WHEAT-CHICKPEA YIELD PERFORMANCE, COMPETITION AND RESOURCE USE IN INTERCROPPING, UNDER RAINFED CONDITIONS OF SOUTH AUSTRALIA

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ABSTRACT

Wheat-chickpea yield performance, competition and resource use in intercropping, under rainfed conditions of South Australia

Many studies have indicated that intercropping may increase and stabilise crop yield in conditions of limited water, and may assist in uptake of nutrients. In South Australia water and nitrogen commonly limit crop yield. Thus intercropping may be an appropriate means to improve the productivity of low input cropping systems in the Mediterranean rainfed conditions of South Australia.

The aim of the study presented in this thesis was to quantify yield performance, the competition effects and the capture and utilisation of resources of some important winter cereals and legumes as intercrops. To address this aim a series of field experiments were conducted to evaluate species and varieties, population density, plant arrangement, irrigation and N fertiliser effects on intercrops and corresponding sole crops. A number of different methods (univariate analysis, bivariate analysis, regression analysis, indices and graphical methods) were used to analyse the results of intercrop performance.

The study covered three aspects of intercropping. Firstly, species and varietal aspects of intercropping were studied, and binary mixtures of two cereal species (wheat or barley) in combination with three legume species (faba bean, field pea or chickpea) were compared to their sole crops. Land Equivalent Ratio (LER), which is a measure of biological efficiency, was used for comparison of the relative performance of various sole and mixed cropping systems. LER was slightly higher in the barley-based intercrops than the wheat-based intercrops. However, barley was much more aggressive and caused a large reduction in the growth of the intercropped legumes. The wheat-chickpea intercrop had slightly higher LER for grain yield than other wheat based mixtures. Despite the fact that LER for grain was less than 1 showing no benefit from intercropping, the LER values obtained for biomass indicated a potential for greater biological efficiency in intercropping than sole cropping. Thus for the remainder of the research undertaken wheat and chickpeas were chosen as the intercrop species for study. Further, in a varietal experiment it was found that the varieties Excalibur wheat and Semsen chickpea were preferable to Machete (wheat) and Desavic (chickpea) respectively.

In the second phase of the study the effects of different agronomic practices such as seeding rate, row arrangement, fertiliser and irrigation on grain yield, competition and efficiency of some intercropping systems were studied in three field experiments. Generally, reducing the population of wheat and maximising the population of chickpeas reduced competition in the mixture, thereby improving the performance of the legume component of the mixture. Also, the greater the separation of the rows of wheat from the rows of chickpea, the better the chickpea yield in the mixture. However, separating the rows of chickpea by replacing rows of wheat with chickpeas decreased the productivity of the cropping system. Overall, double alternate rows of wheat and chickpea provided the best intercrop option. Addition of water under irrigated conditions had a positive effect on the yield of both sole and mixed crops. Irrigation also decreased the competition between wheat and chickpeas. However, irrigation and N fertiliser application had little influence on the LER of the system, compared with rainfed and without N fertiliser situations.

Resource capture and use were studied in the third phase. Here it was shown that wheat in mixtures absorbed most of the available water and nitrogen and, probably because of fast growth early in the season, suppressed the legume component of the mixture. At the same time this use of N by the wheat crop appeared to promote additional N_2 fixation in the intercropping systems, with evidence of the fixed nitrogen transferring to the wheat crop in the mixture. Given access to most of the available soil resources (e.g. water and nitrogen) the wheat crop in the mixture had similar biomass to the sole wheat crop which almost compensated for the reduction in plant population. Thus in mixture chickpeas were not able to efficiently utilise available soil resources. There was also evidence of a wetter soil profile under the mixture than under the sole wheat crop at maturity. Overall use of soil resources seemed to be less in intercropping. Whilst LER for the mixture was around 1, showing no advantage or disadvantage of intercropping, the mixture improved the productivity of the system compared to a sole chickpea situation, but more importantly provided a situation of lower water uptake and N saving under intercropping compared with sole wheat. Thus intercropping had not affected overall grain yield and may have a positive effect on the growth of subsequent crops through conservation of soil resources.

The findings of this study indicate that there is scope for more productivity and stability in low input rainfed regions of the southern Australia, by utilising carefully planned and managed intercrop systems.

DECLARATION

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

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Plate 1. The view of 1995 intercropping experiments; in the foreground, a double alternate row of dryland wheat and chickpea is shown near maturity.

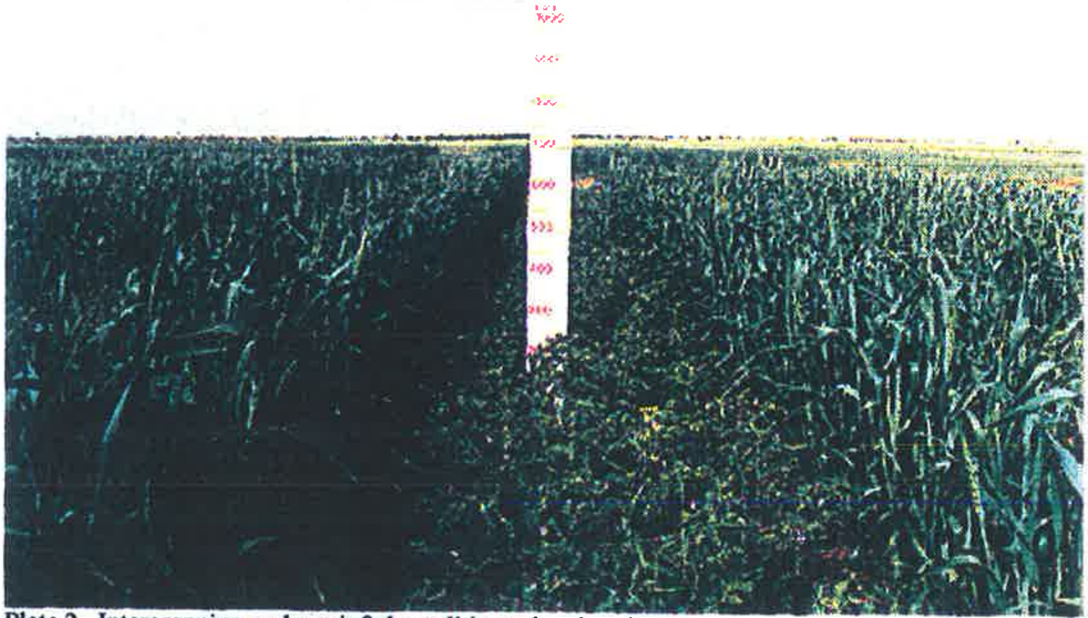


Plate.2. Intercropping under rainfed conditions showing the arrangement of two rows of wheat to four of chickpea at flowering, 1995.

1. GENERAL INTRODUCTION

Intercropping, an old agricultural practice (Federer *et al.*, 1982), is the growing of two or more crop species simultaneously on the same area of land (Willey, 1979a). Many studies in semi-arid and monsoonal environments indicate that intercropping may increase and stabilise yield in water stress situations, and might assist in the uptake of phosphorus (P) and potassium (K) (Morris and Garrity, 1993a) compared to sole crops. Moreover, if a legume is part of the mixture, additional benefits related to nitrogen (N) fixation may accrue, i.e. a transfer of N fixed by legume to non-legume and residual N for subsequent crops (Stern, 1993a). Ofori and Stern (1987) also presented some examples of greater light use efficiency in cereal-legume intercropping systems. Other possible advantages of intercropping include better control of pests and weeds, a higher nutritional value of herbage and better conservation of soil.

Agricultural regions of South Australia (S.A.) have a semi-arid Mediterranean climate (Khan, 1991). In this region dryland farming is the most common type of agriculture. Water and N commonly limit crop yield in such regions (Squires, 1991). More efficient use of resources and greater stability of yield are two desirable characteristics of a cropping system which might suit these conditions. Greater resource use efficiency and yield stability are considered to be two main criteria for intercropping. Thus, intercropping might be an appropriate means to improve the productivity of cropping systems in the Mediterranean environment of S.A.

The main areas where intercropping is practised are in the tropics, especially where there are small farms (Okigbo, 1990). In these areas the labour is often the farmer's family and many practices such as sowing, weeding and harvesting can be done manually. However, interest in cereal-legume intercropping is increasing in other regions with warm climates such as Australia (Ofori and Stern, 1987a). Most of the intercropping done to date in Australia has concerned only pasture species and mixtures for hay, such as oats and vetch, and there is very limited information on intercropping of winter grain crops. In S.A. there has been some preliminary work on a mixture of canola (*Brassica napus*) and field pea (*Pisum sativum*) with promising results (Mayfield, pers. comm., 1993).

Despite the advantages claimed for intercropping, many workers initially found it difficult to initiate intercropping research programs (Willey, 1979a). For example, because of the multivariate responses which occur in intercropping systems, the statistical analysis is more complex than the univariate analysis for monocultures (Federer, 1993). Moreover, adaptation of intercropping to extensive farming systems such as that practised in the wheat belt of Australia can be quite difficult because of a lack of appropriate seeding equipment, harvesters and weed control methods. However, in general, the advantages of intercropping out-weigh the disadvantages (Tofinga, 1990) (see Chapter 2), and it is possible that intercropping could improve the productivity of cropping systems under the moisture and nutrient constraints of the Mediterranean environment of South Australia.

The research needs and requirements for intercropping have been discussed by many scientists (Fukai and Midmore, 1993), (Parkhurst and Francis, 1986). Following their recommendations the sequence for initiating intercropping experiments for a specified region is the selection of appropriate species and cultivars and then the investigation of appropriate agronomic practices. Moreover, understanding the utilisation and requirements of radiant energy, soil water and soil nutrients will facilitate the development of improved management strategies for further increasing the productivity of intercropping systems (Midmore, 1993).

The aim of the study discussed in this thesis is to quantify yield performance, competition effects and the capture and utilization of resources of some important winter cereals and legumes as intercrops under dryland farming conditions in S.A. The specific aims are:

(i) To determine appropriate winter cereal and legume species for intercropping (after this experiment wheat and chickpea were chosen for subsequent experiments);

(ii) To compare the varietal effects of wheat and chickpea as intercrops;

(iii) To examine the effects of different plant densities, row arrangements, nitrogen fertiliser application and irrigation on wheat and chickpea intercrops;

(iv) To study the resource use efficiencies of wheat and chickpea mixtures and sole crops.

In this study five field experiments were conducted to address these aims.

2. LITERATURE REVIEW

2.1 Introduction

Deficiencies of resources such as water and nitrogen are the main biophysical limitations to agricultural production in dryland farming areas (Webber *et al.*, 1976). Any attempt to overcome these limitations might increase the productivity of these agricultural systems. Intercropping has been suggested as a means of increasing the capture and use of biophysical resources, leading to increased yields (Natarajan and Willey, 1986).

Intercropping is a complex field of agronomy (Willey and Rao, 1979). Despite the fact that intercropping is a primitive agricultural practice dating from antiquity (Arnon, 1992), the systematic and scientific approach to it is new. One of the first reviews on intercropping was done by Aiyer (1949). Interest in the systematic and scientific approach to intercropping was particularly strengthened and given momentum by a thorough review by Willey (1979a and 1979b) titled "Intercropping - its importance and research needs." Thereafter valuable reviews and books on different aspects of intercropping have been published by Francis (1986b), Francis (1989), Ofori and Stern (1987a), Vandermeer (1989), Federer (1993) and Fukai (1993).

This chapter presents a review of the literature on the main topics of this research. Firstly, a general review of different kinds of intercropping systems and their advantages and disadvantages is provided. In the following sections competition and intercropping, some agronomic aspects of intercropping systems, the role of bio-physical resources in intercropping and the evaluation of intercropping systems are reviewed.

2.2 Intercropping systems

Before starting this section it has to be mentioned that there has been some confusion about the terminology of intercropping and some general concepts of intercropping systems (Francis, 1986a). However, to avoid more confusion, and for the sake of simplicity and consistency, the relevant terms used in this thesis have been chosen mainly from the works of Andrews and Kassam (1976), and Francis, 1986a).

Multiple cropping is the growing of two or more crops on the same field in a year (Francis, 1986a). The principal multiple cropping patterns are sequential cropping, double cropping, triple cropping, quadruple cropping, ratoon cropping and intercropping (Andrews and Kassam, 1976). This thesis deals with intercropping, which is growing two or more crops at the same time and on the same area, so that there is intercrop competition during all or part of the crop's life (Andrews and Kassam, 1976). Some scientists e.g. Freyman and Venkateswarlu (1977) suggest that the term 'intercropping' should be used only for the more specific situations where crops are grown in separate rows; otherwise it should be defined as mixed cropping. However Willey (1979a) chooses to use the term of 'intercropping' in a general sense to simplify reference to previous literature in both research and farming practices. This will be the preference in this thesis as well.

Sole cropping is the opposite of intercropping, which means one crop variety is grown alone in a pure stand at normal density (Francis, 1989). In this thesis sole cropping is also a situation where the crop is grown as a pure stand, at densities including other than normal density.

Willey (1979a) indicates that in competition studies in multiple cropping systems, the use of the intercrop terms are usually not very satisfactory. Some of the intercropping terms and their synonyms and definitions are presented in Table 2-1.

In this thesis intercropping terms and their competition related synonyms have been used interchangeably.

Table 2-1. Some intercropping terms and their synonyms and definitions in competition studies (Willey, 1979a)

Intercropping term	Competition term	Definition
Intercropping	Mixture	Growing two or more crops at the same time and on the same area, so that there is intercrop competition during all or part of the crop's life cycle
Component crop	Component species	Either of the individual crops making up the intercropping situation
Intercrop yield	Mixture yield (of a species)	Yield of a crop species when grown in intercropping
Combined intercrop yield	Combined mixture yield	Combined yields of both intercrops
Sole crop	Pure stand (monoculture)	Component crop grown alone
Combined sole crop yield	Combined pure stand yield	Combined yield achieved when the unit area is divided between two sole crops at the given proportions

There are different forms of intercropping. Andrews and Kassam (1976) recognized four main types of intercropping systems:

(i) *Mixed intercropping*: growing component crops together at the same time without distinct row arrangement, ie. within the same row. In this system crops are planted very close together and may interact with each other more intensively than if in adjacent rows. Under conditions of stress this might result in the dominant crop severely suppressing the dominated one.

(ii) *Row intercropping*: growing component crops at the same time in separate rows. This method gives a better opportunity to reduce competition by spacing of rows or plants in rows. Ofori (1986) reported that mixed intercropping is practiced in labour-intensive subsistence farming, while row intercropping is used in mechanised farming. Row intercropping has been used for the present study.

(iii) *Strip cropping*: growing component crops at the same time in different strips that are narrow enough to permit some interactions. However, the amount of interaction is minimal in this system and the most important advantage is that it allows the use of machinery for planting, maintenance and harvest.

(iv) *Relay intercropping*: growing two or more crops with overlapping life cycles. Because the rainfall season in southern Australian dryland cropping is variable and normally less than 7 months, it is probably too short for relay cropping.

2.3 Advantages and disadvantages of intercropping

Vandermeer (1989) addresses the question of whether there is any advantage of intercropping in a simple but qualitative manner: "If so many traditional agriculturalists do it, there must be some advantages to it." Further, there is a very strong body of reviews recording many advantages and disadvantages of this agricultural practice (Francis, 1986a). The main advantages claimed for intercropping are: better capture and utilisation of environmental resources by intercropped species; better control of pests, greater yield stability, higher nutritional value of the combined product and better conservation of soil in the agricultural land.

Some advantages of intercropping:

(a) A more efficient use of growth resources such as water, light and nutrients is a major advantage given for intercropping over other cropping systems (Keating and Carberry, 1993). A fuller explanation will be presented in Section 2.6.

(b) Greater stability of yield over a range of different seasons might occur in an intercropping system. If for any reason such as drought or pest damage one of the component crops fails or produces a poor yield, the other intercrop might compensate (Willey, 1979a). The greater stability in intercropping systems can be considered as an insurance against failure in food production in subsistence agriculture (Tofinga, 1990). However, Trenbath (1974) reported only marginal improvements in yield stability and Harwood and Price (1976) observed the opposite, a greater yield stability for sole crops than in intercrops. Such differences depend mainly on the individual circumstances of the researcher. For example Harwood and Price (1976), based on their experience at IRRI, state that, "If a crop in mixture is to be differentially eliminated or reduced in yield by some factor, it will normally happen after considerable vegetative growth has occurred. The non yielding crop will exert its competitive effect without producing anything, resulting in lower productivity of the mixture than from the separate monoculture planting."

(c) Better control of weeds, pest and disease is another quoted advantage of intercropping (Chatterjee *et al.*, 1993). For instance, if the combined population density of component crops of a mixture is higher than that of the sole crops, this often provides the mixture with a greater competitive advantage over weeds than sole cropping (Altieri and Liebman, 1986). Thus some farmers under low input conditions achieve weed control by means of intercropping (Okigbo, 1990). Allelopathy has been implicated by Gliessman (1983) as a means of weed control. Some experiments have shown the ability of *Cucumis sativus*, *Digitaria decumbens*, *Pennisetum clandestinum* and *Leucaena leucocephala* to suppress weeds in pastures, forests and forest/pasture intercropping systems through allelopathic effects (Chou and Putnam, 1986).

Intercropping can reduce the incidence of insect pests and disease (Tofinga, 1990). Potts (1990) considered exploitation of diversity in spatial arrangement, physical and temporal obstacles, microclimate transformation, olfactory effects, and colour and trapping effects amongst intercrop components to be responsible for reducing pest or disease development or benefiting their natural enemies. For example, when a susceptible crop is interplanted with a resistant crop, dispersal and spread of insects and disease organisms might be more limited, and sometimes one crop might act as an attractant to reduce the possible insect and disease damage to the other crop.

d) A more continuous leaf cover may give better protection against soil erosion (Aslam, 1988).

(e) Adding legumes to intercrops provides a higher nutritional value to the diet of resource poor farmers. It can also provide a higher percentage of protein in animal feed (Aiyer, 1949).

Some disadvantages of intercropping are:

(a) Some crops interact adversely in mixtures; thus a considerable amount of yield decrease might occur in the overall yield of the intercrops. An example of this situation is called mutual inhibition, where the yield of each of two species in a 50:50 mixture is less than half of their yield in pure stands (Willey, 1979a). Donald (1946) observed mutual inhibition between the pasture species Kentucky bluegrass and white clover.

(b) Allelopathy may also happen in intercropping. In this case one crop has a harmful effect on the other one through production of a chemical that enters the soil environment (Loomis and Connor, 1992). For instance Wahua and Miller (1978) found that if soybean was intercropped with sorghum, the oil content of soybean was decreased by about 20% due to the allelopathic effect of sorghum.

(c) There may be some difficulties in practical management of intercrops, particularly in the use of machinery. Harvesting can be difficult because of different crop sizes and/or different times of harvesting (Tofinga, 1990), and also in the application of chemicals especially herbicides (Willey, 1979a). Different requirements for fertilisers and pesticides can make it difficult or impossible to manage different crops in mixture.

Regarding the constraints of the Mediterranean type environment of South Australia, the advantages of intercropping that may be of importance are greater capture and utilisation of resources (particularly water) and greater yield stability.

A possible disadvantage under the extensive dryland farming systems of South Australia is a yield decrease as an effect of competition due to similar growth durations, so the intercrops compete intensively for resources, especially in cereal-legume intercropping systems due to inherent characteristics of legumes such as a strong rooting system (Ofori and Stern, 1987a). It is possible then that the cereal may capture the available resources excessively and restrict the legume intercrop severely. Another possible disadvantage is the difficulty in the practical management of intercrops under extensive farming such as a requirement to modify machinery, which can be quite expensive.

2.4 Competition and complementarity

The improvement of an intercropping system is possible through minimising the intercrop competition and maximising the degree of complementarity between intercrops (Willey, 1979a).

Competition

Competition is probably the most important interaction that happens between components of an intercropping system (Tofinga, 1990). When plants are growing together, they generally satisfy their requirements for resources (e.g. water, light and nutrients) from the same environmental sources. Exceptions to this are when legumes use (fix) atmospheric nitrogen or when different species gain water from different depths in the soil. If the supply of any of these resources is less than the collective requirements of a population of plants, then competition (interference) occurs. Plant competition has been described by many scientists, for instance Harper (1961) explains various approaches to the study of plant competition in different fields of plant science (e.g. agronomy, ecology and genetics). Understanding and application of the basic principles of population interaction which are discussed in ecology can be useful to develop agronomic research on intercropping (Hart, 1986). Therefore in this review an agro-ecological definition by Vandermeer (1989) is preferred, that is, competition is the process by which two individual plants or two populations of plants interact such that at least one exerts a negative effect on the other.

In an intercropping system there are two kinds of competition: (a) the responses to the crowding of crops of the same species called intra-specific competition, and (b) the competition amongst different species, called inter-specific competition (Loomis and Connor, 1992).

In most situations one of the intercrops grows faster than the other and uses the resources more successfully and thus it produces a greater biomass and yield than expected from its proportional population density. This crop is called dominant or aggressive and the other is called dominated or suppressed (Fukai and Trenbath, 1993). Commonly, the other crop is correspondingly less successful than expected (de Wit, 1960).

Before further explanation of competition it is necessary to define the term "niche". The niche concept has been used in population studies of intercropping by many scientists, e.g. Trenbath (1986), Vandermeer (1989) and Loomis and Connor (1992). Begon *et al.* (1996) define niche as: "The limits, for all important environmental features, within which individuals of a species can survive, grow and reproduce". Loomis and Connor (1992) further define this term by saying, "the habitat or functions that an organism might use and perform represent its **fundamental niche**, and those which it actually uses and performs constitute its **realised niche**."

When two species have very similar resource requirements they occupy the same niche, interfere with each other's activity and compete intensely with each other. Given a long enough time one of them may even be excluded (strong competition). Donald (1958) reported almost a complete suppression of the dominated crop in the mixture of two grasses (*Lolium perenne* and *Phalaris tuberosa*) as a result of strong competition. Since plants in a mixture of cereal and legume might have several N resources (e.g. symbiotic N_2 fixation, organic N, NO_3^-–N and NH_4^-–N. Handley and Scrimgeour (1997) propose the term "plant N-niche" to describe the differentiation of the single resource N.

Complementarity

In an intercropping system, morphological and physiological differences among intercrops might result in them occupying different niches (Trenbath, 1986). Then both crops may finish their life cycle, and if the competition is weak enough the mixture will be more productive than sole crops (Vandermeer, 1989). Here component crops are not competing exactly for the same overall resources and the inter-crop competition is less than intra-crop competition and intercrops may complement each other. Complementarity can be defined as: the beneficial interaction between crops that can increase the overall output of the cropping systems. This implies minimising competition (Midmore, 1993). An example of the complementary effects of cropping systems was shown by Willey *et al.* (1983). In their work they showed that in sorghum-pigeonpea and millet-groundnut mixtures complementarity was achieved by sharing environmental resources more fully over time or more efficiently over space. This phenomenon (complementarity) is very similar to what Vandermeer (1989) defined as facilitation, which is the process in which two individual plants or two populations of plants interact in a way that at least one benefits.

Complementarity in intercrops can be achieved in two ways:

a) By collecting resources from different spaces. This is most likely to happen in soil rather than shoot environments. Loomis and Connor (1992) stated that: “There is little opportunity for complementary use of aerial resources because CO_2 and light can be fully intercepted by any canopy at full cover. Full cover is just as easily achieved with sole crops as it is with mixtures. In addition, the lower leaves of sun plants adapt to the low light levels within the canopy as well as a ‘shade’ plant might. With less than full cover, as frequently is the case when soil resources are limiting, it makes little difference what canopy is displayed because all leaves are then in bright sun. Then, final yield is limited largely by limiting soil resources.” Most research reported on this aspect of complementarity suggests that root competition was more intense and started earlier than shoot competition (Aslam, 1988). Complementarity might occur in different ways in soil. For example, intercrops might be capable of absorbing resources from different parts of a soil profile. In Vertisols in India Arihara *et al.* (1991) showed that in a wheat-chickpea mixture, chickpea collected water from deeper soil layers than wheat, resulting in a better use of resources and complementarity. Legumes fixing atmospheric nitrogen can be regarded as using a partially different space compared with non legumes.

b) The second way of achieving complementarity is by collecting resources at different times. This is more likely to happen in a long growing season (Loomis and Connor, 1992). For instance pigeonpea and sorghum in India are both planted at the beginning of the rainy season. However, sorghum is harvested after 3.5 to 4.5 months while pigeonpea matures 3 to 6 months later. Both intercrops are planted at full density. Since they capture the resources partly at different times the productivity of this system has been reported to be 66% higher than that of sole cropping (Rao, 1986). Because of a short and variable growing season in the cereal zone of South Australia, this approach does not seem to be applicable.

Competition between crops can be manipulated by choosing appropriate species and cultivars and by application of different agronomic practices. Despite the fact that to some extent complementarity and competition operate together, the stage at which complementarity is replaced by competition is important and in most situations should be delayed as long as possible. For instance, a row intercropping system might have an earlier start in competition than a planting pattern with wider strips of intercrops (Midmore, 1993) thus reducing the opportunity for complementarity.

2.5 Some agronomic aspects of intercropping systems

Agronomic practices can have a positive effect on the yield performance of field crops by permitting a planned sharing of natural resources by intercrops (Midmore, 1993). However, sole crop technology is not always suitable or even possible in intercropping systems and might need modification. Some agronomic aspects of intercropping systems will be discussed in the following section.

2.5.1 Choosing species and varieties for intercropping systems

As mentioned in Chapter 1, many scientists believe that the primary key to introduction of intercropping in a region is the selection of appropriate species and cultivars. According to Gauses's exclusion hypothesis the more the niches of two species are alike the greater the intensity of competition between them (Vandermeer, 1989). Inherent genetic properties along with the environmental conditions for growth affect morphological and physiological properties of intercrops and possibly allow them to occupy different ecological niches (Trenbath, 1986). So, an appropriate selection of species and varieties might reduce the competition between component crops of an intercropping system, and therefore might increase its productivity. Depending on climate, local preference and other site-specific factors, several combinations of species are possible including cereal/root crop, cereal/pulse, cereal/oilseed, root crop/root crop, cereal/cereal, pulse/pulse and forage crop systems (Barker and Francis, 1986).

The objective of the species and variety selection is to minimise inter-crop competition and to maximise complementary effects (Willey, 1979b). As mentioned above, this complementarity can be obtained in time (temporal dimension) or space (spatial dimension) or both (Francis, 1986a). In many cropping systems the major source of complementary effects is temporal difference in growth cycle (Willey, 1979b). Crop development rates and maturity rates are very important traits for temporal complementarity (Smith and Zobel, 1991). One of the best examples is the intercropping of pigeonpea and sorghum in India (Willey *et al.*, 1983) which has already been discussed.

Selection for improved spatial complementarity is another way to increase the productivity of intercropping systems. Canopy architecture and root characteristics are the main factors affecting complementarity in mixtures. For example Babalola (1980) in his experiment on water relations of three cowpea cultivars concluded that in choosing cultivars for intercropping the depth of rooting, lateral rooting spread and root density, which affect water extraction, should be considered.

In selection of the varieties for intercropping identification, as far as possible of appropriate characteristics from sole crops (e.g. yield, time of flowering and disease resistance) is recommended. However, when crops are mixed they behave differently (e.g. time of flowering, size of productive organs), and it is difficult to predict their behaviour from sole cropping. Therefore, it is better to evaluate them when they are grown in mixtures (Harper, 1963). Some of the important criteria for selecting and developing intercrop varieties are presented in Table 2-2 (adapted from Francis (1985)) which can be useful in selection or development of species and varieties for intercropping.

Table 2-2 Specific genetic traits which may be important in developing varieties for multiple cropping systems (adapted from Francis (1985))

Characteristic	Specific need for intercropping
Maturity	Short crop duration needed for understory species, cash crops, or double-cropping; long season varieties needed for use of late rains or residual moisture
Photo period sensitivity	Insensitivity needed in most varieties, to give flexibility in design of cropping patterns; sensitivity needed for some specific situations
Temperature sensitivity	Tolerance to low temperatures needed when season is short; high temperature tolerance needed if this condition coincides with available rainfall
Plant morphology	Short, erect, upright-leaf cereals desirable to permit lower story crop development; differential heights between components important
Root system	Complementary rooting habits important so two or more species explore different strata of the total soil mass
Early seedling growth	Vigorous growth may be needed in low temperatures, partially shaded conditions, or zero tillage in an intercrop pattern
Population density	Component crops which respond to increased density give more flexibility in design of patterns; competitive ability important

2.5.2 Plant population density and row arrangement

Manipulating plant population density and row arrangement of crops might offer a practical way to maximise inter-specific complementarity especially under low input agricultural systems (Midmore, 1993).

2.5.2.1 Plant population densities

In plant population studies of intercropping systems the population of all component crops (total population) along with the population density of each component should be considered.

There are different methods to vary plant population density in intercropping systems. The most commonly used method is the replacement series (de Wit, 1960), in which the population of sole crops is taken as 100, and the component populations in the mixture are expressed on proportional bases, i.e. the two proportions in the mixture must always add up to 100. For example, a mixture comprising 75% of sole crop **A** population density and 25% of crop **B** can be described as a 75:25 mixture, and when both intercrops **A** and **B** have half of their sole crop density it is considered as a 50:50 replacement mixture. Willey (1979b) has suggested that the sole crops should be sown at their optimum population density (taken as 100), and the intercrop populations can then be expressed on a simple proportional basis. If the intercrop components add up to more than 100, the design is called additive. For example, full sole crop population of **A** crop plus half of the **B** is a 100:50 mixture.

Rerkasem et al (1980) studied replacement series under a wide range of total overall densities and differentiated between yielding ability and competitive ability. According to Tofinga (1990) recent research of Firbank and Watkinson (1986) and Connolly (1986) show that replacement series may be inadequate to assess the competitive interactions and might give misleading results. He indicates that the main problem with this technique is that it confounds the inter- and intra-species competition, i.e. increasing the density of one component is accompanied by a decrease in the density of the other component. Thus if the separate effects of each component on the other are to be identified, the density of each component must be varied independently. This is achievable only by additive designs.

Willey (1979b) indicates that because of the ability of mixed crop stands to make better use of resources, it seems likely that the extent to which the population must be increased should be related to the magnitude of the yield advantages. For a situation where there are large temporal differences in maturity, Rao (1986) suggested using the additive design by having the early maturing components at 100 percent of the sole crop population, while the other component may require 100 percent of sole crop or even more.

However, there is a risk that in the additive design, inter-specific competition is confounded with the total density effect. The replacement (substitutive) design has the advantage that it shows the effect of replacing a certain proportion of one species with the same proportion of the other on the yield of each species. When these yields are compared with monoculture yields, relative competitive abilities can be determined.

In practical terms, Davis and Woolley (1986) implied that, in environments with a short growing season or under resource-stressed conditions, the total population can be kept the same in sole crop and mixture (using replacement designs). Regarding the population of component crops, Ofori and Stern (1987b) suggested that in a cereal-legume intercrop, even though the cereal component determines the level of the combined mixture yield, and the yield of the legume component is normally reduced markedly by high densities of the cereal component, the efficiency of the system follows the trend of the legume component. The main reason for this is that since land equivalent ratio (LER) is the combination of relative yields of both legume and non-legume, any increase in the amount of relative yield of the legume has a great influence on LER. Moreover, the legume part of an intercropping system has normally higher nutritional and monetary value than the cereal component.

In the study reported in this thesis a number of different population densities in both additive and replacement designs were used to examine population effects on the productivity of intercropping systems under dryland conditions of South Australia.

2.5.2.2 Spatial arrangement

Spatial arrangement is defined as: the physical or spatial organisation of component crops in an intercropping system (Francis, 1986a). Willey (1979b) proposed that two points should be considered regarding the spatial arrangement of the intercrops: (a) the proportional areas designated to each crop at sowing time and (b) how proportional areas are arranged with respect to each other. For example, an intercrop which has proportional areas of 50:50 can be arranged as: (i) single alternate rows (SAR), (ii) double alternate rows (DAR) or (iii) alternate plants mixed in rows (MIR) (Figure 2-1). Row proportions (ratios) for SAR and DAR are: 1-1 and 2-2 respectively, and two rows of crop **A** and three rows of crop **B** would be shown as 2-3.

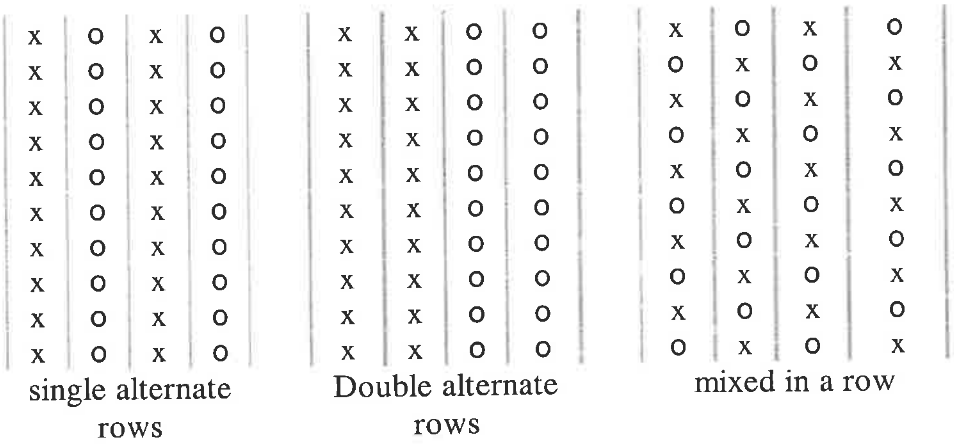


Figure 2-1 Different row arrangements (o = chickpea plant, x = wheat plant)

The intimacy of crops in most cases has an effect on competition. Andrews (1972) indicated that to obtain maximum complementary effects, crops should be planted as close as possible. This seems to be more true in cases when an intercrop is used as a physical support for the other intercrop such as for pea-cereal intercropping, or in mixtures where there is a transfer of N from an adjacent legume. In contrast, Rao (1986) stated that, "Generally, the dominant cereal has to be spaced wide enough (from legumes) to minimise the competition between species". Willey (1979b) also suggested that the more competitive a component, and the more favourable its spatial plant arrangement, the more likely it is to show a growth response to an increase in population density in intercropping similar to that in sole cropping. Regarding cereal-legume intercropping Ofori and Stern (1987) indicated that the yield of the cereal component is usually less affected by densities and row spacing. This might be because cereal yield can be maintained over a wide range of spatial arrangement patterns and using lower population densities. Thus using low densities of cereals in mixtures might enhance the yield of the second crop (Freyman and Venkateswarlu, 1977). However where a component is dominated and has a less favourable spatial arrangement its yield may differ greatly from that in sole cropping. Widening cereal inter-row spacing in order to include more rows of legume can improve the yield of the legume and its efficiency in an intercropping system. There are many studies that show that having intercrops in alternate rows is more beneficial than if they are mixed in a row and, in the case where there is greater need for light penetration, even the use of double rather than single alternate rows has been beneficial (Ofori and Stern, 1987a).

In the study reported in this thesis a range of different spatial arrangements was used to investigate their effect on the productivity of the wheat-chickpea intercropping system.

2.5.3 Time of sowing

Generally, time of sowing is one of the most important agronomic determinants of yield for both sole and intercropping. In an intercropping situation simultaneous planting or staggering (planting component crops at different times) has a great influence on the final yield. For example, in dryland conditions planting the crops at the earliest opportunity may safeguard the crops against drought conditions at the end of season, but to reduce intercrop competition the sowing dates of the component crops may be staggered. Thus careful choice of relative planting date may increase the total yield provided moisture at the end of the season is adequate (Andrews, 1972). Willey (1979b) suggested that staggered sowing may be a valuable way to increase yield through increasing the temporal differences between crops and to achieve complementarity. However, an earlier sown crop usually becomes more competitive and a later sown one less competitive than if they are sown simultaneously. For example, Francis *et al.* (1982) found that Land Equivalent Ratio (LER) (Section 2.7.4.1) was higher in a maize-bean intercrop if the bean was sown 5-10 days earlier to reduce the dominance of the maize. However, Ofori and Stern (1987b) found that staggered sowing of intercrops in a maize-cowpea intercrop system had no advantage over simultaneous sowing.

In the South Australian Mediterranean climate, because of time constraints due to a short growing season, a simultaneous planting pattern seems more practical than staggered planting. However because of the possibility of severe competition from cereals against legumes, staggered planting may modify the competitiveness of component crops and improve productivity (Midmore, 1993).

In conclusion, in southern Australian dryland areas the successful application of intercropping seems closely related to choice of appropriate species and cultivars and of agronomic practice. Row arrangements and proportions, the population density of each crop and also time of sowing seem to be the most important tools available for achieving successful intercropping in this region.

2.6 The role of bio-physical resources in intercropping

Fukai and Trenbath (1993) proposed that the main aim of intercropping is to improve land productivity by maximising capture of the biophysical resources by two or more plant species grown together. Often the combined capture of these resources by a community of intercropped plants is greater than that possible with a community of a single plant species. The productivity of a plant community is generally proportional to the quantity of the resources captured.

$$\text{yield} = c\,Q$$

Equation 2-1

where **c** is a crop's specific constant denoting the efficiency with which the crop utilised a particular resource, and **Q** is the quantity of the resources captured. In a community of plants the productivity will therefore depend not only on the amount of resource capture, but also on the efficiency with which the component species uses the most limiting resources (Fukai and Trenbath, 1993). The issue of resource capture is dealt with in some detail by Trenbath (1986).

In most cropping environments, the major factors determining grain yield are:

a) solar radiation,

b) soil moisture and

c) soil nutrients.

In any given environment crop yield will be determined essentially by the availability of the most limiting of the three resources. In semi-arid environments, such as the wheat-belt area of southern Australia, soil moisture is the most limiting resource (Siddique and Sedgley, 1987). With intercropping the aim is to engender the sharing of available resources over time and space. Variation between component crops in their characteristics such as canopy development and architecture, physiological adaptation and other morphological traits, e.g. rooting pattern and depth, will all have significant impacts on the efficiency of a given species in capturing the resources. In intercropping, sharing of resources to the mutual benefit of the species concerned is not always possible since often one or more resources may be limiting and the species may have to compete to gain access. Thus, the species will interfere with each other both above- and below-ground.

To gain a full understanding of the processes determining productivity of wheat-legume intercrops in the Mediterranean environment of southern Australia, it is imperative to analyse further the roles of these biophysical resources in determining the yields of component species.

2.6.1 Solar radiation

About 50% of total global short-wave radiation has a spectral wave band between 0.4 to 0.7μm, i.e. the visible range, which is termed photosynthetically active radiation (PAR) (Gardner *et al.*, 1985). Plants intercept incident radiation and convert this energy to chemical energy in the form of carbohydrates during photosynthesis. Solar radiation could be the most important factor limiting crop production if the supply of other resources is adequate (Willey and Roberts, 1976; Charles-Edwards, 1982). Despite the supply of solar radiation being more reliable than other resources in most situations in dryland regions, it cannot be stored for later use (Keating and Carberry, 1993). Increases in productivity under intercropping have been associated with a better capture of light. For instance, Ali (1993) in a wheat-chickpea mixture and Marshall and Willey (1983) in a millet-groundnut mixture reported higher yields for the mixtures in relation to pure stands mainly due to greater interception of radiation by the mixed crop canopies.

