ANALYSIS OF YIELD ADVANTAGE IN INTERCROPPING

A thesis presented in partial fulfillment for the requirement of M.Sc. in Crop Science (Production) at Wageningen Agricultural University.

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EXECUTIVE SUMMARY

It has long been recognized that intercropping can give yield advantages over sole cropping. Various approaches for identifying such yield benefits have been developed. This thesis reviews the additive and replacement design as well as the hyperbolic regression approach. Specific objectives were to examine and compare these three approaches for investigating intercrop productivity and use this experience for directing future research in Southern Tanzania on mixed cropping of sesame and maize. An experiment on an intercrop of barley and oats, grown in both additive and replacement series, was used as a case study. Data on shoot biomass and kernel yield were collected and analyzed using the standard procedures for additive and replacement design as well as the descriptive regression approach.

For additive design, average yields obtained in intercrops were significantly higher compared to yields obtained in monocultures. On average 10% more land was required for monocultures to produce the intercrop yield. Analysis with the hyperbolic regression approach demonstrated that this yield benefit could be fully accounted for by the increased densities used in mixtures of the additive design. This was in line with the observation on yield-density response of barley in monoculture, where it was found that densities of barley in monoculture were too low to give maximum yield. Therefore, it was concluded that higher yields would also have been achieved by growing barley in monocultures at a higher density. This stresses the need to grow monocultures in optimum density, when using the additive design.

For replacement design, average yields obtained in the intercrops were not significantly different from the yields obtained in monocultures. This finding was in line with the outcome of the descriptive regression approach, which indicated that barley and oats grown in mixtures did not promote each other. Analysis of intermediate harvests showed that values for Relative Yield Total of unity might either reflect the use of low densities or true exclusion of species for use of resources. This points at the need for using optimum densities in

monocultures of the replacement design. This issue is particularly relevant since there are clear indications that in Southern Tanzania sesame and maize are grown at below-optimum densities.

The hyperbolic regression approach was able to simultaneously analyze various density-combinations of barley and oats. For this approach a range of densities is required to be able to determine the strength of intra- and interspecific competition. Determination of the relative competitive ability reveals the true nature of the interaction between the component species of a mixture and through this the possibilities for a 'true' yield advantage. Furthermore, this method enables the simulation of expected yield, and yield advantage, for various density combinations. In this way contributing to the determination of optimum densities and mixing ratios for intercropping.

Both advantages and limitations have been identified for each design. Therefore, it is recommended that researchers have to analyze the crop-crop system to be addressed and choose an appropriate approach, based on their specific objectives. For analyzing the sesame-maize mixed cropping system in Southern Tanzania, additive design and the descriptive regression approach are recommended. The additive design seems appropriate since it reflects the actual cropping system; a fixed density of maize is grown with various densities of sesame. In this case a preliminary experiment should be conducted to determine optimum densities of sole crops, at input levels used by farmers. A more appealing alternative would be to grow sole crops and mixtures of sesame and maize at a range of densities and analyze the experiment by using the regression approach.

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1. INTRODUCTION

1.1 Background information

In Tanzania, sesame (*Sesamum indicum*) is an important traditional oilseed crop. Its value exceeds that of most other crops, particularly in areas where marketing and haulage systems are efficient. Sesame has become a cash crop as early as 1949, and in 1959 about 3,600 tones of seed were exported (Weiss, 1983). Slightly over 78% of national sesame production comes from Mtwara and Lindi Regions in the Southern Zone and approximately 14% is produced in the Ruvuma Region in the Southern Highlands (Appendix 1). In these regions in south-east Tanzania, sesame is the second most important cash crop after cashew. On the other hand, maize (*Zea mays*) is one of the most important staples and cash crops in this region. This is based on the results of the survey carried out in Farming System Zone 8 in 1992 (Appendix 2). The survey was conducted by the Southern Zone Farming Systems Research Team in collaboration with the extension staff. Most farmers in the surveyed area practice mixed cropping of sesame and maize, sometimes combined with other crops (e.g. cassava, sorghum, pigeon pea). Mixed cropping is a centuries-old technique, that has been practiced by farmers in this area for varied reasons such as better exploitation of the environment, reduced risk through stability of production, spreading labor demand and satisfying dietary requirements.

Presently, yield of maize and sesame under mixed cropping are very low. Data from survey and on-farm research showed that yields of sesame and maize only amounted to an average of 250 and 380 kg/ha, respectively. These were generally caused by poorly distributed rainfall, high weed and insect pest infestations, low soil fertility status, use of low yielding cultivars and low densities in the mixtures (Katinila *et al., 1995*). High weed infestations are caused by labor shortage and inefficient weed control, as land preparation and weeding are mainly conducted by hand hoe. Sesame flea beetle (*Alocypha bimaculata*) and snails are the most important pests of sesame. Low soil fertility arises due to the fact that farmers do not use fertilizers because the input is not readily available and whenever available costs are high. Consequently, a declining soil fertility status is observed, resulting from continuos mining of soil. Use of low yielding cultivars arises due to the fact that improved cultivars are not readily available. Low densities of the species in the mixtures is a traditional way of sowing, which farmers have been practicing for decades. This is one of the major reasons for the low yields of sesame and maize in the mixtures. Therefore, optimization of plant densities of the species in the mixtures and better proportions might improve productivity of the system.

Two research questions should be answered to address the productivity of sesame-maize mixed cropping systems in Southern Tanzania:(1) What is the nature of the interaction of the species in this mixture and (2) Which densities and mixing ratios are required to obtain economically maximum yields in the mixture of the two species. In response to this situation, the Naliendele Agricultural Research Institute is planning to carry out a study so as to investigate the nature of interaction between sesame and maize and to use this understanding for improving productivity of this system by determining optimum sowing densities and mixing ratios. However, a preparatory study is required to gain better insights into the current designs used in intercropping experiments. This thesis reviews the additive and replacement design as well as the descriptive regression approach described by Spitters (1983). The reviews are illustrated with an experiment on an intercrop of barley and oats grown in both additive and replacement series. This study will assist in giving future direction for improving productivity of the traditional sesame and maize mixed cropping in Southern Tanzania.

1.2 Specific Objectives:

- To examine and compare the additive and replacement designs as well as descriptive regression approach for investigating intercrop productivity.
- Use this experience for directing future research in Southern Tanzania on mixed cropping of sesame and maize.

1.3 Review of literature on Intercropping

1.3.1 The basis of intercrop productivity in general

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. 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 mixtures (Ranganathan, 1993). Plants compete for growth factors such as light, water, nutrients, oxygen and carbon dioxide and the outcome of this competition is a general 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 were able to conclude that greater and better exploitation of resources was probably the most common basis for higher yields (Willey *et al.*,1986; Innis, 1997; Fukai and Trenbath, 1993). 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, Keating and Carberry, 1993), greater nutrient uptake (Hall, 1974a,b, Morris and Garrity, 1993b) and improved water use efficiency (Vorasoot, 1982, Morris and Garrity, 1993a).

The capture and utilization of P and K, two non-labile soil resources, were examined by Morris and Garrity (1993b). On average, intercrops took up 43% more P and 35% more K than the sole crops. It was observed that integration of root surface areas over time is larger for intercrops, enabling diffusion of P and K sorbed on soil particles to pass across a surface area which exceeds that of either sole crops. Water utilization efficiency by intercrop, however, greatly exceeded water utilization efficiency by sole crops, often by more than 18% and by as much as 99%. Morris and Garrity (1993a) also reported that variation in plant density of species often affects water-utilization efficiency.

Fukai and Trenbath (1993) argue that intercrops are more productive when their component crops differ greatly in growth duration so that their maximum requirements for growth resources occur at different times. For high intercrop productivity, plants of the early maturing components should grow with little interference from the late maturing crop. The latter may be affected somewhat by the associated crop, but a long time period for further growth after harvest of the first crop should ensure good recovery and full use of available resources. Compared with a sole crop, the reduced size of non-harvestable organs of the late maturing crop can result in improved assimilate partitioning to the harvested organ during the later part of the growth period and consequently a higher harvest index. Because of the differences in growth rhythm between component crops, there tends to be little interaction between relative performance of component crops, and growth environment and hence productivity of this type of intercrop is often insensitive to management intervention.

In contrast, when growth duration of components are similar, the crops compete more intensively for available resources. Their relative performances can then be greatly affected by small changes in growth environment. 'Additive' intercrops of this type may nevertheless be productive particularly where growth resources are more completely captured than in corresponding sole crops. However, if non-replenished growth resources are utilized too rapidly, the less competitive component may suffer greatly. 'Replacement' intercrops of this type are not so productive in high yielding environments. When the growth environment is not favorable however, their total lower plant population compared to additive intercrops may allow yields of replacement intercrops to be less depressed. Where similar duration crops are grown in variable environments, replacement intercrops may therefore be preferred due to their greater yield stability. When a dominant crop uses available resources excessively and inefficiently, agronomic manipulation in favor of the usually suppressed component seems most likely to improve productivity of the whole intercrop.

