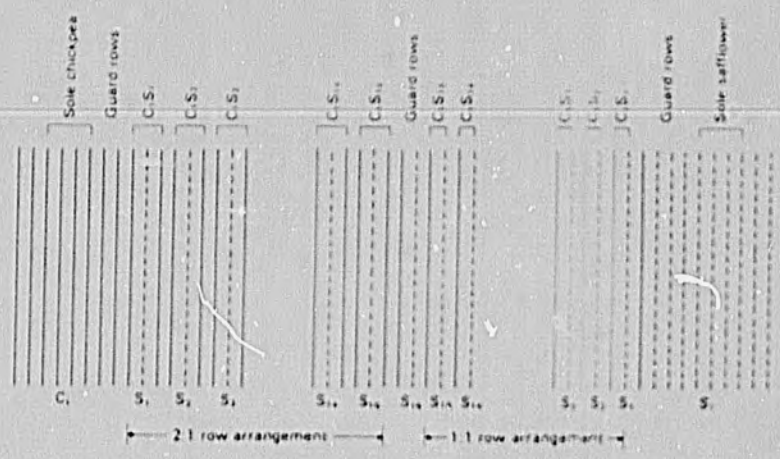
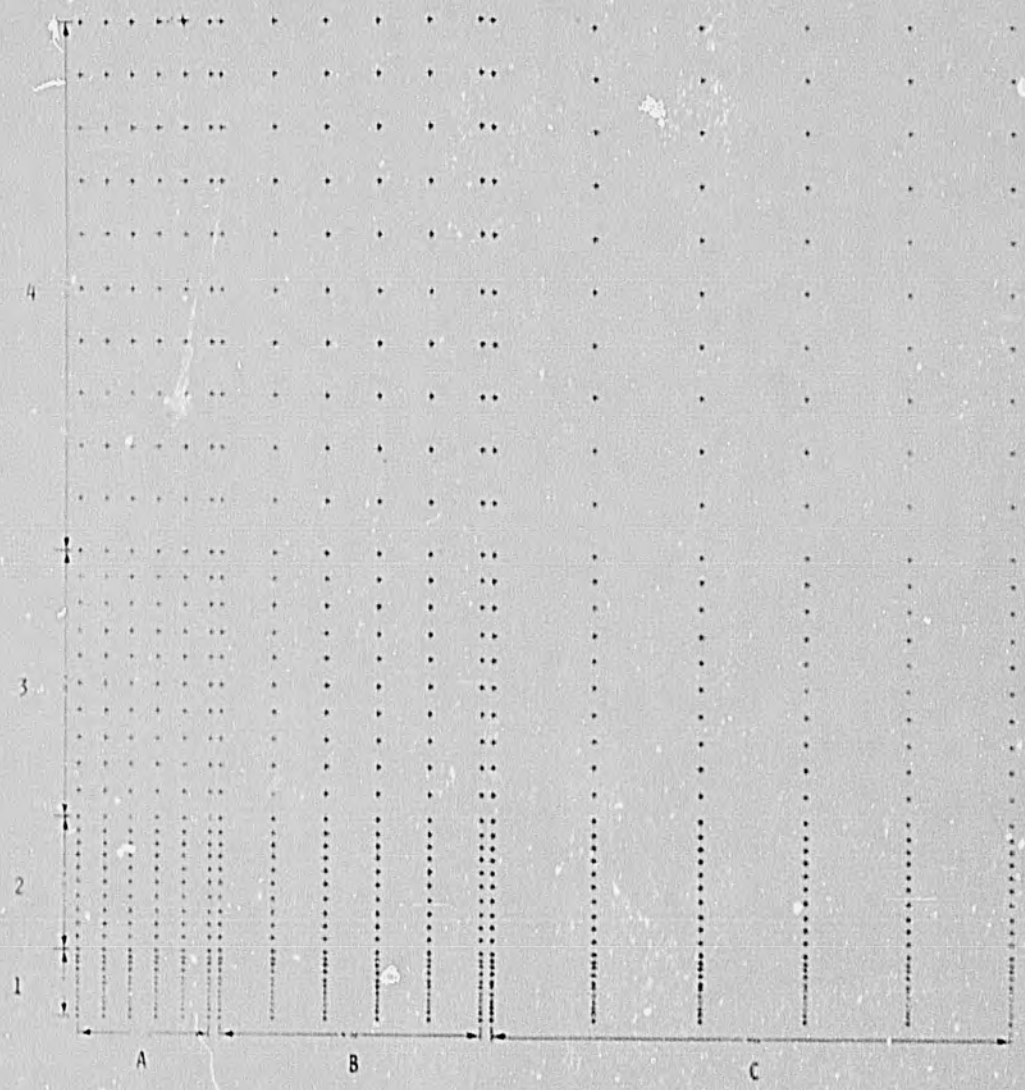


Fig. 2. Lay-out of a chickpea strip (at C_1 population as an example) and sole plots showing number of rows harvested (S_1 to S_{14} = range of systematic safflower populations).