However, attributing a yield increase solely to greater light interception is debatable. Midmore (1993) showed that an increase in dry matter yield by the intercrops occurred despite their peak light interception being similar to that of the sole crops. This phenomenon has been observed in intercrops with different growth cycles (Natarajan and Willey, 1980) and also within mixtures with similar growth duration (Ahmed and Rao, 1982). Thus, the increased productivity in intercropping is probably due to a more efficient use of light, rather than greater interception of light, i.e. the process is more qualitative than quantitative.

The efficiency of intercropping systems can be increased by improving the distribution of light amongst the component canopies. This can happen in intercropping systems of species with temporal differences in phenology. A typical example would be a combination of a short-season but fast growing cereal with a long-season pigeonpea. The cereal component has an initial rapid canopy growth rate and achieves a high degree of light capture. Morphological differences between intercropped species may also create a better light use efficiency. Trenbath (1974), using a simulation model, proposed an ideal canopy of mixed wheat cultivars. He suggested a mixture containing plants with non-overlapping leaves and no stems, in which the top cultivar has an erect habit and the lower cultivar has a prostrate habit. He calculated an increase in photosynthesis of only 8.7% for this 'ideal' mixture. However, when he introduced cultivars with overlapping leaves, or with larger or more stems or reduced the difference in mean leaf angle between the two cultivars, the advantages of mixing were diminished. Kasanaga and Monsi (1954) showed that on theoretical grounds high light intensities of direct radiation would be better utilised by a canopy with erect leaves such as a sparse canopy of a tall cereal, with a denser canopy of legume to utilise the low intensities of the mostly diffused radiation underneath. Another way to maximise use of light is to combine a tall C_4 species (high photosynthetic rate), with a short C_3 legume (lower photosynthetic rate), to take advantage of their inherent different responses to light (Marshall and Willey, 1983; Ahmed and Rao, 1982).

Considering the spatial capture and use of light, Willey and Roberts (1976) emphasised that sole crops are themselves usually capable of achieving a peak value of light interception, which leaves little scope for increased spatial interception by intercrops.

The relationship between area of leaves produced and radiation interception by the crop canopy is expressed by Monteith (1965) as:

$$P_i = 1\text{-exp } (\text{-kGAI})$$

Equation 2-2

where P_i is the fraction of radiation intercepted, while GAI is green leaf area index produced by the crop canopy, and k is the extinction coefficient. Generally, the higher the k the more efficient is the canopy in capturing radiation. In intercropping, the fraction of radiation intercepted by the respective intercrop could therefore be obtained from their GAI and k, accounting for height differences where applicable (Wallace *et al.,* 1990 and 1991). For a mixture containing wheat and chickpea, equation 2-2 can be represented as:

$$P_w + P_c = 1\text{-exp } [-(k_w .GAI_w + k_c .GAI_c)]$$

Equation 2-3

In which subscripts w and c refer to wheat and chickpea respectively.

Midmore (1993) concluded that it may be difficult to optimise the amount of photosynthates produced per unit of solar energy absorbed by the crop, i.e. radiation use efficiency (RUE), in intercropping systems because of the differences in the potential yield of the species and the complexity of intercropping systems. Introducing a crop with low radiation use efficiency into a stand of species with high RUE will dilute the combined RUE. In Mediterranean environments RUE for wheat is between 1.08 and 2.40 g DM MJ^{-1} (Yunusa *et al.*, 1993c; Loss and Siddique, 1994). In the research of various scientists such as Hughes *et al.* (1987) in Syria, Thomas and Fukai (1995) in Australia and Singh and Sri Rama (1989) in India, in different environments, the RUE for chickpea ranged between 0.30 and 0.93 g MJ^{-1}. Thus, intercropping of wheat with chickpea in a wheat dominant region may be wasteful of radiant energy, while the reverse may be the case in a chickpea dominant situation.

2.6.2 Soil water

Water being the most limiting factor in the cereal zone of South Australia, the productivity of any intercropping system will depend on the amount and distribution of rainfall. Studies in semi-arid and monsoonal environments indicate that intercropping may increase and stabilise yield (Morris and Garrity, 1993b). Baker and Yusuf (1976) concluded that the better use of water is probably a common cause of yield advantages of intercropping systems in semi-arid tropics. Studies are limited on the dynamics of water use in intercropping systems in dry environments (Francis, 1986a).

An analysis of the growth and yield process in intercrops requires a good understanding of soil water balance. For a vegetated piece of land the soil water balance equation over a period of time takes the form:

$$\Delta S = (P + I) - (R + D + ET)$$

Equation 2-4

where ΔS is change in the storage of soil water; P is precipitation; I is irrigation; R is runoff; D is drainage and ET is evapotranspiration. Both R and D are negligible in most agricultural situations in semi-arid regions and so may be eliminated from equation 2-4 (Arihara *et al.*, 1991).

The pattern of soil water extraction varies widely between species, probably because of their root growth and distribution. For instance, Arihara *et al.* (1991) reported that the deep-rooting habit of chickpea increased soil water extraction and was also a means to improve soil physical and chemical conditions for the companion crop.

Seasonal ET varies widely due to a range of factors including the available soil water, crop species and cropping systems. French and Schultz (1984a) analysed water use of wheat at 61 field locations in South Australia over an 11-year period between 1964 and 1975 and reported a seasonal ET range of 151 to 503 mm. Studies from other Mediterranean environments also report values within a similar range (Gregory *et al.*, 1992). Seasonal ET values for chickpea are often lower than for wheat. A study by Singh and Virmani (1990) found ET values for chickpea of between 110 and 400 mm. In Australia seasonal ET for chickpea is generally around 200 mm (Siddique and Sedgley, 1987).

Studies involving wheat-chickpea intercropping found a wide range of seasonal ET. Singh and Singh (1983) reported that intercropping systems used more water than sole crops of chickpea. Similarly Mandal *et al.* (1986b) compared ET by wheat, chickpea and mustard grown either as sole crops or intercrops for three years, and found seasonal ET to be in the order of chickpea<wheat<wheat-chickpea intercropping. Morris and Garrity (1993b) investigated many intercropping situations and showed that most ET for intercropping systems were about 6-7% greater than for the respective sole crops.

In general, there is a positive relationship between crop yield and the amount of water used during the growing season (French and Schultz, 1984a). The ratio of dry matter (DM) yield to water use is referred to as water use efficiency (WUE). Since root biomass is generally difficult to quantify, WUE is commonly based on above-ground DM produced by the crop (Gregory, 1988). WUE can vary considerably with crop type, environment, season and management practice. For instance, WUE for wheat grain yield in South Australia ranged between 4 and 37.5 kg ha^{-1} mm^{-1} (French and Schultz, 1984b), while for chickpea in Western Australia WUE of 6.5 kg ha^{-1} mm^{-1} was reported by Siddique and Sedgley (1987).

In intercropping systems, WUE of the component crops depends on the amount of competition for soil water between intercrops. In a study by Singh and Singh (1983) where rainfall was supplemented with irrigation in which WUE was calculated on energy basis, wheat-chickpea intercrops produced 0.79 to 1.08 kg ha^{-1} mm^{-1}. They also observed the lowest WUE of 0.51 kg kg ha^{-1} mm^{-1} for the sole crop of chickpea. Data for WUE of sole wheat was not presented in the work. Comparing several intercropping systems, Mandal *et al.* (1986b) found that the WUE was highest for sole wheat, followed by the wheat-chickpea mixture. The chickpea sole crop produced the lowest WUE.

Morris and Garrity (1993b) discussed three ways by which intercropping may enhance WUE. These are: 1) greater transpiration by the intercrops because of their faster canopy cover development compared to sole crops, 2) combining a high WUE species with a species with low WUE, and 3) the possibility of a more favourable microclimate in the intercrop canopy which may enhance WUE. In dryland situations, a potential disadvantage of increasing transpiration could be an earlier water deficit at the end of the season, created by the higher Leaf Area Index.

The main beneficial effects of intercropping on WUE derive mostly from the change in the partitioning of ET between transpiration (T) and soil evaporation (E_s), in favour of the former due to increased canopy cover. The T is the component of ET directly linked to biomass production as a result of the link between CO_2 intake for photosynthesis and water loss by T, both of which occur through the stomata (Singh and Sri Rama, 1989). In contrast to T, E_s is loss of water through the soil surface and thus a waste. Therefore, ET may not always be a good indication of crop productivity, and it should be more meaningful to analyse water use efficiency (WUE) of intercrops on the basis of T rather than simply on ET.

Generally partitioning of ET into its components is difficult, but several different direct and indirect approaches have been developed in recent years to quantify one or both of the components. Recent developments in microlysimetry allow direct measurement of E_s beneath a canopy (Boast and Robertson, 1982). This technique has been tested over a range of conditions with a high degree of consistency. Despite its simplicity, microlysimetry has some problems including high labour requirements and other logistical problems (Yunusa *et al.,* 1993a; Allen, 1990).

An alternative to the direct measurement of E_s is the use of models. Several models have been developed to estimate E_s or T. These models differ in their capabilities and complexities. In a comparison of four of the commonly used models, Yunusa *et al.* (1993b) found that in the dry Australian Mediterranean environments, T or E_s are easily calculated from the fraction of radiation intercepted by, or transmitted through, the canopy, during the wet phase of the season. During the dry terminal phase, E_s and T were dependent on the fraction of the available soil water.

A comprehensive analysis of water use in intercrops will involve estimates of T for each of the component crops. This is a difficult procedure to undertake. However, Yunusa *et al.* (1995) used the vapour pressure deficit weighted transpiration efficiency introduced by Tanner and Sinclair (1983) to estimate T for the component species of an agroforestry system. According to Tanner and Sinclair (1983):

$$\mathrm{TE} = K / (\mathrm{VPD})$$

Equation 2-5

Where TE is transpiration efficiency, *K* is a crop-specific constant, and VPD is vapour pressure deficit, measured in Pascals (*Pa*). Thus, in intercropping, if *K* for each of the individual species is known, their seasonal or temporal T can be calculated from their DM yields and environmental VPD for the corresponding period. For wheat *K* has been reported to range from 2.6-3.0 *Pa* (Yunusa *et al.,* 1993a; Gregory *et al.*, 1992). However, there have not been any *K* values published for chickpea, but *K* ~ 4.0 *Pa* has been found for some C_3 temperate legume crops (Tanner and Sinclair, 1983). Thus, the *K* for chickpea may be close to that for wheat, and since *K* is directly proportional to TE (Tanner and Sinclair, 1983), the relative yields of these two crops, when intercropped, will depend on their quantitative water uptake.

T from a mixture can be represented by the following equation:

$$\mathrm{T} = \frac{VPD.DMa}{K_a} + \frac{VPD.DMb}{K_b} + \frac{VPD.DMc}{K_c} + \cdots$$

Equation 2-6

where subscripts *a, b, c,* represents the various species in the mixture. Thus in the wheat dominated dryland farming systems of South Australia it is possible to improve productivity, by adopting an intercropping system with a high WUE. Intercropping might improve the canopy cover, which might help to improve productivity through a higher proportion of T in ET.

2.6.3 Soil nutrients

An increased nutrient uptake by intercropping systems compared with monoculture has been shown by several workers for N, P, K, Ca, and Mg. The increased nutrient uptake in intercropping might be because the component species may have peak demands for nutrients at different stages of growth (a temporal effect). More obvious may be the differences among component crops in their nutrient requirements, the form of the nutrient and the ability of the crop to extract them (Morris and Garrity, 1993a).

Nitrogen

Of the numerous elements required for crop growth and yield, N is considered the major one, and its availability will have significant effect on underground competition amongst the intercrops (Beets, 1982). N fixation and N transfer are of great importance in the productivity of intercropping systems (Stern, 1993)

In a community of intercrops, below ground competition is largely characterised by availability and acquisition by plant species of water and N (Ong, 1987). The ability of a legume to fix N influences its suitability for intercropping with cereals (Davis and Woolley, 1986). Including a legume in a mixture may reduce competition for soil or fertiliser N, and is one of the reasons for the improved productivity of cereal-legume intercropping. Fixation of atmospheric N by the companion legume does not entirely eliminate competition for N (Ofori *et al.*, 1987). However, application of N fertiliser might impair the fixation of nitrogen, and might cause the 'haying off' phenomenon which reduces the yield of legumes after excessive vegetative growth and consequent shortage of water (Khan, 1991).

Another reported characteristic of legumes in intercropping with non N fixing crops is the possibility of underground transfer of N fixed by legume to non-legume (Stern, 1993). Many studies have shown evidence for the transfer of significant amounts of N from legume to the non-legume crop (e.g. Giller *et al.,* 1991; Hardarson *et al.,* 1988 and Senaratne and Ratnasinghe (1993)). However, many other studies do not show any direct transfer (e.g. Ofori *et al.,* 1987; Danso *et al.,* 1987; Tobita *et al.,* 1994 and Izaurralde *et al.,* 1992).

The ability of an intercrop to absorb and make more efficient use of soil nutrients depends on different factors such as the extent of root growth of the components of the mixture, soil water level, and how the entire root zone is explored by the roots (Francis, 1989). A higher N yield for a mixture was reported by Kushwaha and De (1987) for a mustard-chickpea intercrop because chickpea nodulated better and had larger nodules when grown in mixture and there was also a higher uptake of N by mustard in the mixture. However, Danso *et al.* (1987) found that total N in intercropped faba beans was less than barley in the mixture. Sole crop faba bean absorbed more N than sole barley.

In a cereal-legume mixture because of the possible effect of N fixation and competition for nitrogen, assessment of fixed N may assist understanding of the intercropping systems. Peoples and Herridge (1990) indicated that there is no single correct way of measuring symbiotic N fixation for all different agronomic situations. Different methods of assessing N such as: ^{15}N -isotopic techniques, N-difference method, N balance, N fertiliser equivalence and nodule evaluation have unique advantages and limitations (Peoples and Herridge, 1990). However, Ofori *et al.* (1987) believed that ^{15}N isotopic techniques offer a reliable and direct method for assessing N fixation, and also allow the proportions of N in cereal and legume components gained from soil, fertiliser or air to be distinguished.

Peoples *et al.* (1989) explained that ^{14}N and ^{15}N are the two types of stable isotopes of nitrogen. ^{15}N is the heavy isotope. It occurs in atmospheric N_2 as a constant of 0.3663 atom %. Plant-available N in soil (i.e. nitrate and ammonium) is naturally enriched in ^{15}N due to isotopic fractionation by microbial processes. The natural abundance technique for estimating nitrogen fixation relies upon the small differences between atmospheric N and plant-available N in the soil which lead to differences in ^{15}N values between legume and non-legume plants. The ^{15}N technique can also be applied by using ^{15}N enrichment (Stern, 1993) in which a fertiliser labelled with ^{15}N isotope is added to the soil under both legume and non-legume and uptake is later measured in the plant shoots; non-legume (reference plant) shoots will have higher enrichment than legumes as the nitrogen assimilated from the soil is 'diluted' by atmospheric N_2 of lower ^{15}N abundance fixed in its root nodules. The major assumption of this method is that the legume and the reference plant absorb the same proportion of N from the soil and the added labelled N during the growing period. Using appropriate calculations (see later chapters) the method is capable of estimating a gross rate of N fixation, and measuring nitrogen transfer to the companion crop.

Fukai and Trenbath (1993) reported that in most cases intercropping efficiency was greater under low than high fertility conditions. Davis and Woolley (1986) reported a decrease in the amount of yield of chickpea following application of N due to increased competition by the cereal. Ofori and Stern (1987a) studied the influence of applied N in several studies and found that N application did not improve the LER. However, in a maize-soybean intercropping system under humid subtropics conditions, Clement *et al.* (1992) found that because of complementarity of resource use some higher levels of LER were obtained with application of higher levels of N. Therefore a legume as part of a mixture might confer additional benefits in relation to N fixation, i.e. a transfer of N fixed by the legume to the non-legume and residual N for subsequent crops, which may be of great importance in the low input agricultural systems of South Australia.

2.7 The evaluation of intercropping

Parkhurst and Francis (1986) illustrated the complexity of intercropping systems in comparison with monoculture and showed that if the effects of various factors were considered there would be 105, 325 and 741 possible two-way interactions in monoculture, two crop intercropping and three crop intercropping systems, respectively. Because of the multivariate responses in intercropping systems, the different statistical procedures need to be applied (Federer, 1993).

Moreover, the aims and practical objectives of intercropping have a great influence on its evaluation. Regarding practical aims, Willey (1979a) distinguished three different situations:

(i) Where the full yield of a main crop is a basic requirement but some yield of a second crop must also be obtained. This concept was later broadened by Willey (1985) to include the situation where there is some restraint on the production required of one or both crops. In this situation the yield of the mixture is compared with the most productive monoculture. This is practised mainly in subsistence farming. Most of the common statistical methods such as analysis of variance can be used to assess the yield advantages.

(ii) Where it is acceptable to have any amount or proportion of two intercrops. In such circumstances intercrop yield must exceed the higher sole crop yield. This method has been used in assessing yield advantages in grassland mixtures (Donald, 1963).

(iii) Where the combined yield of intercrops must exceed the combined sole crop yields. This might be required in order to have a higher overall grain yield, to satisfy dietary requirements or to spread labour peaks to guard against market risks. This is the most common situation of intercropping and it is the most difficult one to assess statistically. The first difficulty is that two crops which are very different in type or level of yield must be compared, and the second problem is that the comparison must take into account the competitive relationships between crops (Federer, 1993).

Mead (1986) and Petersen (1994) pointed out the importance of using several different statistical analyses to extract the best information from intercropping experiments. To encompass the range of objectives addressed in this project, in which the third situation is occurring, four forms of assessment (i.e. univariate analysis, bivariate analysis, diagrammatic assessment and indices) are reviewed in the following sections.

2.7.1 Univariate analysis

Most of the statistical analyses undertaken in agronomic experiments consider analysis for a single variable (Federer, 1993). Mead (1981) indicated that univariate analysis can be conducted for the sole-crop yields of each crop, for the individual component crop yields of the intercrop and the total intercrop yield. He emphasised that the principle of comparing 'like with like' should apply in analysing data from intercropping experiments. This principle means a comparison is valid only when the units of measurement are the same. For example, a univariate analysis can only be used to detect the effect of wheat on yield of different varieties of intercropped chickpea, not on yield of different varieties of both wheat and chickpea. Thus only a common variable to which all component yields can be directly converted can be used in intercropping situations. Examples are total biomass, calories, protein and the economic value of the cropping systems. Analysis of variance is the most common way to assess a single variable. If the structure of data is unbalanced, it is inappropriate to use analysis of variance. However, regression analysis can be used to overcome this problem. It should be mentioned that if the data were balanced, the results of the analysis of variance and the regression analysis would be the same.

To detect differences between the means, various methods were applied such as Least Significant Difference (LSD), Tukey's method (HSD) and Scheffé's method (Zar, 1996).

In this thesis univariate analysis was applied to individual yields of each intercrop and some indices, while where treatments were unbalanced (e.g. Chapter 5) regression analysis was applied.

2.7.2 Bivariate analysis

Since in intercropping at least two variables are measured together, the only form of analysis which includes all available information is bivariate analysis. A bivariate analysis is the joint analysis of the pairs of yields for two crops intercropped in an experiment. The philosophy behind the application of this method is that, because two yields from a plot are interrelated then analysing each variable from an experiment separately might provide misleading information or fail to display the full situation; therefore they should be analysed together (Mead (1986) and Mead *et al.* (1993)). Despite the fact the bivariate method provides a valid test of significance for assessing intercropping experiments, some statisticians do not recommend application of this method. For instance, Petersen (1994) considers that bivariate analysis does not provide much value because of difficulties associated with its application as shown below:

1. The assumption that correlation between the yield of two crops is constant and independent of the treatment is very difficult to check. It is also probably incorrect, because competitive effects vary with treatment and time.

2. Bivariate analysis does not permit a comparison of sole crop and intercrop yield.

3. It does not allow a graphical representation and assessment in mixtures with more than two intercrops.

4. The analysis is more complex than univariate analysis.

2.7.3 Graphical presentation and evaluation

2.7.3.1 Bivariate analysis

Bivariate analysis can also be presented graphically using skew axes for the two yields, allowing for the background pattern of random variation in the mixtures (Mead (1986)). Mead *et al.* (1993) said: "Without information about the interdependence of the two variables our eyes may be misled. In this situation we can choose either two re-educated eyes or, alternatively, consider an analysis and method of graphical presentation which makes the eyes' natural interpretation correct. Bivariate analysis and plotting means on skew axes is intended to achieve this". More information about this method can be found in Federer (1993) and Mead *et al.* (1993). In this thesis the graphical method of bivariate analysis is presented. Taking into account the advantages and disadvantages of bivariate analysis, it was used in conjunction with other statistical methods in the present study.

2.7.3.2 Replacement series

There are different methods to vary plant populations in intercropping studies. The most commonly used method to study interspecific competition is the replacement series (de Wit, 1960), in which the population of sole crops is taken as 100, and the component populations in the mixture are expressed on a proportional basis (Figure 2-2a, b, c). This method is based on sown percent of sowing land and the expected yields of the mixture are those that would be obtained if the area was divided into pure stands of two species in the proportion indicated on the horizontal axes, i.e. the combined pure stand yields (Figure 2-2). For example in a 50:50 replacement mixture of wheat and chickpea, half the land would be used for wheat and half for chickpea. The expected yield of the mixture is shown by the upper broken line in Figure 2-2 and shows that expected yields of all replacement mixtures are intermediate between the yields of the two sole crops. A yield advantage of growing the mixture occurs when the yield of one or both intercrops is higher than expected, leading to a higher than expected mixture yield. Such a yield advantage in mixtures is illustrated in Figure 2-2a and b, as the vertical comparison between combined pure stands or expected mixture yield (uppermost broken line) and actual combined mixture yield (top unbroken line).

de Wit (1960) compared the yields of oats and barley in monoculture and mixture in many field experiments and found no yield advantage from mixing the two species. This was because the species were "mutually exclusive" i.e. while the yields of the stronger competitor were higher then expected in the mixture, the yields of the weaker were proportionally lower. This effect was attributed to the two species competing for the "same space" or resources, i.e. they occupied the same niches. In this situation of two species being mutually exclusive, de Wit (1960) calculated the relative crowding coefficient (RCC) to characterise the competitive relationships. The RCC was estimated by a process of iteration. The curves were drawn as examples of hyperbolas. The same formula and the concept of mutual exclusivity were found to hold for replacement series of pasture grasses (van den Bergh, 1968). This corresponds approximately to Willey's (1979a) concept of "compensation" (Figure 2-2b).

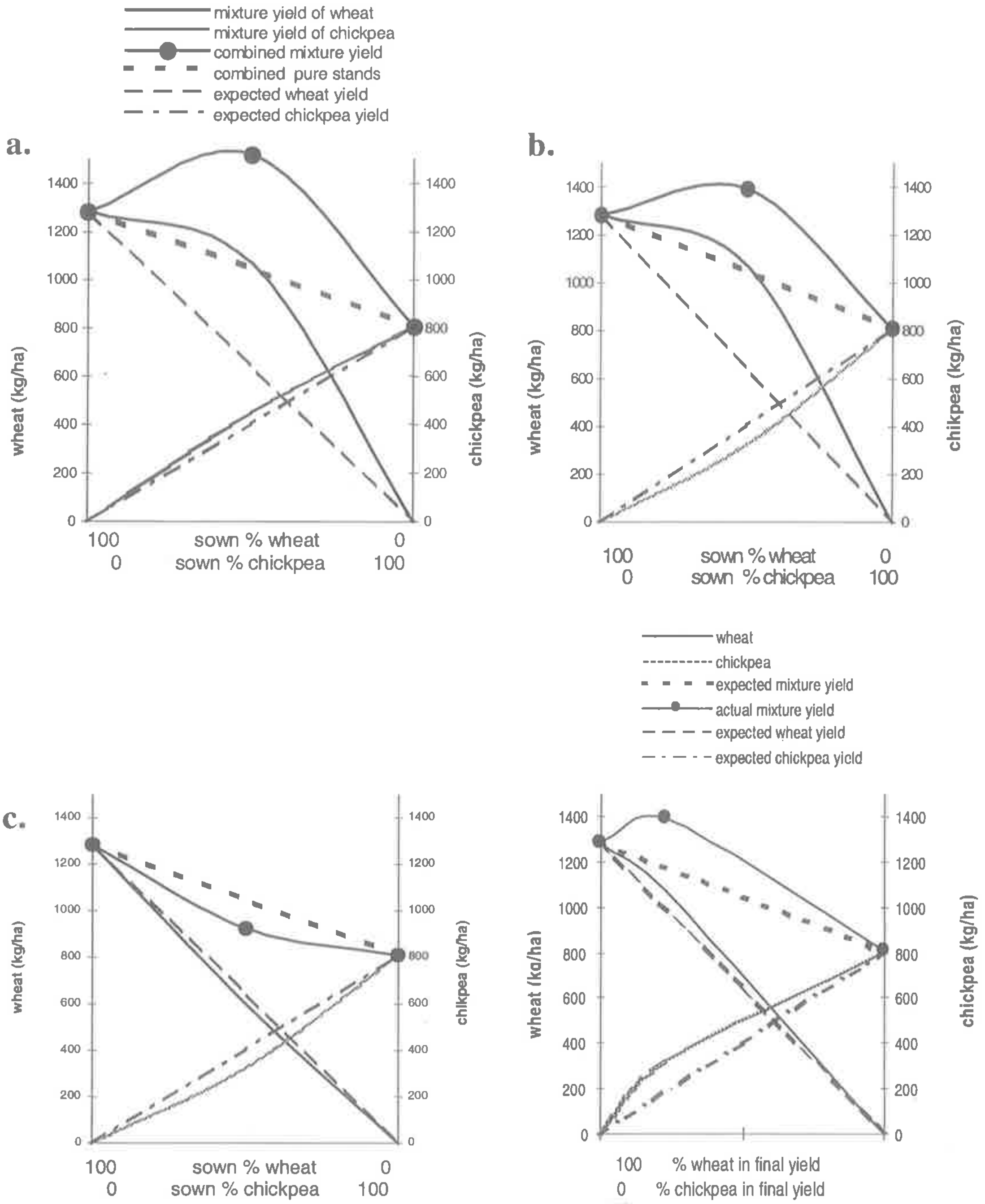


Figure 2-2 Hypothetical representation of competition between species: (a) mutual cooperation, (b) compensation based on sowing rates, (c) mutual inhibition and (d) compensation based on final yield proportions

The concept of mutual exclusivity was found not to apply to a mixture of a grass and a legume (de Wit *et al.*, 1966) because the fixation of nitrogen by the legume provided another N niche, i.e. the two species were not competing for the same space, and they were not mutually exclusive. Furthermore, neither the grass nor the legume in the mixture yielded less than their expected yield. This corresponds to Willey's (1979a) concept of "mutual cooperation", which can be explained, for a mixture of a cereal (grass) and a legume, by N fixation by the legume and transfer of N from legume to grass (de Wit *et al.*, 1966).

Willey (1979a) also proposed the concept of "mutual inhibition" (Figure 2-2c) which de Wit (1960) attributed to a combination of competition and allelopathy.

A disadvantage of the replacement series method is that in a compensation situation the overall advantages of the system might be illusory. In this method if the dominant species yields more than expected in the mixture, the diagrammatic compensation is biased in favour of the mixture, and towards sole cropping if the dominant species has less yield than expected (Mead, 1981). Willey and Osiru (1972) suggested that this bias was removed by calculating the proportions of sole cropping which would give the same final yield proportions as in intercropping (Figure 2-2d). This would then provide a better indication of the relative competitive abilities and also show the actual values of any intercropping yields advantages. In doing so, vertical comparison between yields becomes valid and a better evaluation can be expected. It is the latter type of diagrammatic illustration based on final yield which is analogous to land equivalent ratio (LER). LER is discussed later in this chapter.

2.7.4 Indices

A major difficulty in intercropping experiments is that, since there are at least two species in an intercropping system the yields of these two are not directly comparable. With the help of bivariate analysis (reviewed in 2.7.2), the data of different variables can be combined and analysed. Indices (combinations of data e.g. ratios) may also be used in the assessment of intercropping experiments to summarise and to convert different measurements into one index or unit in order to combine the information. There are many points which must be taken into consideration when indices are used. For example, in most cases there is a loss of information, but the gains from being able to make quantitative conclusions may outweigh the loss. Because different parts of the information may be lost using different indices, it is possible that very different conclusions may be reached from the same set of results by using two different indices (Mead, 1989). There are various ways to categorise the different types of indices (e.g. Willey, 1979b; Mead, 1986; Ofori and Stern, 1987a). In order to summarise the reviewed papers, and despite the possibility of overlaps between different indices, three major categories have been selected: (i) indices of biological efficiencies, (ii) competition indices and (iii) practical indices (monetary and nutrient indices).

In order to clarify the presentation of different indices, some symbols are defined below. The intercrop consists of two component crops, a and b.

Y_{aa} = Pure stand yield of species a

Y_{bb} = Pure stand yield of species b

Y_{ab} = Mixture yield of species a (in combination with b)

Y_{ba} = Mixture yield of species b (in combination with a)

2.7.4.1 Indices of biological efficiency

These indices may be land equivalent ratio or competition indices, and they are used to assess the increased biological efficiency of a given intercropping system as compared to their sole cropping (Willey, 1985).

Land equivalent ratio (LER) and Relative Yield Total (RYT)

Amongst all of the indices which have been suggested for intercropping, the most commonly used is land equivalent ratio (LER). This is a biological index which was proposed by Willey and Osiru (1972), and shows the amount of land needed by sole crops to produce as much total yield as a given intercropping system. For example, an LER of 1.27% means that 27% more land is required for sole crops to produce the same total yield as the mixture sown in the same proportions. When LER is equal to one it means there is no yield advantage or disadvantage of the mixture compared with sole cropping. An LER less than one shows a disadvantage for intercropping over sole cropping.

$$\text{LER} = \frac{\text{Yab}}{\text{Yaa}} + \frac{\text{Yba}}{\text{Ybb}}$$

Equation 2-7

This index is numerically identical to the relative yield total (RYT) (de Wit, 1960) cited in Willey (1979a) and Ofori and Stern (1987a), in which the calculation is based on yield rather than land-area. RYT was originally used in competition studies (de Wit, 1960). A RYT = 1 was regarded as evidence that two competing species were mutually exclusive, i.e. they compete for the same space. In this case, RYT = 1 means that the yield of the mixture is not greater than that of even the highest yielding monoculture. If RYT > 1, the yield of the mixture is greater than that of one or both monocultures, depending on relative sowing proportions, yield potential and resource availability.

The validity of comparing LER values within an analysis of variance is not straightforward. The need to use standardised sole crop yields in calculating LERs was stressed by Mead (1989) and Federer *et al.* (1982). Oyejola and Mead (1982) compared six different ways to standardise sole crop yield for calculating LER (Table 2-3). The criteria used were: 1) normality of the residuals of LER values after fitting blocks and treatment effects, 2) precision of comparisons arising from the analysis of variance, and possible bias in the means. They believed that if the LER is calculated using corresponding sole crops the results are highly unreliable. Mead (1986), Petersen (1994) and Federer (1993) also advise against using separate divisors (e.g. sole crop yields) for each plot. They consider that the fewer divisors required by a standardisation method, the less the doubt about the precision of the treatment comparison. The type of standardisation should vary according to the form and objectives of experiments (Mead and Willey, 1980). A range of different philosophies can be involved in choosing the divisors in intercropping systems (Willey and Rao, 1979). Table 2-3 presents different methods and objectives which have been used to standardise sole crop yield in calculating LER.

In the experiments presented in this thesis separate divisors were used for each experiment and the divisors were chosen according to experimental objectives and considerations. However, using a standardised value for all sole crops might create the risk that the values obtained may be different to that when using non-standardised values for sole crops. In the present study when presenting information from replacement series (section 2.7.3.2) the non-standardised value of sole crops is used. Since using a replacement series (with final yield proportions) is analogous to LER (Willey, 1979a) it can represent situations where LER was calculated with non-standardised values.

Table 2-3 Examples of types of divisors used for standardisation of LER in intercropping experiments

Researcher	Objective	The divisor used for Standardisation
Mead (1989), Oyejola and Mead (1982)	General	A single sole crop yield for each crop and that the same sole crop yield should be used for all blocks
Federer (1993)	General	The average yield of the sole crops in the district for all LERs
Petersen (1994)	General	The average yield of sole crop in experiment for all LERs
Huxley and Maingu (1978)	Population and spacing trials	Sole crops with the highest yield for all LERs
Mead and Willey (1980)	Level of fertility	Sole crops yield at same level of fertility for all LERs
Mead and Willey (1980)	Genotypes	The highest yielding genotype

Competition indices

These indices are used to quantify the degree of competition in intercropping systems. Some of them were explained by Willey and Rao (1980) and are presented in this section. Relative crowding coefficient (RCC), (de Wit, 1960; Hall, 1974a); aggressivity (McGilchrist, 1965) and competition ratio (CR) (Willey and Rao, 1980) are three of the most commonly used indices.

Using RCC, the assumption is that each species has its own coefficient (K) which gives a measure of whether that species has produced more or less yield than expected. For species a in a 50:50 mixture it can be written as:

$$K_{ab}=\frac{\text{Mixture yield of a}}{\text{Pure stand yield of a - Mixture yield of a}} = K_{ab}=\frac{Yab}{Yaa-Yab}$$

Equation 2-8

If the coefficient of a species is greater than one there is a yield advantage, less than one means there is a yield disadvantage and equal to one means there is no difference: The product of the coefficients has been used to examine the yield advantage of mixing: this is called K. If this value is less than, equal to or greater than one the intercrop has produced less yield, the equal amount of yield or more yield than expected. The component with the smaller K is the dominated one (Willey, 1979a). Because RCC is usually based on the yield per plant, the plant population must be constant across the mixture. Its use is limited to replacement series and cannot be used in additive situations.

$$K = Kab \times Kba$$

Equation 2-9

Aggressivity Aab shows how much the relative yield increase in species “a” is greater than that for species “b”. The use of an aggressivity index is also limited to mixtures from a replacement series.

$$Aab=\frac{\text{Mixture yield of a}}{\text{expected yield of a}}-\frac{\text{Mixture yield of b}}{\text{expected yield of b}}$$

Equation 2-10

An aggressivity value of zero indicates that the component species are equally competitive. The greater numerical value the bigger the difference between actual and expected.

The Competition Ratio, CR, measures the intercrop competition by indicating the number of times by which one component crop is more competitive than the other. For a 50:50 mixture it can be calculated as in the following formula:

$$CR_a = \frac{Yab}{Yaa} / \frac{Yba}{Ybb}$$

$$CR_b = \frac{Yba}{Ybb} / \frac{Yab}{Yaa}$$

Equation 2-11

CR can be used to compare the competitive ability of different crops, to measure the competitive changes within a given combination, to identify which characters are associated with competitive ability and to determine what competitive balance between components might give the maximum yield advantage (Willey and Rao, 1980).

Because of the mentioned applications and simplicity, CR was chosen as the competition index in this research.

Practical indices

Monetary indices: Because of economic implications, monetary indices have been widely used in the evaluation of intercropping systems (Willey, 1985). The main criticism of monetary indices is that price fluctuates over time and the ratio might vary considerably (Mead, 1986).

Nutritional indices: These indices show total amount of calories, protein, etc., and are more meaningful in subsistence situations where the crops will be eaten by farmers and their families (Willey, 1985).

3. GENERAL MATERIALS AND METHODS

3.1 Introduction

In this study five field experiments were carried out from 1993 to 1995 to quantify yield performance, competition and resource capture and utilisation of cereal-legume intercrops under dryland conditions (Figure 3-1). The first experiment, in 1993, was designed to investigate the intercropping of winter sown legumes: field pea (*Pisum sativum*), faba bean (*Vicia faba*) and chickpea (*Cicer arietinum*), with cereals: barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*). In a second related experiment, in 1994, the interactions between wheat and chickpea cultivars were studied.

The effect of plant densities on intercropping performance was investigated in three additional experiments. In 1993 the effect of seeding rates on wheat and chickpea intercrops was examined, and a subsequent experiment in 1994 was used to study the effect of row arrangements and seeding rates on wheat and chickpea in mixtures and in comparison with sole crops. After consideration of the information gained from previous experiments, a third experiment in 1995 was established to examine the effects of different row arrangements and densities at two levels of N fertiliser with special reference to resource use efficiencies of wheat and chickpea sole and intercrops under dryland and irrigated conditions.

The materials and methods common to all these experiments are presented in this chapter. Further details of the specific methods for each experiment are given in the relevant chapters (4, 5, and 6).

Views of the experimental site are presented in Plates on page xi.

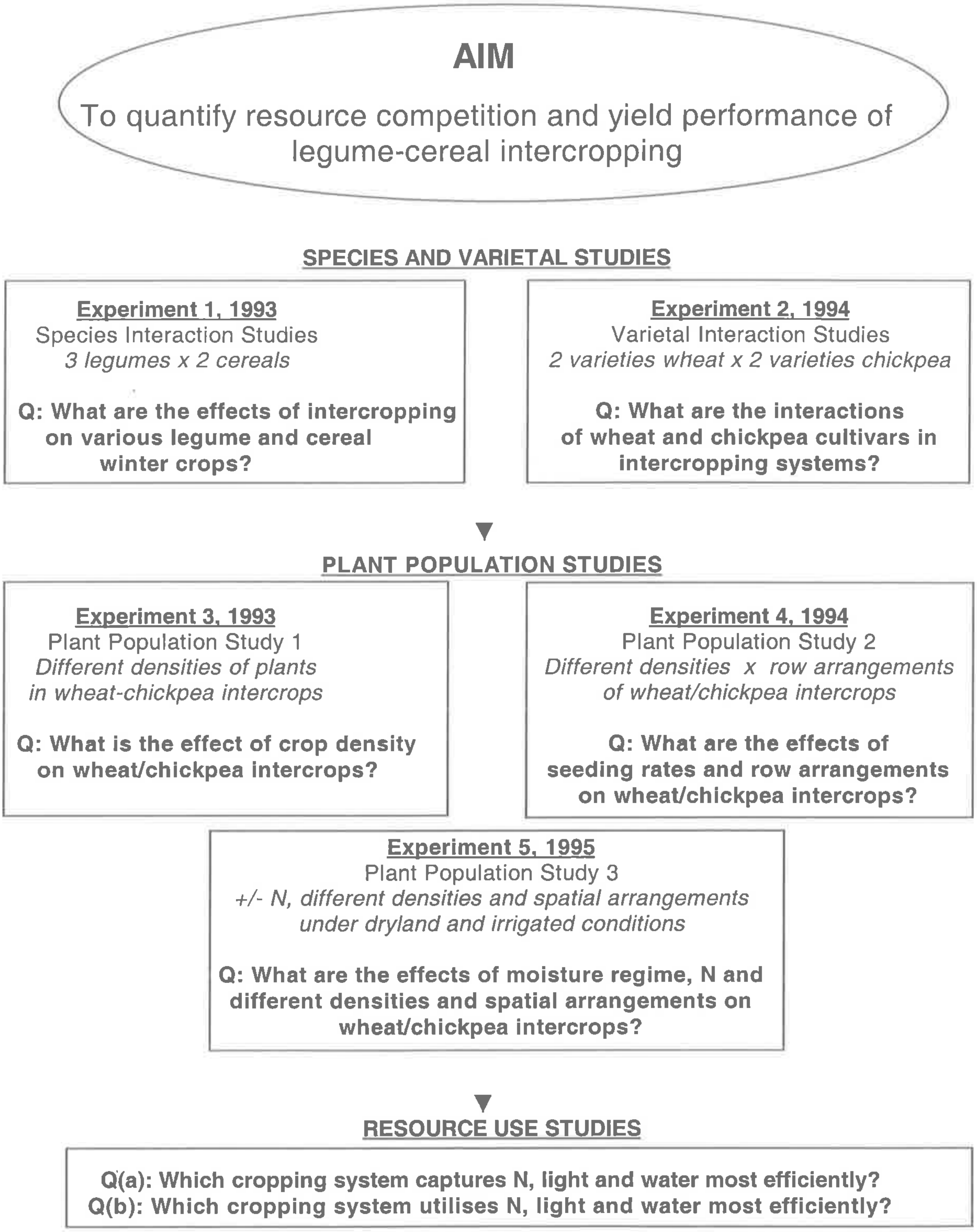


Figure 3-1 Flow chart of the study

3.2 Site and climate

The field experiments were conducted on the farm of the University of Adelaide Roseworthy Campus. This campus is located approximately 50 km North of Adelaide on the Adelaide Plains (latitude 34°32′S, longitude 138°41′E; altitude 64 m).