Intercrop productivity depends on the genetic constitution of component crops, growth environment (atmospheric and soil) and agronomic manipulation of micro-environment. The interaction of these factors should be optimized so that the limiting resources are utilized most efficiently in the intercrops. An understanding of the shared resources among component crops will help to identify more appropriate agronomic manipulations and cultivars for intercrops.

Another aspect of the interaction between crops is population dynamics. Gain in mixed cropping has been said to originate because higher plant densities are possible (Andrews and Kassam, 1976; Davis and Woolley, 1993). The traits required for intercropping are those which enhance complementary effect between species. Cultivars of species which are compatible in this way can be planted at higher density, and this is a major factor contributing to the ability of intercrops to yield more than sole crops (Davis and Woolley, 1993).

1.3.2 Common designs for studying yield advantage in intercropping

1.3.2.1 Additive design

Studies of intercropping systems are generally conducted by either an additive design, replacement design or a descriptive regression approach.

Of these designs, the additive design is the most straight forward. Productivity of two crops in mixture is related to the production of both crops in monoculture, without any further restriction. Generally, this means that the second crop is sown or planted in the first crop and that it is sown in a similar density as in monoculture. The second crop is added to the first crop.

In this design, Land Equivalent Ratios (LER) characterize the performance of the species in mixture. LERs are thus used to assess yield advantage in intercropping where a fixed density of one species is grown with one or a variety of densities of the other. 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. In a mixture of species 1 and 2, LER is calculated as:

$$LER = Y_{1,mix}/Y_{1,mono} + Y_{2,mix}/Y_{2,mono} \quad (1)$$

where $Y_{1,mono}$ and $Y_{2,mono}$ are the yields of the species in monoculture and $Y_{1,mix}$ and $Y_{2,mix}$ are yields in mixture. Usually, the maximum yield of the monoculture obtained at optimum density is used as a reference density (Willey, 1979, cited by Fukai, 1993).

LER is defined as the relative land area under sole crops required to produce the yields achieved in intercropping (Willey, 1979a; Mead and Willey, 1980). Three situations can be distinguished:

- When LER=1. the same yields of each species can be obtained with monoculture at a recommended density as with mixture, without changing the total area of land. This represents a situation when there is no yield advantage in growing a mixture instead of the monocultures.
- When LER < 1. the yields obtained in a mixture can be achieved in monocultures by sowing a smaller area, partly with one crop and partly with the other.
- When LER > 1. a larger area of land is needed to produce the same yield of each species with monocultures at recommended density than with mixture. For, example, when LER=1.2, 20% more land is required to produce the intercrop yield of each species with monocrops. In other words, intercropping gives a yield advantage of 20% compared to growing the monocrops.

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 confounded, that is, the proportional composition and density of the mixture and their effects are completely confounded (Harper, 1977; Trenbath, 1976; Spitters, 1980). 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.

1.3.2.2 Replacement design

Another way to be able to distinguish between density effects and true interference effects is by using the replacement design. This approach to study competition in mixtures was developed by De Wit (1960). In this type of experiment the substitution or replacement principle is used. A range of mixtures is generated by starting with a monoculture of the first species and progressively replacing plants of species one with those of species two until a monoculture of the second species is attained. The experiment thus consists of a series of mixtures in which the proportions of the two species is varied, but the total density is held constant.

De Wit and van den Bergh (1965) characterized the performance of species in 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 of the yield of a species in the mixture to its yield in monoculture. In a mixture of species 1 and 2, RYT is calculated as:

$$RYT = Y_{1,mix}/Y_{1,mono} + Y_{2,mix}/Y_{2,mono} \qquad (2)$$

where $Y_{1,mono}$ and $Y_{2,mono}$ are the yields of the species in monoculture and $Y_{1,mix}$ and $Y_{2,mix}$ are yields in mixture

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.

- 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 (de Wit, 1960).
- 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: In the remainder of this report this will be referred to as 'true yield advantage'.

Jolliffe *et al.* (1984) and Connolly (1986) stated that the conditions of a replacement experiment are so restrictive that no valid generalizations can be made. The experiment is carried out with a single density, and consequently the results only give information of the response for that particular density. 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 the 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 favor 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).

1.3.2.3 Spitters' descriptive, regression approach

Spitters (1983a) developed a model to estimate the degree of intra- and inter-specific competition and niche differentiation from the total biomass yield of species in a mixture. The model is able to deal with data of a set of populations varying in species composition and total density. To estimate the competition effects the model does not require a specific design.

The approach starts from the same principles as the approach of de Wit (1960). The starting point in the derivation of the model is the response of crop yield to plant density, which can be described by a rectangular hyperbola (Wright, 1981; Spitters,1983a; Cousens,1985; Spitters *et. al.*1989; Shinozaki and Kira, 1956; de Wit, 1960):

$$Y = N / (b_0 + b_1N) \tag{3}$$

Where Y is the yield of the crop in monoculture in gm^{-2}, N is the plant density of the crop in numbers m^{-2} and b_0 and b_1 are constants. From equation 3, the average weight per plant is derived as

$$W = Y/N = 1/(b_0 + b_1N) \tag{4}$$

with W in g $plant^{-1}$. To estimate b_0 and b_1 this expression is written in a linear regression form

$$1/W = b_0 + b_1N \tag{5}$$

where b_0 is the intercept and b_1 is the slope of the relationship between 1/W and N. The intercept b_0 is the reciprocal of the virtual biomass of an isolated plant. The slope measures how 1/W increases, and hence how the per-plant weight W decreases with any plant added to the population. The ratio b_1/b_0 expresses this increase of 1/W relative to its value without competition so that it may be used as a measure of intra-specific competitive stress. The coefficient b_1 is the reciprocal of the maximum biomass per unit area achieved at infinite density. If adding plants of the own species affects 1/W additively, then it seems reasonable to assume that adding plants of another species affect 1/W also additively. We can then write the reciprocal of the per plant weight of species 1 in a mixture with species 2 in the multiple linear regression form

$$1/W_1 = b_{1,0} + b_{1,1}N_1 + b_{1,2}N_2 \tag{6}$$

The yield equation for species 1 in a mixture with species 2 can now be written as:

$$Y_{1,2} = N_1/(b_{1,0} + b_{1,1}N_1 + b_{1,2}N_2) \tag{7}$$

where $Y_{1,2}$ is the yield of species 1 in a mixture with species 2, and N_1 and N_2 are the number of plants for species 1 and species 2, respectively.
The parameter $b_{1,1}$ measures intra-specific competition between plants of species 1 and the parameter $b_{1,2}$ measures the inter-specific competition effect of species 2 on productivity of species 1. Thus, in general terms, from the point of species 1 the relative competitive ability of species 1 compared to species 2 is defined by the ratio of the regression coefficients ($=b_{1,1}/b_{1,2}$)

The yield equation for species 2 in a mixture with species 1 can now be written as:

$$Y_{2,1} = N_2/(b_{2,0} + b_{2,2}N_2 + b_{2,1}N_1) \tag{8}$$

where $Y_{2,1}$ is the yield of species 2 in a mixture with species 1. The parameter $b_{2,2}$ measures intra-specific competition between plants of species 2 and the parameter $b_{2,1}$ measures the inter-specific competition effect of species 1 on productivity of species 2. Thus, in general terms, from the point of species 2 the relative competitive ability of species 2 compared to species 1 is defined by the ratio of the regression coefficients ($=b_{2,2}/b_{2,1}$). The parameter values can also be used to derive a niche differentiation index (NDI). This is calculated as

$$NDI= (b_{1,1}/b_{1,2}) * (b_{2,2}/b_{2,1}) \tag{9}$$

If this ratio exceeds unity, there is niche differentiation, indicating that the mixture as a total captures more resources than the respective monocultures .This can be the case when species have different rooting systems, exploiting different compartments of the soil or in the situation of legumes, intercropped with other crops that can use the N fixed by the *Rhizobia*. A ratio less than unity suggests some kind of inhibition. If the NDI is unity, then the two species compete for the same resources equally (Spitters, 1983a,b, Connolly, 1987).

The above regression model is based on a hyperbolic form of the yield-density relationship (Equation 3), which usually holds for biomass and in many species for marketable yield as well. In several crops, however, marketable yields responds to density according to a parabolic shaped curve i.e. at high density, yield decreases with a further increase of plant density (Spitters and Kropff, 1989). When these high densities are considered, the model has to be extended, for instance by introducing a quadratic polynomial term (Spitters, 1983b) or by a power term (Firbank and Watkinson, 1985).

2. MATERIALS AND METHODS

2.1 Experimental set-up

2.1.1 <u>Location, soil and climate</u>

The experiment was carried out at the experimental farm, Wageningen Agricultural University between April and August, 1997. The soil type at the experimental site was predominantly clay with a pH-KCL 7.2, P-scale of 44 and K-scale of 17. The meteorological data (temperature and rainfall) from Wageningen meteorological station during the growing season are summarized in Figures 1 and 2.