(Fig. 2). For each chickpea strip, a sole chickpea plot was included at the 2:1 row arrangement end and a sole safflower plot at the 1:1 end. Within-row spacings for these sole plots were comparable with the rest of the strip (Fig. 1).

Although the layout was arranged to minimize the need for guard rows within the strips, 2-3 rows were included between the sole plot and intercropping part of the strip and between the two row arrangements (Fig. 2). To minimize the possibility of the systematic changes in safflower plant population coinciding with systematic soil fertility changes, these systematic treatments were arranged N to S in two of the replicates and S to N in the other two (Fig. 1).

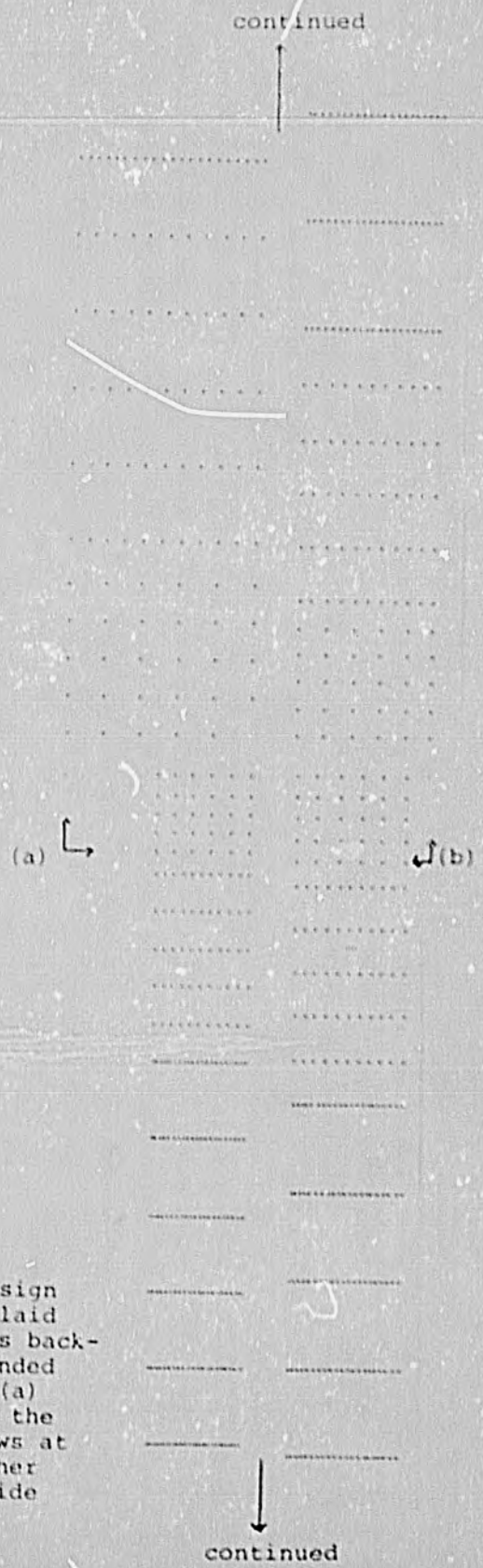


From Getahun, A. and Ndegwa, C.M. 1983. Woodfuel in Kenya: Problems and prospects, pp. 123-146 in Hoekstra, D.A. and Kuguru, F.M. (Eds) "Agroforestry Systems for small-scale farmers". Proc. of an ICRAF/BAT workshop held in Nairobi in September, 1982. ICRAF, Nairobi.

This systematic design tests changes of rectangularity (A-C) at different plant popualtions (1-4), but not both together. It provides a compact field layout and maintains equal sample sizes throughout.

A systematic plot layout
that tests both plant
population per hectare
(A to D) and rectangularity
(1 to 4) simultaneously

- and see over



The previous systematic design would be more effectively laid out with the "denser" parts back-to-back (and possibly extended as shown by the arrows at (a) and (b). This would avoid the need for extended guard rows at this part of the design other than at the remaining outside edges.