South Australia along with many other parts of southern Australia has a Mediterranean type of climate, i.e. rainfall is concentrated into the cooler period of the year. In these areas the growing season starts with the first effective rainfall in autumn, and plant growth occurs in autumn, winter and spring (Khan, 1991). The mean annual rainfall in Mediterranean climate areas varies from 275 to 900 mm. Rainfall variability (White, 1991) may result in a delay in sowing time caused by lateness of the rainfall in autumn or winter and productivity may also be affected by a drought period at the end of growing season (Squires, 1991).

Dryland farming or rainfed agriculture, which is dependent on natural rainfall during the growing season and the water stored during fallow, is practised in the cereal zone of South Australia (Squires, 1991). The area suitable for dryland cropping receives approximately 250 to 500 mm mean annual rainfall (Boyce *et al.*, 1991). The growing season (i.e. when soil moisture is available) is normally from April or May to October or November. The amount of rainfall within the growing season ranges from 230 to 360 mm and potential evaporation varies from 600 to 1500 mm (French and Schultz, 1984a).

One of the main constraints to yield in South Australia is the occurrence of water deficit in spring when crops are finishing their reproductive stage (Richards, 1991). During this time potential evaporation rises as the solar radiation input and vapour pressure deficit increase, while soil moisture also declines because of decreasing rainfall. Grain production is often reduced through the adverse effects of deficient moisture and high temperature stress.

Monthly maximum, minimum and mean temperatures and rainfall data for Roseworthy Campus, for 1993-95 and long term, are presented in Table 3-1. Not only was the total growing season rainfall variable over the three years of this study but its periodicity was also different.

Table 3-1 Monthly maximum (Max.), minimum (Min.) and mean temperatures (T, °C), and rainfall (mm) data for Roseworthy Campus, 1993-1995 and long term

Month	**1993**				**1994**				**1995**				**Long term mean**			
	T Max	T Min.	T Mean	Rain -fall	T Max	T Min.	T Mean	Rain-fall	T Max.	T Min.	T Mean	Rain fall	T Max	T Min.	T Mean	Rain-fall
January	27.0	13.9	21.1	44.4	27.4	14.2	28.8	21.8	33.7	17.0	25.4	18.2	29.8	14.6	22.1	21.0
February	30.8	15.6	23.4	7.1	29.2	15.5	22.4	12.0	33.3	15.4	24.4	29.0	29.6	14.8	22.2	19.0
March	28.3	13.8	20.4	11.8	27.3	13.3	20.3	0.6	25.5	12.6	19.0	14.1	27.4	13.3	20.3	20.0
April	23.8	11.5	18.8	3.1	23.7	12.5	18.1	12.6	21.0	10.4	15.7	27.1	22.7	10.7	16.6	38.0
May	18.8	9.6	15.7	21.3	19.7	9.0	14.4	14.8	19.0	9.2	14.1	44.9	18.8	8.9	13.8	49.0
June	16.2	7.1	11.4	44.9	16.6	8.0	18.1	12.6	16.9	8.9	12.9	55.1	15.8	6.7	11.3	53.0
July	17.0	7.2	11.6	37.5	17.2	7.0	12.1	32.8	14.0	7.2	10.6	87.5	14.8	5.8	10.3	49.0
August	15.7	7.4	13.1	40.0	15.5	5.9	10.7	10.4	17.7	6.6	12.1	16.7	16.1	6.1	11.1	52.0
September	15.5	7.8	13.4	63.7	18.5	7.4	12.9	8.6	19.3	7.0	13.2	18.7	18.9	7.0	12.9	46.0
October	20.3	8.9	15.4	89.4	22.7	10.7	16.7	24.8	23.6	10.4	17.0	49.2	22.0	8.9	15.4	43.0
November	21.9	12.0	19.5	20.2	24.4	12.1	18.2	34.0	26.9	11.8	19.4	7.6	25.6	11.4	18.5	27.0
December	26.2	14.3	21.4	23.6	31.0	14.5	22.8	6.6	26.0	11.3	18.7	8.1	28.0	13.5	20.7	23.0
Total	_	_	_	407	_	_	_	197	_	_	_	376	_	_	_	440

3.3 Soils

The soils of the Roseworthy Campus are typical of semi-arid regions, formed on quaternary sedimentary material deposited during the Pleistocene period. In this area soils are a mixture of solonized brown soils, red brown earth, grey calcareous soils and lighter textured transitional brown soils. The soils are generally shallow and deficient in phosphorus and nitrogen (Webber *et al.*, 1976). The pH of these soils is between 7 and 8.4. Using Northcote's (1979) classification the soils are classified under general profile forms of Um, Gc, Gn, Dr and Db (Harvey *et al.*, 1990).

3.4 Sown species and cultivars

There is a wide range of winter crops that are well adapted to the cropping pasture areas of South Australia. In the Roseworthy area rainfed grain production is traditionally integrated with livestock and pastures. Wheat and barley are the most important cereal crops sown in this area although oats (*Avena* spp.) and to a lesser extent triticale and cereal rye (*Secale cereale*) are also planted. Although pulses (grain legumes) are often seen as being less adapted than cereals to the soils and rainfall of this area, grain legume production with field pea (*Pisum sativum*), faba bean (*Vicia faba*), lupin (*Lupinus albus*), lentils (*Lens esculenta*) and chickpea (*Cicer arietinum*) is common in the Roseworthy area. Some oilseeds such as canola (*Brassica napus*) and safflower (*Carthamus tinctorius*) are also grown in this area, while pastures are mainly based on annual medics (*Medicago* spp.).

Five species of field crops, to include the most important cereals and pulses, were chosen for initial testing comprising two cereals (wheat and barley) and three legumes (field pea, faba bean and chickpea). The cultivars chosen are grown commercially around Roseworthy. Some of the characteristics of the cultivars are described in sections 3.5 and 3.6.

3.5 Cereals

Wheat

Machete is an awnless semi-dwarf, high yielding, broadly adapted line with a very early maturity. It has an Australian Hard quality and is moderately susceptible to stripe rust. It has a compact head which is held very erect, and was the second most widely grown wheat in South Australia (S.A.) (Hollamby *et al.*, 1987).

Excalibur is a semi-dwarf, early maturing cultivar with a very strong straw. It has few but synchronous tillers and heads which are large and have even size. It has hard grain and high grain weight, is resistant to stem rust and moderately susceptible to stripe rust. It is known to be zinc efficient and have moderate resistance to root lesion nematode (*Pratylenchus neglectus*) (Hollamby *et al.*, 1991).

Barley

Schooner is high yielding on most soil types in wet and dry seasons and threshes easily but is susceptible to shattering. It has excellent malting quality characteristics when grown in average to favourable conditions. It is susceptible to cereal cyst nematode (*Heterodera avenae*) (Taylor *et al.*, 1991).

3.6 Legumes

Chickpea

Semsen is a Desi type chickpea which was released is New South Wales and is grown in S.A. This cultivar is medium to tall in height and medium to late maturing with high seedling vigour. Semsen is susceptible to lodging and is moderately susceptible to waterlogging. It yields slightly less than the other Desi varieties but has better marketing attributes. Semsen is susceptible to *Phytophthora*, grey mould and *Sclerotinia* (Lamb and Poddar, 1992).

Desavic is a Desi type erect, medium height and medium maturity cultivar which was released jointly by S.A. and Victoria. It has limited lodging and its seedling vigour is moderate. Desavic is susceptible to waterlogging and *Phytophthora* (Lamb and Poddar, 1992).

Field pea

Alma is a tall, late maturing conventional field pea, with moderate tolerance to black spot (*Mycosphaerella pinodes*). This is the most popular variety in S.A. (Lamb and Poddar, 1992).

Faba bean

Fiord is a short, early maturing, non-shattering, early flowering cultivar which is grown in S.A. It holds its pods close to the ground and is very susceptible to chocolate spot (*Botrytis fabae*) (Lamb and Poddar, 1992).

3.7 Land preparation, sowing, crop maintenance and harvesting

In each season emerged weeds were controlled with 1.5 L ha^{-1} glyphosate before land cultivation. The land was initially cultivated with a disc implement, followed by two cultivations with a spring-tyne scarifier at about one week intervals. In 1994 and 1995 a pre-sowing herbicide (1 L ha^{-1} trifluralin at 400g/litre) was applied and incorporated into the soil at least two weeks before sowing. Fertiliser was also applied pre-sowing.

For the first experiment (1993) sowing was undertaken using a 3-point linkage drill (Connor-Shea), with 2.1 m width and 14 rows. The drill seed box was partitioned for the experiment in order to sow double alternate rows of legumes and cereals.

A six row seeder (Wintersteiger Seedmatic mounted on a Wintersteiger Plotman tool carrier) was used for the rest of the experiments. The seed was preloaded into magazines and separately fed to each row, thus making it simple to change species or seed ratios in individual rows of a plot. The row spacing of both seeders was 17 cm.

A post sowing pre-emergence herbicide (Diuron 1.5 L ha^{-1}) was used in 1994. Further weeding was undertaken by hand if necessary.

In 1993 all plots were mechanically harvested, and then seed of each species was separated manually. In all other experiments, intercrops were harvested separately, by hand or machine. After each hand harvesting, the grains of individual species were cleaned by sieving and aspiration before weighing.

3.8 The evaluation of intercropping and analysis of data

A number of different methods were used to analyse the results of intercrop performance. Univariate analysis was used to analyse the yield of each crop separately and to compare different indices. Bivariate analysis was used to consider interrelationships between crops. Mainly, GENSTAT software was used to analyse the data (Payne, 1993). Graphical methods such as replacement series and bivariate analysis were used in assessment of yield advantages (Pearce and Gilliver, 1979). Indices such as LER and CR are also used in assessment of the different cropping systems (Section 2.6). Bivariate analysis was not performed on Experiment 1 in Chapter 4 or Experiment 3 in Chapter 5.

In this study the type of divisors used for standardisation of LER were chosen according to agronomic considerations (Table 3-2). The CR was also calculated using the relative yields used for calculation of the LER. Where a statistical or graphical method is not used, this is noted in the relevant Materials and Methods section. Appendix 7 presents the non-standardised values of LER and CR.

Table 3-2 Types of divisors used for standardisation of LER

Chapter	Experiment	Objective	Divisor used for standardisation	Recommended by
4	1	General	Average yield of sole crop in experiments for all LERs	Petersen (1994)
4	2	Cultivar comparison	Highest yielding genotype (in the local district)	Mead and Willey (1980)
5	1	General	Same average yield of sole crop in experiment for all LERs	Petersen (1994)
5	2	Population and spacing trials	Highest sole crops yield for all LERs	Huxley and Maingu (1978)
5	3	Comparison of fertility levels	Sole crop yield at same level of fertility for all LERs	Mead and Willey (1980)

4. SPECIES AND VARIETAL STUDIES OF CEREAL-LEGUME INTERCROPPING UNDER RAINFED CONDITIONS

4.1 Introduction

Willey (1983) claims that intercropping is a means of improving the productivity of agricultural systems in low input areas. The need for identification of appropriate species and cultivars for intercropping has been stressed by many scientists (e.g. Francis (1985); Smith and Francis (1986); Smith and Zobel (1991)). A most important criterion for success with intercropping is the extent of competition between the crop species and the range of competitive ability amongst the cultivars (Davis and Woolley, 1993). There have been many studies worldwide to identify suitable species of cereals and legumes (e.g. Dubbs (1971); Clark and Francis (1985); Singh and Yadav (1992)) and also different cultivars of species (e.g. Singh and Chaudhary (1996); Aslam (1988); Tofinga (1990)). However, there have been few attempts to select species and cultivars for intercropping under dryland conditions in Australia.

This chapter provides the results of two field experiments conducted to investigate the yield performance, competition and possible biological advantages of intercrops of (1) two cereals species (wheat and barley) in binary combination with three legume species (faba bean, field pea and chickpea), and (2) two wheat cultivars each with two chickpea cultivars.

4.2 Experiment 1: Yield performance and competition in intercrops of two cereal species with three species of legumes under rainfed conditions in South Australia

4.2.1 Materials and methods

The experiment was conducted in paddock N4 of the Roseworthy Campus of the University of Adelaide from July to December 1993.

Wheat and barley were grown in binary mixtures with the 3 legume crops (field pea, chickpea and faba bean). The combinations were: wheat-chickpea; barley-chickpea; wheat-faba bean; barley-faba bean; wheat-field pea; and barley-field pea. Monocultures of all five crops were also sown. A randomised complete block design was used with 5 replications, a total of 55 plots. Each plot measured 2.25 x 12 m. Blocks were separated by 8 m headlands to allow machinery movements. A plan of the experiment is presented in Appendix 1.

The cultivars used in the experiment were Excalibur wheat, Schooner barley, Semsen chickpea, Alma field pea and Fiord faba bean. The characteristics of these cultivars were presented in Chapter 3.

After land preparation, the crops were sown using a 3 point linkage drill (Connor-Shea). Fertiliser (10, 20, 0: N, P, K) was applied with the seed at 100 kg ha^{-1} using the fertiliser box of the drill. The seeding rates for the monoculture crops of wheat, barley, chickpea, faba bean and field pea were 76, 66, 81, 85 and 100 kg ha^{-1} respectively. The intercrop treatments were sown in double alternate rows with seeding rates per plot half of those used for the monoculture sowing, and thus the same density within each row, in order to achieve a 50:50 mixed component population. There were 15 rows per plot, and the distance between seeding rows was 15 cm.

Crop establishment in each plot was measured four weeks after emergence, on 1 m of row in three randomly selected locations per plot (Table 4-1). For yield component and harvest index (HI) determinations, a 0.33 m^2 quadrat sample was randomly taken in each plot, one week before harvesting with the samples being used for calculation of yield components. For cereals the yield components were: number of heads per m^2, number of heads per plant, number of seeds per pod, grain weight per head and 1000 grain weight. For legumes the yield components were: number of pods per m^2, number of pods per plant, number of seeds per pod, grain weight per pod and 100 grain weight. The crops were harvested with a plot harvester (Hege 1.25B), from a 2.1 x 7.8 m area of each plot. The seeds of crop mixtures were separated after harvesting by sieving. The statistical methods and graphical assessments used are presented in Chapter 3.

4.2.2 Results

4.2.2.1 Crop establishment

The crop establishment measurements for sole species and individual species in mixtures are shown in Table 4-1. These densities are within the recommended range given for this region.

Table 4-1 Mean number of plants m^{-2} four weeks after emergence for sole crops and intercrops

Species	Plants m^{-2}	SEM
C	48.0	2.9
F	28.4	1.7
P	46.6	2.5
W	123.1	5.7
B	116.4	6.9
C in W-C mixture	26.7	2.3
W in W-C mixture	58.9	2.0
C in B-C mixture	22.7	2.2
B in B-C mixture	73.6	6.9
F in W-F mixture	14.4	2.2
W in W-F mixture	66.0	7.3
F in B-F mixture	12.9	0.6
B in B-F mixture	68.7	6.5
P in W-P mixture	22.4	1.2
W in W-P mixture	64.0	2.9
P in B-P mixture	21.6	1.4
B in B-P mixture	56.9	2.7

C = chickpea; W = wheat; B = barley; F = faba bean; P = field pea; SEM = standard error of means

4.2.2.2 Grain yield, yield components and Harvest Index

Wheat. The effects of sole and intercropping on the yield of wheat are given in Figure 4-1. The yield for wheat in monoculture was significantly higher ($P<0.05$) than that of the wheat in intercropping. Intercrop wheat yields were statistically similar, with wheat mixed with chickpea giving the highest yield and producing more than 80% of the yield of wheat grown as monoculture.

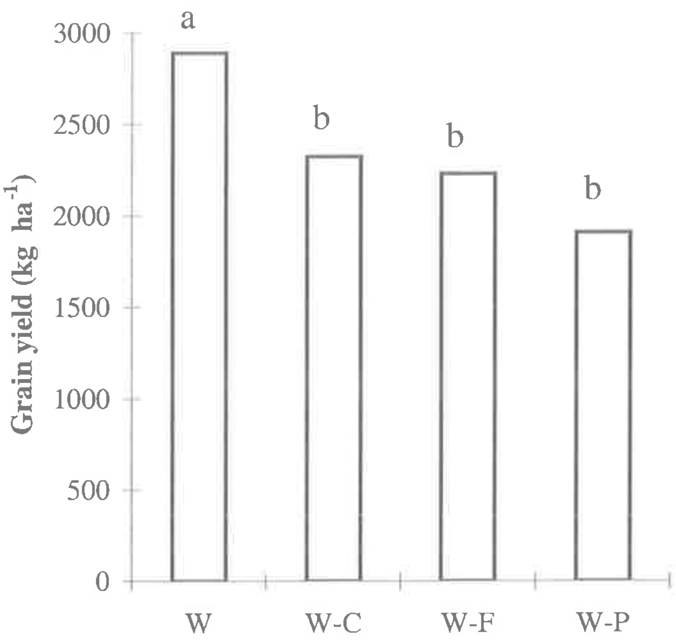


Figure 4-1 **Grain yield of wheat in sole wheat (W), wheat-chickpea (W-C), wheat-faba bean (W-F), and wheat-field pea (W-P) intercrops. Columns with different lower case letters are significantly different at 5% level (HSD)**

Wheat biomass and number of heads m^{-2} were not significantly different among the sole or intercrops ($P=0.05$). However wheat in mixtures with faba bean and chickpea produced greater ($P<0.05$) biomass per plant and number of heads per plant than the sole crop (Table 4-2). Intercropping also had no significant ($P=0.05$) effect on grain weight per head, 1000 grain weight and the HI (Table 4-2).

Table 4-2 **Biomass, number of heads, grain weight per head, 1000 grain weight and Harvest Index (HI) of wheat in sole wheat (W), wheat-faba bean (W-F), wheat-chickpea (W-C) and wheat-field pea (W-P) intercrops**

Cropping system	Biomass (g m^{-2})	Biomass (g plant^{-1})	Heads m^{-1}	Heads plant^{-1}	Grain weight (g head^{-1})	1000 grain weight (g)	HI
W	613a	5.0b	217a	2.0 b	1.4a	44.8a	0.52a
W-F	549a	9.3a	236a	3.4 a	1.2a	43.6a	0.54a
W-C	515a	9.3a	183a	4.0 a	1.3a	44.9a	0.46a
W-P	591a	8.0ab	239a	2.6ab	1.2a	44.6a	0.47a

Within columns, means with different letters are significantly different at the 5% level (HSD)

Barley. With the exception of the barley-faba bean intercrop, the barley yield in each of the barley-based cropping systems was not significantly different to barley as a sole crop (Figure 4-2).

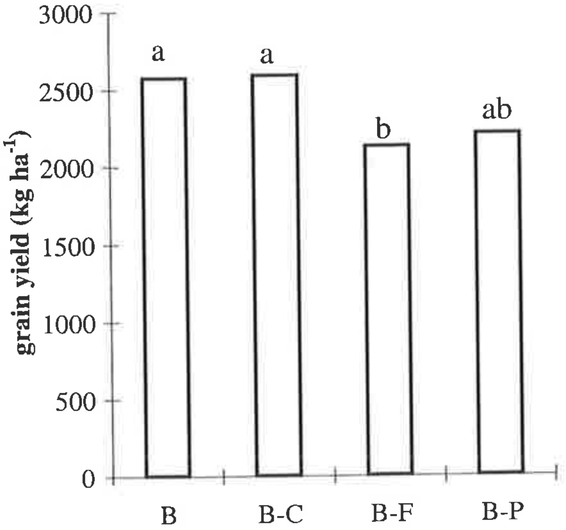


Figure 4-2 **Grain yield performance of barley in sole barley (B), barley-chickpea (B-C), barley-faba bean (B-F) and barley-field pea (B-P) intercrops. Columns with different lower case letters are significantly different at 5% level (HSD)**

As shown in Table 4-3, biomass and the number of heads m^{-2} did not differ significantly among cropping systems ($P=0.05$). However, in almost every case the biomass per plant and the number of heads per plant was greater ($P<0.05$) in intercrops than in the sole crop. Grain weight per head, 1000 grain weight and HI were not significantly affected by cropping system.

Table 4-3 Biomass, number of heads, grain weight per head, 1000 grain weight and Harvest Index (HI) of barley in sole barley (B), barley-faba bean (B-F), barley-chickpea (B-C) and barley-field pea (B-P) intercrops

Cropping system	Biomass (g m^{-2})	Biomass (g $plant^{-1}$)	Heads m^{-2}	Heads $plant^{-1}$	Grain weight (g $head^{-1}$)	1000 grain weight (g)	HI
B	577a	5.2b	290a	2.8b	0.73a	48.9a	0.41a
B-F	554a	8.4a	249a	4.4a	0.78a	50.9a	0.40a
B-C	515a	7.0ab	248a	4.2a	0.96a	45.5a	0.43a
B-P	577a	7.7 a	322a	3.6a	0.73a	51.3a	0.42a

Means with different letters are significantly different at the 5% level (HSD).

Faba bean. Faba bean grain yield was significantly higher in sole crop ($P<0.05$) than in intercrop with cereals (Figure 4-3). In the wheat-faba bean intercrop the average yield of faba bean was 18% of that of faba beans in the monoculture, compared to the barley-faba bean mixture which produced only 8% of the faba bean monoculture yield. The grain yield of faba bean in both mixtures with the two cereals was not significantly different.

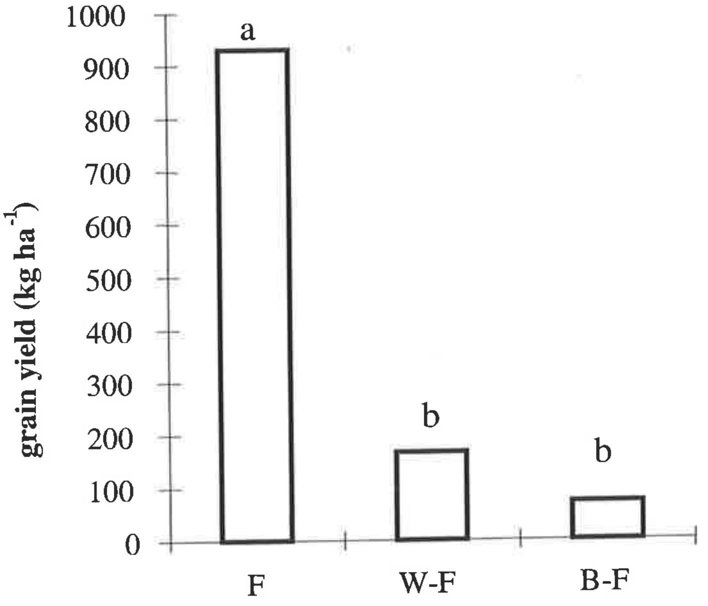


Figure 4-3 **Grain yield of faba bean in sole faba bean (F), wheat-faba bean (W-F) and barley-faba bean (B-F) intercrops. Columns with different lower case letters are significantly different at 5% level (HSD)**

Biomass, yield components, 100 grain weight and HI are shown in Table 4-4. Biomass per m^2, pod number per m^2 and grain weight per plant were significantly higher ($P<0.05$) in monoculture than in mixtures. Biomass and pod number per plant were similar for the faba bean monoculture and the wheat-faba bean mixture, but produced lower values in the barley-faba bean mixture than the other cropping systems. The number of seeds per pod and 100 grain weight were not affected by intercropping (P=0 05). Differences between cropping systems in the HI of faba bean were not significantly different.

Table 4-4 **Biomass, yield components and harvest index (HI) of faba bean in sole faba bean (F), barley-faba bean (B-F) and wheat-faba bean (W-F) intercropping systems**

Cropping system	Biomass (g m^{-2})	Biomass (g $plant^{-1}$)	Number of pods m^{-2}	Number of pods $plant^{-1}$	Number of seeds pod^{-1}	Grain weight (g $plant^{-1}$)	100 grain weight (g)	HI
F	384a	10.6a	266a	7.3a	1.80a	5.89a	44.8a	0.56a
W-F	104b	5.6ab	82b	4.4ab	1.48a	2.25b	45.9a	0.48a
B-F	60b	3.9 b	31b	2.0b	1.48a	1.17b	40.8a	0.34a

Means with different letters are significantly different at the 5% level (HSD)

Field pea. As shown in Figure 4-4 the grain yield of field pea was significantly lower ($P<0.05$) in intercrops than in sole crops. Field pea produced significantly more grain ($P<0.05$) in the wheat-field pea mixture than the barley-field pea mixture. Field pea only yielded 14% of its monoculture yield in wheat-field pea mixture and 5% in barley-field pea mixture. These yield reductions were associated with significantly lower biomass per m^2 in intercrops (Table 4-5.)

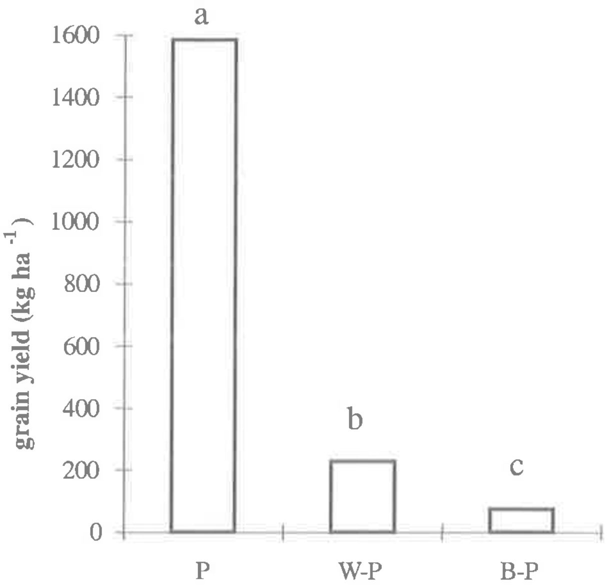


Figure 4-4 **Grain yield of field pea in sole field pea (P) and wheat-field pea (W-P) and barley-field pea (B-P) intercrops. Columns with different lower case letters are significantly different at 5% level (HSD)**

There were no significant differences between treatments in other components, although trends were similar to those for faba bean, i.e. lower values for intercrops than sole crops for biomass per plant, numbers of pods per m^2 and per plant, and grain yield per plant.

Table 4-5 Biomass, yield components and harvest index (HI) of field pea in sole field pea (P), barley-field pea (B-P) and wheat-field pea (W-P) intercrops

Cropping system	Biomass ($g\ m^{-2}$)	Biomass ($g\ plant^{-1}$)	Pods m^{-2}	Pods $plant^{-1}$	Seeds pod^{-1}	Grain weight ($g\ plant^{-1}$)	100 grain weight (g)	HI
P	385a	13.5a	217a	8.1a	3.74a	4.29a	18.92a	0.32a
W-P	150ab	7.8a	108a	5.62a	3.13a	2.51a	14.80a	0.32a
B-P	129a	6.8a	79a	4.61a	2.82a	2.79a	15.37a	0.29a

Means with different letters are significantly different at the 5% level (HSD)

Chickpea. Chickpea produced a much lower yield ($P<0.05$) as an intercrop than grown alone (Figure 4-5). The yield of the chickpea crop grown in intercropping in mixtures with wheat and barley was respectively about 17% and 4% of the monoculture chickpea yield.

The effects of different cropping systems on yield components, 100 grain weight and HI are presented in Table 4-6. Number of pods per plant and weight of grain per plant were different ($P<0.05$) in all treatments. Number of pods per m^2 was significantly higher ($P<0.05$) on average in monoculture than in mixtures. There were no significant differences between the treatments for number of seeds per pod, 100 grain weight and weight of each plant. The HI was significantly different for all cropping systems ($P<0.05$). Biomass production per unit area was not statistically different between monoculture and barley-chickpea, but it was lower ($P<0.05$) for the wheat-chickpea mixture than the sole crop of chickpea. Biomass per plant was significantly higher in monoculture.

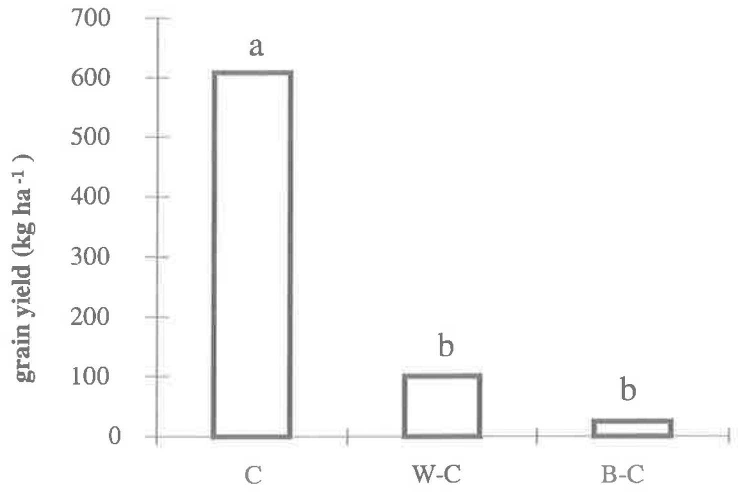


Figure 4-5 Grain yield of chickpea in sole chickpea (C) and wheat-chickpea (W-C) and barley-chickpea (B-C) intercrops. Columns with different letters are significantly different at 5% level (HSD)

Table 4-6 Biomass, yield components and harvest index (HI) of chickpea in sole chickpea (C), barley-chickpea (B-C) and wheat-chickpea (W-C) intercrops

Cropping system	Biomass (g m^{-2})	Biomass (g plant^{-1})	Pods m^{-2}	Pods plant^{-1}	Seeds pod^{-1}	Grain weight plant^{-1}	100 grain weight (g)	HI
C	246a	5.2a	461a	9.64a	1.00a	2.01a	21.27a	0.39a
W-C	88b	4.3a	107b	4.95b	0.97a	1.00b	20.37a	0.23b
B-C	106ab	4.0a	55b	1.93c	1.27a	0.34c	19.76a	0.06c

Means with different letters are significantly different at the 5% level (HSD)

4.2.2.3 Competition and biological advantages

Two graphical methods are used to assess the effects of competition on yield of intercrops, using replacement series (see Section 2.7.3). The first method (Method A) deals with a situation for comparison where the unit area was regarded as being divided between pure stands of two species according to the sowing proportion in the mixture, in this case 50:50 proportion (Figure 4-6). A vertical comparison between the combined pure stand (upper most broken line) and the combined yield of a mixture (top unbroken line) shows that in most cases the total yield of two crops was greater than the expected yield of the cereal and the legume sown separately in half the area (Figure 4-6a, b, d, e and f). The greatest increase appears to be in chickpea-cereal mixtures. Only the wheat-field pea intercrop showed no advantage over expected sole crop yield, in the same proportion (Figure 4-6c). It is also important to note that the combined intercrop yield in no case exceeds the yield of the highest yielding sole crop.

The second method (Method B) is based on the presentation of yield at the final stage, by calculating the proportion of the monoculture yields which would give the same combined yield as occurred in intercropping (Figure 4-7). Thus no appreciable advantage resulted from barley-based intercropping (Figure 4-7b, d and f), and in wheat intercrops (Figure 4-7a, c and e) disadvantage was observed.

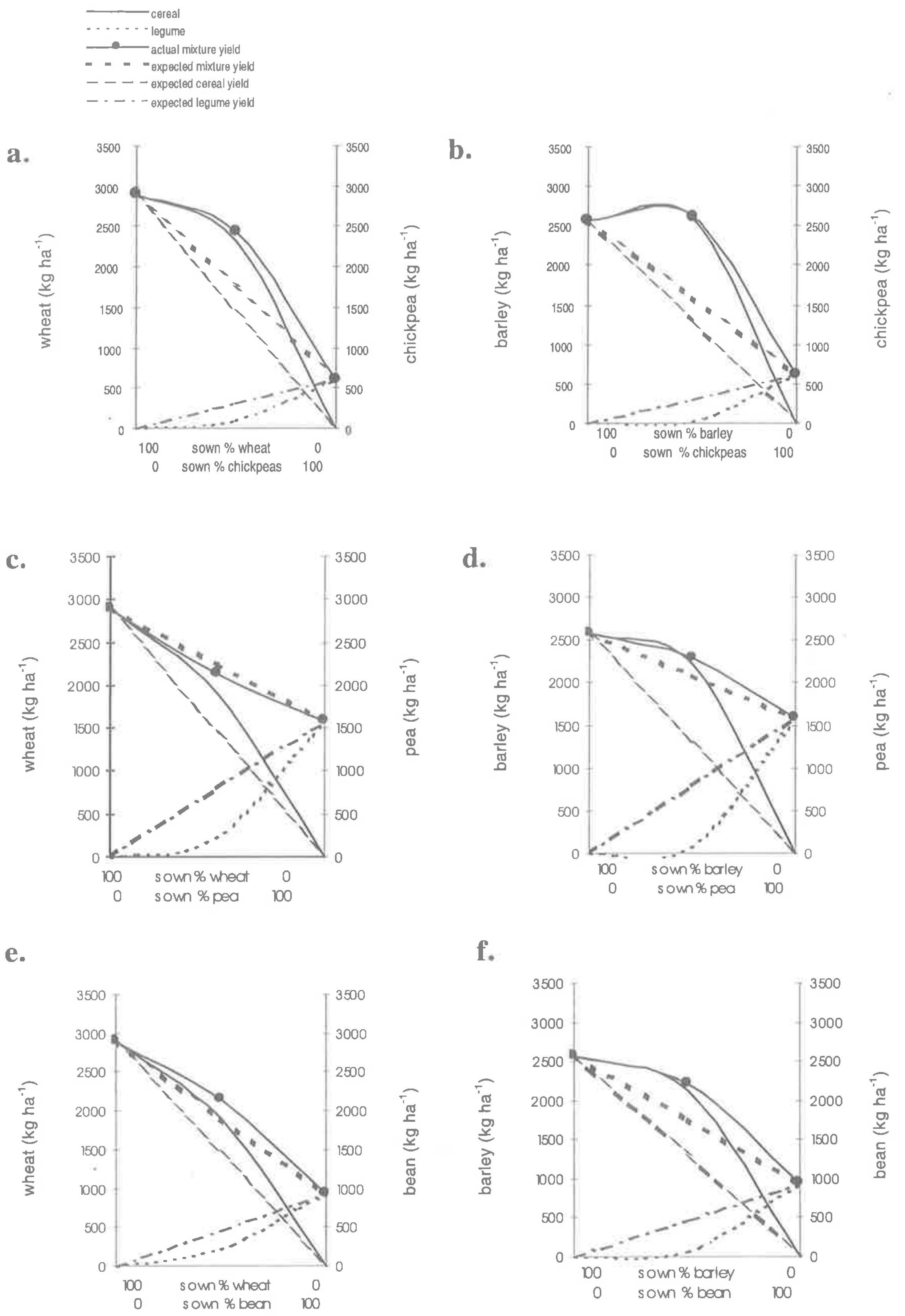


Figure 4-6 Cereal-legume intercrops intercropping systems considering sowing proportions

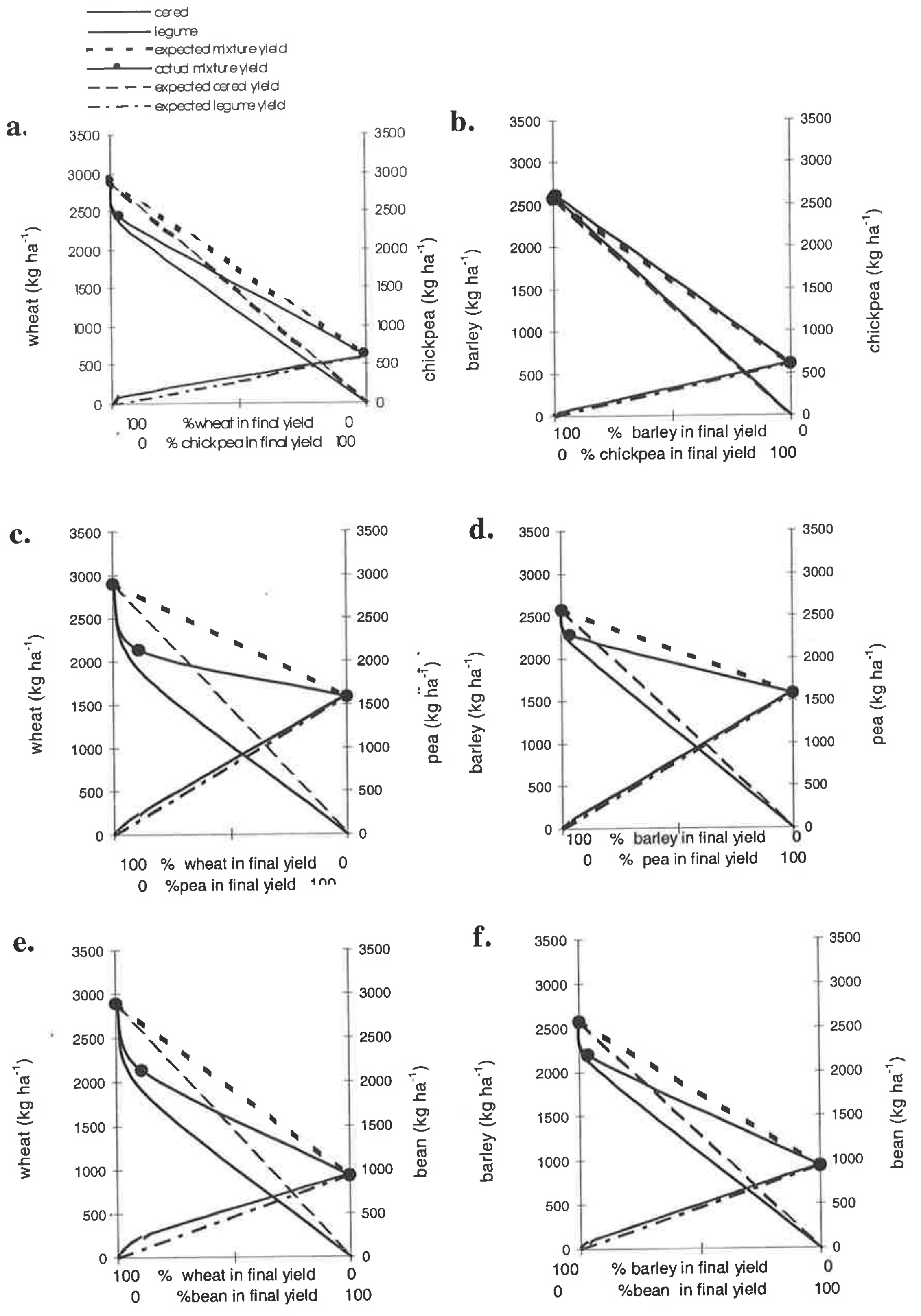


Figure 4-7 **Cereal-legume intercrops intercropping system, considering final yield proportions**

4.2.2.4 Land Equivalent Ratio

Land Equivalent Ratio (LER), calculated using average yield of sole crops (see Table 3-2), was used to evaluate the biological efficiency of different cropping systems in both grain yield and total biomass (Table 4-7). Appendix 7 presents the non-standardised values of LER. For the wheat based intercropping systems, the wheat-chickpea system had the highest LER_{grain} and the wheat-field pea mixture the lowest. In barley based cropping systems the highest LER_{grain} was seen in its mixture with chickpea and the lowest was observed in the barley-field pea and barley-faba bean mixtures. The highest LER_{grain} in the entire experiment was obtained in the barley-chickpea intercropping system.