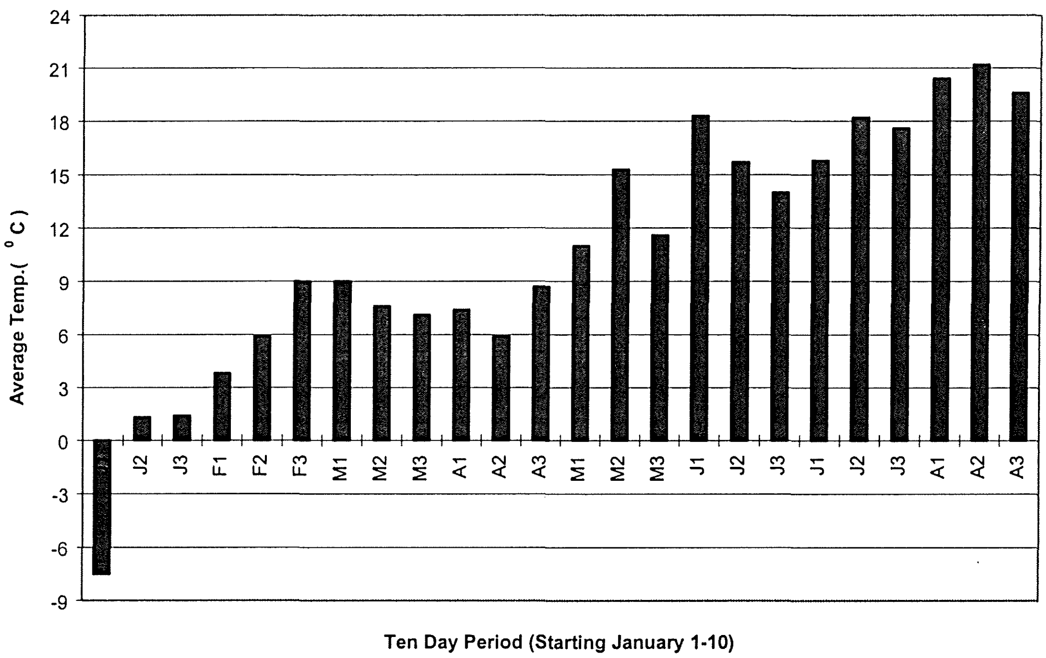


Figure. 1. Average ten days period temperature distribution in Wageningen from January to August, 1997 (Source: Wageningen meteorological station).

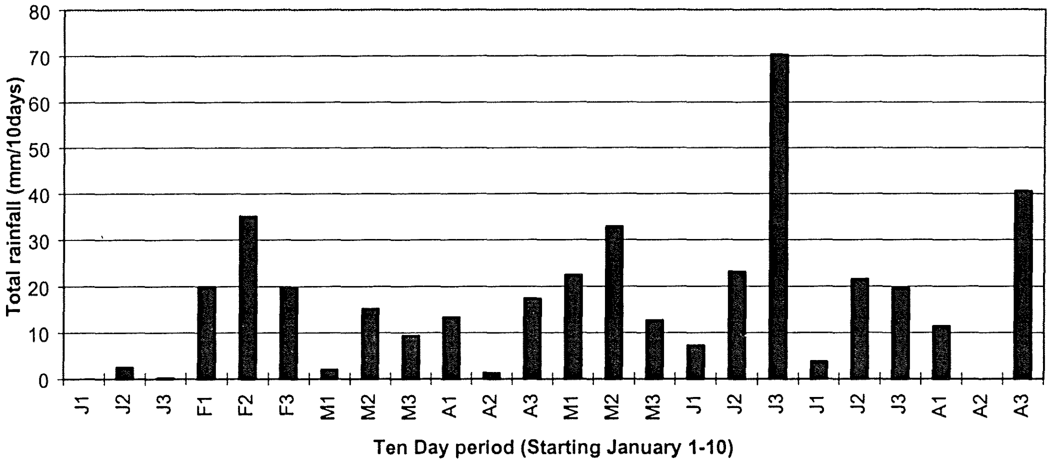


Figure 2. Total 10- day period rainfall distribution in Wageningen from January to August, 1997 (Source: Wageningen meteorological station).

2.1.2 Design and Treatments

Intercrops of barley (*Hordeum vulgare* var. Riff) and oats (*Avena sativa* var. Valiant) were grown in both additive and replacement series. A randomized complete block design with five replications was used. Each replicate consisted of two blocks; one block for the additive design and one block for the replacement design. Each block consisted of 15 plots in which barley was grown at three densities (three plots), oats was grown at three densities (three plots), and mixtures of barley and oats were grown at all possible combinations of 3x3 densities (nine plots). These treatments were randomly assigned to the experimental units. A plot size of 6 x 3 m^2 was used.

Mixtures in additive and replacement series were exactly the same. The difference between the two blocks was found in the monocultures of each block. In the additive series, plant densities were only half of the densities in replacement series. This was established by maintaining an identical within row spacing and using a double between row spacing in the additive series (25 cm compared to 12.5 cm in replacement series).

The second plant density level of the monocultures for replacement design was obtained by sowing the advised seed amount used by farmers (110 kg/ha for barley and 115 kg/ha for oats). The first (B_1, O_1) and the third (B_3, O_3) plant density level were achieved by sowing 20% less and 20% more than the standard amount of seed used by farmers, respectively, (Table 1).

Table 1. Amount of seed used in pure stands (kg/ha) and mixtures of replacement and additive series.

Combination	Replacement series		Additive series	
	Barley	Oats	Barley	Oats
Barley alone (B_1)	82.5	-	41.5	-
Barley alone (B_2)	110	-	55	-
Barley alone (B_3)	137.5	-	68.5	-
Oats alone (O_1)	-	86	-	43
Oats alone (O_2)	-	115	-	57
Oats alone (O_3)	-	114	-	72
Barley and Oats (B_1 O_1)	41.5	43	41.5	43
Barley and Oats (B_1 O_2)	41.5	57	41.5	57
Barley and Oats (B_1 O_3)	41.5	72	41.5	72
Barley and Oats (B_2 O_1)	55	43	55	43
Barley and Oats (B_2 O_2)	55	57	55	57
Barley and Oats (B_2 O_3)	55	72	55	72
Barley and Oats (B_3 O_1)	68.5	43	68.5	43
Barley and Oats (B_3 O_2)	68.5	57	68.5	57
Barley and Oats (B_3 O_3)	68.5	72	68.5	72

2.1.3 Varieties Used

For barley variety *Riff* and for oats variety *Valiant* was selected. Uniform maturity was the criterion used for variety selection, to facilitate mechanical harvesting. Attainable yield of both varieties is about 7000 kg/ha.

2.1.4 Sowing the experiment

Both barley and oats were sown at the same time on two successive dates i.e. April, 17 and 18, 1997. Row sowing was carried out by a machine according to seed rates. Alternate rows of barley and oats were used in the mixtures of additive and replacement series.

2.1.5 Fertilizer application and weeding

NPK (17-17-17), at a rate of 400 kg/ha was mechanically applied before sowing on March 18. Weeding was accomplished by spraying herbicide lentrol-combin (mixture of MCPA and MCPP) at a rate of 6 l/ha on May 8. There was no spraying against pests and diseases.

2.2 Data collection

2.2.1 Emergence

Number of emerged plants was recorded at two day intervals from sowing until the time when the number of plants had stabilized. Countings were made in all plots with pure stands of barley and oats of two randomly selected blocks with additive design. Two rows of 0.5 m each were counted in each plot. Data were analyzed to obtain average time to 50% emergence.

2.2.2 Plant Densities

Plant densities in all plots containing pure stands in both replacement and additive series were counted on May 14, after emergence had stabilized. Two random samples of 1 m^2 each were used. Densities of barley and oats were not counted in mixtures, because it was difficult to distinguish between both crops at that early stage. At later stages, when the crops could be distinguished, the crops started to produce tillers making it difficult to distinguish individual plants. Since no differences were expected between monocultures and mixtures, the densities in pure stands were used to estimate the proportions of barley and oats in mixtures.

2.2.3 Intermediate harvests

Intermediate harvests were taken at four different crop growth stages: 39, 60, 81 and 102 days after sowing. At each stage, data on biomass and leaf area were collected. Two samples of 0.25 m^2 were taken from opposite borders of each plot, excluding two border rows. The middle rows were left for final harvest. In mixtures, one row of barley and one row of oats were harvested. In pure stands, one row of either barley or oats was harvested for additive design and two rows for replacement design.

Fresh weight of the samples was recorded by using a weighing balance. Representative sub-samples of about 200 g were taken from these samples and weighed. The sub-samples were dried at 105^{0}C for 16 hours to determine dry weight. In addition, at each harvest date, two blocks in additive design and two in replacement design were randomly selected for determination of leaf area index. From the sub-samples, the leaves were separated from the stems and leaf area was determined by using a leaf area meter.

2.2.4 Final harvest

Final harvest was done at 123 days after sowing. Data on biomass were collected in the same way as described for intermediate harvests. Sub-samples were used to determine kernel yield. From the sub-samples, the panicles were separated from the stems and leaves. The panicles were then threshed to determine kernel yield. Harvest index was also determined by taking the ratio between kernel yield of a species and its total biomass. Weight of 500 kernels was also determined.