$LER_{biomass}$ showed advantages in biological efficiencies (i.e. LER>1). Again barley based intercrops seemed to have marginally greater LER than the wheat based intercrops. In this situation, field pea based cropping systems showed a higher LER.

Table 4-7 Land equivalent ratio (LER) in different cereal-legume intercropping systems

Cropping systems	wheat-chickpea	wheat-field pea	wheat-faba bean	Barley-chickpea	barley-field pea	barley-faba bean
LER_{grain}	0.97	0.80	0.95	1.05	0.90	0.90
$LER_{biomass}$	1.20	1.32	1.17	1.25	1.36	1.23

4.2.2.5 Competition ratio of cereals with respect to legumes

Competition Ratio (CR) for yield was used to establish the extent to which the dominant crops (wheat and barley in this study) were more competitive than the dominated ones (field pea, chickpea and faba bean). CR for wheat was similar with respect to all the legume species investigated (Figure 4-8). Appendix 7 presents the non-standardised values for CR. However, barley was much more aggressive than wheat, especially with chickpea.

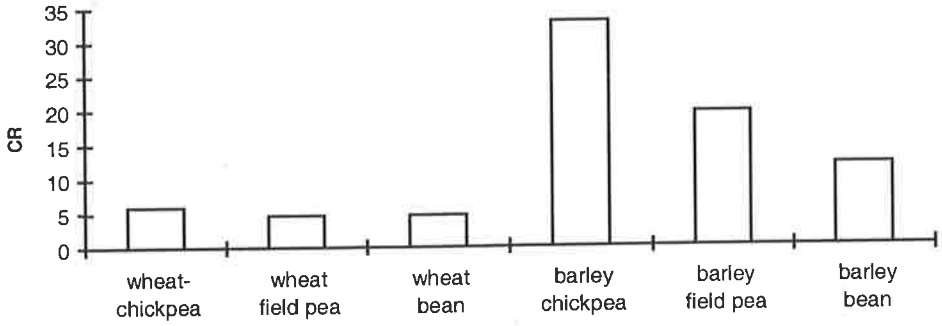


Figure 4-8 **Competition ratio (CR) of wheat and barley with respect to three pulses**

4.3 Experiment 2: The effect of varietal selection on intercropping of wheat and chickpea

4.3.1 Materials and methods

The experiment was carried out in field E7 of the Roseworthy Campus of the University of Adelaide from July to November 1994. There were eight treatments comprising monocultures of chickpea (cultivars Semsen and Desavic) and wheat (cultivars Excalibur and Machete) and their 50:50 mixtures. The plan of the experiment is shown in Appendix 2. Each plot was 2.4 m wide and 10 m long, separated by a 1 m wide pathway.

After cultivation, 20 kg ha^{-1} phosphorus was applied to the soil. Chickpea seeds were inoculated with the appropriate commercial rhizobium three hours before planting. Seeding rates for wheat and chickpea were 76 and 85 kg ha^{-1} respectively. The seed was sown using a Wintersteiger seeder (Section 3.7). The intercrops were sown in double alternate rows (Section 3.7) with seeding rates per ha half of those used for sowing sole crops. The distance between each row was 20 cm. Crop establishment was estimated by recording plant density in 50 cm sections of rows at 4 random locations in each plot. Weeds were controlled using glyphosate and trifluralin (Section 3.7). Yield components and HI were measured on two randomly selected 0.4 m^2 quadrats per plot. The chickpea crop was hand harvested and wheat was machine harvested with a Wintersteiger harvester; in order to avoid any edge effects, two outside rows from each plot were not harvested. Details of statistical and graphical assessments are presented in Chapter 3.8.

4.3.2 Results

4.3.2.1 Crop establishment

The crop establishment results (Table 4-8) showed that the population of all varieties was within the acceptable range for the area (Taylor *et al.* (1991) and Lamb and Poddar (1992)).

Table 4-8 The population density (plants m^{-2}) of wheat and chickpea cultivars as sole crops and intercrops

Crop	Cultivar	Sole crop	Intercrops
Chickpea	Semsen	30	15
Chickpea	Desavic	32	16
Wheat	Excalibur	128	64
Wheat	Machete	108	52

4.3.2.2 Grain yield, yield components and harvest index

Wheat. The effects of different cropping systems on the grain yield of wheat are given in Figure 4-8. The yield of Excalibur in monoculture was similar to that of Excalibur in the Excalibur-Desavic and Excalibur-Semsen mixtures and was greater ($P<0.05$) than the yield of Machete in all cropping systems. With the exception of Excalibur in monoculture all treatments had similar grain yields. However, Excalibur produced about 84% of its monoculture yield in the Excalibur-Semsen mixture, and Machete up to 94% of its monoculture yield in the Machete-Semsen mixture.

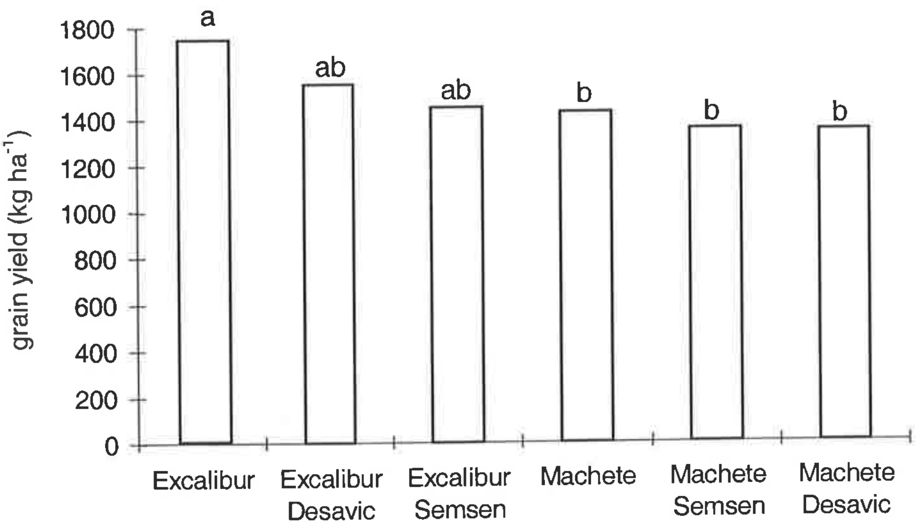


Figure 4-8 **Grain yield (kg ha $^{-1}$) performance of wheat cultivars in sole crops and C50:W50 mixtures with chickpea. Columns with different letters are significantly different at 5% level (HSD)**

As shown in Table 4-9 biomass per m^2 tended to be highest in sole crops, and biomass per plant to be highest in intercrops, although not all differences were significant. Number of heads per m^2 was significantly higher in sole crops than in intercrops. There was a tendency for the reverse trend to occur for the number of heads per plant, but the only significant effect ($P<0.05$) was for Machete with Semsen to be significantly higher than the sole crops and the Excalibur intercrops. There were no significant differences for the other components or for HI.

Table 4-9 Grain yield, biomass, yield components and harvest index (HI) of wheat varieties in sole crops and intercrops with chickpea

Cropping system	Biomass (g m^{-2})	Biomass (g $plant^{-1}$)	Heads m^{-2}	Heads $plant^{-1}$	Spikelets $head^{-1}$	Grain weight (g $head^{-1}$)	Grains $head^{-1}$	1000 grain weight (g)	HI
Excalibur	431a	2.81c	215a	1.40b	13.63a	1.5a	29.7a	39.2a	0.39a
Machete	416ab	3.20bc	230a	1.76b	13.76a	1.4a	29.9a	38.6a	0.37a
Excalibur Desavic	301ab	3.92abc	132b	1.75b	13.99a	1.8a	33.6a	39.6a	0.41a
Excalibur Semsen	324ab	4.29ab	148b	1.97b	14.05a	1.7a	33.7a	37.8a	0.41a
Machete Desavic	285b	4.61a	129b	2.10ab	14.53a	1.6a	33.2a	37.3a	0.39a
Machete Semsen	293b	4.28ab	142b	2.77a	14.75a	1.6a	30.4a	40.4a	0.40a

Means with different letters are significantly different at the 5% level (HSD)

Chickpea. The effect of different cropping systems on grain yield of chickpea is shown in Figure 4-9. Yields of chickpea in monoculture were significantly higher than in the intercropping systems. The Desavic based mixtures produced only 4% of the yield of Desavic in monocultures and for the Semsen based mixture the yield was 8% of that of sole Semsen.

Biomass, yield components and HI of chickpea varieties are presented in Table 4-10. Biomass of sole Desavic was similar to that of sole Semsen, but each sole crop produced much greater ($P<0.05$) biomass than in all mixtures. Number of seeds per m^2, number of seeds per plant, grain weight per plant and 100 grain weight were all lower ($P<0.05$) in mixtures compared with the respective monoculture. Chickpea in the Excalibur-Semsen intercrop had the lowest number of branches. HI was greater ($P<0.05$) in chickpea monocultures than any of the mixtures, and Desavic-based mixtures showed the lowest ($P<0.05$) HI.

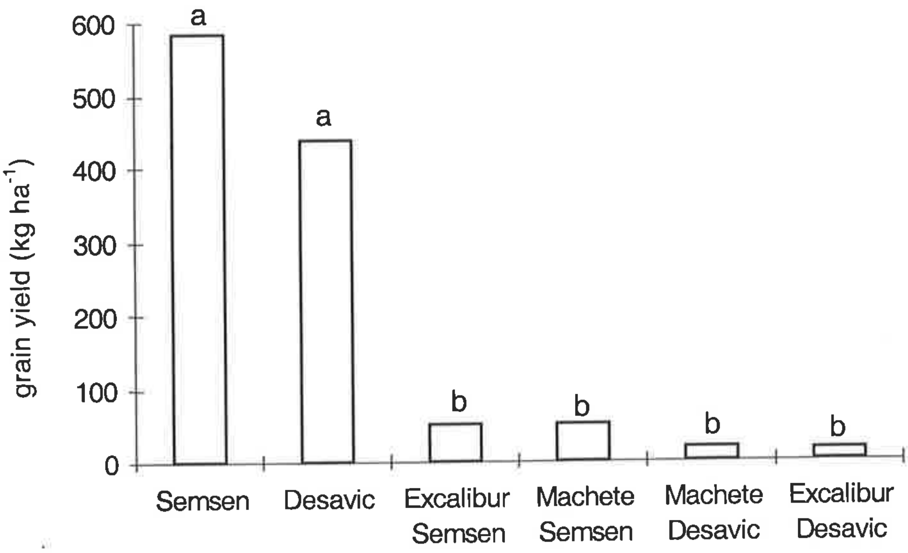


Figure 4-9 Grain yield of two chickpea cultivars as sole crops and as intercrops with two wheat cultivars. Columns with different letters are significantly different at 5% (HSD).

Table 4-10 Yield, biomass, yield components and harvest index (HI) of chickpea varieties in sole crops and intercrops

Cropping system	Biomass (g m^{-2})	Biomass (g plant^{-1})	Seeds m^{-2}	Seeds plant^{-1}	Branches plant^{-1}	Grain weight (g plant^{-2})	100 grain weight (g)	HI
Desavic	195.9a	5.25a	391a	10.49a	4.0a	2.50a	23.3a	0.47a
Semsen	188.8a	5.53a	441a	12.88a	4.1a	2.62a	20.3a	0.47a
Excalibur Desavic	28.4b	2.03b	19b	1.68b	4.0a	0.28b	13.6b	0.11c
Excalibur Semsen	31.8b	1.78b	56b	3.15b	2.8b	0.50b	15.9b	0.28b
Machete Desavic	21.6b	1.43b	18b	1.48b	3.8ab	0.23b	13.0b	0.11c
Machete Semsen	28.7b	1.79b	49b	3.06b	3.3ab	0.41b	14.9b	0.26b

Means with different letters are significantly different at the 5% level (HSD)

4.3.2.3 Bivariate analysis

A bivariate analysis was performed to determine the varietal differences between the cultivars. No differences between varieties of wheat were detected, however a significant difference was seen between chickpea cultivars with Semsen performing better in mixture with wheat than Desavic (Figure 4-10).

4.3.2.4 Competition and biological efficiency

The effect of competition in a situation where the unit area was divided into pure stands of two species in the proportion (50:50) is shown in Figure 4-11. In this situation the complementary effect of intercropping caused grain yield advantages in all of the intercropping systems. However, chickpea was at a severe competitive disadvantage with respect to wheat. Thus, if the proportions of the sole crops' yield which would give the same yield proportion as occurred in the intercropping is considered (Figure 4-12), the diagrammatic illustration does not show any advantages over monoculture. With this type of evaluation, Machete-Desavic and Machete-Semsen mixtures appeared to show higher values than the others but there was still no biological advantage over monoculture.

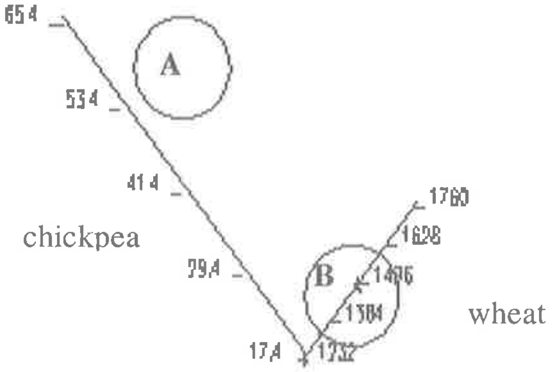


Figure 4-10 Graphical performance of the intercropping systems using a bivariate analysis of the grain yield of chickpea varieties (kg ha^{-1}) for C50:W50 intercropping with wheat, of A: Semsen, B: Desavic; error is shown by the circles

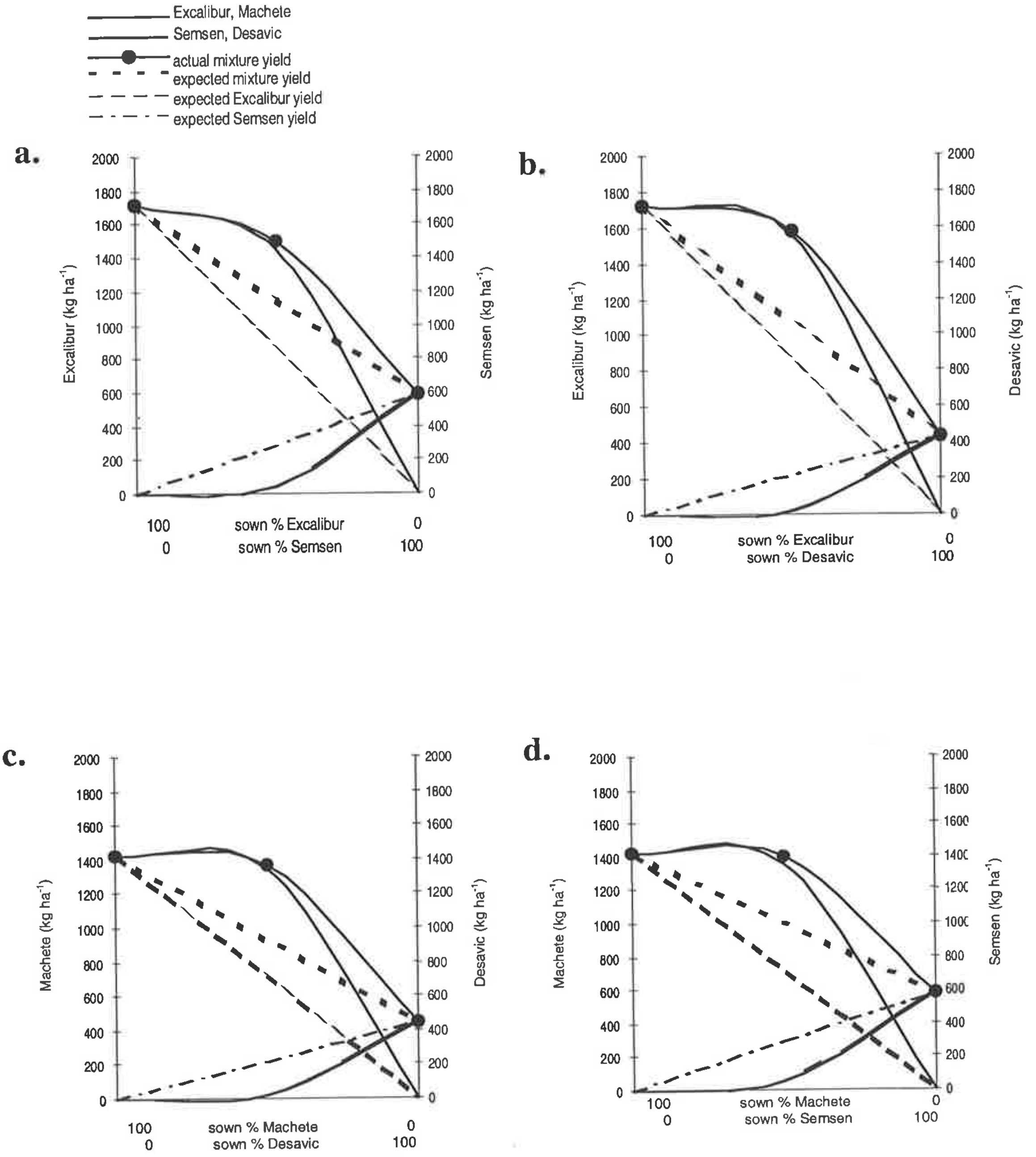


Figure 4-11 **Varietal differences in wheat-chickpea intercrops, considering sowing proportions**

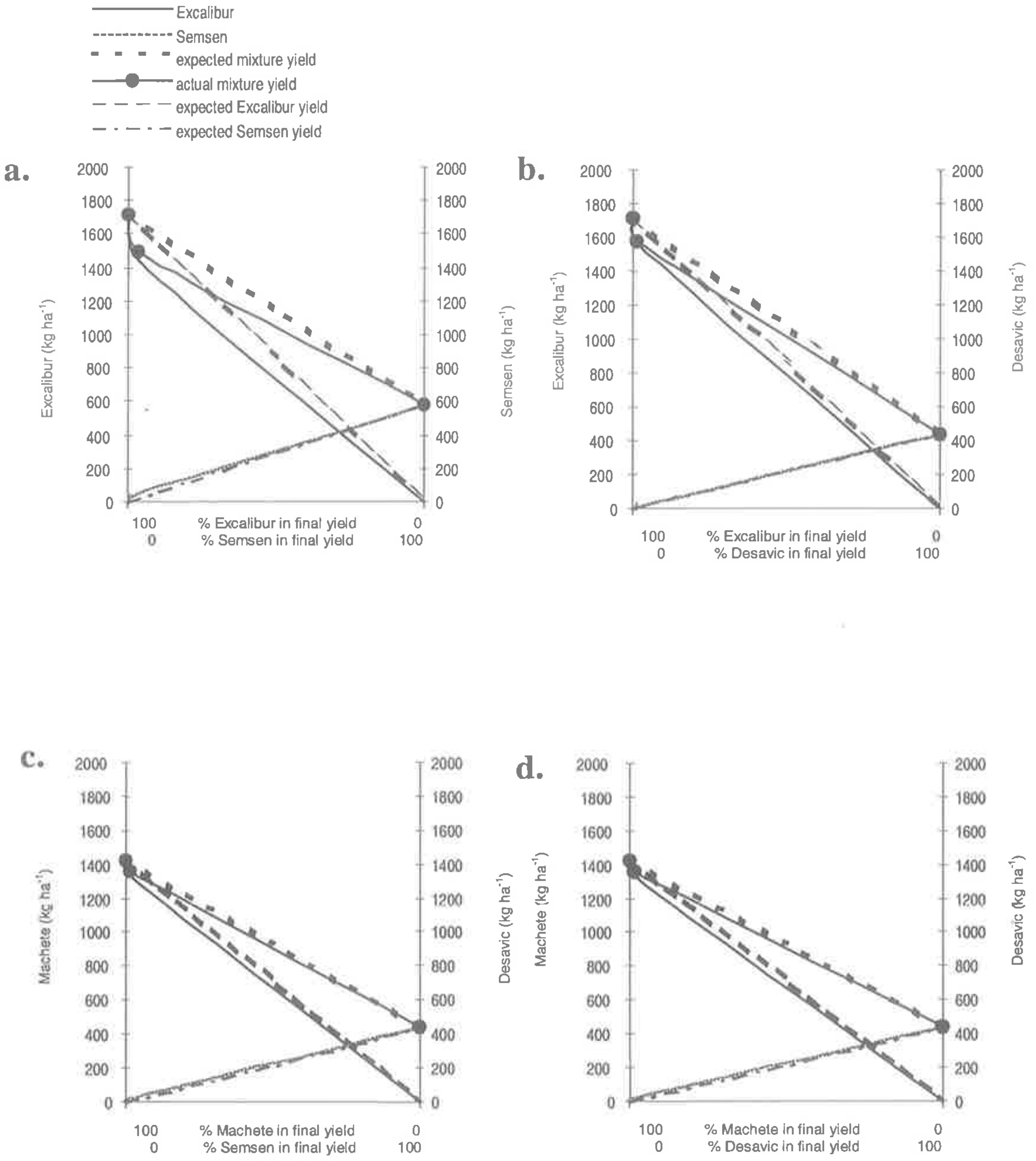


Figure 4-12 **Varietal differences in wheat-chickpea intercrops, considering final yield proportions**

Land equivalent ratio

From Table 4-11, it can be seen that LER for Excalibur-Semsen was significantly higher ($P>0.05$) than for Machete-Desavic, but was not statistically different from Excalibur-Desavic and Machete-Semsen. The highest LERs are from Excalibur based mixtures.

Competition ratio of wheat cultivars with respect to chickpea cultivars

Wheat was significantly more competitive in Desavic based mixtures than Semsen based mixtures (Table 4-11).

Table 4-11 Competition ratio (CR) of wheat cultivars with respect to chickpea cultivars and Land equivalent ratio (LER)

Cropping system	Excalibur-Desavic	Machete-Desavic	Excalibur-Semsen	Machete-Semsen
LER_{grain}	1.03ab	0.89b	1.05a	1.01ab
CR	21.28a	19.07a	7.98b	8.43b

Means with different letters are significantly different at the 5% level (HSD)

4.3.3 Discussion

4.3.3.1 Grain yield, yield components and harvest index

Despite the fact that cereal intercrops occupied only half of each plot at sowing time, they produced up to 80% of the sole wheat grain yield in the wheat-chickpea mixture and up to 102% of sole barley yield in the barley-chickpea mixture (Experiment 1, Figure 4-1 and Figure 4-2). A possible explanation for the lack of, or small differences between, sole and intercrop cereals is that intercrops had larger plants with more heads per plant than sole crops, thus producing similar numbers of heads per m^2 while also maintaining similar grain weight per head. Likewise, Reynolds *et al.* (1994) reported that faba bean had no effect on the yield of wheat or barley in comparison to the sole crop controls. Reynolds *et al.* (1994) suggested that the increased productivity of the intercropping systems was gained by an increase in the amount of light energy absorbed. However, in the current experiment wheat was less successful than barley in mixtures, and the yield increase per wheat plant in intercrops was insufficient to compensate fully for the yield reduction resulting from fewer plants per unit area in the mixtures. This result is similar to that of Wallace *et al.* (1996) in which the increase of various yield components of intercrops could not compensate for the decrease in plant density.

Unlike the cereals, legumes in the mixtures produced much lower grain yields (Figures 4-3, 4-4 and 4-5) than sole crops because they produced fewer pods per unit area and less grain weight per plant than in monoculture (Tables 4-4, 4-5 and 4-6). Overall, this reduction was much more severe in barley based intercrops. This observation is in accordance with those of Singh and Yadav (1992) in their wheat-chickpea intercropping trial, Tofinga *et al.* (1993) in a cereal-pea experiment and Martin and Snaydon (1982) in a barley-faba bean mixture.

In Experiment 2 (Figure 4-9), the yield of chickpea varieties in mixtures was even more dramatically reduced than in Experiment 1. This resulted from much lower values for biomass, seed numbers, seed weights and Harvest Index. The significantly lower HI in Desavic than in Semsen is the only indication of varietal differences in performance as intercrops. Again, this result is similar to that of Singh and Singh (1983) who reported that chickpea produced much higher yields as a sole crop than when it was intercropped with wheat, and to that of Singh and Yadav (1992) where the reduction in yield of chickpea when in mixtures with wheat was due mainly to lower values of yield components. Reasons for such reductions may be the poor development of plants, lack of sunlight due to the shading effect of the cereal component (Tofinga *et al.*, 1993) and competition for water. Cereals were therefore much more competitive than legumes in obtaining below-ground and other resources.

4.3.3.2 Competition and biological efficiency

In the first experiment the LER_{grain} in all but one of the intercropping systems was less than 1, showing a disadvantage compared to sole crops (Table 4-7). The exception was in the barley-chickpea mixture, where the LER was 1.05, which may indicate a greater biological efficiency than in monoculture. Moreover, LER in the wheat-chickpea mixture was very close to 1, which shows a greater biological efficiency than the other wheat based intercropping systems. Izaurralde *et al.* (1990) and Banik (1996) also could not show an LER greater than unity for their cereal-legume cropping systems. In contrast, several other researchers have shown greater biological efficiency for grain yields in intercropping situations. An LER greater than one was obtained by Reynolds *et al.* (1994a) with wheat-based intercropping, Chowdhry and Gliddon (1992) with barley-faba bean, and Mandal *et al.* (1996) with wheat-chickpea intercropping systems. A possible reason for the lower LER for grain in the present experiment is that the legume component was suppressed severely by intercropping resulting in an LER value of 1.

However, the $LER_{biomass}$ of all the intercropping systems reported here was greater than 1 (Table 4-7), ranging from 1.17 in the wheat-faba bean mixture to 1.36 in the barley field pea mixture, showing greater biological efficiency than in monocultures. This result is consistent with that of Tofinga *et al.* (1993) for LER of biomass in a wheat-field pea mixture and Chowdhry and Gliddon (1992) in a wheat-faba bean mixture. Different reasons have been given for situations where higher LER values were obtained. For example, Tofinga *et al.* (1993) explained that the high LER was achievable because of improved light interception, and Martin and Snaydon (1982) in their study explained greater LER to be due to the use of different resources by species in mixtures. In addition, N fixation could be assisting the legume to be competitive. In general, any better use of resources could be the reason for this complementary effect. The reason behind the lower biological advantages shown in grain yield, possibly due to water stress at the end of the growing season, could be sought through the lower HI of grain legumes. To address this problem, future work on improving HI is required, as this may be a key to better resource use efficiency.

Using Competition Ratio (CR) as an indicator, legumes were always considerably less competitive than cereals (Figure 4-8 and Table 4-11). This differs from the results of Tofinga *et al.* (1993) who found field pea to be more competitive than cereals, and indicated that because the seed size of field pea is at least 6 times that of cereals, the legume can exploit the limiting factor better and thus has a better competitive ability. Wheat showed a similar competitive ability against all the legumes (Figure 4-8). However, barley was much more aggressive with chickpea than the other crops. This observation is similar to that of Ofori and Stern (1987a) who concluded that morpho-physiological differences and agronomic factors regulate the competition between component crops for limiting factors such as water, light and nutrients and that the cereal component is more effective in competition because of its higher growth rate, taller growth habit and more extensive root system, and is thus the dominant crop. The main mechanism for exploiting more resources seems to be through producing more tillers (or heads) per plant in an intercropping situation.

The competitive abilities of mixtures were also examined by two types of diagrammatic illustration models (Figures 4-11 and 4-12). The first model deals with a situation where the unit area was divided between pure stands of two species according to a given sowing proportion. In this case the proportion is 50:50 and the assumption is that half the land is sown with each crop. Except in wheat-field pea mixtures, application of the first model showed advantages for intercropping over monoculture (Figure 4-11). This occurred where the competitive ability of two species obviously differed (i.e. one species yielded more and one less than expected, which is called compensation (Willey, 1979a). In the wheat-field pea mixture, however, the field pea was suppressed by wheat, resulting in a high reduction of grain yield in comparison with monoculture.

The second model (Figure 4-12), which deals with final yields in mixtures showed disadvantages in all situations except in barley-chickpea where there were no advantages or disadvantages. This can be explained by severe suppression of the legume in the mixture.

Regarding intercropping of different varieties of wheat and chickpea, only Excalibur based intercrops produced yields similar to sole Excalibur, which was the highest yielding variety in this experiment. This seems to be because the Excalibur based intercrops had similar biomass and HI to those in monoculture and could therefore fully compensate for the lower number of plants and lower number of heads per m^2. This result contrasts with that of Banik (1996), who found that the wheat and chickpea yields of pure stands maintained supremacy over their intercrops due to a lower proportion of sown area in intercropping.

LER$_{grain}$ for most of the cropping systems (i.e. Excalibur-Desavic, Excalibur-Semsen and Machete-Semsen) was greater than 1. LER of more than one was also reported by Mandal *et al.* (1986a) in a wheat-chickpea mixture, and they indicated that the greater biological efficiency in this system might be due to complementary effects. Overall the Excalibur based cropping systems showed a higher LER.

Competition ratio showed that wheat yielded between 8 to 21 times more than chickpea and was much more competitive than chickpea. Therefore, wheat was the dominant crop. This is consistent with the findings of Mandal *et al.* (1996a) who showed that wheat was more aggressive than chickpea in intercropping.

The diagrammatic illustration which considers sowing proportions (Figure 4-11) showed that intercropping was clearly more advantageous than a monoculture in a situation where half of the land is planted to each crop. However, the second method (Figure 4-12) which deals with the final yield proportions did not show any considerable advantage. This was at variance with the observations for LER. The reason for this difference seems to be that in the diagrammatic illustration the intercrop yield was compared with the relevant sole crop for each variety, whereas in the calculation of LER the most popular variety of a given region was used as the sole crop.

4.4 Summary and conclusions

LER was slightly higher in the barley based intercropping systems and barley was very competitive in the barley-legume mixtures. Since wheat was not as competitive, the proportion of legume was higher in the wheat based mixtures. For this reason wheat was chosen as the cereal for further studies. In the mixtures of wheat with legumes, chickpea had slightly higher LERs than the other crops and also considering data from a separate experiment conducted in the same year (Chapter 5.2), chickpea was chosen as the preferable legume crop for ongoing studies. Using bivariate analysis on the grain yield, Semsen based intercrops showed greater advantages over Desavic based mixtures. Moreover, a comparison of CR showed that Desavic in mixtures was suppressed more severely than the Semsen variety. Thus, Semsen became the preferred chickpea variety for future work. Despite the fact that the differences in grain yield, LER and CR between Excalibur and Machete were not significant, in all cases Excalibur was apparently slightly superior. Therefore, Excalibur was chosen as the wheat variety for all later investigations.

The higher $LER_{biomass}$ for legume-cereal intercropping in the first experiment, together with the marginally higher LER_{grain} in some of the treatments in the varietal experiment, lead one to conclude that there is preliminary evidence that intercropping with mixtures of cereals and legumes might increase the biological efficiency of cropping in dryland farming regions of South Australia. There is also a possibility of increasing the productivity of the intercropping system through agronomic practices. Therefore, the second phase of the study, which is described in Chapter 5, considered the effects of seeding rate, row arrangements, fertiliser and moisture environments on yield performance, competition and biological efficiency of the intercropping system.

5. AGRONOMIC ASPECTS OF WHEAT-CHICKPEA INTERCROPPING

5.1 Introduction

Genetic characteristics of crops (species and cultivar), growing environment (climate and soil) and agronomic manipulation of the microenvironment define the productivity of intercropping systems (Fukai and Trenbath, 1993). In the preceding chapter results of species and varietal studies of cereal-legume intercropping were reported. The growing environment cannot be changed easily. However, agronomic inputs can be modified relatively easily and in this chapter the effects of seeding rate and row arrangement are presented. Thus data from these experiments may allow understanding of the competitive and complementary relationships between crops as affected by agronomic treatments. This may enable the development of management systems for mixed crops for specific purposes.

Correct choice of density and crop geometry (e.g. row arrangement) can enhance the use of resources, minimise competition and probably lead to a yield advantage. For resource-poor farmers such management changes often offer the most practical way to maximise inter-specific complementarity. They can permit a planned sharing of natural resources, e.g. increasing the rectangularity in geometry of the main crop can enhance transmission of light to shorter crops (Midmore, 1993).

Row spacing and population density of intercropping systems have been investigated in many crops, but few such studies have been done with intercrops of wheat and chickpea. For example, in India Sharma *et al.* (1987), Banik (1996) and Mandal *et al.* (1985) conducted experiments on wheat-chickpea row arrangement and population density. However, these studies seem to be site specific and highlight the need to examine the effects of row arrangements and densities on the productivity of wheat and chickpea under dryland conditions in South Australia.

In the research reported in this chapter, three field experiments were conducted to investigate some agronomic aspects of wheat-chickpea intercropping systems. In the first experiment the effect of row arrangement on yield performance, competition and biological efficiency of wheat-chickpea intercropping under supplementary irrigation was examined. The purpose of the second experiment was to study the effects of both row arrangement and seeding rate, and their possible interaction, on the productivity of the intercropping systems. In a third experiment the effect of nitrogen fertiliser and combinations of different densities and row proportions on the wheat-chickpea intercrops and their sole crops under irrigated and unirrigated (dryland) conditions were studied.

5.2 Experiment 1: The effect of seeding rate on wheat-chickpea intercropping systems

5.2.1 Materials and methods

Wheat (cultivar Excalibur) and chickpea (cultivar Semsen) were sown in monoculture and intercropping at various seeding rates in the field (H10) at the Roseworthy Campus of the University of Adelaide in 1993.

Seeding rate treatments were:

(a) sole wheat at 100% the recommended rate of seed (RRS) 70 kg ha^{-1} (W100),

(b) sole chickpea at 100% its RRS 85 kg ha^{-1} (C100),

(c) intercropping of 50% RRS for each species,

(d) intercropping of 75% RRS for each species (C75:W75),

(e) intercropping of 100% RRS for each species (C100:W100) and

(f) intercropping of 100% RRS for wheat with 50% RRS for chickpea (C50:W100).

The intercropping treatments were sown in single alternate rows of each species. The experiment was laid out in a randomised complete block design of three blocks (see Appendix 3). After land preparation plots were sown with a Winterstieger 6 row seeder on 16 September 1993. Each plot was six rows wide with 17 cm between rows and 34 cm between plots. Plots were 5 m long and sown with a 1 m pathway in the direction of seeding.

Chickpea seeds were inoculated with a preparation of squashed fresh nodules from established chickpea plants immediately prior to seeding. Rainfall was supplemented by weekly irrigation of about 8 mm. Weeds were manually removed when necessary.

To avoid edge effects, outside rows were not included in sampling. Crop establishment was measured by counting plants in 3 x 42 cm row lengths per plot three weeks after emergence. Each species was separately harvested by hand at maturity and threshed in a stationary thresher.

The details of the statistical analysis and graphical assessments is presented in Chapter 3.

5.2.2 Results

5.2.2.1 Crop establishment

The crop establishment measurements for sole crops and intercrops are shown in Table 5-1. These densities are close to expected values.

Table 5-1 **Mean plant density m^{-2} of wheat (W) and chickpea (C) in sole crops and intercropping, three weeks after emergence**

Crop	Sole (C100:W100)	C50:W50	C75:W75	C100:W100	C50:W100
Wheat	155	76	107	148	135
SEM	4	4	7	7	5
Chickpea	55	30	36	47	27
SEM	5	3	0.01	9	1

Numbers in each set are percentage of recommended seeding rate for chickpea (C) and wheat (W); SEM = standard error of mean

5.2.2.2 Grain yield

The effects of different seeding rates on wheat-chickpea intercropping systems are shown in Figure 5-1. Wheat in the C50:W50 mixture yielded almost as much as in monoculture (W100). Moreover, wheat in the C50:W50 had a similar yield to the C100:W100 intercrop but significantly more than in the C50:W100 and C75:W75 intercrops.

Chickpea in monoculture had a greater yield than in all mixtures, and intercrop chickpea yields were similar.

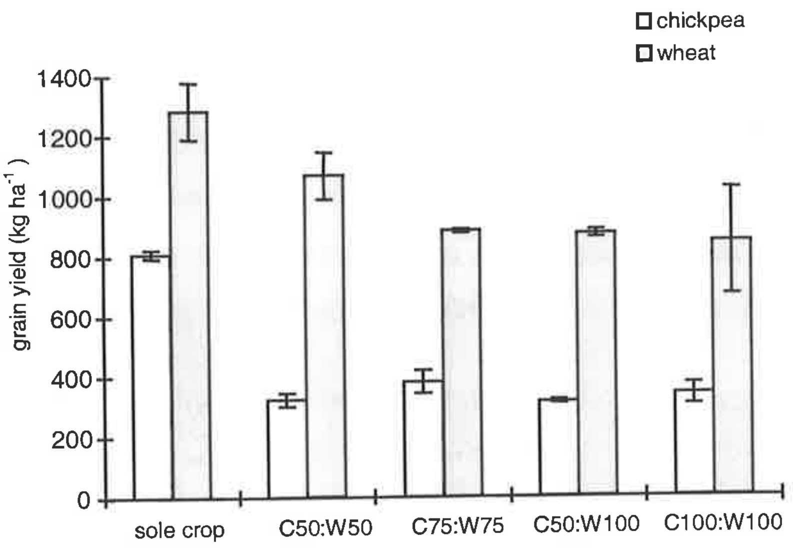


Figure 5-1 Grain yield of chickpea and wheat in sole crop and intercropping; the numbers for each set show the percentage of recommended seeding rates; error bars indicate the standard error of mean

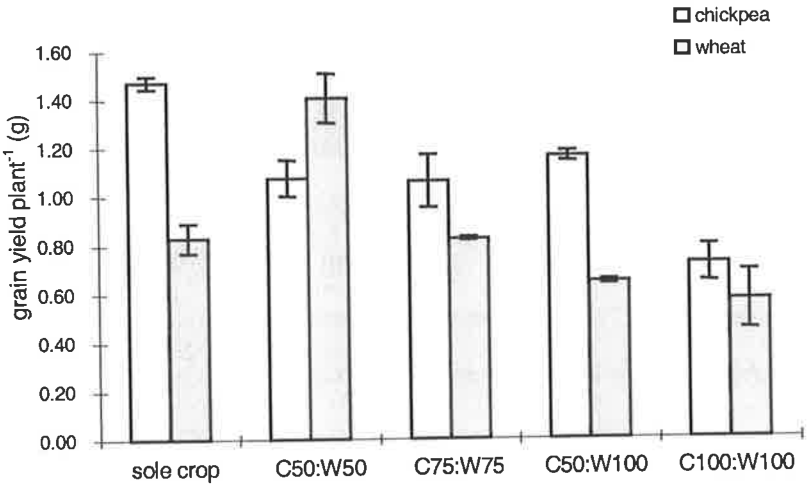


Figure 5-2 Grain yield plant^{-1} of chickpea and wheat in sole crop and intercropping; the numbers for each set show the percentage of recommended seeding rates; error bars indicate the standard error of mean

5.2.2.3 Yield per plant

Wheat in the C50:W50 mixture produced significantly higher yields per plant than monoculture and other mixtures (Figure 5-2). However at the higher mixture plant densities, the yield of wheat per plant decreased. Wheat in the C75:W75 seeding rate had a similar yield to sole wheat and they both had a greater yield than C50:W100 and C100:W100 intercrops.

Chickpea performed better as a monoculture than in mixtures. The C50:W50, C75:W75 and C50:W100 had similar yields, with the poorest performance per plant in the C100:W100 mixture, i.e. at the highest total density.

5.2.2.4 Bivariate analysis of total grain yield in mixtures

From the bivariate analysis it can be concluded that there were no significant differences between the four intercropping treatments. Therefore the results are not presented.

5.2.2.5 Competition and biological efficiency

5.2.2.5.1 Diagrammatic illustration

The effect of competition in a situation where the unit area was divided into pure stands of two species in the proportion C50:W50 is shown in Figure 5-3. This situation is based on the assumption that half of the land is used for wheat and half for chickpea. From the diagrammatic illustration it can be concluded that there were complementary effects from intercropping.

Moreover, if the monoculture yields which would give the same yield proportion as occurred in intercropping are considered there are again advantages of intercropping over monoculture (Figure 5-4).

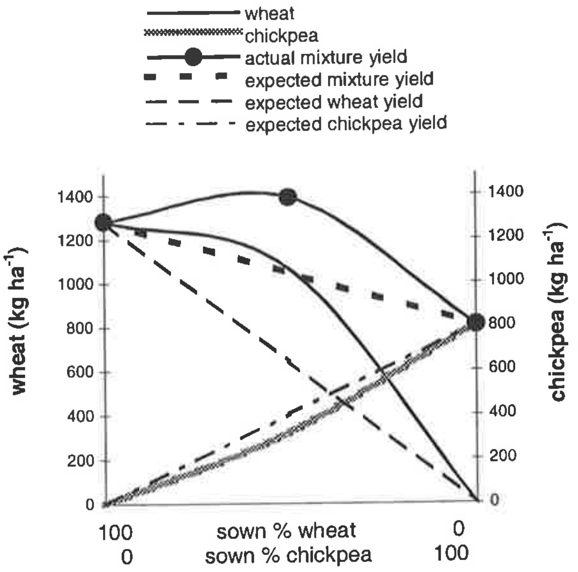


Figure 5-3 Wheat-chickpea intercropping in a 50:50 replacement series, considering sowing proportions.

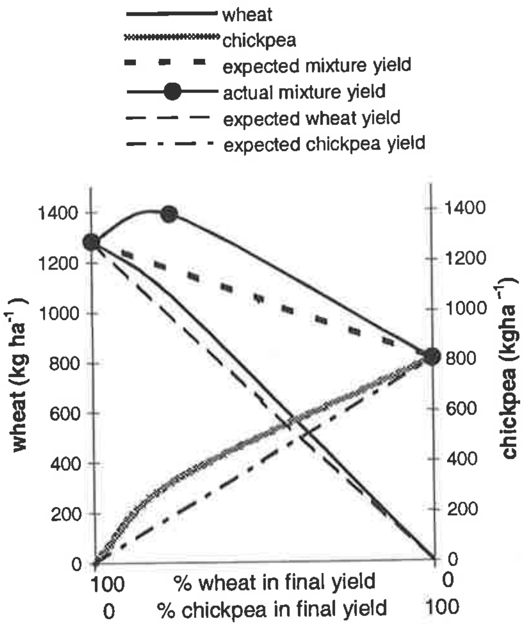


Figure 5-4 Wheat-chickpea intercropping in a 50:50 replacement series, considering final yield

5.2.2.5.2 Land Equivalent Ratio

The LER values (Table 5-2) of different cropping systems were not significantly different (P=0.05). However all of the LER values were greater than 1, indicating improved biological efficiency of intercropping over monoculture. The amount of yield in wheat at W100 and chickpea at C100 were used to standardise the LER values.

5.2.2.5.3 Competition Ratio

Wheat was not significantly (P<0.05) more competitive in different mixtures than chickpea (Table 5-2). The range of CR values of about 1.5 to 2 shows that wheat did not markedly suppress chickpea.

Table 5-2 Land equivalent ratio (LER), and Competition ratio (CR) of wheat (W) with respect to chickpea (C); the numbers in the first row show the percentage of recommended seeding rates

Cropping system	C50:W50	C75:W75	C50:W100	C100:W100
LER	1.25a	1.16a	1.07a	1.07a
CR	2.08a	1.49a	1.75a	1.63a

Different lower case letters within a row are significantly different at the 5% level (HSD)

5.3 Experiment 2: The effect of seeding rate and row arrangement on wheat-chickpea intercropping systems under dryland conditions

5.3.1 Materials and methods

The experiment was carried out in paddock E7 of the Roseworthy Campus of the University of Adelaide from July to November, 1994.

Treatments included the following sole and mixed crop sowing rates (Table 5-3).

Table 5-3 Percentage of recommended seeding rates for sole and intercrops

Treatment	Percentage of recommended seeding rates Chickpea	 Wheat
C100	100	-
C150	150	-
C200	200	-
W100	-	100
W150	-	150
W200	-	200
C50:W50	50	50
C75:W75	75	75
C100:W100	100	100
C100:W50	100	50
C50:W100	50	100

The recommended rates of seed for wheat and chickpea were 70 kg ha^{-1} and 80 kg ha^{-1} respectively

In addition mixed crops were grown in three different row arrangements, namely single alternate rows (SAR), double alternate rows (DAR) or alternate plants mixed in rows (MIR) (Section 2.5.2.2). Therefore, there were 21 treatments in total, consisting of 15 intercrops and 6 sole crops.

A randomised complete block design with 4 replicates was used; a plan of this trial is presented in Appendix 4. Each plot was 2.40 x 12 m, separated by 1 m wide headlands.

After cultivation, 20 kg P ha^{-1} in the form of superphosphate was applied to the soil. Weeds were controlled by glyphosate and trifluralin before planting (Section 3.7). The cultivars Excalibur (wheat) and Semsen (chickpea) were used in this experiment.

Chickpea was inoculated just prior to seeding. Seed was preloaded into magazines in accordance with the layout. The seed was planted using a Wintersteiger seeder.

The distance between each crop row was 20 cm. A week after planting (before crop emergence) the site was sprayed with Diuron to complete the weed control.

Crop establishment was estimated by measuring 4 x 50 cm row lengths per plot four weeks after emergence. Dry matter production was measured at tillering and anthesis of wheat. Yield components and Harvest Index (HI) were determined at maturity with measurements done by processing two randomly selected 0.4 m^2 quadrats per plot. Chickpea was hand harvested and wheat was harvested with a Wintersteiger harvester. To avoid any edge effects the two outside rows on either side of each plot were not harvested.

In order to assess possible yield advantages, the yield components were analysed using different statistical methods, which are discussed in the Results section. More information on statistical analysis and graphical assessment methods is presented in Chapter 3.8.

5.3.2 Results

5.3.2.1 Crop establishment

Plant populations four weeks after germination are presented in Table 5-4.

Table 5-4 Means of crop establishment density (plants m^{-2}) for wheat (W) and chickpea (C) in sole and intercropping

Crop	SAR d1	SAR d2	SAR d3	SAR d4	SAR d5	DAR d1	DAR d2	DAR d3	DAR d4	DAR d5	MIRd 1	MIR d2	MIR d3	MIR d4	MIR d5	100	150	200
C	18	23	32	18	25	16	26	30	17	30	17	28	33	20	34	34	49	63
SEM	2	2	2	1	2	2	1	2	1	2	4	3	4	2	3	2	2	4
W	60	84	96	106	61	54	77	102	108	56	67	87	125	111	64	118	166	237
SEM	2	4	11	5	4	6	4	6	6	3	5	6	10	6	5	2	5	2

Row arrangements: SAR= single alternate row; DAR= double alternate rows; MIR = mixed in a row; different seeding rates: d1 = C50:W50, d2 = C75:W75; d3 = C100:W100; d4 = C50:W100; d5 = C100:W50; numbers in the first row and in the seeding rate description show the percentage of each sole or intercrop according to the recommended seeding rates for sole crops; SEM = standard error of mean seeding rates

5.3.2.2 Grain yield

Several statistical methods were used to assess the yield advantages of different cropping systems including intercrops and sole crops.

The data were analysed using randomised complete block design, factorial design and regression analysis.

Randomised complete block design. Firstly, a randomised complete block design with analysis of variance was used to examine the effects of the different cropping systems including sole crops and intercrops (all treatments together), on yields of wheat or chickpea (Table 5-5). The advantage of this method is that the yield of both sole crops and intercrops can be examined at the same time. However, it does not allow examination of the effect of row arrangement and density.

The results of this analysis indicate that wheat had a similar yield (P=0.05) under all the different cropping systems. For chickpea the results show that the sole crop treatments, C100, C150 and C200, had similar grain yields and that they were greater than those of all intercrop treatments (P<0.5). There was no evidence, using this method, of significant differences between the yields of chickpea intercropping treatments (Table 5-5).

Table 5-5 Grain yield of sole crop and intercropped chickpea (kg ha^{-1})

Crop	SAR d1	SAR d2	SAR d3	SAR d4	SAR d5	DAR d1	DAR d2	DAR d3	DAR d4	DAR d5	MIRd 1	MIR d2	MIR d3	MIR d4	MIR d5	C100	C150	C200
Mean	19	29	27	17	41	53	44	42	46	73	8	7	4	3	28	520	506	502
	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	a	a	a

SAR = single alternate row; DAR = double alternate rows; MIR = mixed in a row; Seeding rates: d1 = C50:W5O, d2 = C75:W75; d3 = C100:W100; d4 = C50:W100; d5 = C100:W50; numbers in the first row and in the seeding rate description show the percentage of each sole or intercrop according to the recommended seeding rates for sole crops; means with different lower case letters are significantly different at the 5% level (HSD)

Factorial design. In the second approach a factorial structure for the experiment was obtained by excluding sole crops from the analysis. This method made it possible to detect possible interactions between row arrangement and seeding rates by using analysis of variance. The reason for undertaking intercropping research as presented here is to question the hypothesis that intercropping is capable of producing a higher yield than monoculture. Thus an analysis which ignores sole crop data may be unsuitable if used as the sole tool of analysis and interpretation. However, the results of this approach can be an aid in interpretation of the other results.

From the analysis of wheat yield, it can be concluded that there is no significant interaction between arrangement and density, nor were there significant differences between row arrangements or seeding rates.

For chickpea yields a similar analysis showed no evidence of an interaction between density and arrangement, but there were differences between the main effects of density and row arrangement. Double alternate rows had significantly higher grain yields than other row arrangements (Table 5-6).

Table 5-6 **The effect of row arrangement on grain yield (kg ha^{-1}) of intercropped chickpea averaged across densities**

Row arrangement	SAR	DAR	MIR
Mean	26b	50a	10b

SAR = single alternate row; DAR = double alternate rows; MIR = mixed in a row; means with different letters are significantly different at 5% level (HSD)

For seeding rates, the highest grain yield of chickpea was achieved in C100:W50 and the lowest yield was observed in C50:W100 (Table 5-7).

Table 5-7 **The effect of seeding rates on grain yield (kg ha^{-1}) of chickpea in a wheat (W)-chickpea (C) intercrop averaged across row arrangements**

Seeding rate	C50:W50	C75:W75	C100:W100	C50:W100	C100:W50
Mean	27b	25b	25b	19c	47a

Numbers for each set show the percentage of recommended seeding rates; means with different letters are significantly different at 5% level (HSD)

Regression analysis. In the third approach, the sole crops were assumed as another row arrangement, making four row arrangements, and the three sole crop seeding rates were added to the five seeding rate levels, making a total of eight seeding rates (Table 5-8).

Thus, an unbalanced factorial structure was obtained, which made it impossible to use a standard analysis of variance. To overcome this, the data were analysed using a regression technique. It should also be noted that if the data were balanced, the results of the analysis of variance and the regression analysis would be the same.

Using this technique, the sole crops were taken into account while the factorial structure of the experiments was maintained, so the interaction and effects of the two factors were detectable.

Table 5-8 **Ability of regression analysis to show a result: 100, 150, 200, C50:W50, C75:W75, C100:W100, C100:W50, and C50:W100, with the different seeding rates**

	Row arrangement			
Seeding rate	Sole	SAR	DAR	MIR
100	+	—	—	—
150	+	—	—	—
200	+	—	—	—
C50:W50	—	+	+	+
C75:W75	—	+	+	+
C100:W100	—	+	+	+
C100:W50	—	+	+	+
C50:W100	—	+	+	+

+ result available; — result unavailable; SAR = single alternate row; DAR = double alternate rows; MIR = mixed in a row

However, the unbalanced nature of the data gives difficulties. Fewer replications of sole crops than of intercrops, as well as consequential difficulties in interpretation of the data when interactions occur, and the possible variation of data under severe moisture stress, may mean that the analysis might be unable to detect differences in some circumstances. To obtain a more accurate judgment using regression analysis, it was decided that the averages of the main effects and standard error of means (which is a descriptive measure of the amount of variation around the mean) and the results of statistical analysis be shown on the same diagram. Using this new approach the regression analysis provides the level of significance, and the graphic presentation makes it possible to observe any variation which might have been missed by the regression method. This third approach was used for the assessment of yield.

Wheat. From the regression analysis it can be concluded that at the 5% significance level there was no evidence of an interaction between density and arrangement, nor any main effect of density or arrangement (Figure 5-5 and Figure 5-6). The results of the other two statistical methods support this finding.

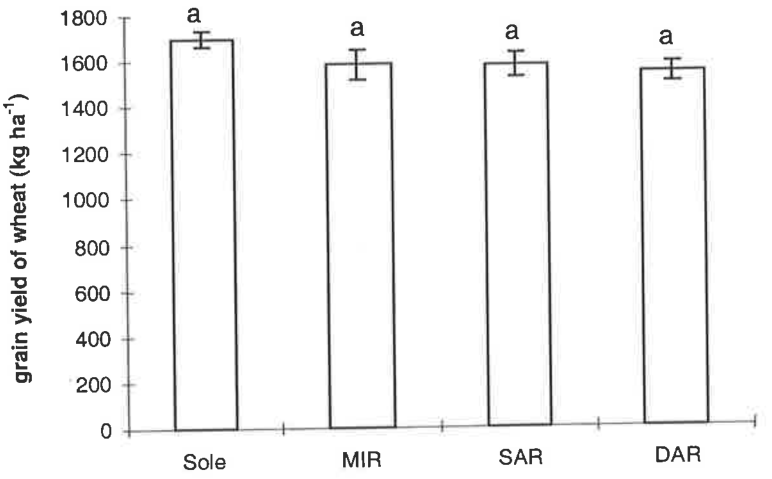


Figure 5-5 The effects of different row arrangements on grain yield (kg ha^{-1}) of wheat in sole crop, mixed in a row (MIR), single alternate rows (SAR) and double alternate rows (DAR); error bars indicate the standard error of means; columns with different letters are significantly different at the 5% level (Scheffé) averaged across row arrangements

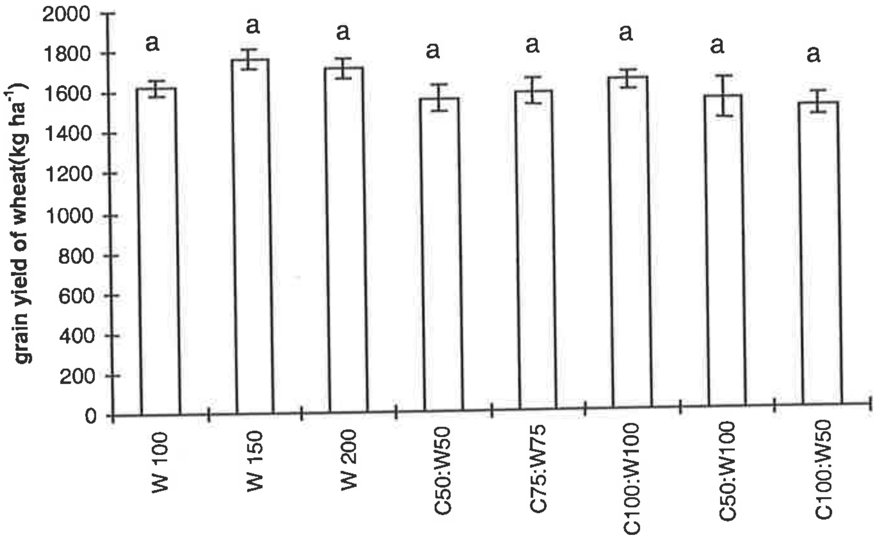


Figure 5-6 The effects of different seeding rates on grain yield of wheat; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; error bars indicate the standard error of means; columns with different letters are significantly different at 5% level (Scheffé) averaged across densities

Chickpea. There was no evidence of an interaction between density and arrangement (P=0.05). However, on their own both plant densities and arrangement had a significant effect on chickpea grain yield. The data were log transformed in the analysis to satisfy assumptions of normality.

The effect of different row arrangements is shown in Figure 5-7. Sole crops had a greater yield than all intercrops and DAR produced significantly higher yield than SAR and MIR (P<0.05).

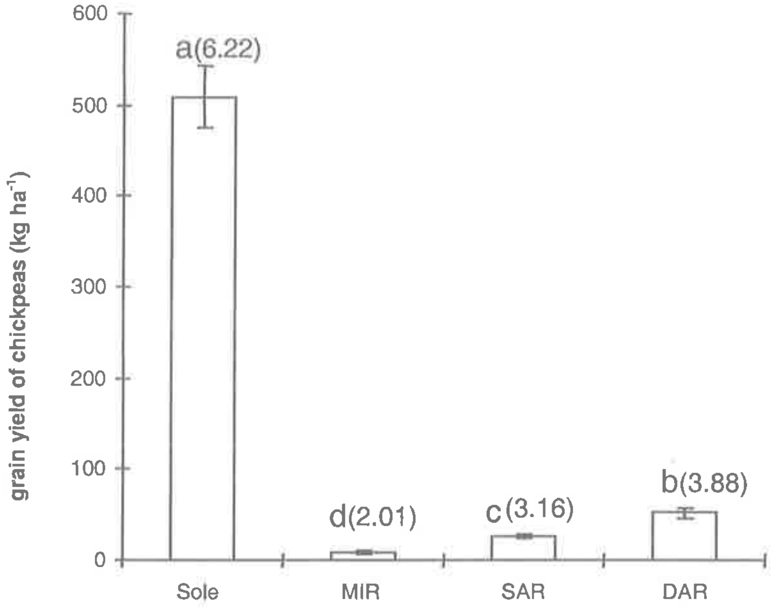


Figure 5-7 The effects of different row arrangement on yield of chickpea; sole crops, mixed in a row (MIR), single alternate rows (SAR) and double alternate rows (DAR); the data were log transformed in the analysis and the numbers in parentheses are the averages of transformed values for each row arrangement; error bars indicate the standard error of means; columns with different letters are significantly different at 5% level (HSD)

In Figure 5-8, the effects of different seeding rates on the grain yield of chickpea are shown. C100, C150 and C200 (sole crops) had greater yields than intercrop based seeding rates. C100:W50 had a significantly higher yield than any other intercrop treatment. The lowest yield was obtained from the C50:W100 treatment.

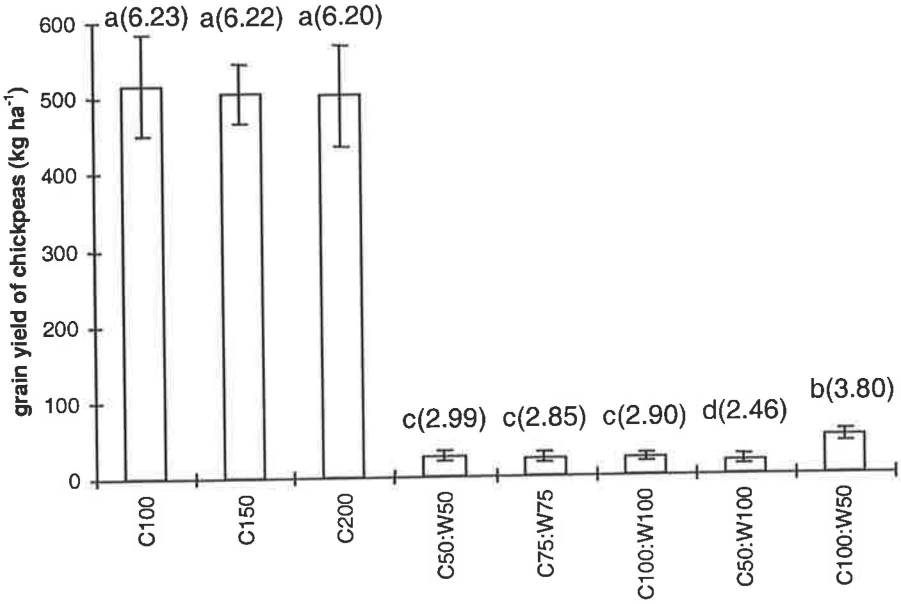


Figure 5-8 **The effects of different seeding rates on the yield of chickpea; the numbers for Wheat (W) and Chickpea (C) show the percentage of recommended seeding rates for sole crop; data were log transformed in the analysis; numbers in parentheses are the averages of transformed values of each seeding rate; error bars indicate the standard error of means; columns with different letters are significantly different at 5% level (HSD)**

5.3.2.3 Yield components

Regression analysis did not show any interactions between row arrangement and seeding rates in yield components ($P=0.05$).

Wheat.

Number of heads per m^2. Sole crops had significantly higher ($P<0.05$) head density per m^2 than other arrangements, and SAR and DAR had significantly fewer head densities per m^2 than MIR (Figure 5-9a).

The regression analysis indicated that W150 and W200 had significantly higher head densities than all the intercrops except that of C100:W100 which was similar to W100 and W150 (Figure 5-10).

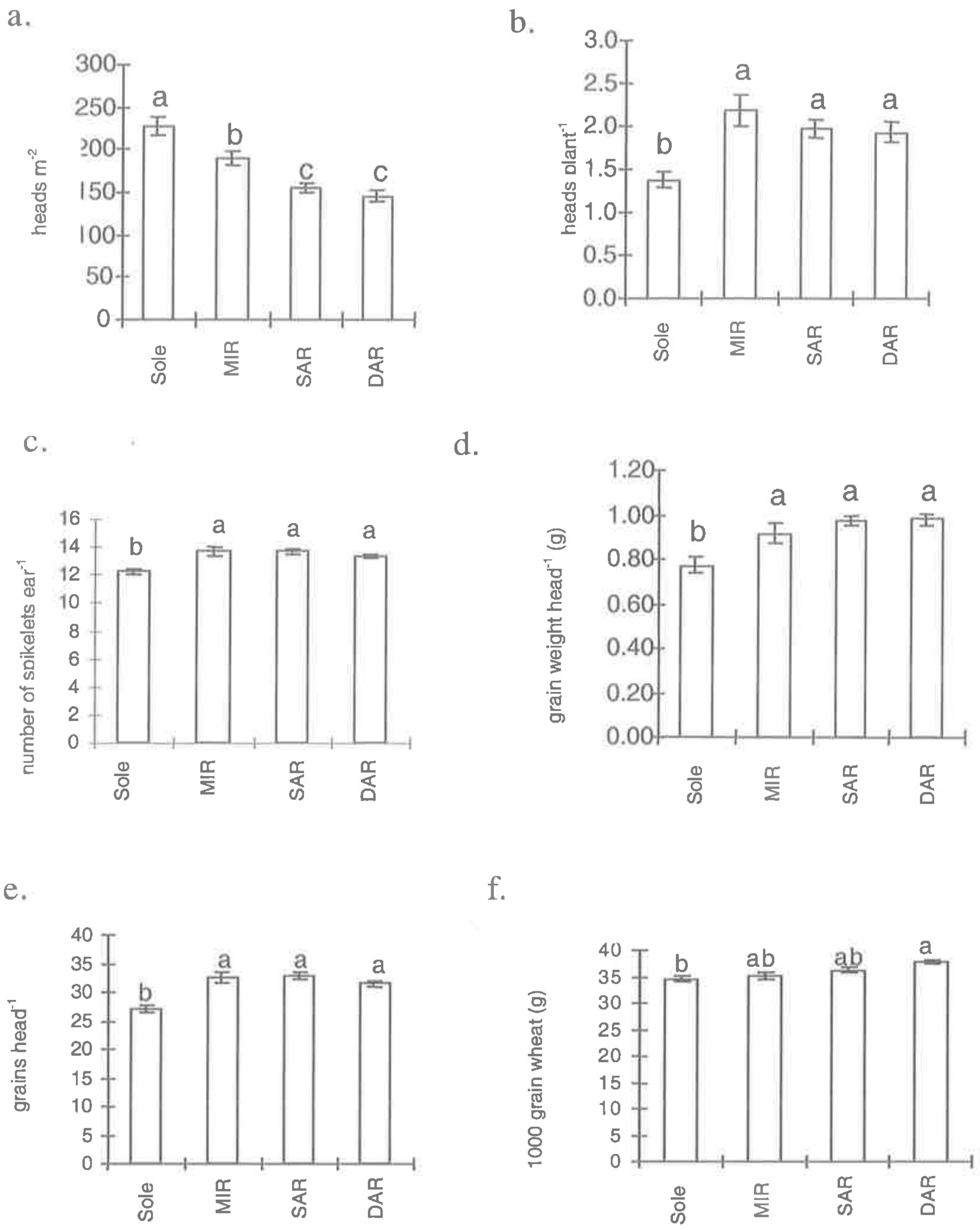


Figure 5-9 The effects of different row arrangement on yield components of wheat; Sole, MIR, SAR and DAR (sole crops, mixed in a row, single alternate rows and double alternate rows respectively); error bars indicate the standard error of means; columns with different letters are significantly different at 5% level (HSD)

Number of heads per plant. The effect of different row arrangements on the number of heads per plant is shown in Figure 5-9b. The number of heads per plant was significantly lower in sole crops than SAR, DAR and MIR ($P<0.05$). The intercrop arrangements had similar head production ($P=0.05$).

For number of heads per plant there was a significant difference between seeding rates ($P<0.05$). Seeding rate C50:W100, had greater number of heads per plant than C100:W100, C100:W50 and all sole crop seeding rates. The lowest number of number of heads per plant was observed in W200 (Figure 5-10b).

Number of spikelets per head. There was no evidence of significant differences between seeding rates for head size (Figure 5-10c).

The effect of different row arrangements on the number of spikelets per head is shown in Figure 5-9c. MIR, SAR and DAR had similar number of spikelets per head and these were significantly higher than sole wheat.

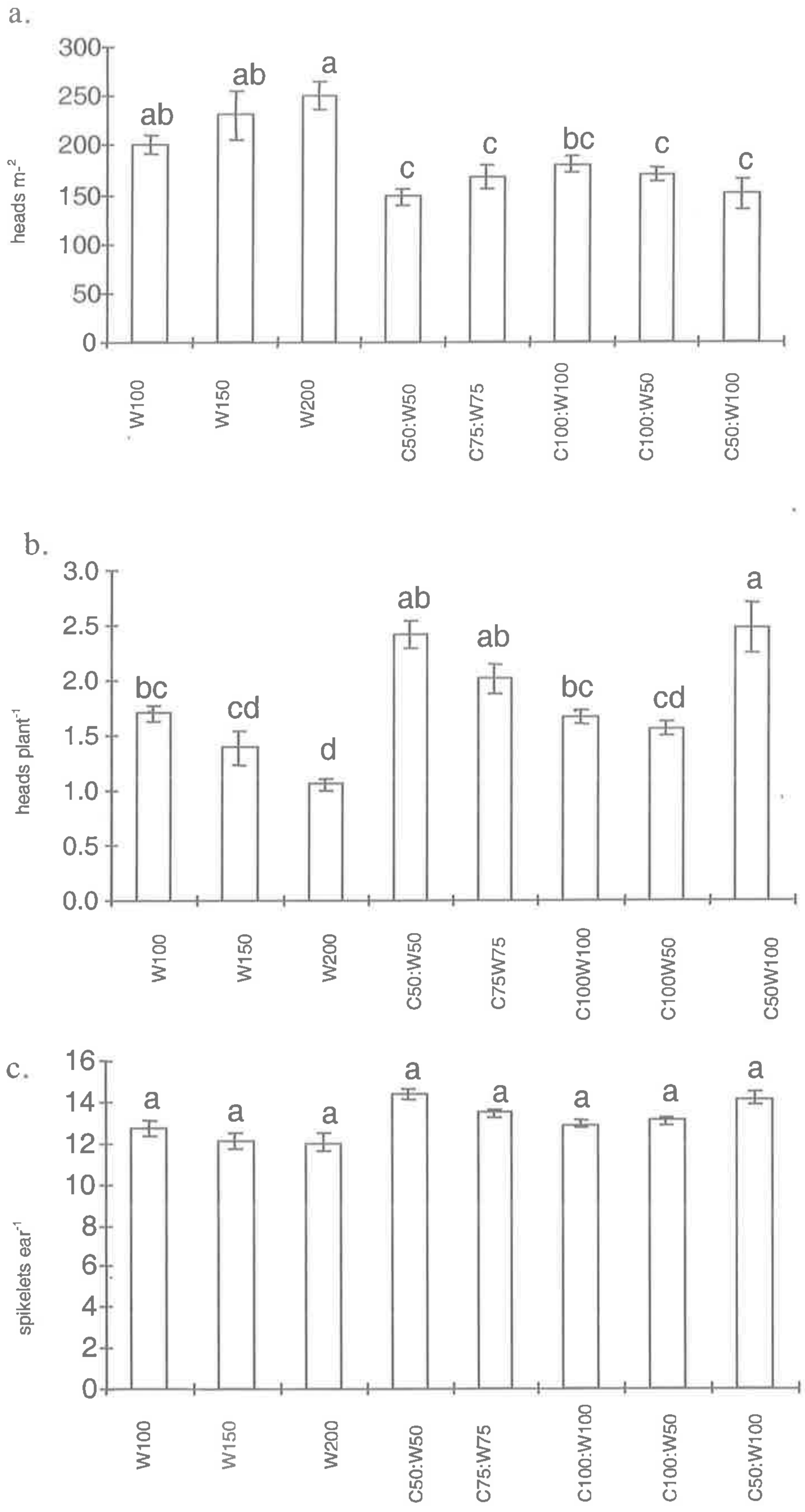
Grain weight per head. The effect of different row arrangements on grain weight per head is shown in Figure 5-9d. Intercrops had significantly higher grain weight per head than sole crops. However, the row arrangements (SAR, DAR and MIR) had a similar grain weight per head ($P=0.05$).

The regression analysis showed that seeding rates C50:W50, C75:W75 and C50:W100 had significantly higher grain weight per head than seeding rate W200 ($P<0.05$). However, the seeding rates C50:W100 and C50:W50 tend to have greater grain weight per head than the other treatments (Figure 5-10d).

Number of grains per head. The regression analysis showed that there was no interaction between density and row arrangements. However, there were significant differences between different densities ($P<0.05$).

The number of grains per head in MIR, DAR and SAR was similar (Figure 5-9e) and greater than that of the sole crops ($P< 0.05$).

Seeding rates C50:W50 and C50:W100 showed greater number of grains per head than sole crop's related seeding rates (Figure 5-10e).


a.
heads m^{-2}
300
250
200
150
100
50
0
ab
ab
a
c
c
bc
c
c
W100
W150
W200
C50:W50
C75:W75
C100:W100
C100:W50
C50:W100
b.
heads plant^{-1}
3.0
2.5
2.0
1.5
1.0
0.5
0.0
bc
cd
d
ab
ab
bc
cd
a
W100
W150
W200
C50:W50
C75W75
C100W100
C100W50
C50W100
c.
spikelets ear^{-1}
16
14
12
10
8
6
4
2
0
a
a
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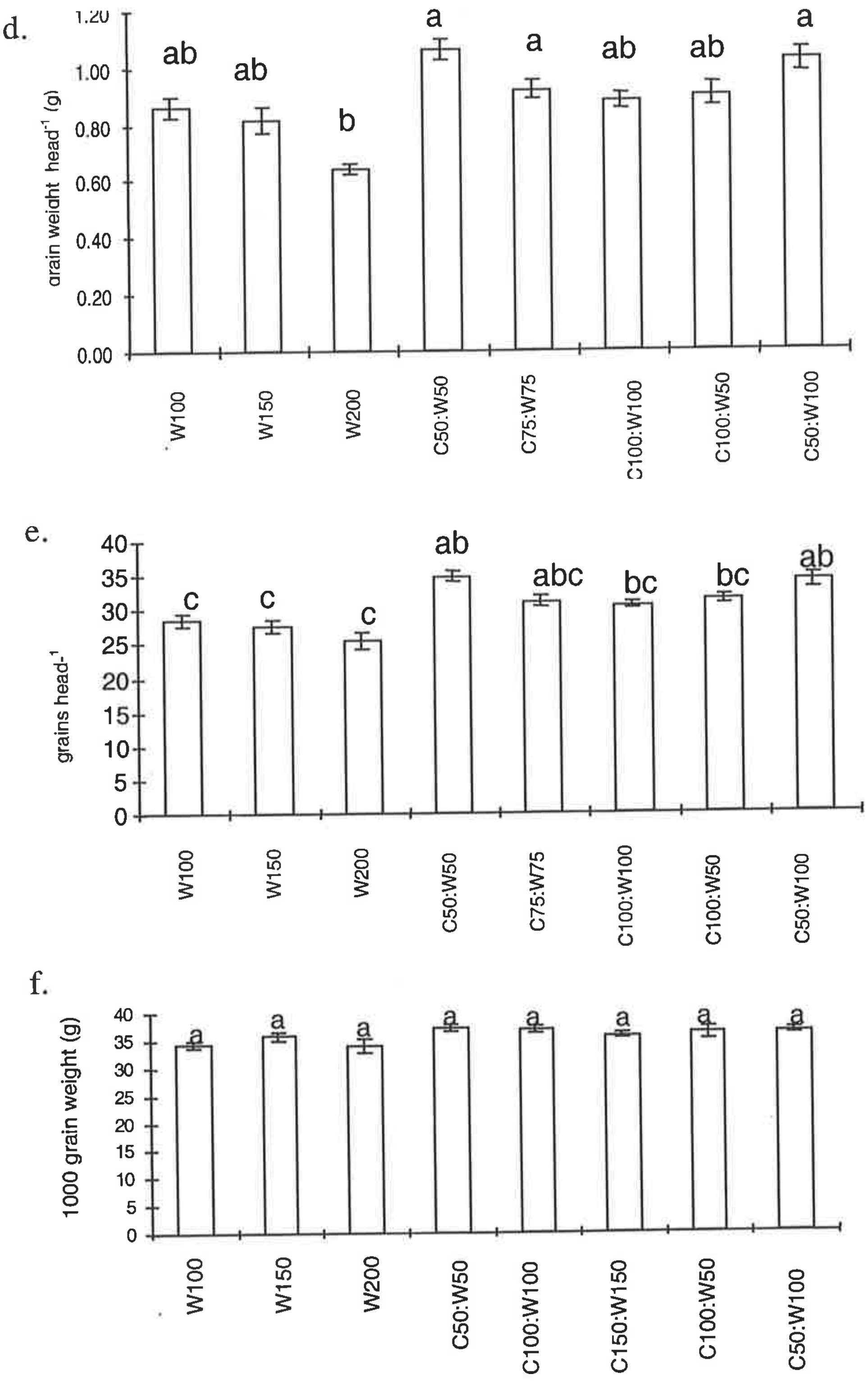


Figure 5-10 Effects of different seeding rates on yield components for wheat; numbers for W (wheat) and C (chickpea) are percentages of recommended seeding rates; error bars indicate the standard error of means; columns with different letters are significantly different at 5% level (HSD)

1000 grain weight. The regression analysis showed no interaction between the main factors, and there were no significant differences between the different densities, but there is a significant difference between row arrangement (P= 0.05) (Figures 5-9f and 5-10f). DAR had a greater 1000 grain weight than sole crop and it was similar to the other row arrangements.

Chickpea

Number of seeds per plant. The yield components of number of seeds per plant and 100 grain weight were measured. The data were log transformed, to satisfy the assumptions of normality. As can be seen in Figure 5-11, the sole crop had a greater number of seeds per plant than the other arrangements. Of the intercrop planting arrangements, DAR had the greatest and MIR the lowest number of seeds per plant ($P > 0.05$).

The effect of different seeding rates on the number of seeds per plant is shown in Figure 5-12. Seeding rates C150 and C200 had similar numbers of seeds per plant. However, C100 had significantly higher number of seeds per plant than other seeding rates. C100 had the highest number of the sole crops, and sole crops had higher numbers of seeds than intercrops.

100 grain weight. The regression analysis shows that there is no evidence of an interaction between density and arrangement, and plant density did not show any significant effect on 100 grain weight. However, there are significant differences between densities (Figure 5-12). Figure 5-11 shows that sole crops had significantly higher 100 grain weight than the other row arrangements, followed by DAR. MIR had the lowest 100 grain weight of all arrangements.

The effect of different seeding rates on 100 grain weight is shown in Figure 5-12. Considering the standard error of means, there is a considerable variation between replicates of treatments. This may be a reason why the regression analysis was not able to show significant differences between the seeding rates. Thus the results of this analysis should be used with caution.