2.3 Data Analysis

2.3.1 Pure stands

Pure stand data for total dry matter production from intermediate and final harvests were summarized by fitting a hyperbolic relationship between plant density and dry matter for each harvest date:

$$Y_c = N_c / (b_0 + b_c{*}N_c) \qquad (3)$$

where Y_c = is the yield of the crop in monoculture in gm^{-2}, N_c = is the plant density of the crop in numbers m^{-2}, b_0 = is the intercept and b_c is the slope of the relationship between N/Y and N.

Additionally, a similar curve was fitted to kernel yield at final harvest. The ratio between b_c/b_0 is a measure of intra-specific competition and was calculated for biomass and kernel yield of barley and oats. Total biomass, kernel yield and harvest index at final harvest were subjected to analysis of variance. Least Significant Difference values were calculated to compare treatment means.

2.3.2 Mixtures

Data on biomass and kernel yield of the additive series, were used to calculate land equivalent ratios (LER):

$$LER = Y_{barley,mix}/Y_{barley,mono} + Y_{oats,mix}/Y_{oats,mono} \qquad (1)$$

where $Y_{barley,mono}$ and $Y_{oats,mono}$ are the yields of barley and oats in pure stands respectively, and $Y_{barley,mix}$ and $Y_{oats,mix}$ are yields in mixture. The ratios were calculated for all nine density combinations block-wise. Data were subjected to statistical analysis using Genstat program. Two sided t- test was used to assess whether the indices for the overall mean, the density means of barley and oats and each specific density combination differed significantly from one.

Data on biomass and kernel yield of the replacement series, were used to calculate relative yield totals (RYT):

$$RYT = Y_{barley,mix}/Y_{barley,mono} + Y_{oats,mix}/Y_{oats,mono} \quad (2)$$

where $Y_{barley,mono}$ and $Y_{oats,mono}$ are the yields of barley and oats in pure stands respectively, and $Y_{barley,mix}$ and $Y_{oats,mix}$ are yields in mixture. The ratios were calculated for all nine density combinations block-wise. Data were subjected to statistical analysis using Genstat program. Two sided t- test was used to assess whether the indices for the overall mean, the density means of barley and oats and each specific density combination differed significantly from one.

To estimate the relative competitive ability of both species with respect to productivity of the first crop and productivity of the second crop, the original model of Spitters:

$$Y_{1,2} = N_1/(b_{1,0} + b_{1,1}N_1 + b_{1,2}N_2) \quad (7)$$

was rewritten as:

$$Y_{1,2} = N_1{*}Wm_1/(1 + a\,(N_1 + (1/\varepsilon)N_2)) \quad (10)$$

in which:

Wm_1 = the apparent weight of an isolated plant (= $1/b_{1,0}$) in g

a = a parameter characterizing intra-specific competition ($b_{1,1}/b_{1,0}$)

ε = relative competitive ability, or an equivalence coefficient, describing how many individuals of species 2 each individual of species 1 is equivalent to (=$b_{1,1}/b_{1,2}$).

Parameter ε thus represents the relative competitive ability. Independent of Spitters, this form of the equation was derived by Watkinson (1981). The advantage of using the formula in this way is that the relative competitive ability is directly estimated and an error estimate of ε is obtained.

Non-linear regression analysis by SPSS was conducted to determine the best fit and to obtain an estimate for the relative competitive ability. Analysis was conducted using data for additive and replacement series separately and for both series combined. The results of all blocks were used to obtain one estimate for the relative competitive ability. Relative competitiveness of the species with respect to productivity of barley ($b_{b,b}$/ $b_{b,o}$) and productivity of oats ($b_{o,o}$/ $b_{o,b}$) was determined. Both estimates were then used for the computation of niche differentiation indices (($b_{b,b}/b_{b,o}$) * ($b_{o,o}/b_{o,b}$)) as described by Spitters (1983a).

3. RESULTS

3.1 Growth of Barley and Oats in Monocultures

3.1.1 Emergence

Cumulative percentage of emergence for barley and oats in monocultures is shown in Figure 3. For both barley and oats cumulative percentage of emergence evolved according to a logistic curve, and differences between both species were only minor. Density hardly seemed to influence the shape of this curve. Barley and oats started to emerge at about seven days after sowing. For both crops emergence percentages of 50 and 100% were reached at about two and three weeks after sowing, respectively.

Table 2. Observed densities in pure stands (plants m^{-2}) and estimated densities in mixtures for replacement and additive series.

Combination	Replacement series		Additive series	
	Barley	Oats	Barley	Oats
Barley alone (B_1)	154 (0.91)	-	80 (0.77)	-
Barley alone (B_2)	169 (1.00)	-	104(1.00)	-
Barley alone (B_3)	206 (1.22)	-	112 (1.08)	-
Oats alone (O_1)	-	175 (0.78)	-	90(0.79)
Oats alone (O_2)	-	224(1.00)	-	114(1.00)
Oats alone (O_3)	-	263(1.17)	-	138(1.21)
Barley and Oats (B_1 O_1)	77	87	80	90
Barley and Oats (B_1 O_2)	77	112	80	114
Barley and Oats (B_1 O_3)	77	132	80	138
Barley and Oats (B_2 O_1)	84	87	104	90
Barley and Oats (B_2 O_2)	84	112	104	114
Barley and Oats (B_2 O_3)	84	132	104	138
Barley and Oats (B_3 O_1)	103	87	112	90
Barley and Oats (B_3 O_2)	103	112	112	114
Barley and Oats (B_3 O_3)	103	132	112	138