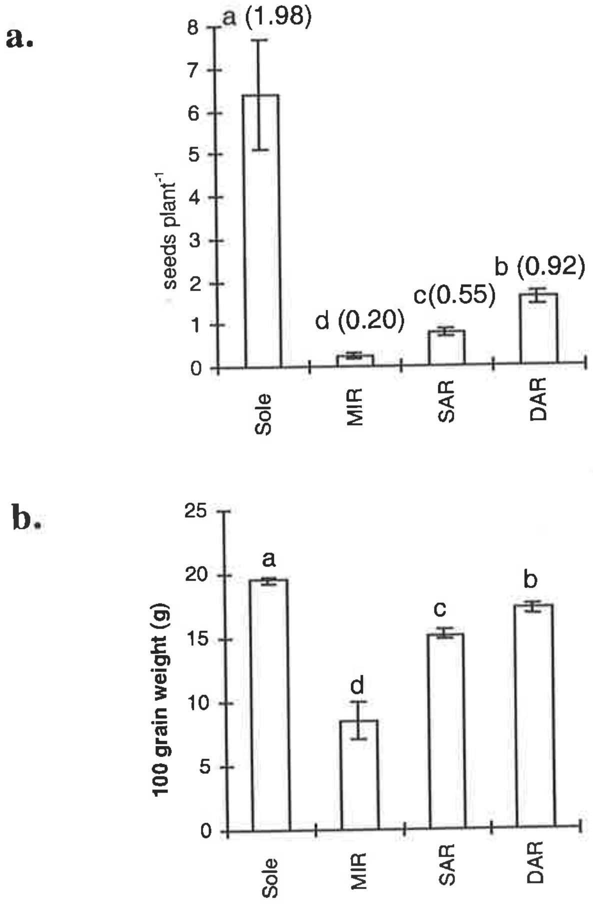


Figure 5-11 The effects of different row arrangements on (a) the number of seeds plant^{-1} and (b) 100 grain weight for chickpea intercropped with wheat; sole crop, mixed in a row (MIR), single alternate rows (SAR) and double alternate rows (DAR); numbers in parentheses are the log values of each row arrangement; error bars indicate the standard error of means; columns with different letters are significantly different at 5% level (HSD) averaged across densities

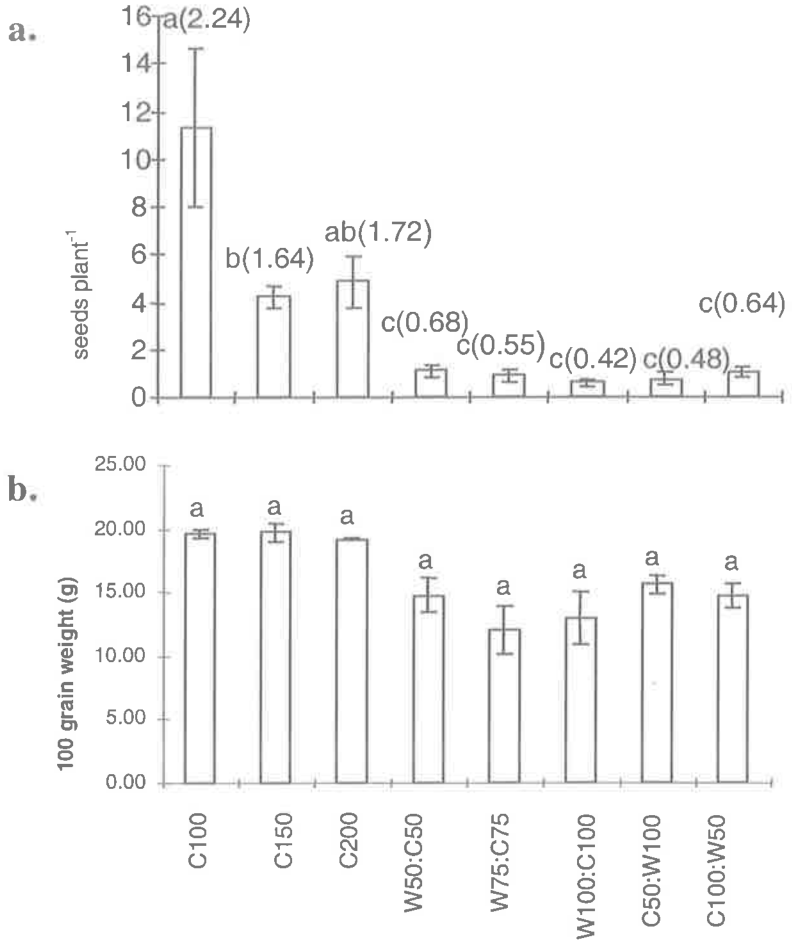


Figure 5-12 **The effects of different seeding rates on (a) number of seeds per plant and (b) 100 grain weight of chickpea intercropped with wheat; the numbers for W (wheat) and C (chickpea) are percentages of recommended sole crop seeding rate; numbers in parentheses are log values of each seeding rate; error bars indicate the standard error of means; columns with different letters are significantly different at 5% level (HSD) averaged across plant density**

5.3.2.4 Bivariate analysis of total grain yield

A bivariate analysis was performed to determine which intercrop combination produced the highest grain yield of wheat and chickpea (Figures 5-13 and 5-14). From the bivariate analysis it can be concluded that there is no evidence of an interaction between density and arrangement (P=0.05). However, it appears that there are significant differences in the yields of wheat and chickpea at different densities (Figure 5-13). It clearly shows that C100:W50 performed better than other seeding rates. The results of the bivariate analysis also identified significant differences between the yields of different row arrangements. There is evidence of better performance for the double alternate row arrangement.

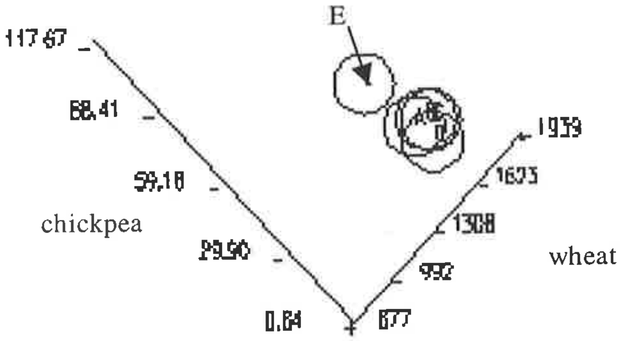


Figure 5-13 **Graphical performance of the intercropping system using a bivariate analysis of seeding rates; A = C50:W50; B = C75:W75; C = C100:W100; D = C50:W100; E = C100:W50; numbers in each set are percentage of recommended seeding rates; error is shown by the circles**

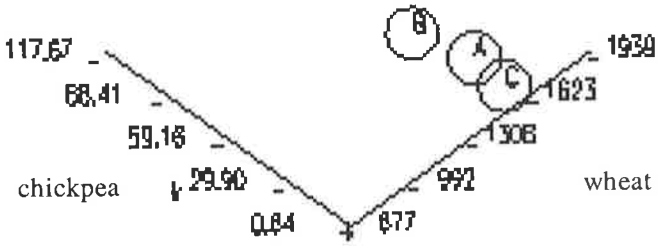


Figure 5-14 **Graphical performance of the intercropping system using a bivariate analysis of row arrangements; A = single alternate rows; B = double alternate rows; C = mixed in a row; error is shown by the circles**

5.3.2.5 Dry matter production and Harvest Index

Dry matter production was measured at tillering of wheat, and at anthesis and maturity for both species. There was no interaction between seeding rates and row arrangement.

The effect of row arrangements on dry matter production

Wheat. At all phenological stages, sole crops and MIR produced a similar amount of dry matter per m^2. Sole crop and MIR had similar dry matter production at all phenological stages, and were higher producing than both DAR and SAR. The differences between dry matter production of sole crops, MIR, DAR and SAR increased at anthesis and further at maturity (Figure 5-15) but the greatest reduction in yield was only about 25% of sole crop yield.

Chickpea. Absolute differences were quite small at branching but increased markedly over time. At all stages sole crops had by far the highest dry matter production of all the arrangements (Figure 5-15). MIR, SAR and DAR had similar dry matter at the early stages, but at flowering time of chickpea they diverged, and at maturity DAR had a higher dry matter production per unit area than SAR. MIR had the lowest dry matter production of all the different row arrangements.

The effect of seeding rates on dry matter production

Wheat. The effect of different seeding rates on dry matter production is shown in (Figure 5-16). At tillering the seeding rates W100, W150 and W200 (sole crops) had slightly higher dry matter production than the other treatments. At flowering the only seeding rate which showed a lower yield than sole crops was C75:W75. At maturity all intercrop related seeding rates had similar dry matter yields.

Chickpea. The effect of different seeding rates on dry matter production of chickpea per m^2 and per plant is shown in Figure 5-16. Dry matter production per m^2 was similar for sole crops and much higher than that of intercrops. The difference between sole crop and intercrop dry matter production increased towards the end of the season. At maturity seeding rate C100:W50 produced the highest dry matter of all the intercrops while the lowest was expressed in treatment C50:W100 (Figure 5-16).

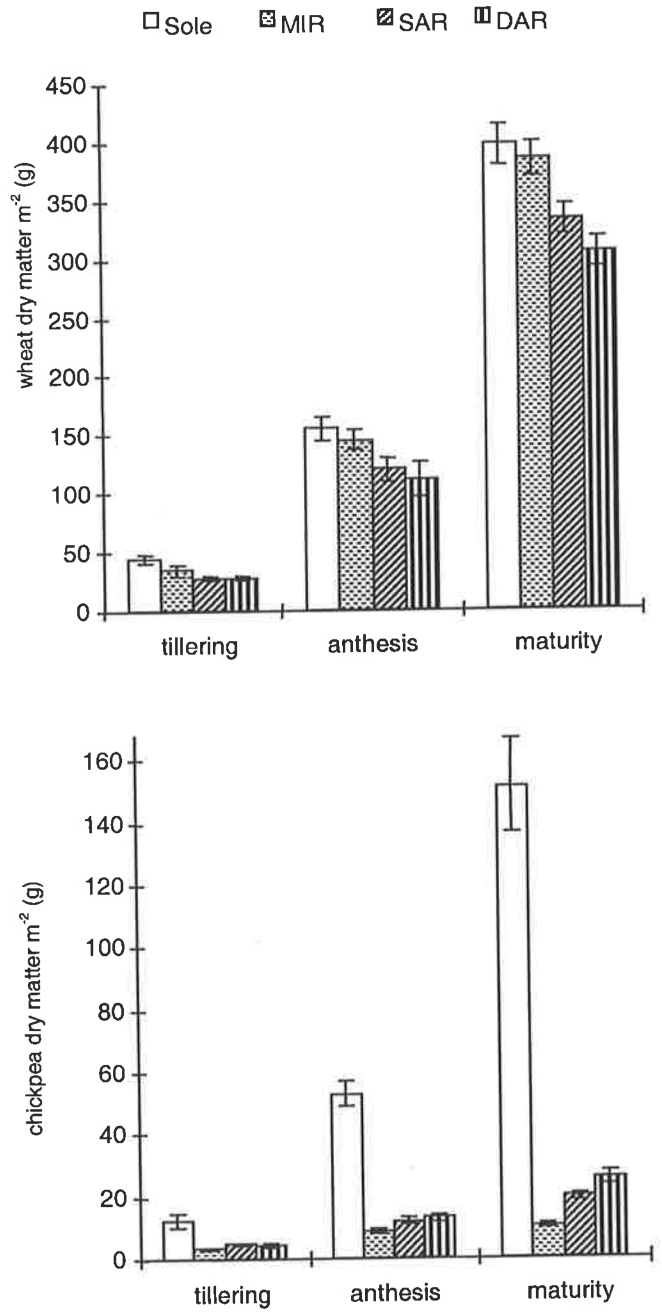


Figure 5-15 The effects of row arrangement on dry matter production of wheat and chickpea m^{-2} at different phenological stages; sole crops, mixed in a row (MIR), single alternate rows (SAR) and double alternate rows (DAR); error bars indicate the standard error of means

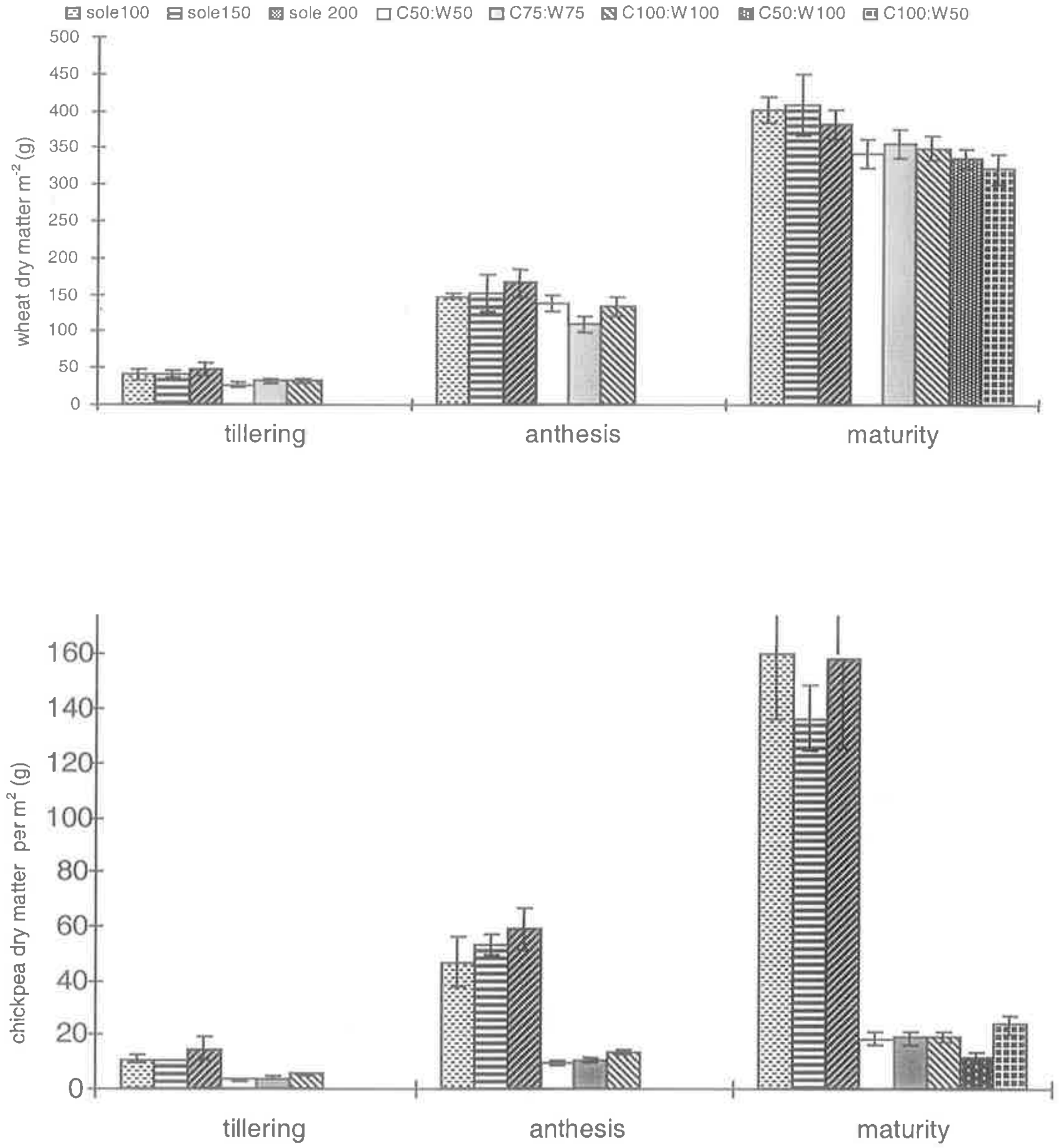


Figure 5-16 **The effects of seeding rates on dry matter production of wheat and chickpea m^{-2} at different phenological stages; the numbers for C (chickpea) and W (wheat), 100, 150 and 200 show the percentage of recommended sole crop seeding rates; error bars indicate the standard error of means**

Harvest index (HI)

The effect of different row arrangements on the harvest index of wheat and chickpea is shown in Figure 5-17.

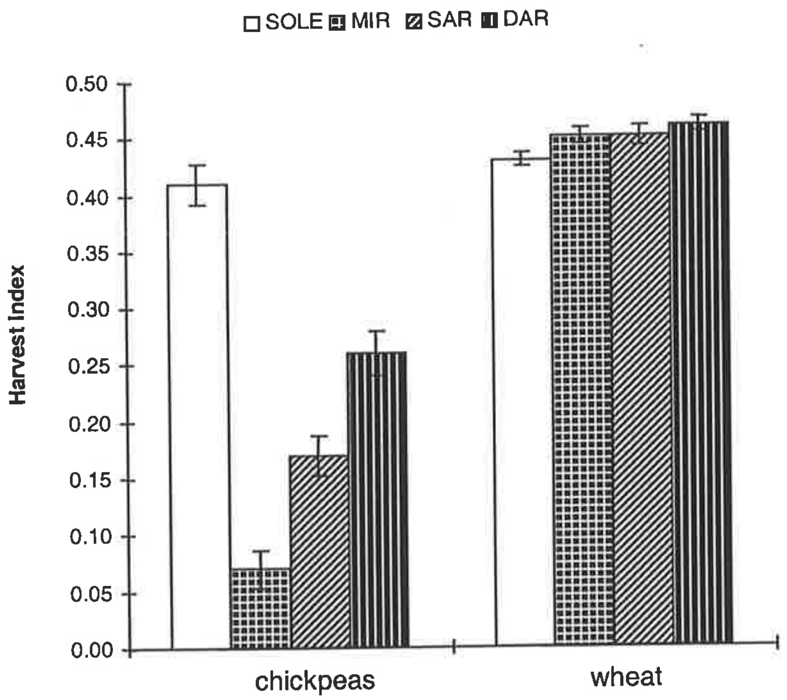


Figure 5-17 The effect of row arrangements on Harvest Index of sole crops, mixed in a row (MIR), single alternate rows (SAR) and double alternate rows (DAR); error bars indicate the standard error of means

HI of wheat was very similar under different row arrangements. In contrast, for chickpea the highest harvest index was observed in sole crop and of the intercrops DAR had the highest and MIR the lowest HI.

The effect of seeding rates on the harvest index of wheat (Figure 5-18) was small and usually not significant. In chickpea, C100 had a greater HI than at higher densities of sole crops. Intercropping significantly reduced HI by more than 50% of sole crop values. Chickpea at high density intercropped with high density wheat (C100:W100) had a significantly lower HI than where it was grown at low density with low density wheat (C50:W50).

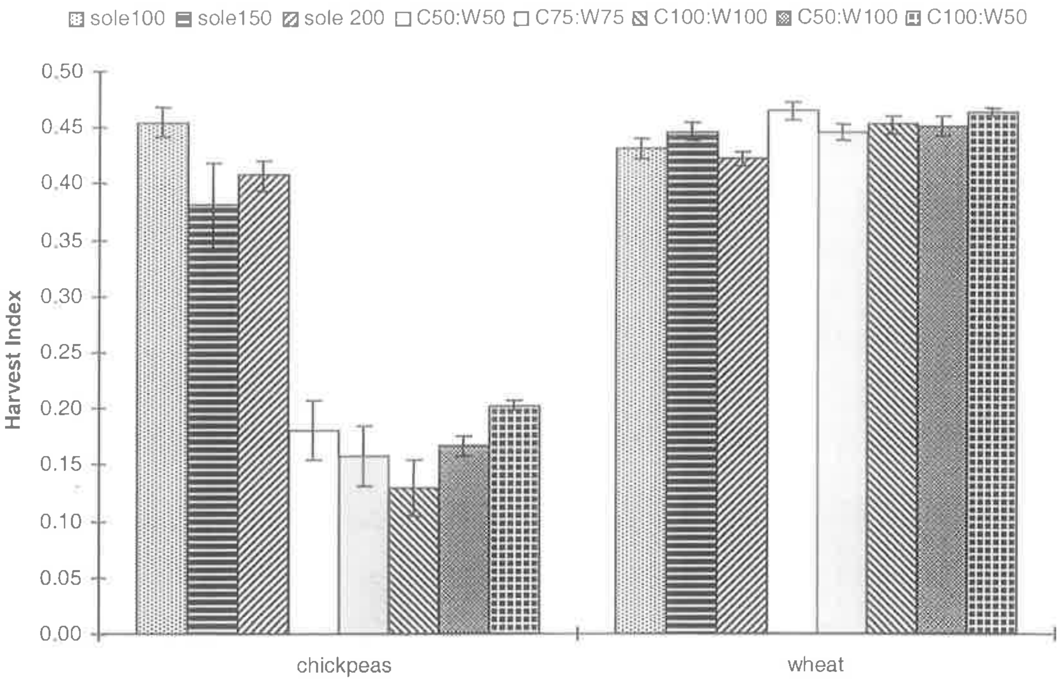


Figure 5-18 **The effect of seeding rates on harvest index; numbers for C (chickpea) and W (wheat), 100, 150 and 200 show the percentage of recommended seeding rates; error bars indicate the standard error of means**

5.3.2.6 Competition and biological efficiency

5.3.2.6.1 Diagrammatic illustrations

In this experiment the replacement series diagram was applied. It is only possible to have three points on the curve using replacement series when the C150, W150, C100:W50, C50:W100 and C75:W75 treatments were selected (Figure 5-19). Figure 5-19a based on sowing rates shows small biological advantages for intercropping over sole cropping. However, Figure 5-19b based on final yield shows disadvantage. These illustrations also show that chickpea in intercropping was severely suppressed by wheat. It appears that the two species were mutually exclusive.

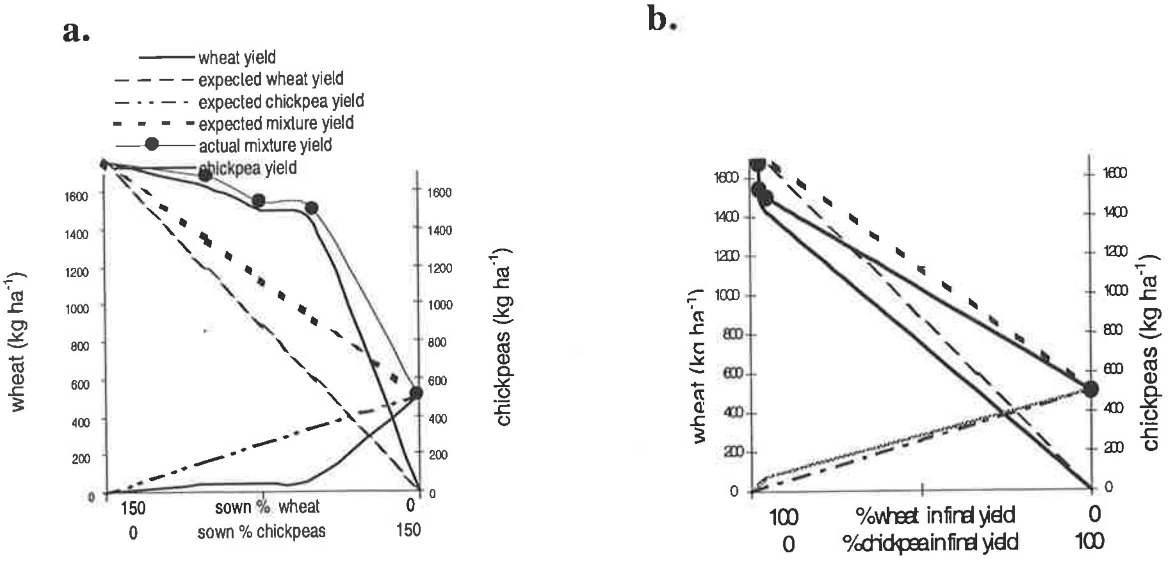


Figure 5-19 Wheat-chickpea in replacement series, considering (a) recommended sowing rates and (b) final yield

5.3.2.6.2 Land Equivalent Ratio and Competition Ratio

Table 5-9 presents the effect of different row arrangements on $LER_{biomass}$, LER_{grain} and CR of wheat with respect to chickpea. $LER_{biomass}$ was greater than one in all situations. However, there is no significant difference between the effect of different row arrangements on $LER_{biomass}$. LER for grain yield was not significantly different between row arrangements and the values were less than one. CR was highest when chickpea was mixed in a row with wheat indicating that wheat is the dominant crop, severely suppressing chickpea when they are planted together in a row. However, there was no significant difference between single rows and double rows in competitive ability. Double alternate rows in all cases tend to show the most favourable results (i.e. higher LER and lower CR).

Table 5-9 **The effect of different row arrangement on land equivalent ratio (LER) of $LER_{biomass}$, LER_{grain} and competition ratio (CR)**

Indices	Single alternate row	Double alternate row	Mixed in a row
$LER_{biomass}$	1.08a	1.09a	1.02a
LER_{grain}	0.95a	0.97a	0.91a
CR	27.10b	13.20b	85.7a

Different letters indicate a significant difference at the 0.05 probability level (HSD)

In Table 5-10 the effects of different seeding rates on LER_{grain}, $LER_{biomass}$ and CR are presented. There were no significant advantages or disadvantages of any of mixtures for $LER_{biomass}$ or LER_{grain}. There were significant differences between different seeding rates in relation to CR. The highest CR of wheat with respect to chickpea was found in C50:W100 and the lowest in C100:W50.

Table 5-10 **The effect of different seeding rates on land equivalent ratio (LER) of $LER_{biomass}$, LER_{grain} and competition ratio (CR)**

Indices	C50:W50	C75:W75	C100:W100	C50:W100	C100:W50
$LER_{biomass}$	1.03a	1.12a	1.11a	1.00a	1.05a
LER_{grain}	0.93a	0.95a	0.98a	0.93a	0.95a
CR	35.10c	41.4bc	49.9b	69.7a	14.2d

Different letters indicate a significant difference at the 0.05 probability level (HSD)

5.4 Experiment 3: The effect of nitrogen fertiliser and combinations of different densities and row ratios on wheat-chickpea intercrops and their sole crops under irrigated (wet) and non-irrigated (rainfed) conditions

5.4.1 Materials and methods

Wheat (cultivar Excalibur) and chickpea (cultivar Semsen) were sown in mixtures and as sole crops with different seeding rates and row arrangements with and without nitrogen application, under irrigated and nonirrigated conditions in field E7 at the Roseworthy Campus of The University of Adelaide in 1995.

5.4.1.1 Cropping systems

The row arrangements were: 2 rows of chickpea alternating with 2 rows of wheat (2-2), 3 rows of chickpea alternating with 2 rows of wheat (3-2) and 4 rows of chickpea alternating with 2 rows of wheat (4-2). For sole wheat these densities were either 155 plants m^{-2} (W100 is the recommended rate for the region) or 275 plants

Table 5-11 Ratios and row arrangements for mixtures of wheat and chickpea

Seeding rates and row arrangements	% of normal chickpea population	% of normal wheat population	Chickpea rows	Wheat rows
C50:W50 (2-2)	50	50	2	2
C100:W50 (2-2)	100	50	2	2
C100:W100 (2-2)	100	100	2	2
C60:W40 (3-2)	60	40	3	2
C67:W33 (4-2)	67	33	4	2

Normal densities for these species are 155 plants m^{-2} for wheat, and 32 plants m^{-2} for chickpea; numbers in parentheses show the ratio of chickpea rows to wheat rows

(W200), and for sole chickpea they were 32 plant m^{-2} (C100 is the recommended rate for the region) or 63 plants m^{-2} (C200). Mixtures were created at five levels of competitive pressure, as shown in Table 5-11, each with and without nitrogen application. W100, C200, C100, W50 (2-2) were used for detailed studies reported in Chapter 6.

5.4.1.2 Design and field work

A randomised complete block design with seven replications and split plot structure were used for this experiment. The main plots were 2.4 x 15 m of mixed or sole crops. Each plot was split into two sub-plots consisting of 12 rows spaced 0.2 m apart. At the tillering stage for wheat 40 kg N in the form of ammonium sulfate was applied to one randomly selected subplot. The design of the experiment is presented in Appendix 5.

After a pre-sowing cultivation, 20 kg ha^{-1} phosphorus in the form of super phosphate was applied. Weeds were controlled before seeding using glyphosate and trifluralin. During the season weeds were manually removed when necessary.

Chickpea seeds were inoculated with the appropriate commercial rhizobium. Seed was preloaded into magazines and planted using a Wintersteiger seeder (Section 3.7).

To evaluate the effect of soil moisture, three replications were irrigated during the season. The first irrigation of 20 mm was applied at tillering and thereafter irrigation 37 mm was applied at 10 day intervals until physiological maturity. These irrigated blocks are referred to as being under 'wet' conditions in comparison to 4 non-irrigated blocks under 'rainfed' conditions. Chickpea was hand harvested while wheat was harvested with a Wintersteiger harvester. To minimise edge effects two rows either side of each plot were not harvested.

5.4.1.3 Measurements

Grain yield was measured for all treatments. Yield components, soil water storage, green area index (GAI), canopy light interception (P_i), dry matter and N content of plants were only measured for the C200, W100 and C100:W50 treatments. In this chapter mainly yield measurements and some relevant calculations are presented, while details of other measurements are presented in Chapter 6. More information on statistical analysis and graphic assessments is presented Section 3.8. Assessments of yield were applied only on (2-2) row arrangements, while assessments of LER and CR were used on all seeding rates and row arrangements. When interactions were detected an interaction plot is presented (which is a descriptive way to represent the significant interactions). Bivariate analysis was not performed for this experiment.

5.4.2 Results

5.4.2.1 Grain yield

To assess the yields of intercropping systems in these experiments, firstly the results of dryland conditions were considered, secondly the results of irrigated conditions were examined and finally the effect of the moisture environments (irrigated and rainfed) were analysed simultaneously.

Wheat

Under rainfed conditions plant densities had a significant effect on the yield of wheat ($P<0.05$) (Figure 5-20). However, the effect of nitrogen and the interaction of nitrogen and density were not significant. Two sole crops (W100 and W200) had similar yields, and these yields were significantly higher than intercrop treatments ($P<0.05$) (Figure 5-20). All intercrop plant densities had similar yields ($P=0.05$).

In the irrigated treatments the effects of densities, nitrogen levels and their interaction were significant. As can be seen from Figure 5-21, generally higher densities of wheat in mixtures showed a greater response to N fertiliser both in sole crop and intercrops.

Considering irrigated and rainfed environments, all effects and interactions were statistically significant (P<0.05). In Figure 5-21 the interaction of environment, N and densities is shown.

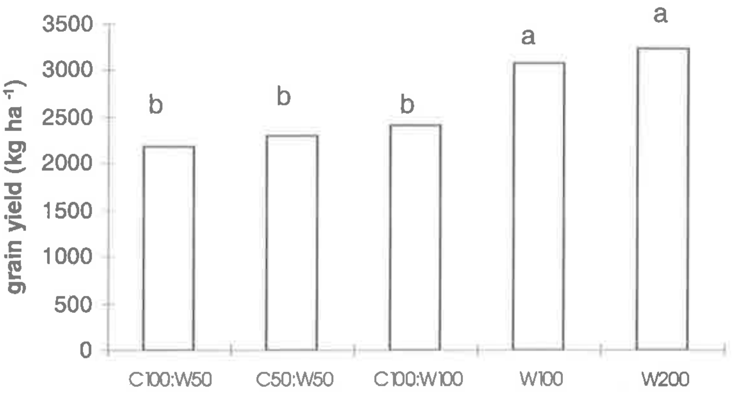


Figure 5-20 **The effects of different seeding rates on grain yield of wheat under rainfed conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; columns with different letters are significantly different at 5% level (LSD)**

Irrigation significantly increased the yield of sole wheat compared to rainfed conditions, and application of nitrogen fertiliser increased the yield only under irrigated conditions (Figure 5-21). With nitrogen application and irrigation, sole crop yield was higher at W200 than at W100. Intercrop wheat yield was only slightly improved by irrigation and nitrogen.

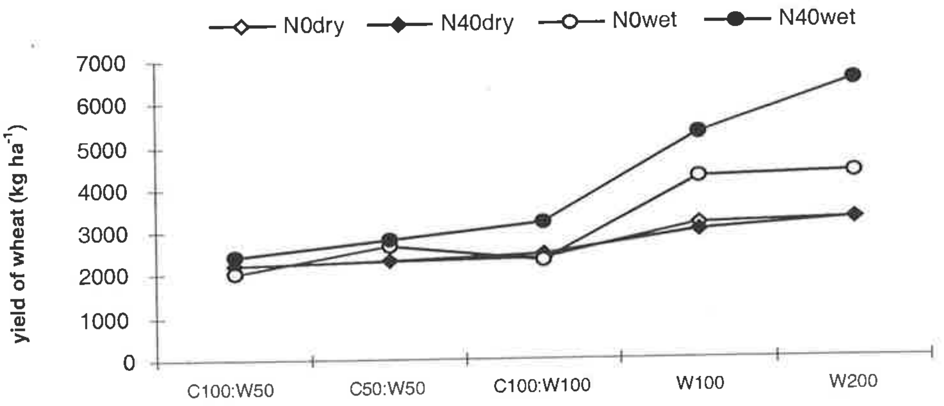


Figure 5-21 **Interactions obtained for wheat yield with cropping system, N fertiliser responses and environments; numbers in each set are the density percentages for chickpea (C) and wheat (W) in the mixtures; W100 and W200 show the density percentage for sole crops of wheat according to their recommended densities; N0 = no fertiliser application; N40 = 40 kg ha^{-1} of N was applied; wet = irrigated; dry = rainfed; LSD value = 690 kg ha^{-1}**

Chickpea

Under rainfed conditions the main effect of N on the grain yield of chickpea was not significant, and no interaction was detected between N and different densities. However the effect of seeding rate on yield was statistically significant (P<0.05), indicating a higher yield for sole crop treatments than mixtures. The intercrop density treatments had similar yields (P=0.05) (Figure 5-22).

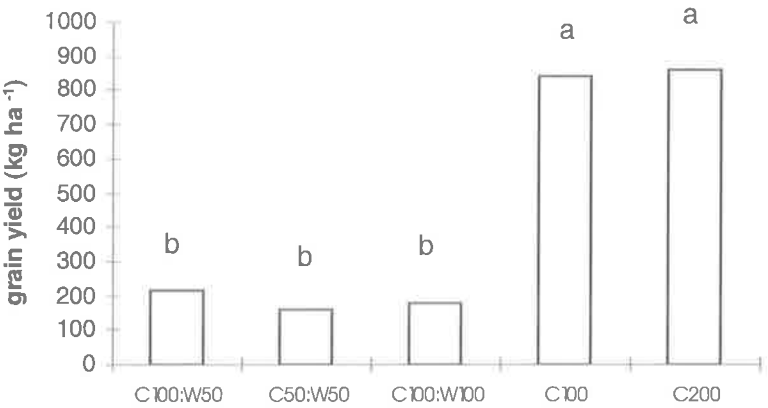


Figure 5-22 **The effects of different seeding rates on grain yield of chickpea under rainfed conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; columns with different letters are significantly different at 5% level (LSD)**

Under irrigated conditions, as for rainfed conditions the only significant difference was observed between densities, showing a higher yield for sole crops in comparison with intercrops (P<0.05). The yields of intercrops at all densities were similar (Figure 5-23).

The effects of environment and densities were significant (Figure 5-24). However, the effect of nitrogen and its interactions with other factors were not significantly different (P=0.05). Chickpea showed a greater response to increasing plant density in sole crops under irrigated conditions.

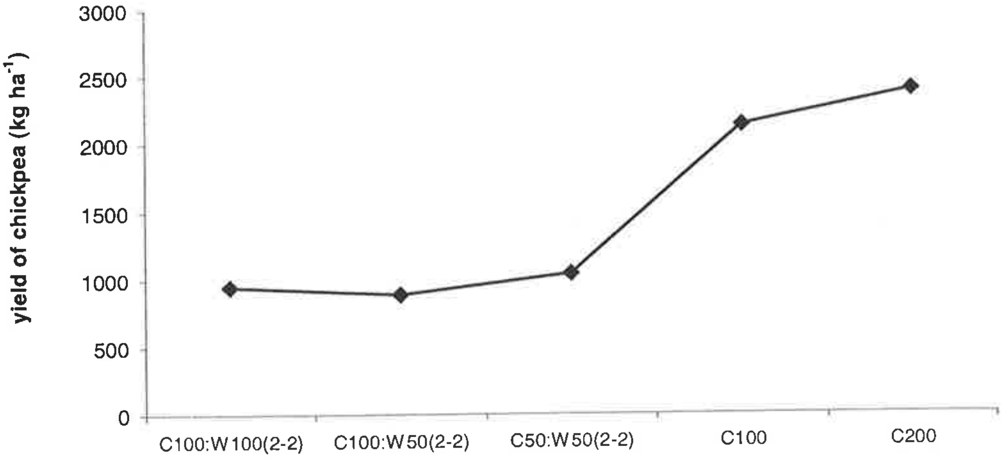


Figure 5-23 The effects of different seeding rates on grain yield of chickpea under irrigated conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops

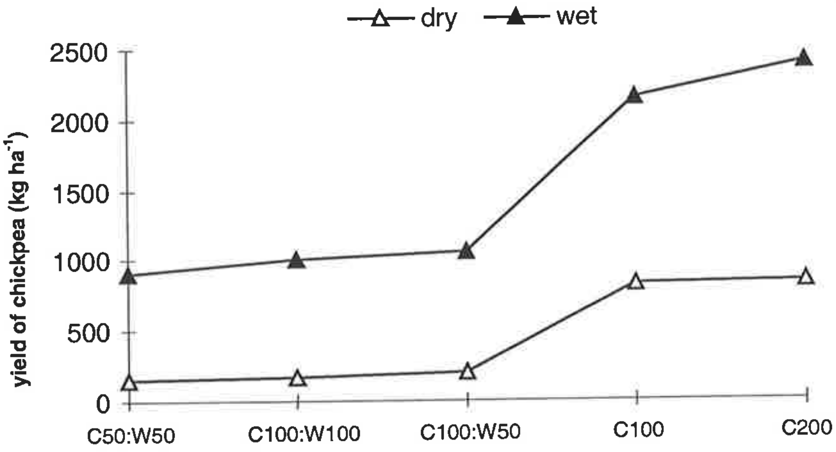


Figure 5-24 Interactions obtained for chickpea yield for cropping system and environments; numbers in each set are the density percentages for chickpea (C) and wheat (W) in the mixtures; C100 and C200 show the density percentage for sole crops of chickpea according to their recommended densities; wet = irrigated; dry = rainfed; LSD value = 273 kg ha^{-1}

5.4.2.2 Yield components

The effects of intercropping on yield components of wheat under irrigated and rainfed conditions are shown in Table 5-12. The mean number of heads per m^2 was higher in sole crop than intercrops in both moisture conditions, and the number of heads per plant in sole crops was 74% and 66% of that in mixed cropping under irrigated and rainfed conditions, respectively. However, the numbers of heads per plant were greater in mixtures than sole crops. Under both rainfed and irrigated conditions, the number of spikelets per head and also the number of grains per head were significantly higher in mixtures than sole crops. 1000 grain weight was slightly lower under irrigated than rainfed conditions. Sole crops and mixtures had similar HI under rainfed conditions, although under irrigated conditions the sole crop had a greater HI than mixtures. HI was higher under rainfed than irrigated conditions.

Table 5-12 The effect of different cropping systems on yield components and harvest index of wheat under irrigated and rainfed conditions for C100:W50 seeding rate and the related sole crops

Cropping system	Rainfed sole wheat	Rainfed mixed wheat	Irrigated sole wheat	Irrigated mixed wheat
Number of heads m^{-2}	267.3±15.2	198.0±14.5	302.6±43.7	202.0±19.4
Number of heads plant^{-1}	1.8±0.1	2.7±0.2	2.0±0.3	2.7±0.3
Average number of spikelets	14.8±0.2	15.9±0.2	14.6±0.4	16.4±0.5
Number of grains stem^{-1}	32.4±2.2	40.8±2.2	31.5±2.9	39.5±1.5
1000 grain weight (g)	48.6±2.7	50.0±0.3	41.2±2.0	39.7±1.5
Harvest Index	0.48±0.01	0.49±0.01	0.43±0.04	0.31±0.0

± (value) shows the standard error of means

The effect of intercropping on yield components of chickpea under irrigated and rainfed conditions is shown in Table 5-13. The number of seeds per m^2 was greater in sole crops than intercrops under both moisture conditions. The number of seeds per plant was significantly higher in sole crops than intercrops under rainfed conditions, but under irrigated conditions there was little difference between mixtures and sole crops. Weight of seeds per plant was significantly higher in the sole crop under rainfed conditions but it was similar between sole and mixed crop under irrigated conditions. The 1000 grain weight was similar between sole and the mixed crops and it seems that there was also no significant difference between irrigated and rainfed conditions. HI was similar between sole crop and mixture under rainfed conditions. However, under irrigated conditions the HI was higher in mixture than sole crop.

Table 5-13 The effect of different cropping systems on yield components and harvest index of chickpea under irrigated and rainfed conditions, for the C100:W50 seeding rate and the related sole crops

Cropping system	Rainfed sole chickpea	Irrigated sole chickpea	Rainfed mixed chickpea	Irrigated mixed chickpea
Number of seeds m^{-2}	582.9±69.13	994.8±98.64	145.5±28.22	560.8±31.06
Number of seeds $plant^{-1}$	11.11±1.08	19.13±1.9	5.25±1.21	15.16±0.84
Weight of the seed $plant^{-1}$	2.27±0.25	3.57±0.22	0.95±0.22	3.3±0.18
100 grain weight (g)	20.39±0.28	19.03±2.08	18.12±0.42	21.81±0.65
Harvest Index	0.44±0.02	0.36±0.01	0.37±0.03	0.52±0.06

5.4.2.3 Competition and biological efficiency

5.4.2.3.1 Land equivalent ratio (LER)

Under rainfed conditions, application of nitrogen fertiliser had no significant effect on LER. There was no interaction between nitrogen and plant densities. However, different densities had a significant effect on LER. The C60:W40 (3-2) and the C67:W33 (4-2) treatment had the lowest LER values. (Figure 5-25).

In the irrigated treatments the effect of densities, nitrogen levels and their interactions on LER were significant ($P<0.05$). LER decreased with application of nitrogen, however C100:W50 with no N showed a sharper decrease than with addition of 40 kg N ha^{-1}. Adding rows of chickpea tended to decrease the value of LER with or without N fertiliser (Figure 5-26). Application of nitrogen fertiliser showed a negative effect on LER under irrigated conditions.

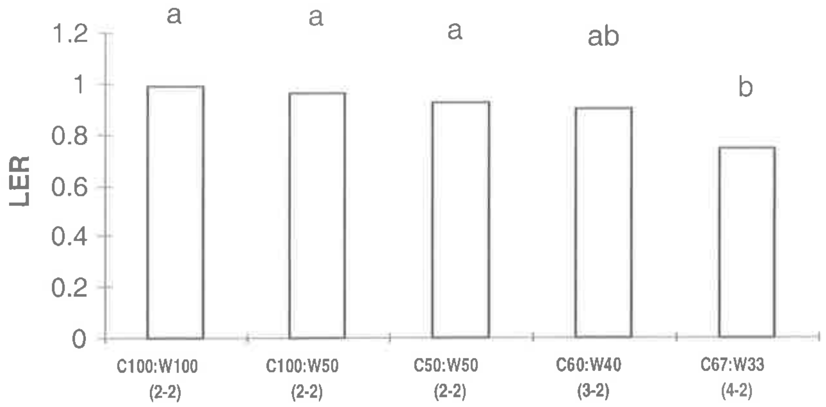


Figure 5-25 **The effects of different seeding rates on Land Equivalent Ratio (LER) under rainfed conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; numbers in parentheses show number of rows for the respective crops; columns with different letters are significantly different at 5% level (LSD)**

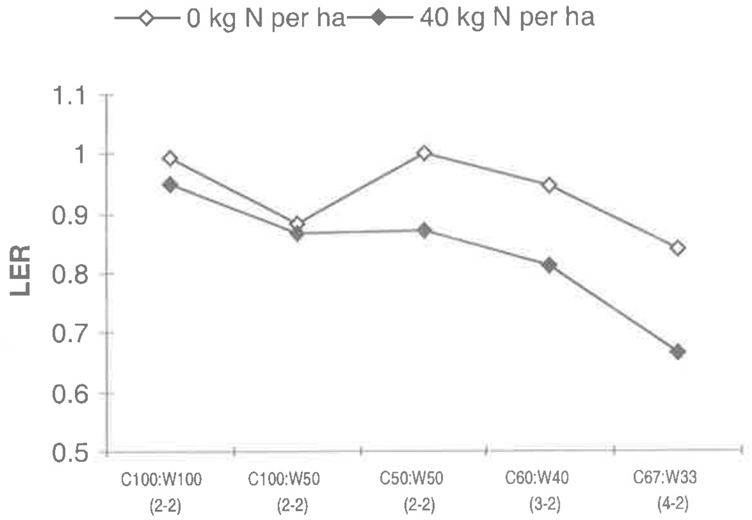


Figure 5-26 **Interactions obtained for different seeding rates and N fertiliser on Land Equivalent Ratio (LER) under irrigated conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; numbers in parentheses show number of rows for the respective crops; LSD value = 0.11**

The main effect of irrigated and rainfed environments on LER, the interaction of environment with seeding rate and the interaction between environment, seeding rate and N fertiliser were non-significant (P=0.05). However seeding rates showed a significant (P<0.05) effect on LER (Figure 5-27). The highest LER observed was in the C100:W100 (2-2) treatment, and the lowest in C50:W50 (4-2). The 2-2 row arrangement showed a higher LER than 3-2 or 4-2. The interaction of moisture environment and N fertiliser was significant (P<0.05) (Figure 5-28). Application of N fertiliser had no significant effect on LER under dryland conditions, however LER decreased with N fertiliser application under irrigated conditions.

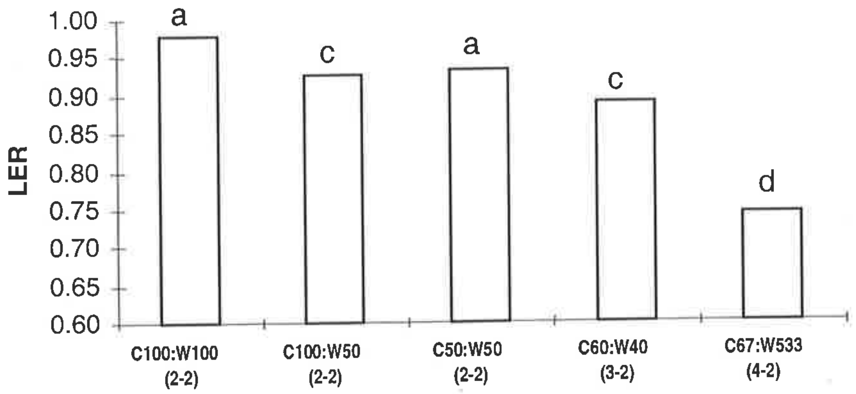


Figure 5-27 **The effects of different seeding rates on Land Equivalent Ratio (LER) under rainfed and irrigated conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; numbers in parentheses show number of rows for the respective crops; columns with different letters are significantly different at 5% level (LSD)**

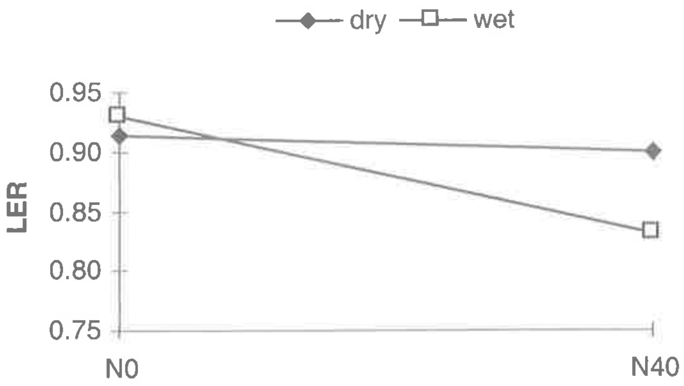


Figure 5-28 **Interactions obtained for the effects of N fertiliser and different moisture environments on Land Equivalent Ratio (LER); N0 = no fertiliser application; N40 = 40 kg ha^{-1} of N applied; wet = irrigated; dry = rainfed; LSD value = 0.056**

5.4.2.3.2 Competition ratio (CR) of wheat with respect to chickpea

There was no significant interaction between nitrogen and density. The main effect of seeding rate on yield was significant at ($P<0.05$) level but the main effect of nitrogen fertiliser was not significant.

Under rainfed conditions, C100:W100 (2-2) and C50:W50 (2-2) had a significantly higher CR than the other treatments. C67:W33 (4-2) had the lowest CR. It appears that the more rows and the higher the population of chickpea relative to wheat, the lower the competitive ability of wheat (Figure 5-29). Application of N fertiliser under rainfed conditions increased the CR from 2.47 with no fertiliser to 2.85 with fertiliser.

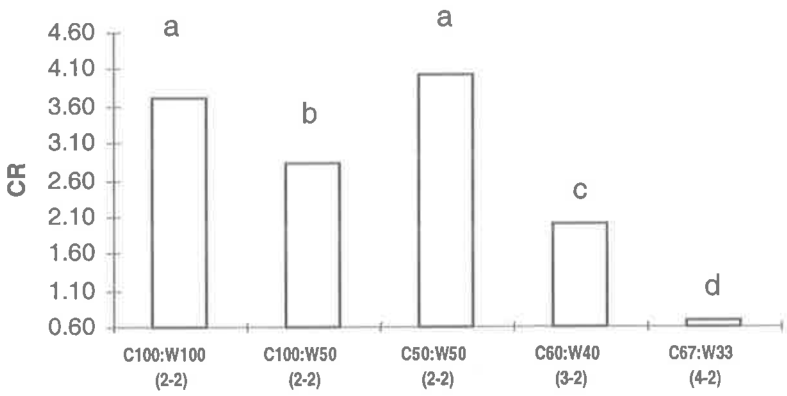


Figure 5-29 **The effects of different seeding rates on Competition Ratio (CR) of wheat with respect to chickpea under dryland conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; numbers in parentheses show number of rows for the respective crops; columns with different letters are significantly different at 5% level (LSD)**

With irrigation, C50:W50 (2-2) and C100:W100 (2-2) had a significantly higher CR than C60:W40 (3-2) and C67:W33 (4-2) ($P<0.05$) (Figure 5-30). Under irrigated conditions there was no significant interaction between nitrogen and density, and there was no main effect of nitrogen.

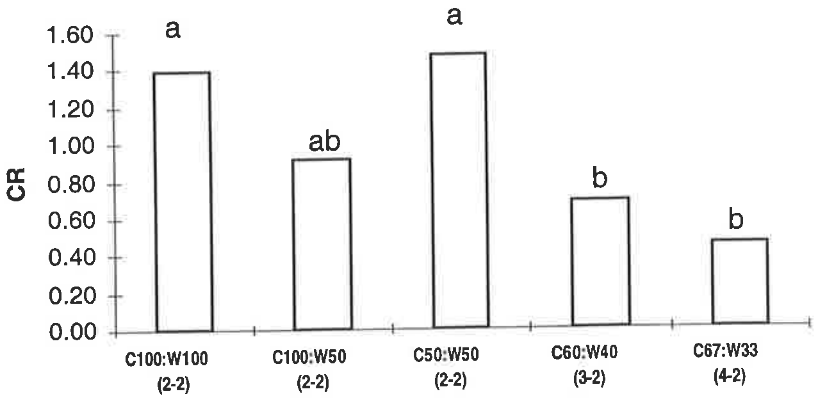


Figure 5-30 The effect of different seeding rates on Competition Ratio (CR) of wheat with respect to chickpea under irrigated conditions; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; numbers in parentheses show number of rows for the respective crops; columns with different letters are significantly different at 5% level (LSD)

The moisture regime x density interaction was significant ($P<0.05$) (Figure 5-31). The competition ratio decreased with increasing proportions of chickpea (either related to relative sowing rates or relative numbers of rows), especially without irrigation. Some values were slightly less than 1, indicating that chickpea was more competitive than wheat in those treatments.

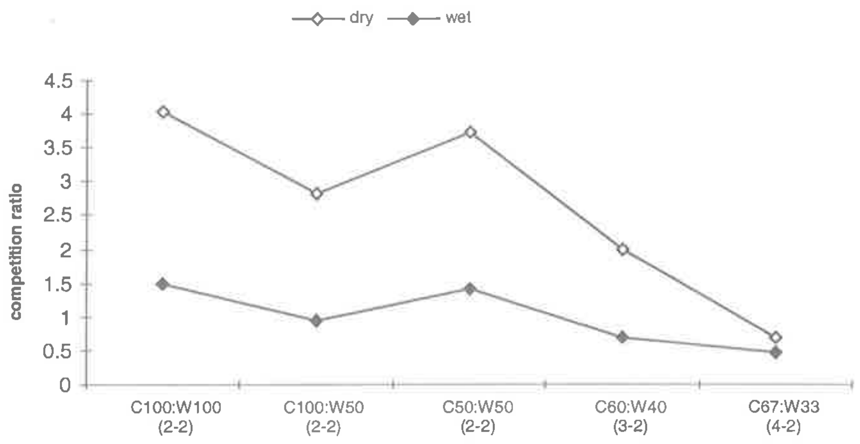


Figure 5-31 **Interactions obtained for the effects of seeding rate and moisture environments on Competition Ratio (CR) of wheat with respect to chickpea; numbers for W (wheat) and C (chickpea) show the percentage of recommended seeding rate for sole and intercrops; numbers in parentheses show number of rows for the respective crops; wet = irrigated; dry = rainfed; LSD value = 0.81**

The moisture environment x nitrogen interaction was significant ($P<0.05$). CR was much higher without than with irrigation. With irrigation, CR values were close to 1. Without irrigation, nitrogen application increased the CR but with irrigation there was a tendency for a decline of CR (Figure 5-32). Wheat was much more competitive in rainfed than irrigated environments especially with applied nitrogen.

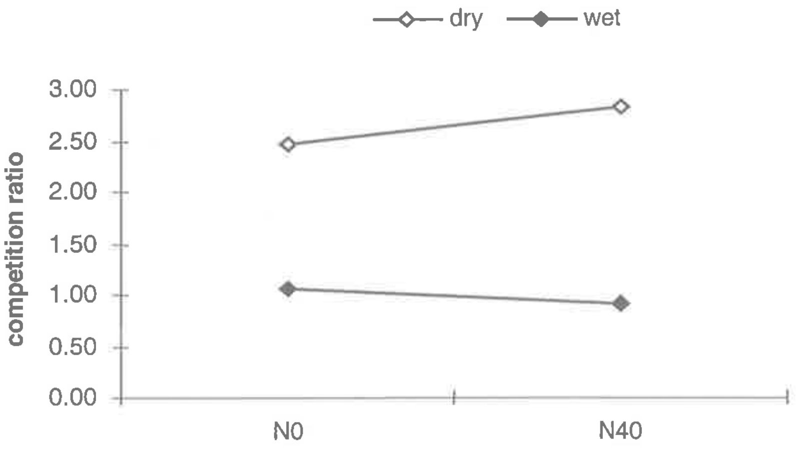


Figure 5-32 **Interactions obtained for the effects of nitrogen fertiliser and moisture environments on Competition Ratio (CR) of wheat with respect to chickpea; N0 = no fertiliser application; N40 = 40 kg ha^{-1} of N applied; wet = irrigated; dry = rainfed; LSD value = 0.33**

5.4.2.3.3 Diagrammatic illustrations

Using sowing rates and final yield replacement series diagrams were developed to illustrate the competition of wheat-chickpea intercrops with and without N fertiliser under different 2-2 row ratios (i.e. C50:W50 (2-2), C100:W50 (2-2) and C100:W100 (2-2)) under irrigated and rainfed conditions.

As can be seen in Figure 5-33, under rainfed conditions all treatments showed yield advantages. Wheat was the dominant and chickpea was the dominated crop in mixtures. However the response of mixtures under irrigation was different with C100:W50 showing a yield disadvantage, while C50:W50 and C100:W100 had no advantages or disadvantages over sole crops (i.e. wheat and chickpea were equally competitive).

Wheat-chickpea intercropping with 40 kg ha^{-1} N under different 2-2 row arrangements is shown in Figure 5-34. Under rainfed conditions all treatments showed small advantages. Under irrigation, C50:W50 showed no advantage or disadvantage, and C100:W50 and C100:W100 showed slight disadvantage.

Figures 5-35 and 5-36 present final yield results. With and without nitrogen and under irrigated and rainfed conditions, the diagrammatic illustration showed disadvantage over intercropping. It seems that irrigated and fertilised mixtures had a higher degree of disadvantage due to competition than the mixtures without N fertiliser under dryland conditions.

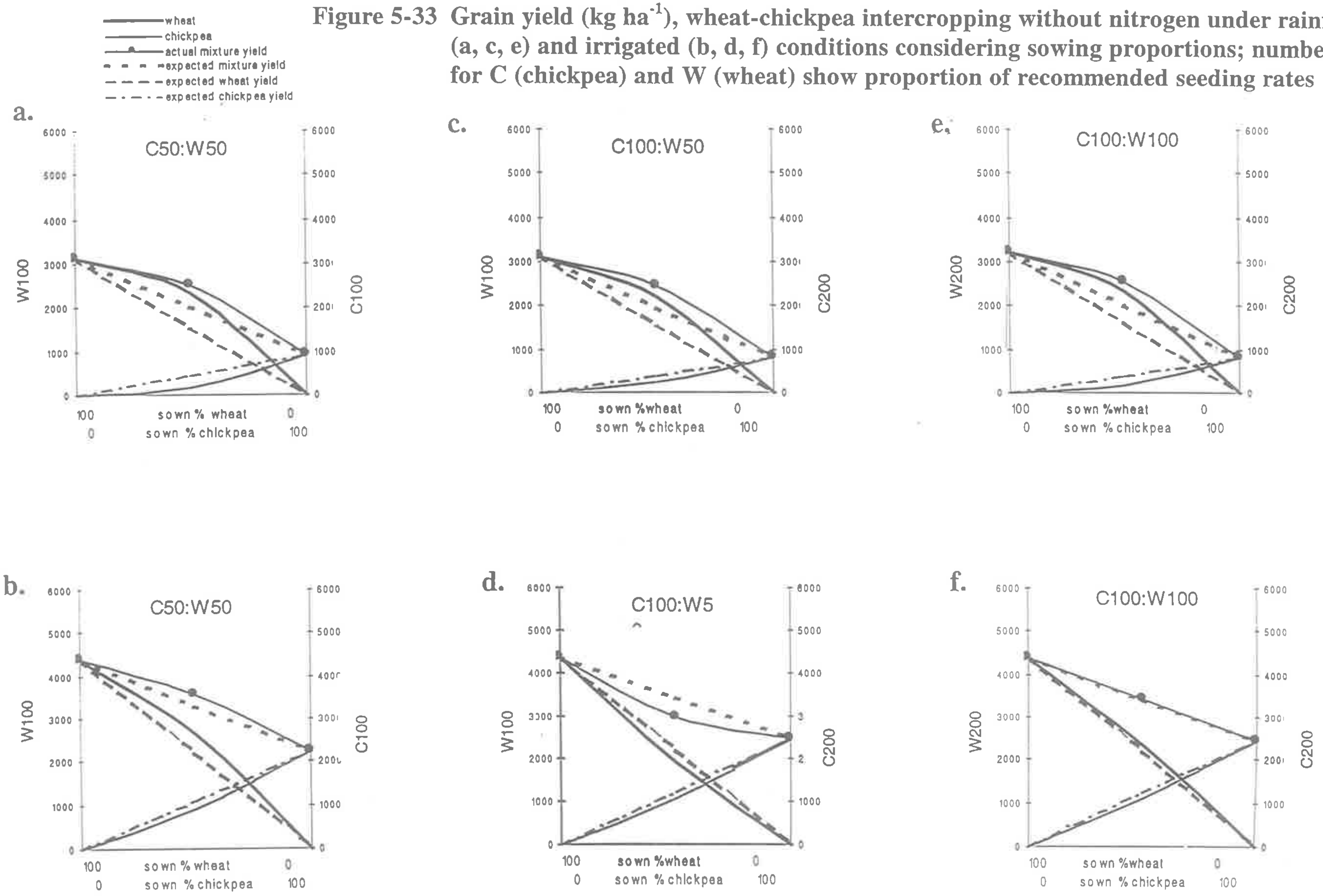


Figure 5-33 Grain yield (kg ha^{-1}), wheat-chickpea intercropping without nitrogen under rainfed (a, c, e) and irrigated (b, d, f) conditions considering sowing proportions; numbers for C (chickpea) and W (wheat) show proportion of recommended seeding rates

Figure 5-35 Grain yield (kg ha^{-1}), wheat-chickpea intercropping with 40 kg ha^{-1} nitrogen under rainfed (a, c, e) and irrigated (b, d, f) conditions considering sowing proportions; numbers for C (chickpea) and W (wheat) show proportion of recommended seeding rates

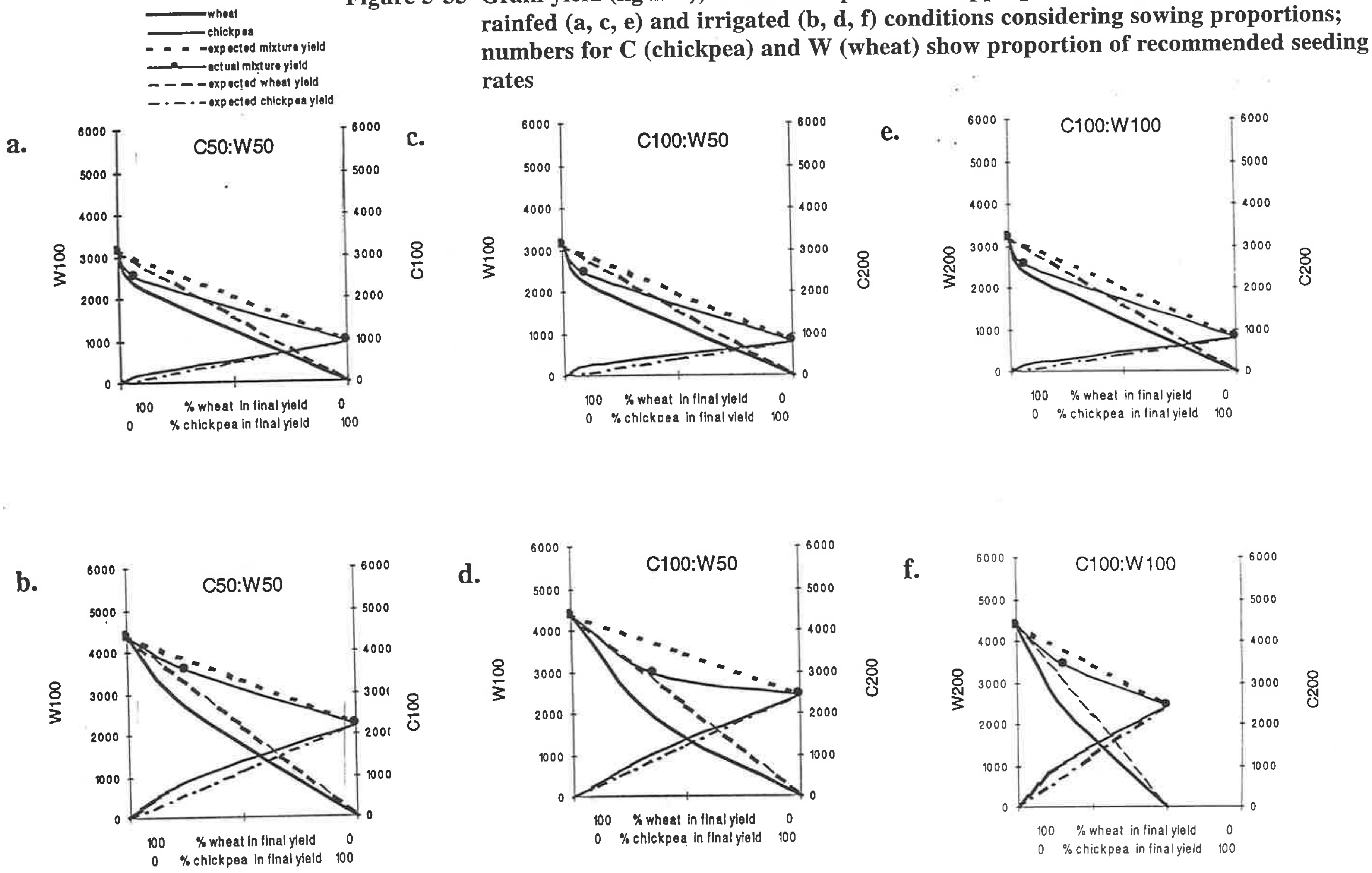


Figure 5-34 Grain yield (kg ha^{-1}), wheat-chickpea intercropping without nitrogen under rainfed (a, c, e) and irrigated (b, d, f) conditions considering final yield; numbers for C (chickpea) and W (wheat) show proportion of recommended seeding rates

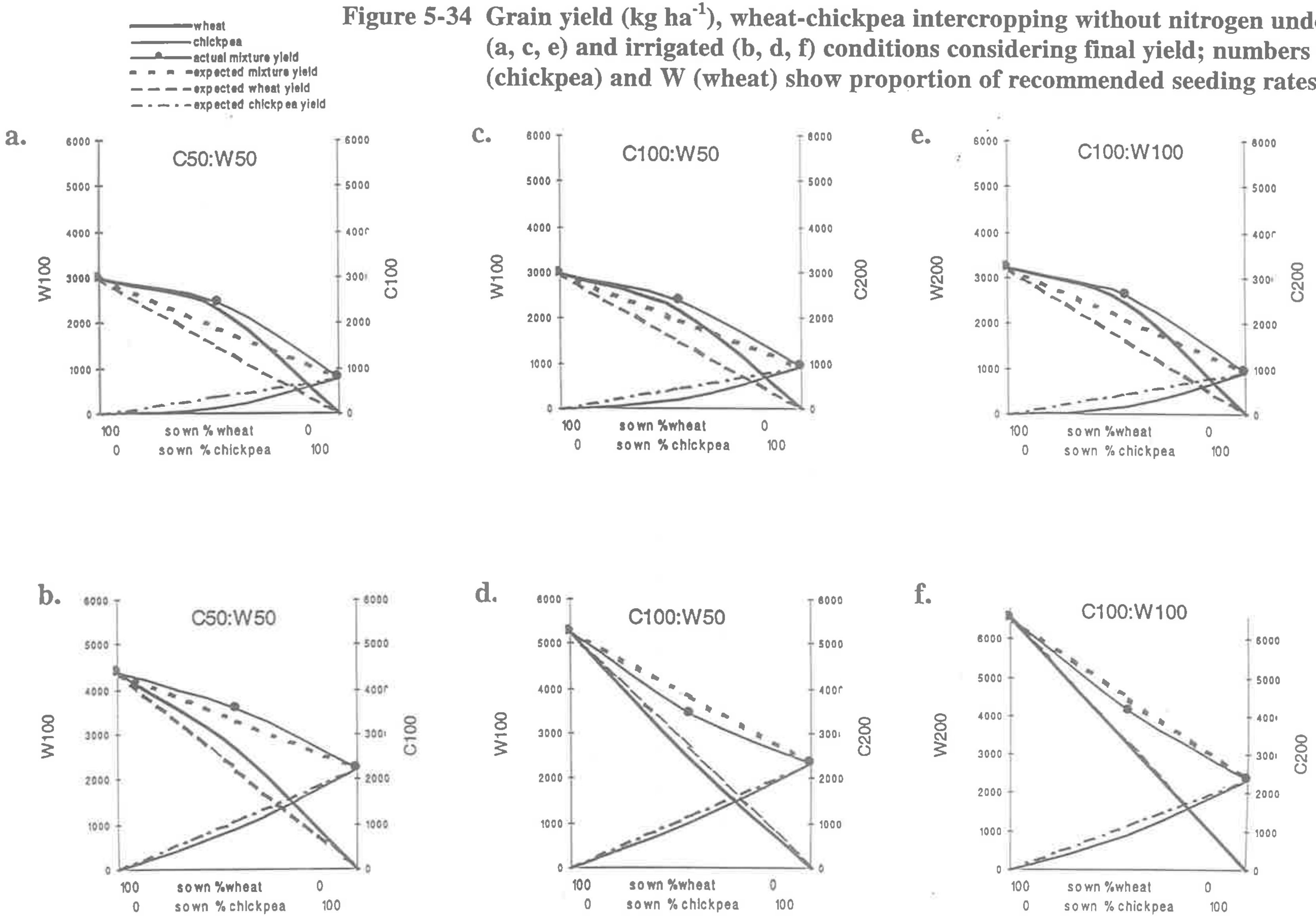
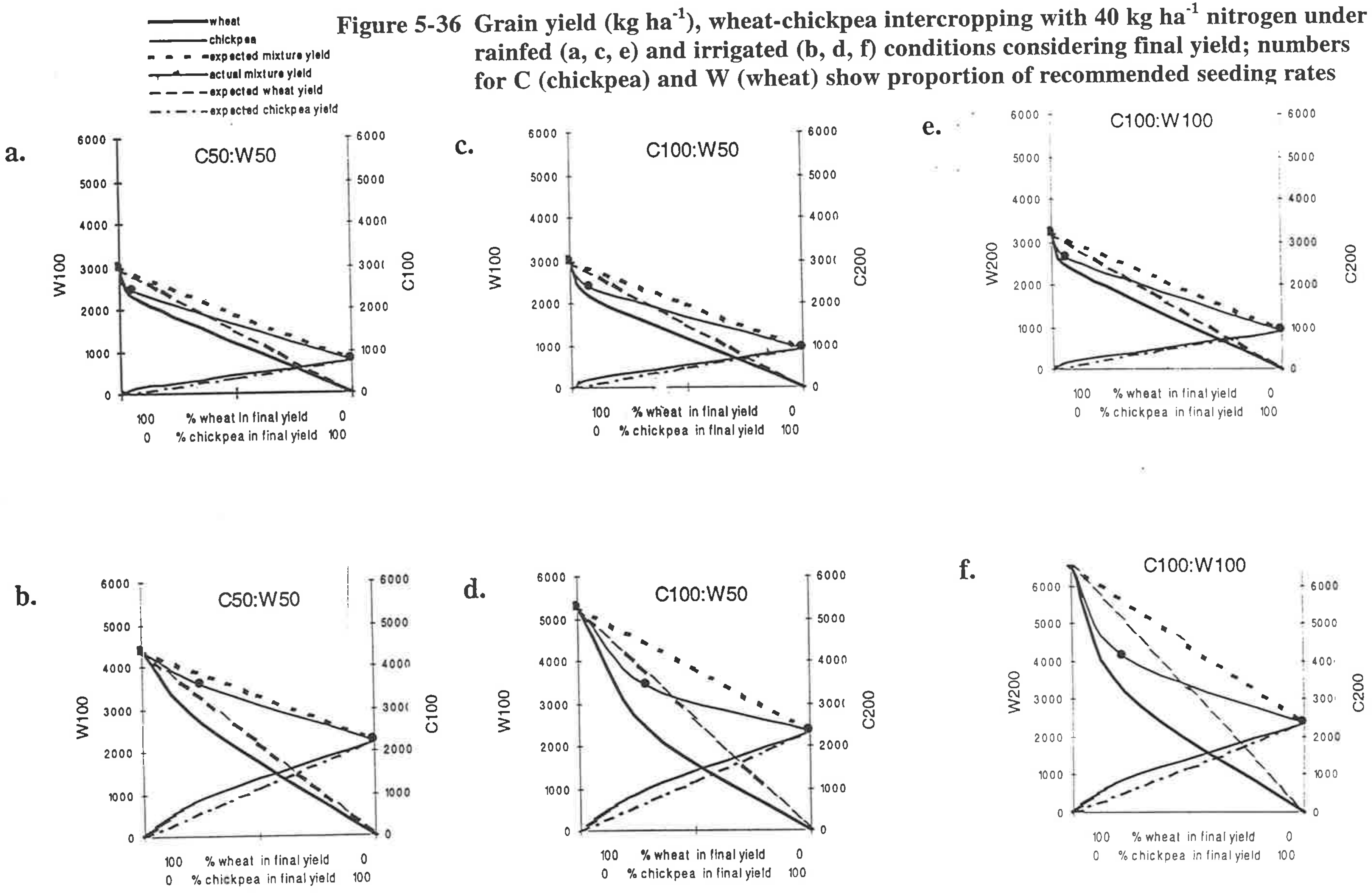


Figure 5-36 Grain yield (kg ha^{-1}), wheat-chickpea intercropping with 40 kg ha^{-1} nitrogen under rainfed (a, c, e) and irrigated (b, d, f) conditions considering final yield; numbers for C (chickpea) and W (wheat) show proportion of recommended seeding rates



5.5 Discussion

The aim of the experiment described in this chapter has been to determine whether agronomic manipulation and inputs such as varying plant density and row arrangement and application of nitrogen fertiliser and irrigation could improve the productivity of intercropping systems relative to that of sole crops. Such improvement is likely to be related to the reduction in competition and an increase in complementarity between intercrop components. Whether a substantial improvement in productivity is gained or not, quantification and understanding of competitive and complementarity relationships will assist in identifying further research and strategies for improving intercropping systems.

5.5.1 The effect of seeding rate

The effect of seeding rate on yield performance, competition and biological efficiency will be discussed in this section. Many researchers have shown that cereal yields are maintained over a wide range of spatial arrangement patterns and densities in intercrops (e.g. Rao, 1986; Ofori and Stern 1987a; Soetono and Puckridge, 1982). In this study wheat remained stable under different seeding rates. For instance, in the rainfed experiment which was conducted in the dry year of 1994 wheat had similar grain yields under different seeding rates in all intercropping systems (Figure 5-6). The same occurred in 1995 in both dryland and irrigated conditions (Figures 5-20 and 5-21). Moreover, under very dry conditions in 1994 intercropped wheat had similar amounts of grain yield to wheat in sole crops (Figure 5-6). In the late sown experiment with supplementary irrigation, in which some heat stress was experienced (1993), the yield of wheat in the C50:W50 treatment was similar to the sole crop yield (Figure 5-1). In the rainfed experiment of 1995, which was a normal rainfall year, wheat in mixtures produced about 73% of monoculture. This clearly shows that intercropped wheat under dryland conditions is capable of capturing and using available resources i.e. it was the superior competitor. However, in the same year but under irrigation wheat in mixtures produced only around 50% of monoculture. It seems that in harsher conditions wheat is more competitive and able to produce as much as sole crops. The mechanism for this yield plasticity is mainly through changes in yield components (Figure 5-10). Generally, the smaller the population of wheat, the greater the number of heads per plant and the number of grains per head, and the greater the grain weight per plant, which results in similar yields for different seeding rates.

In contrast, in all experiments under different seeding rates, the yield of chickpea was greater in monoculture than in all the mixtures (Figures 5-1, 5-7 and 5-22). However, seeding rates had an important effect on the yield of chickpea. In 1994, C100:W50 gave significantly higher chickpea yields than other chickpea seeding rates. The same trend, though not significant, occurred in 1995 when C100:W50 on both rainfed and irrigated sites had higher yields than other intercrops of chickpea (up to 25% and 15%, respectively). This suggests that the less the proportion of wheat and the greater the proportion of chickpea in an intercrop, the greater the grain yield of chickpea (Figure 5-13). Ofori (1986) also indicated that the yield and growth of a legume in mixtures decreases markedly when intercropped with high densities of a cereal.

Using bivariate analysis, it was evident that having a low density of wheat in mixture with a high portion of chickpea was beneficial under the dryland conditions of South Australia (Figure 5-13). Rees (1986) also indicated that in dry regions, having a strong rooting crop in the mixture (e.g. cereal) might, at a high density, lead to a large reduction in the productive yield of the other component (legume). For that reason in dry regions with unreliable rainfall intercropping having a lower density of cereal in intercropping may be slightly advantageous.

Ofori (1986) also indicated that the density of the cereal component determines the level of the combined mixture yield, whereas LER follows more the trend in yield of the legume component. Rao (1986) also believes that the characteristic of most cereals to show a wide plateau in their yield response to plant populations, enables a choice of a density that is less competitive with the other component while maintaining a higher potential yield. In this study a higher population of chickpea (C100) with a lower density of wheat (W50) seemed to be the most appropriate (Figure 5-13).

Kushawah and De (1987) observed results similar to the findings in this study, using a higher percentage of chickpea and a lower density of mustard as the non-legume intercrops. They found that numbers of primary and secondary branches and pods, seed yield per plant and 1000 grain weight increased in mustard but decreased in chickpea when intercropped, and they observed decreases in these traits with increasing plant density. For both species optimum plant density was lower when intercropped than when grown alone. The 34% mustard:66% chickpea mixture gave the greatest yield advantage. The reason for higher productivity in this cropping system was that chickpea in this mixture had the most nodules and the highest dry weight of nodule. This combination also had the highest green area index (GAI), removed more N from the soil, had better water use efficiency and caused less soil moisture depletion than the single crops.

There might also be a decrease in yield of both crops with increasing density of both crops. Chowdhury and Gliddon (1992) conducted a series of experiments in order to investigate the intra- and inter-specific complementarity between wheat and broad beans. Yields for wheat and beans decreased with increasing plant density. They concluded that this might be due to a considerable overlap in the resource zone for the two species.

A different result was seen by Yunusa (1989) who studied the effects of planting density and plant arrangement pattern on growth and yield of maize and soybeans in mixture. He found that a 67:67 mixture produced a greater total grain yield and LER than lower densities, by allowing better exploitation of available resources by the crops.

The present study also shows that the greater the chickpea population and the less the wheat population in intercrops, the more dry matter (DM) chickpea will produce. For example DM of wheat in mixtures with different seeding rate was similar in early growth stages, and towards the end of the season DM production in mixtures tended to be as high as in sole crops (Figure 5-16). However chickpea sole crops at any seeding rate showed much greater yields than chickpeas in intercrops at any seeding rate. At maturity, C100:W50 tended to produce more dry matter than the other intercropping seeding rates, while C50:W100 produced least.

The partitioning of assimilates was also measured by considering the Harvest Index (HI) results. For instance, in 1994 in experiment 2 (Figure 5-18), a slightly higher HI for wheat was seen in all seeding rates in mixtures compared to that of sole crops. This was another likely reason for the maintenance of the same level of yield in all seeding rates in 1994. For wheat the C50:W50 showed a higher HI than other seeding rates, while in chickpea a monoculture had the highest HI (C100). HI of chickpea in intercropping systems was less than 50% of the sole crop's value. Chickpea intercropped with high density wheat (C100:W100) had a significantly lower HI than when it was grown with low density wheat (W50:C50). The effect of intercropping on the HI of chickpea can be interpreted in relation to the fact that competition for water at the end of season created water stress, resulting in a decrease in partitioning of assimilate to seed. Rees (1986) reported that water stress at the end of the season resulted in decreased production of dry weight allocated to grain in a cowpea-sorghum intercrop in Nigeria. Generally in the present experiments, the higher the population of wheat, the greater the reduction of HI.