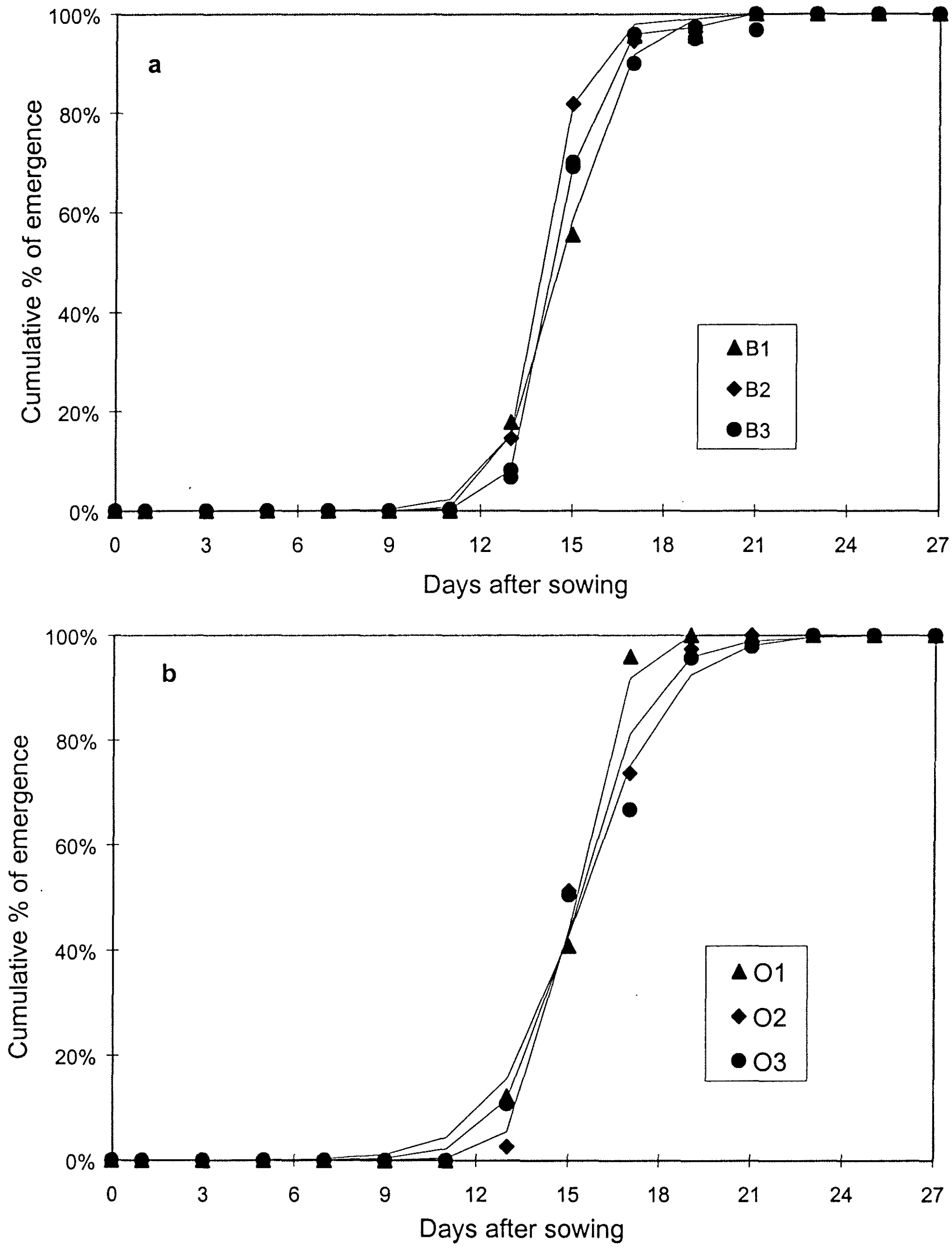


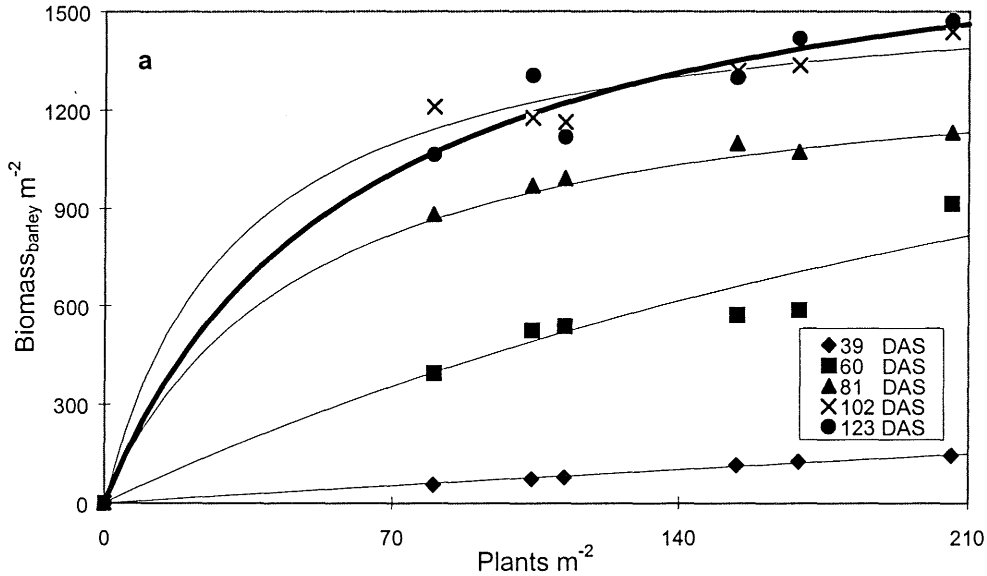
Fig. 3 a,b. Relationship between cumulative percentage of emergence and number of days after sowing of barley (a) and oats (b) at three densities in monoculture.

Observed densities in pure stands (plants m^{-2}) were determined and used to calculate the densities in the mixtures for replacement and additive series (Table 2). Pure stand densities in replacement design were generally twice as high as that in additive series. This concurred to our expectation, since in monocultures of the replacement design the between rows distance was only half of that in monocultures of the additive design. The second density level of the monocultures in the replacement design was obtained by sowing the advised seed amount used by farmers (110 kg/ha for barley, 115 kg/ha for oats). This resulted in a much higher plant density of oats, since 1000 kernel weight of oats is smaller than that of barley. For the first and the third density level the plant densities aimed at were -20% and +20% of the advised seed amount, respectively. In general, this was achieved. In replacement series however, B_1 had 10% higher plant density than expected, whereas in additive series B_3 had a 10% lower plant density than expected.

3.1.2 Dry matter production

The relationship between plant density and biomass for barley and oats at consecutive days of harvests (39, 60, 81, 102 and 123 days after sowing) is presented in Figure 4. During the first harvest , a linear increase of biomass with plant density was observed for barley and oats. This indicates that plants were so small and separated that they did not hinder each other. During this time, most of the space around the plants had not yet been occupied and there was no mutual shading. At this growth phase the supply of resources surpassed demand. This indicates that rather than the availability of resources, the uptake ability of resources by the crop limited biomass production. An increase in plant density resulted in an increase in uptake ability and consequently in a higher biomass production.

Intra-specific competition for resources started from the second harvest onwards and became stronger with increasing plant density and during later harvests. The response of barley and oats at final harvest (123 days after sowing) clearly indicated a hyperbolic relation between yield and plant density. At higher densities, yield reached an equilibrium level and became less responsive to further changes in plant density. This was probably due to complete use of available resources at higher plant densities. In this case biomass production was not so much determined by plant density, but almost completely determined by availability of resources like water, radiation and nutrients.



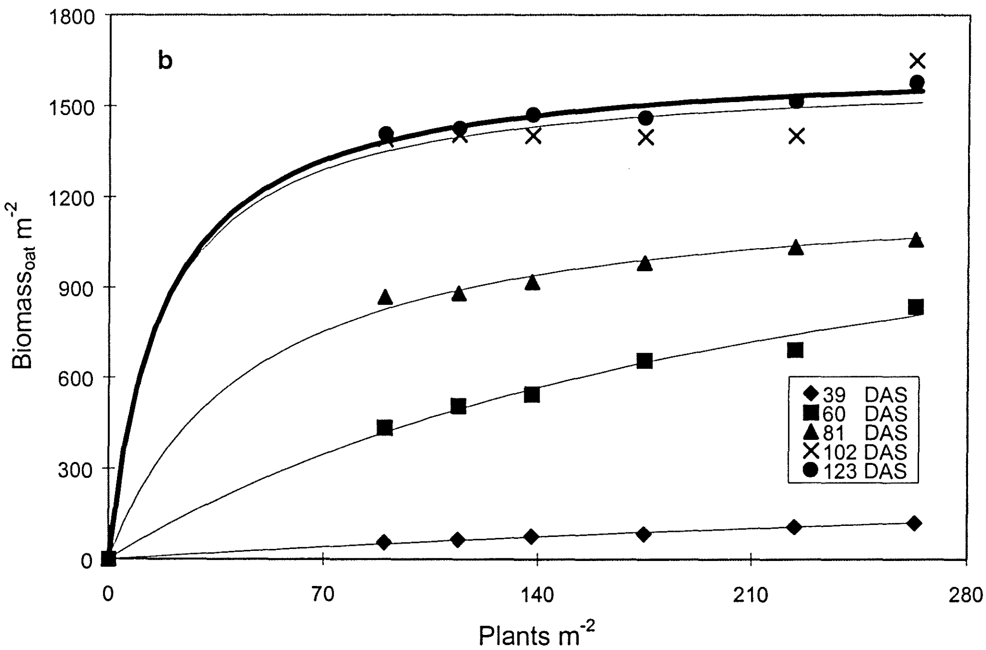


Fig. 4 a,b .Relationship between plant density and biomass of barley (a) and oats (b) at five different days after sowing (DAS).

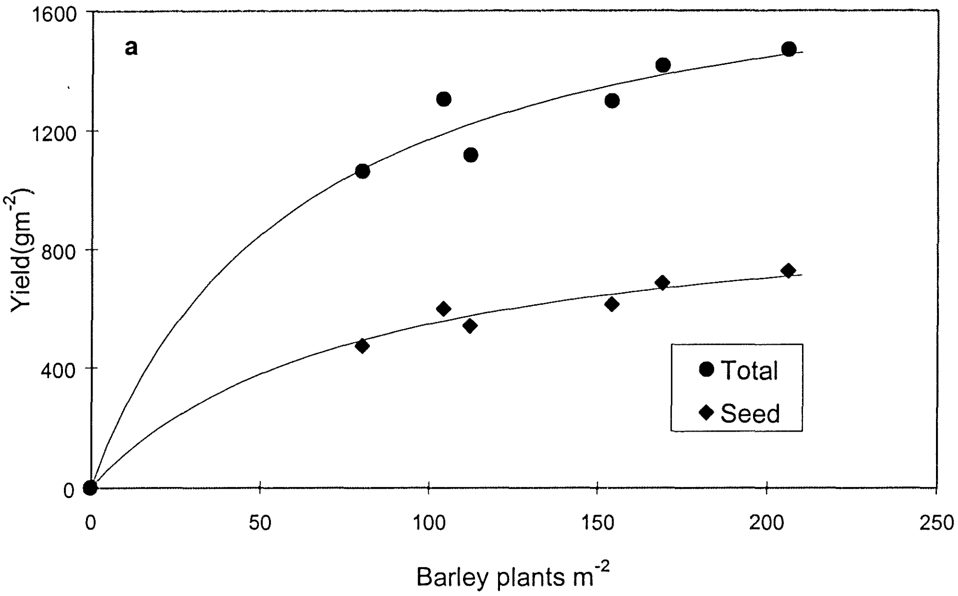
The relationship between density and final yield (biomass and harvestable) for barley and oats is shown in Fig. 5. Solid lines represent the best fitting hyperbolic relationship between plant density and yield (Equation 3) as determined with the non-linear regression option of Genstat. Estimated parameters are presented in Table 3.

Table 3. Estimated parameters and intra-specific competitive stress for barley and oats in monoculture

	Parameters		intra-specific competitive stress
	b_1	b_0	b_1/b_0
Barley (biomass)	0.00053	0.032	0.017
Barley (kernel)	0.00102	0.080	0.013
Oats (biomass)	0.00061	0.011	0.055
Oats (kernel)	0.00149	0.010	0.148

For barley, biomass and harvestable yield responded in the same way. Yield kept on increasing with increasing plant density, indicating that higher plant densities were required to maximize biomass and kernel yield. This suggests that intra-specific competition between individual barley plants was relatively low. For biomass and kernel yield values of 0.017 and 0.013 were found, respectively.

For oats, there also was not much difference in the response of biomass and kernel yield on plant density. Compared to barley, maximum yield was clearly attained at lower plant density. This indicates that intra-specific competition between oats plants was much greater than that of barley plants. This is confirmed by the values in Table 3 where the intra-specific competitive stress for biomass and kernel yields of oats are presented. Values of 0.055 and 0.148 were found for biomass and kernel yield, respectively. The high value for harvestable yield of oats indicates that intra-specific competition for kernel yield was stronger than for shoot biomass. This suggests that for oats lower plant densities than for barley are required to obtain maximum harvestable yield.



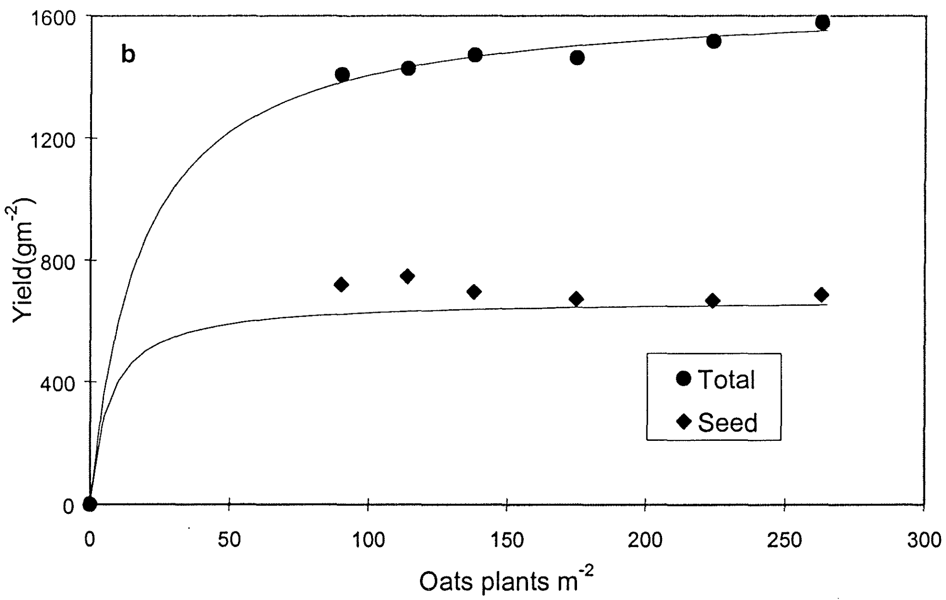


Fig 5 a,b. Relationship between plant density and yield (biomass and harvestable) for barley (a) and oats (b) at final harvest.

Average yield and harvest index in pure stands for barley and oats are shown in Tables 4 and 5. For barley, biomass and kernel yield increased with increasing plant density. Harvest index indicated a similar trend but there was no significant difference. For oats, harvest index decreased with increasing plant density. For biomass and kernel yield no significant density response was found.

Table 4. Average yield (gm^{-2}) and harvest index of barley in pure stands

Estimated density (barley plants m^{-2})	Yield and harvest index: Biomass	Kernel	HI
80 (Ba_1)	1063 a	474 a	0.45
104 (Ba_2)	1305 b	599 bc	0.46
112 (Ba_3)	1116 a	541 ab	0.49
154 (Br_1)	1299 b	613 bc	0.47
169 (Br_2)	1416 cb	685 cd	0.48
206 (Br_3)	1470 c	726 d	0.49
LSD(P=0.05)	145.4	89.1	NS
CV(%)	8.62	11.14	7.36

Means in the column followed by the same letter do not differ significantly at P=0.05

Table 5. Average yield (gm^{-2}) and harvest index of oats in pure stands

Estimated density (Oats plants m^{-2})	Yield and harvest index: Biomass	Kernel	HI
90 (Oa_1)	1406 a	720 a	0.51 ab
114 (Oa_2)	1426 a	747 a	0.53 a
138 (Oa_3)	1470 a	697 a	0.47 abc
175 (Or_1)	1461 a	673 a	0.46 bc
224 (Or_2)	1516 a	668 a	0.45 bc
263 (Or_3)	1577 a	686 a	0.45 c
LSD(P=0.05)	NS	NS	0.052
CV(%)	14.28	13.75	8.36

Means in the column followed by the same letter do not differ significantly at P=0.05

3.2 Interference of Barley and Oats in Intercropping System

3.2.1 Additive series approach-Land Equivalent Ratios (LERs)

Land Equivalent Ratios (LER) for biomass and kernel yield at final harvest were calculated for all possible density combinations of barley and oats (Tables 6, 7). Results for biomass and kernel yield were more or less identical. On average LER exceeded one, indicating that for the range of densities used in this experiment (80 to 112 plant m^{-2} for barley and 90 to 138 plants m^{-2} for oats), yields obtained in the intercrops were higher compared to yields obtained in monoculture. On average 10% more land was required for monocultures to produce the intercrop yield. Average LERs obtained for the three different densities of oats hardly differed from each other and were significantly larger than one. Also, average LERs for low (B_1) and high (B_3) densities of barley were significantly larger than one. The average LERs for mixtures of barley and oats with intermediate density of barley (B_2) did not differ significantly from one. Although most of the LERs calculated for nine specific density combinations of barley and oats were larger than one, a significant difference was only obtained for three combinations (B_1O_2, B_1O_3 and B_3O_1).

Table 6. Land equivalent ratios for various density combinations of barley and oats calculated for observed biomass at final harvest

	B_1	B_2	B_3	Mean
O_1	1.02	1.07	1.21*	1.10*
O_2	1.24*	1.02	1.08	1.11*
O_3	1.16*	1.05	1.08	1.10*
Mean	1.14*	1.05	1.12*	1.10*

LERs followed by an asterisk are significantly different from one at P=0.05 .

Table 7. Land equivalent ratios for various density combinations of barley and oats calculated for observed marketable yield at final harvest

	B_1	B_2	B_3	Mean
O_1	0.98	1.06	1.17*	1.07
O_2	1.23*	0.99	1.01	1.08
O_3	1.27*	1.04	1.11	1.14*
Mean	1.16*	1.03	1.10*	1.10*

LERs followed by an asterisk are significantly different from one at P=0.05.

In Table 8 it is shown how the average LER for shoot biomass evolved over time. There was a dramatic decline of LERs with time of harvest, that is there were high values during the first harvest and these became smaller and smaller at later harvests. This means that in the early stages individual plants did not compete very strongly and adding a second crop had a positive influence on total biomass production. Later on the value of LER became much smaller, indicating that the initial advantage diminished strongly because of a stronger competition between individual plants. Nevertheless LER still exceeded unity at final harvest.

Table 8. Time course of average Land Equivalent Ratios (LER) for shoot biomass of intermediate and final harvests. (LER for specific density combinations of the intermediate harvests are presented in appendix 3).

Time of harvest (DAS)	LER (average)
39	1.74
60	1.25
81	1.21
102	1.11
123	1.10

3.2.2 Replacement series approach-Relative Yield Totals (RYTs)

Relative Yield Totals (RYT) for biomass and marketable yield at final harvest were calculated for all possible density combinations of barley and oats (Tables 9, 10). Results for biomass and kernel yield were more or less identical. On average RYT did not exceed one, indicating that for the range of densities used in this experiment (154 to 206 plant m^{-2} for barley and 175 to 263 plants m^{-2} for oats), intercropping did not lead to yield advantage over monoculture. Replacing every second row in a monoculture of one crop by a row of the second crop did not result in a yield that differed significantly from the yield attained in monocultures. Average RYTs obtained for the three different densities of barley and oats and RYT attained for nine specific density combinations were also not significantly different from one.

Table 9. Relative yield totals for various density combinations of barley and oats calculated for observed biomass at final harvest

	B_1	B_2	B_3	Mean
O_1	1.04	1.05	0.95	1.01
O_2	1.04	0.94	0.90	0.96
O_3	0.96	1.01	0.99	0.99
Mean	1.01	1.00	0.94	0.99

RYTs are not significantly different from one at P=0.05

Table 10. Relative yield totals for various density combinations of barley and oats calculated for observed marketable yield at final harvest

	B_1	B_2	B_3	Mean
O_1	1.09	1.04	0.95	1.03
O_2	1.09	1.04	0.90	1.01
O_3	1.04	1.02	1.08	1.05
Mean	1.07	1.04	0.98	1.03

RYTs are not significantly different from one at P=0.05

Time course of average relative yield totals (RYT) of intermediate and final harvests is shown in Table 11. For all stages, average RYT did not differ from unity. For the first harvest this might be because rows of barley and oats were too far apart to affect one another. During the later stages it was obvious that there was some kind of interference. A value of one then indicates that the species were excluding one another.

Table 11. Time course of average relative yield total (RYT) for shoot biomass of intermediate and final harvests. (RYT for specific density combinations of the intermediate harvests are presented in appendix 4).

Time of harvest (DAS)	RYT (average)
39	1.03
60	0.91
81	0.98
102	1.00
123	0.99

3.2.3 Descriptive Regression Approach-niche differentiation indices (NDIs)

Relative competitive ability for biomass and kernel yield of barley and oats were calculated based on data from, additive, replacement and both series combined (Table 12, 13). Relative competitive abilities were multiplied to obtain niche differentiation indices. For biomass the results for the additive series and for the replacement series were very similar. Barley was as strong a competitor for itself as oats was for barley. On the other hand, oats was only 0.87 times as strong a competitor for itself as barley was for oats.

Table 12. Relative competitive ability and niche differentiation indices (NDI) for additive, replacement and both series combined for biomass at final harvest

	Barley	Oats	
	$b_{b,b}/b_{b,o}$ SE	$b_{o,o}/b_{o,b}$ SE	NDI SE
Additive	1.05 ± 0.27	0.83 ± 0.17	0.86 ± 0.41
Replacement	1.05 ± 0.09	0.86 ± 0.10	0.90 ± 0.17
Additive + replacement	0.96 ± 0.08	0.87 ± 0.07	0.84 ± 0.13

Table 13. Relative competitive ability and niche differentiation indices for additive, replacement and both series combined for kernel yield

	Barley	Oats	
	$b_{b,b}/b_{b,o}$ SE	$b_{o,o}/b_{o,b}$ SE	NDI SE
Additive	0.74 ± 0.28	0.93 ± 0.24	0.69 ± 0.43
Replacement	0.84 ± 0.09	1.06 ± 0.11	0.88 ± 0.18
Additive + replacement	0.74 ± 0.07	1.11 ± 0.10	0.82 ± 0.15

In the mixtures of barley and oats, biomass productivity of barley plants was hardly affected, whereas biomass productivity of oats was negatively affected. This resulted in a niche differentiation index of 0.84. From these observations it is concluded that barley and oats grown in mixture did not promote one another.

Also for kernel yield, the results obtained from the additive series did not differ significantly from the results of the replacement series. Combining the results of both designs it was observed that the response of kernel yield were opposite of the results for biomass yield. For kernel yield, barley plants received less hinder from individuals of their own species than from oats plants. Oats plants on the other hand received more hinder from plants of their own species than from barley plants. Clearly, with respect to kernel yield, oats plants were more competitive than barley plants, and therefore barley was better yielding in monoculture.

Table 14. Average harvest indices (HI) of barley in monocultures and mixtures with different densities of oats in additive and replacement design.

	Harvest index				
	Monoculture	Mixtures			
Barley		O_1	O_2	O_3	$LSD_{0.05}$
Additive	0.46	0.45	0.45	0.45	NS
Replacement	0.48	0.45	0.44	0.44	0.0087

Table 15. Average harvest indices (HI) of oats in monocultures and mixtures with different densities of barley in additive and replacement design.

	Harvest index				
	Monoculture	Mixtures			
Oats		B_1	B_2	B_3	$LSD_{0.05}$
Additive	0.50	0.52	0.51	0.51	NS
Replacement	0.45	0.52	0.51	0.51	0.0237

The negative effect on productivity of barley in mixture with oats is not outweighed by the promotion of oats as is reflected in the low value of the niche differentiation index (=0.82). Similar to the results for biomass, it is concluded that barley and oats grown in mixture did not promote one another.

For kernel yield the results in mixture were opposite to the results obtained for biomass. For biomass, barley was not affected, whereas oats was inhibited by barley. For kernel yield on the other hand, barley was inhibited and oats was slightly promoted. This result is reflected in the harvest indices for barley and oats in monocultures and mixtures of the replacement design (Table 14, 15). Harvest index of barley was significantly higher in monoculture than in mixtures. On the other hand, harvest index of oats was significantly higher in mixtures than it was in monoculture. In additive design, there was no significant difference in harvest index between monocultures and mixtures, although the trends were similar to those in the replacement design.

4. DISCUSSION

Monocultures

For both barley and oats it was observed that the response of biomass production to plant density could be accurately described by a rectangular hyperbola. Still, clear differences were observed in the response of barley and oats. For barley, biomass continued to increase with higher densities, at least for the range of densities used in this experiment (between 80-210 plants/m^2). Intra-specific competition between individual barley plants was relatively low, and maximum biomass production would only be obtained at even higher plant densities. For oats a different response was observed. At the lowest density used in this experiment (90 plants/m^2), already 90% of biomass production obtained at the highest density (260 plants/m^2) was realized. This demonstrates that intra-specific competition for oats plants was much stronger than for barley plants. Maximum biomass production for oats was thus obtained at much lower plant densities than for barley.

Also the response of grain yield to plant density could be accurately described by a rectangular hyperbola. For both cereal crops, the response of grain yield to plant density was very similar to the response of biomass. For barley, harvest index was fairly constant over the entire range of plant densities used. Only for oats a significant decrease of harvest index was observed with increasing plant density. This means that the intra-specific competition of oats with respect to grain yield was even stronger than for biomass production. It has been reported that in cereals the ratio between seed yield and biomass (harvest index) is generally constant over a wide range of densities in which the crop is able to form a closed canopy (Kropff and Goudriaan, 1994). Cereal plants have a characteristic of a determinate growing point that terminates in an ear or panicle for every tiller that survives. Interplant competition determines tiller survival and not so much the size of the ears.

Methodologies to evaluate productivity in intercropping

From the results of the additive design it can be concluded that, for the densities used in this experiment, it was beneficial to grow barley and oats in a mixture. On average 10% more land was required in monocrops to obtain a yield similar to the yield obtained in mixture. This yield advantage might result from a 'true' yield advantage, for instance because oats and barley are complementary in resource use, or might simply result from a density effect, since overall density of the mixtures was higher than the densities used in pure stands. With the additive design it is difficult to identify the actual cause of yield advantage, because the effect of plant proportion and the effect of plant density are confounded (Harper, 1977; Trenbath, 1976; Spitters, 1980). This problem is clearly illustrated when investigating the time course of LER for shoot-biomass based on intermediate harvests. Initially, in the early stages, plants were far apart. Addition of plants from a second species then resulted in a higher total shoot-biomass, and accordingly in high values for LER (1.75 at 39 DAS). At later stages plants started to interfere, and the value for LER dropped, although values for final harvest were still significantly greater than one. As long as plant densities used in monocultures are below optimum densities, the value for LER will, at least partly, reflect a density effect, and it remains difficult to make a valid conclusion on the nature of the interaction between the species. In this experiment for instance, it was clearly shown that densities of barley in monoculture were below optimum. Therefore, it might be that the 10% yield advantage was completely caused by increased densities in mixtures. This is in full agreement with findings of Andrews and Kassam (1976), Davis and Woolley (1993), and Willey and Osiru (1972) who observed that gaining in mixtures is caused by higher plant densities. Yield advantage could also be obtained by growing the crops in monocultures at a high density and sometimes the highest yield is achieved with better monocrop (Willey, 1979a,b; Kropff and Goudriaan, 1994; Spitters and Kropff, 1989).

From the replacement series approach, relative yield totals for shoot biomass and kernel yield of unity were obtained. This indicates that barley and oats excluded each other. This observation is in line with the results of a replacement experiment of barley and oats described by de Wit (1960). This result implies that, from a yield-perspective, growing barley and oats as an intercrop does not lead to any advantage compared to growing them as sole crops. However, there still might be other reasons why an intercrop is preferred (e.g. reduced risk through stability of production, spreading labor demands, satisfying dietary requirements and controlling insect pests and weeds). From this perspective it should be noted that also no yield decrease is expected when barley and oats are grown as an intercrop.

Also with replacement design, there might be a problem with the interpretation of indices, specially when one is interested in the true nature of the interaction between species. This is clearly demonstrated when looking at the time course of average relative yield totals (RYT) for shoot-biomass for intermediate harvests. A RYT of unity during the first harvest implies that species in a mixture did not interfere, which is quite different from exclusion. At 39 DAS the plants were so small and separated that they could not hinder each other. Most of the space around the plants had not yet been occupied and there was no mutual shading. At later harvests, it was obvious that there was some kind of interference. At that stage, a RYT of unity suggests that the species excluded each other. As with the additive design, this observation stresses the need of growing monocultures of the replacement design in optimum densities. In many situations the optimum densities will not be known before hand, and therefore experiments repeated at a range of densities are said to be the only suitable design (Silvertown, 1987).

When using a range of densities, as was done in this experiment, the descriptive regression approach is very suitable. This approach allows the simultaneous analysis of various density combinations. Equations 7 and 8 were used to simulate kernel yield for additive and replacement series, using the previously estimated parameter-values. Estimated yield data were then used to calculate LERs and RYTs for all nine specific density combinations of barley and oats, according to Equations 1 and 2. The results are presented in Tables 16 and 17.

Analysis of data for both the additive design and the replacement design with the descriptive regression approach gave similar results. This outcome emphasizes the strength of this methodology: it is clearly shown that although conclusions based on the values of LER and RYT apparently seemed to be different, the nature of the interaction in the two experimental designs was, as might be expected, exactly the same.

Table 16. Estimated Land Equivalent Ratios for marketable yield. Values were obtained by simulation of kernel yield based on the hyperbolic yield density relationship, using parameter-estimates of the additive design. Simulated kernel yields were used to calculate LER. (Observed LER's are in brackets).

	B_1	B_2	B_3	Mean
O_1	1.10 (0.98)	1.07 (1.06)	1.07 (1.17)	1.08 (1.07)
O_2	1.09 (1.23)	1.07 (0.99)	1.06 (1.01)	1.07 (1.08)
O_3	1.08 (1.27)	1.06 (1.04)	1.05 (1.11)	1.06 (1.14)
Mean	1.09 (1.16)	1.07 (1.03)	1.06 (1.10)	1.07 (1.10)

Table 17. Estimated Relative Yield Totals for marketable yield. Values were obtained by simulation of kernel yield based on the hyperbolic yield density relationship, using parameter-estimates of the replacement design. Simulated kernel yields were used to calculate RYT. (Observed RYT's are in brackets).

	B_1	B_2	B_3	Mean
O_1	1.00 (1.09)	0.99 (1.04)	0.96 (0.95)	0.98 (1.03)
O_2	1.02 (1.09)	1.01 (1.04)	0.99 (0.90)	1.00 (1.01)
O_3	1.03 (1.04)	1.02 (1.02)	1.00 (1.08)	1.02 (1.05)
Mean	1.02 (1.07)	1.01 (1.04)	0.98 (0.98)	1.00 (1.03)

Compared to observed values (values in brackets), the estimated values for LER and RYT for the nine density combinations of barley and oats were quite stable. Much of the noise that was caused by experimental error was removed in this way, because the simulated values were based on a much larger number of observations than the earlier calculated values for LER and RYT. Clear density responses of LER and RYT to barley and oats can be observed, although the differences in this specific example are only minor, due to the nature of the interaction between barley and oats. However, it is clear that the outlined procedure is helpful in determining the optimum density combination when two crops promote one another.

Another advantage of the descriptive regression approach is that it addresses the nature of the interaction between two species. Relative competitive abilities between the two crops with respect to the productivity of crop 1 and crop 2 are calculated. As outlined by Spitters (1983a) these relative competitive abilities can be combined to obtain the niche differentiation index. This parameter indicates whether combining two crops to an intercrop does make sense from a yield perspective. Such a generalization is much more difficult to obtain when only a LER or a RYT is calculated. Nevertheless it should be realized that also the regression approach is a descriptive approach. It summarizes the experimental results obtained for a specific site under specific conditions. Whether this result is transportable in space (to different sites) or time (different years) remains an open question.

Productivity of the barley - oats intercrops

The study clearly shows that there is no true yield advantage in growing barley and oats in a mixture. Although in the additive design a yield advantage of 10% was obtained in mixtures, it was clearly shown that densities of barley in monocultures were too low to give optimum yield. Analysis confirmed that the 10% yield advantage of the mixture could solely be accounted for by increased densities. Higher yields would also have been achieved by growing barley in monoculture at a higher density and had nothing to do with complementary of species for use of resources (Willey, 1979a,b; Kropff and Goudriaan, 1994; Spitters and Kropff, 1989). More evidence for this was obtained from replacement approach. This approach is much more suitable to address the questions related to real yield advantage of intercropping over monocropping, because the relative total densities are the same in mixtures and monocultures. Hyperbolic regression approach clearly confirmed that barley and oats grown in a mixture did not promote each other. Farmers may intercrop these species for other benefits, but maximization of yields is not a valid justification.

5. FUTURE DIRECTION OF RESEARCH IN SOUTHERN TANZANIA ON MIXED CROPPING OF SESAME AND MAIZE

It is quite clear from this study that each of the approaches used to investigate yield advantages in intercropping has both advantages and limitations. It is the responsibility of a researcher(s) to analyze the crop-crop system to be addressed and formulate the objectives of the study before choosing an appropriate approach. In southern Tanzania, maize is grown with a variety of densities of sesame. Therefore, the additive design seems an appropriate design, since it truly represents the system under study. However, optimum plant densities of the sole crops, at input levels used by farmers, must be determined before implementing an intercrop experiment.

Alternatively, an intercropping experiment might be carried out using a wide range of densities. In this way it is possible to determine the optimum sole crop densities for that site and season. Thus the confounding effects of total plant density and a high density of one crop on the other will be eliminated (Harper, 1977; Trenbath, 1976; Spitters, 1980). Consequently, an overestimation of yield advantages in intercropping is likely to be avoided. Subsequently, the descriptive regression approach might be used for simultaneous analysis of various density combinations. The regression approach is suitable for revealing the relative competitive ability of sesame and maize and to resolve the nature of interaction of the species. Apart from that it will be possible to estimate yields of sesame and maize using regression parameters as outlined by Spitters (1983a). LERs might then be calculated to understand the level of intercrop yields for various density combinations. In case sesame and maize are found to promote each other, the optimum densities and mixing ratios can then be determined to economically maximize seed yields of the species in a mixture.

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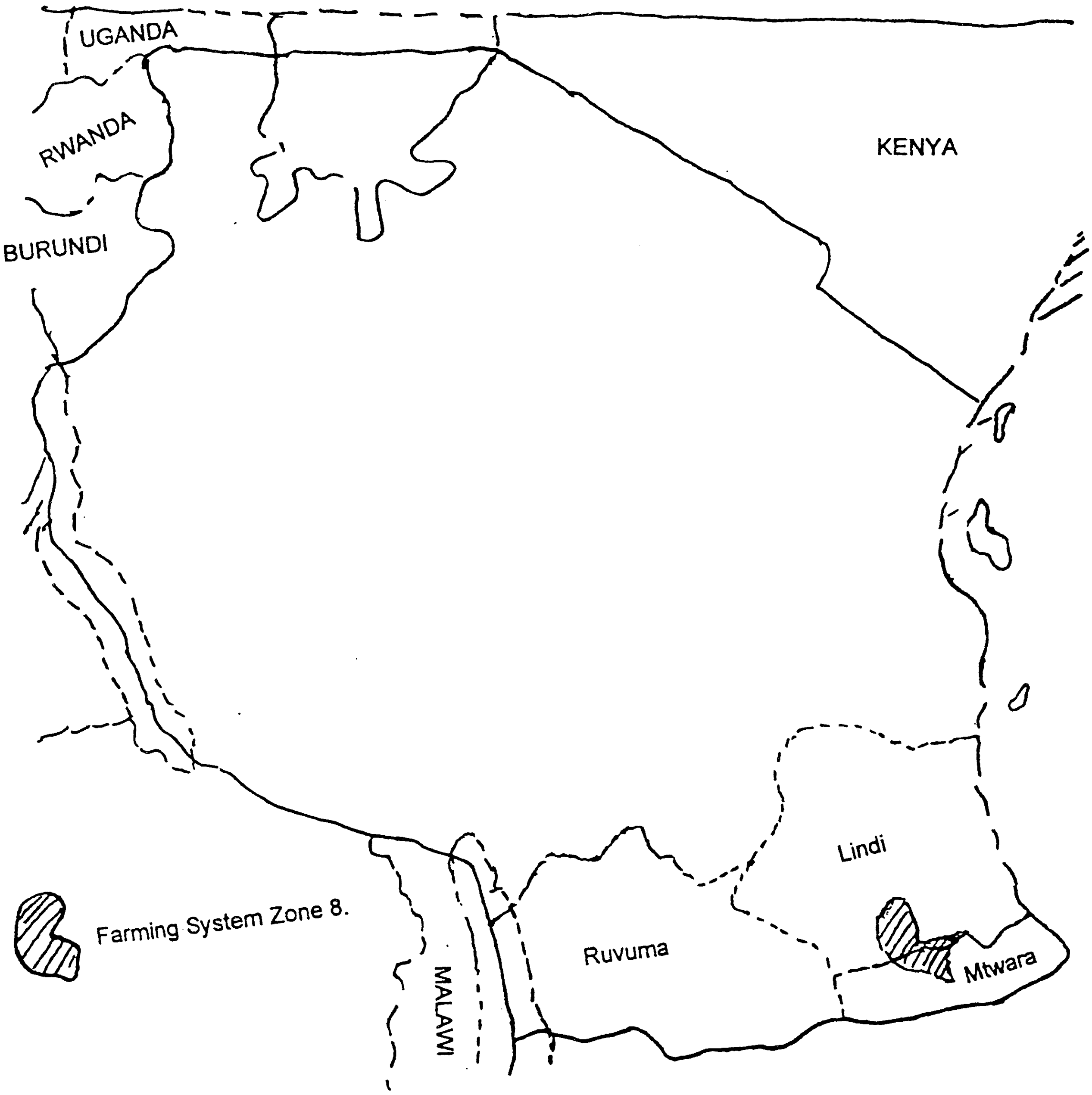
7. APPENDICES

Appendix 1 A map of Tanzania showing the position of Farming System Zone 8- a major area for sesame and maize production in Southern Zone



Appendix 2 A detailed map of Farming System Zone 8-proposed study area