When the number of rows of wheat and chickpea remained constant in intercrops, the statistical analysis did not show any significant effect of seeding rates on LER under dryland conditions (Table 5-10 and Figure 5-25) or supplementary irrigation (Table 5-10). This was mainly because the changes in yield of one component of the mixture were compensated by a reverse change of the other component. Rao and Willey (1980) also indicated that while the proportional yields of intercrops might change over a limited range of seeding rates, the yield advantage of intercropping may not change much.

However, in some experiments reported in the present study, up to 18% was not significant (in 1993 with supplementary irrigation). Mandimba *et al.* (1993) have investigated the effect of different plant population in a maize-groundnut mixture. Due to a combination of poor and variable yields of groundnut, high yield of maize and standardisation by single crop value, any significant differences among the different cropping systems were not detected. This also may be a possible reason for the lack of differences in LER amongst different plant populations. However, in 1993 all of the seeding ratios were more efficient than sole crops at the ratio concerned. The LER values were also higher in comparison with the other experiments ranging from 7% to 25%. The results of diagrammatic illustrations also show a higher biological efficiency, whether based on sowing rate or final yield. The reason might be that, in this experiment, wheat was not as aggressive as in the other experiments. Thus, both crops complemented each other. The reason for this seems to be that the late sowing led to temperature and photoperiodic reactions, so that wheat flowered earlier and yielded less than average. This gave chickpea the chance to use resources more efficiently at the end of experiment.

In 1994 LERs of different seeding rates were close to 1. $LER_{biomass}$ values for this year were mostly more than 1 showing up to 12% more biological efficiency. These results support the theory of Harper (1977) that the weaker competitor in mixtures is more responsible for variation in LER than the dominant crop. The results of the present study also support Harper (1977) and Orofi (1986) as when the yield of chickpea was higher in mixture in the late sown experiment (Figure 5-1 and Table 5-2), the LER was higher in comparison with the rainfed experiment of 1994 in which the yield of chickpea in mixture was low (Figure 5-8 and Table 5-10). Islam *et al.* (1991) also investigated the effect of mixed cropping lentil with barley at different seeding rates. LER was highest with 100 lentils:30 barley. He indicated that the increase in the yield of the mixture might be due to a beneficial effect of lentil on barley.

The CR of wheat with respect to chickpea in 1993 ranged between 2.08 to 1.63 (Table 5-2). In 1994 the lowest competition was observed in C100:W50 and the highest in C50:W100 ranging between 14.2 to 69.7 (Table 5-10). In 1995 in dryland conditions for C100:W50 the CR was 2.82 (Figure 5-29). However the CR of C100:W50 was 0.92 under irrigated conditions (Figure 5-30), which indicates that for the only time in all the experimental situations in this study chickpea was slightly more aggressive than wheat. Therefore it seems that chickpea under irrigation is more competitive against wheat. This shows that competition for water was the main reason for the suppression of chickpea in mixture under dryland conditions.

In this study a higher population of chickpea (C100) with a lower density of wheat (W50) seemed to be the most appropriate of the arrangements tested in this study.

In this situation chickpea normally produced more grain yield than any other combination and competition in the mixture was less.

5.5.2 The effect of row arrangement

The row arrangement study was conducted in two ways. In 1994 the number of rows of chickpea and wheat were equal in each plot. The three arrangements were single alternate rows (SAR), double alternate rows (DAR) and mixed in a row (MIR). DAR produced greater grain yield (Figure 5-7), number of seeds and grain size (Figure 5-11) than SAR and MIR. In this situation the closer the chickpea plant is to the wheat plant, the lower its yield. In cereal-legume intercropping Ofori and Stern (1987a) indicated that the yield of the cereal component is usually less affected by densities and row spacing. This statement is supported by the results of the current study. Wheat performed very well in the mixtures under different row arrangements (Figure 5-5). This adaptation was achieved through changes in yield components in different situations. In all the different intercropped row arrangements, wheat produced up to 90% of the number of heads per area produced by the sole crop (Figure 5-9a). Moreover, the number of spikelets per head, number of grains per head and grain weight per head were higher for all the intercropping row arrangements (Figure 5-9). However, chickpea performed poorly. Generally chickpea in sole crops had much greater grain yield (Figure 5-7), number of seeds and 100 grain weight than in the different intercropping row arrangements.

Wheat DM production in early growth stages depended more on the population of the crops, but toward the end of the season there was a tendency towards less DM production when rows of wheat were further apart (Figure 5-15). For chickpea, DM production in DAR was higher than other intercropping arrangements especially toward the end of the season. At maturity, sole crops at all seeding rates showed much greater yields than intercrops at any seeding rate. This illustrates that the further apart the rows of chickpea are from wheat rows, the higher the DM of chickpea in the mixture.

In wheat the HI was similar in sole crops and intercrops (Figure 5-17). However, there was a tendency towards a higher HI in intercropping than sole crops. For chickpea, the closer the rows were to wheat in intercrops the lower the HI (Figure 5-17). Similarly, the higher the population of wheat compared to chickpea the greater the tendency towards a lower HI.

Row spacing also had an important effect on competitive relations. CR results (Table 5-9) showed that wheat mixed in a row with chickpea was 86 times more aggressive than chickpea, while in double alternate rows it was 13 times more competitive.

However, LER values of grain showed relatively less biological advantage in intercropping situations (Table 5-9). The LER for biomass was greater than 1 in all situations (up to 9% in DAR), showing a relatively greater biological efficiency for intercrops. This clearly shows that the closer wheat and chickpea are, the greater the competition; the yield of chickpea in mixture decreases and the the system is less productive. Therefore, DAR seems to be more appropriate for system productivity than other row arrangements (Figure 5-14). Similarly Cenpukde and Fukai (1992) demonstrated that planting of paired rows instead of single alternate rows of a cassava-legume intercrop, reduced competition. Putnam and Allan (1992) studied the mechanisms for overyielding in a sunflower-mustard intercrop and found that when sunflower and mustard were grown in a more intimate pattern of closely planted rows, competition between the species increased and LER values decreased by up to 43% compared to use of strip cropping patterns. DAR is probably easier to plant and manage than SAR.

These findings support Rao's (1986) statement that, "Generally, the dominant cereal has to be spaced wide enough (from legumes) to minimise the competition between species". In contrast, Andrews (1972) stated that to obtain maximum complementary effects, crops should be planted as close as possible. This seems to be more applicable in cases where an intercrop is used as a physical support for the other intercrop such as for pea-cereal intercropping, or in mixtures where there is a transfer of N from an adjacent legume to a non-legume.

A further experiment (1995) was undertaken to establish if adding further rows of chickpea improved the productivity of the intercropping system. Here, the LER tended to decrease when adding more rows in both dry and wet conditions and the 2-2 arrangement performance was better than the other situations (i.e. 3-2 and 4-2) (Figure 5-27). CR decreased when adding rows of chickpea, due to the smaller amount of wheat in the canopy (Figures 5-29 and 5-30). However the use of 2-2 arrangements was unable to improve the total efficiency of the system. Ali (1993) also conducted some experiments on wheat-chickpea intercropping under late-sown conditions. Of the three populations tested (2-2, 2-1 and 3-1 row ratios of wheat:chickpea), the 2-2 row ratio allowed more light interception and transmission to the lower canopy and gave significantly higher yield and LER than the other treatments. In contrast Sharma *et al.* (1987) investigated the potential of wheat and chickpea in sole and intercrops. The recommended seed rates of wheat and chickpea were mixed in 1:1, 2:1, 3:1 and 5:1 ratios. The highest values for LER were obtained when wheat and chickpea seeds were mixed in 5:1 ratio. This was because chickpea yield remained constant in all the mixtures, giving a high value to LER. Thus advantageous LER values can be obtained from various mixtures and row arrangements, some favouring wheat and others chickpea. The desirable formula could come down to the grower's aim for more production of one species rather than the other.

The results of the present study support the proposition that the arrangement of rows has a direct effect on absorption of resources by the component crops. Ofori and Stern (1987a) indicated that row arrangement, in contrast to manipulation of plant population, improves the amount of light transmitted to the lower legume canopy. Morris and Garrity (1993b) indicated that "Reducing the space for the dominant crop, beside limiting their access to solar radiation, will reduce the size of their soil moisture and nutrient pool, with consequent limitations on their competitive ability over that of the understorey crop." It appears that DAR, by providing less competition in comparison with SAR and MIR, provides a better living habitat for chickpea. In dryland situations also, because of the very competetive root system of wheat under rainfed conditions, when crops are mixed in rows wheat collects the majority of the limiting resources and can completely suppress chickpea in mixtures. Widening the rows of chickpea under both wet and dry conditions results in less interaction with wheat and although chickpea performs better this results in a decrease in the productivity of the system as a whole.

5.5.3 The effect of moisture environments and nitrogen

The irrigated environment gave a significant increase in yields of sole and intercrops compared with rainfed conditions (Figures 5-21 and 5-23), and application of nitrogen fertiliser increased the yield of wheat only under irrigated conditions (Figure 5-21). Singh and Singh (1991) in experiments on grain yield and water use by crops in linseed based intercropping systems as influenced by irrigation, found that irrigation increased grain yield appreciably. Similarly in non-limiting water environments of northern Thailand, Fujita *et al.* (1992) reported that in a maize-rice bean mixture, application of N fertiliser improved the DM, grain yield and N yield of intercrops. In the present study for irrigated treatments the effect of densities, nitrogen levels and their interaction was significant for wheat. Generally higher densities of wheat in mixtures showed a greater response to N fertiliser both in sole crop and intercrops.

In both environments the effect of N on the yield of chickpea was not significant, and no interaction was detected between N and different densities under rainfed conditions. Davis and Woolley (1986) also reported a decrease in the yield of chickpea with application of N, due to increased competition by the cereal.

In dryland farming wheat, as the dominant component of any mixture, absorbed most of the nitrogen in the system. Also, possibly because of adverse effects of nitrogen on the yield of chickpea, there was a reduction in the grain yield of chickpea, resulting in higher aggressivity of wheat, or vice versa the positive influence of nitrogen on wheat enabled it to be more aggressive and so depress chickpea yield. Therefore under rainfed conditions nitrogen increased the CR (Figure 5-32). However, with irrigation there was a tendency for a decline in CR of wheat with N application. When water was not a limiting factor chickpea in mixture had better growth and it was more competitive resulting in lower CR in mixtures. Schultz *et al.* (1987) have also reported that irrigation relieves the effect of over-crowding in mixtures.

Fukai and Trenbath (1993) reported that in most cases intercropping efficiency is greater under low rather than high fertility conditions. In the experiments reported here application of fertiliser also showed a negative effect on LER (Figure 5-28). This was probably because under irrigation the sole crops of wheat and chickpea benefited more than their mixtures, in comparison with their performance in the dryland situation. Similarly Ofori and Stern (1987a) studied the influence of applied N in several studies and found that intercrop cereal with N application increased yield, but that the yield of the legume decreased, and they showed that N application did not improve the LER. Cowell *et al.* (1989) studied the response of pea and lentil to intercropping and N application at five locations throughout Saskatchewan in 1987. At each site one of the following combinations was tested: lentil and flax, pea and rape, pea and yellow mustard or pea and oats. All treatments received 10, 30 or 50 kg N ha^{-1} as urea. LER tended to be lower under application of nitrogen fertiliser. Conversely, in a maize-soybean intercropping system under humid subtropical conditions, Clement *et al.* (1992) found higher LER values with the application of higher levels of N. They indicated that this higher LER was due to complementarity of resource use. Putnam and Allan (1992) studied sunflower-mustard intercrops in 1988 and found that when the distribution of N-nitrite for mixed sunflower was less than its monoculture, sunflower was suppressed in mixture. LER of the mixture with 112 kg N ha^{-1} was higher (0.90) than when there was no N fertiliser supply to crops (0.82). However, in 1989 when both sole crops and their intercrops had similar distribution of N-nitrite, the LER of nil N was higher (1.08) than with application of 112 kg N ha^{-1}.

The effect of different wet and dry environments on LER was non-significant, showing that irrigation although improving the competitive ability of chickpea and improving its yield, was not successful in improving the productivity of the intercropping system. Willey *et al.* (1993) also indicated that under five levels of irrigation in sorghum-groundnut mixtures, the lower the irrigation the higher the LER. Baker and Norman (1975) said when water is the most limiting factor, intercrops may offer a temporal and spatial advantage in water use. Mandal *et al.* (1986) experimented with wheat and chickpea under four moisture regimes and observed that wheat-chickpea intercrops were most efficient with one irrigation while LER beyond two irrigations decreased, and the lowest LER was observed with 4 irrigations.

5.6 Summary and conclusions

Experiment 1 clearly showed that intercropping of wheat and chickpea might improve the biological efficiency of the cropping system. This experiment also confirmed that manipulation of seeding rates might have an effect on the production of the component crops. For instance, when chickpea had a lower density, wheat had a higher grain yield resulting in a LER of 1.25 (the highest in the study). However, that study was conducted under atypical seasonal conditions and thus there was a need for further experiments. In the second experiment, wheat was relatively stable in performance across the different seeding rates. Here, chickpea yielded much less in mixture than in sole crop, and the highest yield for chickpea was in the C100:W50 mixture. A lower CR for wheat with respect to chickpea, and similar LER_{grain} and $LER_{biomass}$ were the reasons that the C100:W50 seeding rate was chosen for the more detailed studies of the subsequent experiments. The double alternate row (DAR) (2-2) row arrangement showed a relatively better yield performance than the other row arrangements. A similar LER to the other row arrangements was obtained, with less competition from wheat in respect to chickpea, thus DAR was the preferred row arrangement. In the third experiment the effects of widening the rows of chickpea, seeding rates and N fertiliser application were examined under irrigation and rainfed conditions. Irrigation improved the yield of sole and intercrops, and also increased the effect of N fertiliser and seeding rates on the yield of wheat. The 2-2 row arrangement was preferred to 3-2 and 4-2. However, irrigation and the application of N fertiliser either did not improve, or decreased, the efficiency of the system, in comparison with rainfed conditions without N application.

It can be concluded that a higher density of chickpea with a lower density of wheat in a mixture can improve the productivity of the system. The DAR arrangement is the most appropriate row arrangement for the mixture. It can be concluded also that intercropping might be more successful in low input situations (less moisture and N). However, in most cases LER values were close to 1, showing neither advantage nor disadvantage of intercropping compared to sole crops. However there was no information about the effect of such intercrops on stored water and nitrogen, which might contribute to improvements in the productivity of subsequent crops; in other words, there may be a possibility of an indirect increase in the productivity of the whole rotation over more than one year. Moreover, understanding the dynamics of radiant energy, soil water and nutrition of intercropping systems is necessary to understand and possibly improve management strategies and productivity of the cropping rotations (Midmore, 1993). Therefore, a study was undertaken on the effect of intercropping on the capture and utilisation of resources, and this is presented in the next chapter.

6. CAPTURE AND USE OF BIOPHYSICAL RESOURCES BY WHEAT AND CHICKPEA IN SOLE AND INTERCROPS

6.1 Introduction

Increase in total output from intercropping is often associated with better capture and use of biophysical resources by a community of mixed species compared to pure stands of a single species. The most important of these biophysical resources are radiation, soil water and nutrients. Improvements in the use of biophysical resources result from either (a) an increase in the total amount of the resources utilised by all the species in the mixture, or (b) temporal/spatial differences in the use of resources by the component species, or (c) one or more of the species may be physiologically more efficient in the use of resources captured (Keating and Carberry, 1993). Thus, understanding the dynamics of radiant energy, soil water and soil nutrients in intercropping systems will enhance the development of improved management strategies to increase the productivity of these systems (Midmore, 1993).

Most researchers of intercropping have used final yields, and sometimes total dry matter produced, to assess the benefit of the system. Rarely is any consideration given to radiation, water and nutrient use and how they affect productivity (Francis, 1989). Likewise, in the previous chapter the effect of species and varietal selection and the impact of some agronomic practices on the productivity of the intercropping system were studied, with little emphasis on resource capture and use. Studies which only consider crop yield, with no exploration of the physiological basis for the yield obtained, do not provide any insight into the processes that determine intercrop productivity, which is needed for designing improved management practices (Fukai and Trenbath, 1993). There have been very few intercropping experiments under the dryland conditions of South Australia (Mayfield, pers. comm., 1993), and none has examined resource capture and use in intercropping systems. In this chapter, the yield of wheat and chickpea in intercrop situations is compared to sole crops on the basis of radiant energy, soil water and soil N dynamics. The objectives were to (1) quantify the use of biophysical resources in sole crops and mixtures, (2) partition the use of the resources between wheat and chickpea in the mixtures, and (3) further evaluate the efficiency of mixed cropping in the use of biophysical resources and in terms of land equivalent ratio (LER) and competition ratio.

6.2 Materials and methods

Treatments, field preparation and statistical analysis were detailed in Section 5.4. Measurements of soil water, radiation interception and N uptake were made on three dryland cropping systems: W100, C200 and C100:W50 in double alternate rows.

6.2.1 Measurements

To evaluate the role of biophysical resources in the productivity of wheat and chickpea mixtures, soil water, radiation interception and nitrogen (N) uptake were measured in the above selected treatments of the experiments described in Chapter 5.

Soil water storage. This measurement was made on unirrigated (rainfed) plots. Soil water stored in the 1.25 m depth root zone was determined using a neutron moisture meter (Campbell Pacific Nuclear model 503, CA, USA). Steel access tubes of 37.5 mm internal diameter and 1.5 m length were installed in an inter-row space near the middle of each plot, leaving 0.15 m of the tube protruding above the soil surface. Measurements of soil water were made at depths of 0.2, 0.4, 0.6, 0.8, 1 and 1.25 m beginning on 9 September (wheat tillering stage), and repeated at approximately fortnightly intervals. The water in the top 0.2 m of the soil profile was measured by the gravimetric method. Soil water at the start of the season was obtained from measurements taken in an adjoining paddock which had a similar cropping history as the paddock used for the current study. The fraction of available soil water (FAW) was calculated as given by Yunusa *et al.* (1992).

The neutron meter was calibrated at the site gravimetrically using soil cores extracted near selected access tubes. The cores were sectioned into appropriate depth intervals and the samples dried at 105°C for 48 hours. The gravimetric moisture content was calculated from the difference between the wet (original) and dry weights, and was converted to volumetric water content (θ) by multiplying with bulk density which averaged 1.3 in the top 0.4m of the profile and 1.65 in the lower depth.

The crop water use or evapotranspiration (ET) was calculated from the changes in the storage of soil water and rainfall data using Equation 6-2. Drainage and runoff were considered negligible on this site (C. Hignett, pers. comm., 1996) and were omitted in the calculation of ET:

$$\Delta S = (P + I) - (R + D + ET)$$

Equation 6-1

where ΔS is change in soil moisture storage; P is precipitation; I is irrigation; R is runoff; D is drainage and ET is evapotranspiration. Both R and D are often negligible in most agricultural situations in semi-arid regions and so eliminated from equation 6-1 (Hillel, 1971).

The ET was partitioned into transpiration (T) and soil evaporation in two stages following the procedure used by Yunusa *et al.* (1994). During the first stage, when rainfall was frequent and available soil water was relatively high, T was calculated with the following formula:

$$T = E_p\,(e^{k.\mathrm{GAI}})$$

Equation 6-2

Where E_p is potential evapotranspiration according to Penman-Monteith's equation (Monteith and Unsworth, 1990), *k* is the radiation extinction coefficient and GAI is green area index, both described below. Equation 6-2 was used until the fraction of available soil water fell to 0.35. The FAW of 0.35 was found to be the critical stage below which T in wheat began to be restricted on a red brown earth (Yunusa *et al.*, 1994). A similar critical FAW value was found for chickpea (Siddique and Sedgley, 1985). Hence, T for the three cropping systems during the terminal phase was taken as a function of soil water storage (SW) according to Yunusa *et al.* (1994):

$$T = (0.014 + 2.25\ SW)/E_p$$

Equation 6-3

Soil evaporation (E_s) was obtained as the difference between ET and T:

$$E_s = ET - T$$

Equation 6-4

Green area index (GAI). The ratio of green surface area produced by the crops to the land area (GAI) was determined from sub-samples containing six plants of wheat and three plants of chickpea. These were taken from a 0.8 m^2 quadrat in each plot at 41, 73, 86, 95 and 115 days after sowing (DAS). These dates coincided with early tillering, jointing, late booting, flowering and grain filling in wheat. The green areas of the sampled plants were measured with a planimeter (Patten Electroplate Electronic, model EP711, SA, Australia).

Canopy radiation interception (P_i). A sunfleck ceptometer (Decagon Devices Inc., type CEP, WA, USA) was used to measure the photosynthetically active radiation (400-700 *nm*) (PAR) intercepted by the canopy. This was achieved by taking PAR readings above and below the crop canopy. The 'above canopy' measurements (F_a) were taken at approximately 1.5 m above the soil surface, and the 'below canopy' measurement was the mean of four separate readings (F_b) taken at ground level, beneath the canopy, across the entire plot width. All measurements were taken between 11 a.m. and 1 p.m. on cloudless days, at 53, 68, 80, 98, 110 and 121 days after sowing (DAS) on unirrigated plots, and only once, at flowering, on the irrigated plots. The fraction of PAR intercepted (F_i) was obtained as:

$$P_i = 1 - (P_b/P_a)$$

Equation 6-5

The extinction coefficient (k) of the canopies was calculated by regressing $ln(1-P_i)$ against GAI (Monteith, 1965). The slopes of the regressions were taken as k without consideration of the arithmetic sign.

The relationship between area of leaves produced and radiation interception by the crop canopy is expressed by Monteith (1965) as:

$$P_i = 1\text{-exp } (-k.\text{GAI})$$

Equation 6-6

where P_i is the fraction of radiation intercepted, while GAI is leaf area index produced by the crop canopy, and k is the extinction coefficient. Generally, the higher the k the more efficient is the canopy in capturing solar radiation. In intercropping, the fraction of radiation intercepted by the respective intercrops could therefore be obtained from their respective GAI in the mixture and their k, also accounting for height differences where applicable (Wallace *et al.*, 1990 and Wallace, 1991). A mixture containing wheat and chickpea can be represented as:

$$P_w + P_c = 1\text{-exp } [(-k_w \text{ . GAI}_w + - k_c \text{ . GAI}_c)]$$

Equation 6-7

In which subscripts w and c refer to wheat and chickpea respectively.

The quantity of PAR intercepted by the crop canopy was obtained as the product of P_i and the incident PAR radiation. The PAR was taken as half of the incidentr solar radiation.

Dry matter. Above ground dry matter produced by the crop was measured six times by taking two random quadrat (0.5 x 8m) samples from each plot at 41, 73, 86, 95, 115 and 126 DAS from the unirrigated plots. This measurement was made only at 95 and 126 DAS for the irrigated plots.

Yield components. Yield components were measured just before harvest on mature plants taken randomly from two quadrats (0.5 x 8m) in each plot. For wheat the number of heads m^{-2}, number of heads per plant, number of spikelets per head, number of grains per stem and 1000 grain weight were measured. For chickpea the numbers of seeds m^{-2}, number of seeds per plant, weight of the seed per plant, and 100 grain weight were determined.

Water use efficiency for above-ground dry matter (DM) production was obtained as DM/ET (kg per ha per mm); similar calculations were made based on grain yield to estimate grain water use efficiency (WUE_{grain}) or grain yield/ET (kg ha^{-1} mm^{-1}). Radiation use efficiency (RUE) was also determined (Monteith, 1977):

$$RUE = \Delta DM / PAR_i$$

Equation 6-8

where ΔDM is change in dry matter (g) produced, and PAR_i is photosynthetically active radiation intercepted (MJ per m^2) by the canopy during that period.

Plant N content. N contents of seed were determined for both irrigated and unirrigated treatments, using a nitrogen analyser (Leco CN-2000, Leco Corporation, MI, U.S.A.). The samples were collected at flowering and harvest.

^{15}N study. An unconfined microplot 1m x 1m was marked out of each plot. The equivalent of 40 kg ha^{-1} as ^{15}N ammonium sulfate (10 atom % excess ^{15}N) was carefully watered onto each microplot at the early tillering stage of wheat. Ammonium sulfate was applied at the same rate to the remainder of the plot. Natural abundance measurements were made on plots not receiving N fertiliser. Samples (3 plants) were randomly taken from the marked area at flowering time. Grain samples were also taken. The analysis were carried out by an automatic nitrogen and carbon analyser linked to a mass spectrometer (ANCA-MS) (2020, Euro Scientific, Crewe, UK).

The following formula was used to calculate the percentage of shoot nitrogen derived from the atmosphere (Peoples *et al.*, 1989):

$$\%\text{Ndfa} = \frac{\delta^{15}\text{N reference plant} - \delta^{15}\text{N legume}}{\delta^{15}\text{N reference plant} - \text{B}} \times 100$$

Equation 6-9

Where Ndfa is the percentage of plant nitrogen derived from the atmosphere, B is a measure of the isotopic fractionation which can occur during N_2 fixation which for chickpea has been quoted as 1.34 (Unkovich, pers. comm., 1999), and $\delta^{15}N$ = natural abundance of ^{15}N isotope expressed as a delta (per mil) value. Sole crop wheat was used as the reference plant.

Using simple isotope dilution procedures N transfer from the legume to the non-legume was calculated (Senaratne and Ratnasinghe, 1993):

$$\%\text{ of N transfered to wheat in mixture} = 100 - \frac{\delta^{15}\text{N sole crop wheat}}{\delta^{15}\text{N the mixed crop}} \times 100$$

Equation 6-10

Nitrogen fertiliser use efficiency (N-FUE) was calculated using the following formula:

$$\%\text{N-FUE} = 100 \times \frac{\text{atom \% excess } ^{15}\text{N plant}}{\text{atom \% excess } ^{15}\text{N fertiliser}}$$

Equation 6-11

Weather variables. Daily weather data on minimum and maximum temperature, solar radiation, humidity, wind direction and speed and rainfall were recorded at a nearby weather station. E_p and vapour pressure deficit were calculated daily from the weather data following the procedures of (Monteith and Unsworth, 1990).

6.3 Results

6.3.1 Crop growth and yield

Dry matter (DM) production. The DM produced per unit area during the season is shown in Figure 6-1a and b. Sole chickpea produced significantly less dry matter than wheat (P<0.05) throughout the season. The combined dry matter produced by both wheat and chickpea in mixture was similar to that produced by sole wheat throughout the season (Figure 6-1a).

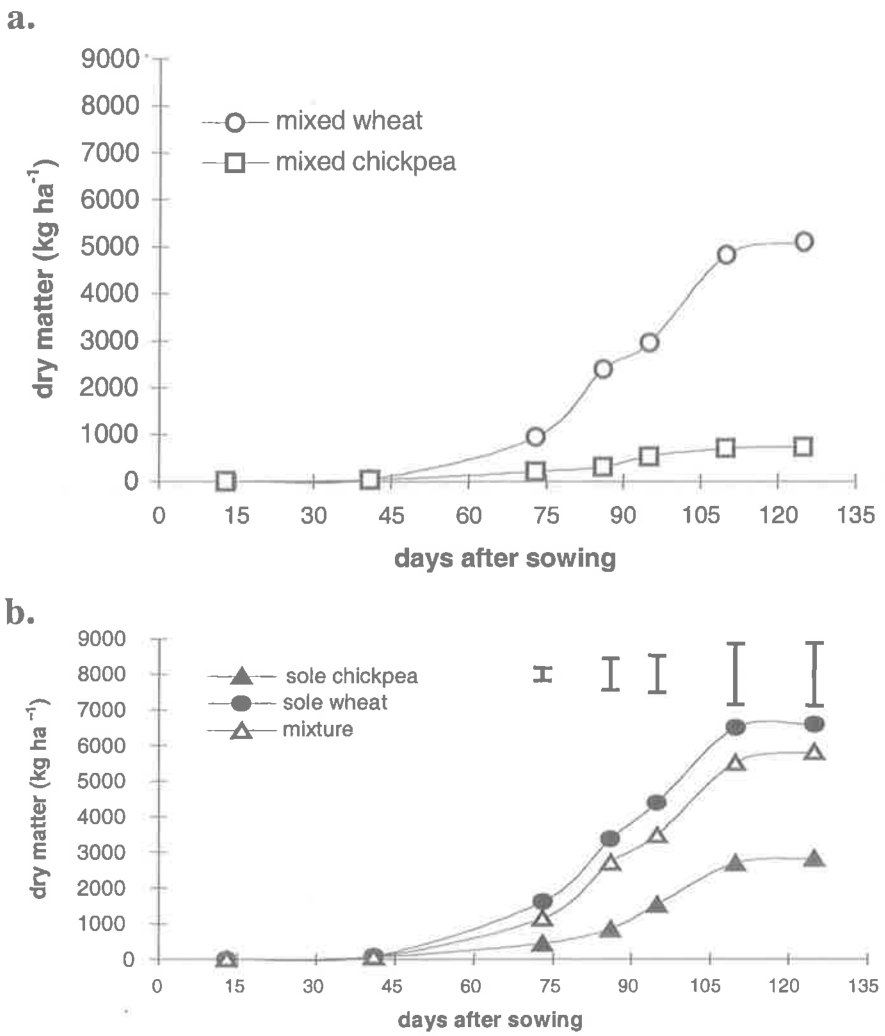


Figure 6-1 **Cumulative dry matter (kg ha^{-1}) for (a) chickpea and wheat in their sole crops and their combined yield in mixture, and (b) wheat and chickpea in mixtures. The vertical bars indicate LSD values (P=0.05)**

Chickpea in mixtures performed poorly in terms of DM produced compared to the sole crop. At 41 DAS chickpea DM in the mixture (Figure 6-1) averaged 55% less than in its sole crop, but this difference increased to 74% later in the growing season. Wheat DM produced in the mixture at the beginning of season was about 50% of that in the sole crop, but at the end of the season DM for the sole wheat was only 22% greater than for wheat in the mixture.

Logistic curves were fitted to these DM data (Figure 6-1b), and the parameters of the curves are presented in Table 6-1.

Table 6-1 Parameters for fitted logistic curves relating days after sowing with dry matter from Figure 6-1. The general equation is of the form: C/(1 + exp (-B/D (X-M)))

Parameters and their standard errors	Chickpea in sole crop	Wheat in sole crop	Chickpea in mixed crop	Wheat in mixed crop	Mixed crop
M	94.9	87.5	87.8	91.2	90.7
SE	1.6	1.0	2.4	1.9	1.4
C	3027	6972	771	5449	6211
SE	130	183	46.3	272	280
B	70.25	144.57	15.18	108.20	123.80
SE	6.28	9.79	2.17	11.0	9.16
D	126.7	123.0	125.2	128.2	127.7
SE	5.2	3.7	8.6	6.7	4.8
R^2 (%)	99.6	99.8	98.8	99.4	99.7

M = days after sowing required for crop to reach their maximum growth; C = maximum dry matter production (kg ha^{-1}); B = maximum growth rate rate (kg ha^{-1} d^{-1}); D = estimated duration of growth; X = days after sowing; SE = standard error of the parameters

Chickpea in the mixture had a low rate of DM production compared to sole wheat and the mixtures. The maximum rate of growth for chickpea in the mixture was 15 kg per ha per day, and the duration of growth was 125 days. Chickpea sole crop had higher growth rates than in mixture. The maximum growth rate for sole chickpea was about five times greater than that of chickpea in the mixture. Maximum growth rate for wheat in the mixture was 75% that of sole wheat. Wheat in mixture had five days longer growth duration than sole wheat. The maximum growth rate for the mixture was 1.75 times greater than that for sole chickpea, but only 88.5% of that for sole wheat. The duration of growth for the mixture was two days longer than for the sole chickpea, and five days more than for sole wheat.

Green area index (GAI). Sole wheat generally had significantly higher GAI than either sole chickpea or the intercrops (P<0.05) until after flowering. During the post-flowering period GAI for sole wheat fell rapidly and was significantly lower (P<0.05) than that for chickpea, intercrop wheat and the mixture (Figure 6-2). Chickpea in sole crop and in the mixture had a slower but more sustained increase in GAI than wheat, while wheat in sole and in mixed crops intercrop had a rapid decline in GAI towards the end of the growing season (Figure 6-2).

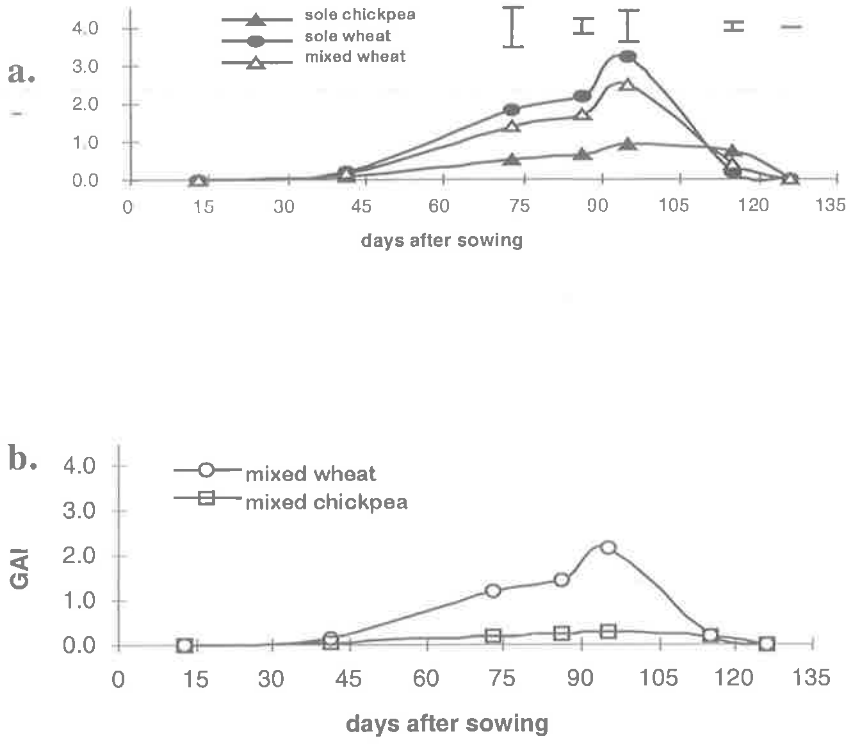


Figure 6-2 **Green area index (GAI) produced by (a) sole wheat, sole chickpea and their mixtures and (b) by wheat and chickpea in mixtures; bars indicate LSD (P=0.05) values**

Grain yield. The grain yield for wheat and chickpea in mixture were significantly lower than for sole wheat and for sole chickpea (Figure 6-3). The grain yields were in the order wheat>mixed wheat>sole chickpea>mixed chickpea. The yield of mixed wheat was reduced by 30% in mixture, and that of chickpea by 74% when grown in mixture with wheat.

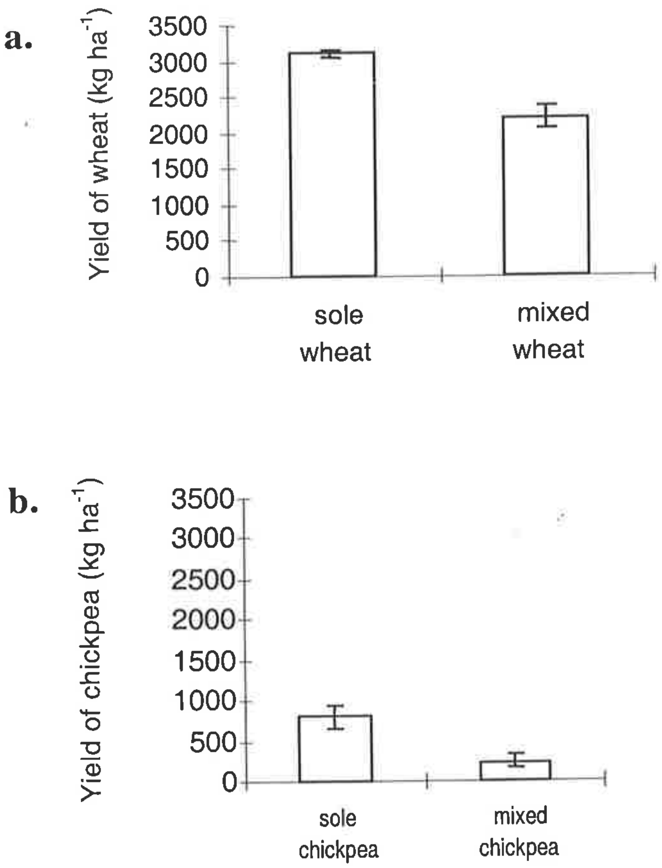


Figure 6-3 Grain yield of (a) wheat and (b) chickpea in sole and intercropping; error bars indicate the standard error of mean

6.3.2 Use of biophysical resources in intercropping

6.3.2.1 Radiation interception and use

The fraction of PAR intercepted by the plant canopy (P_i) during the season is shown in Figure 6-4. P_i was similar for all the treatments early in season up to

53 DAS (P = 0.05). Between 60 and 90 DAS (tillering stage of wheat) the highest P_i was observed in sole wheat, and the lowest in the sole chickpea. However, from 100 DAS (wheat flowering) onwards, P_i was similar for the three cropping systems (P<0.05).

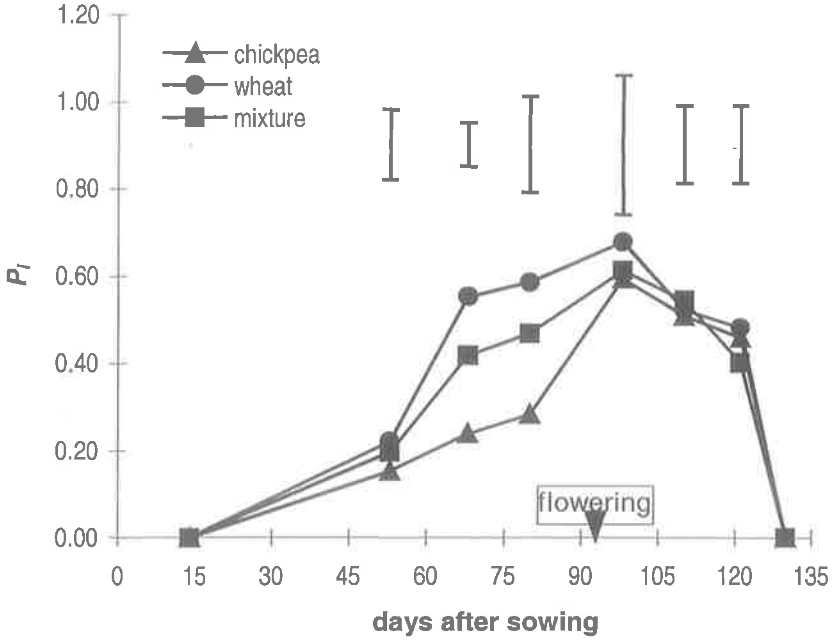


Figure 6-4 **The fraction of PAR intercepted *(Pi)* by wheat and chickpea in sole crops and by the mixed crop; bars indicate LSD values, upturned arrow indicates time of flowering of wheat and chickpea**

The data in Figure 6-2 and Figure 6-4 were used to determine the extinction coefficient (*k*) for the canopies produced by the various cropping systems. This was achieved by regressing *ln* (1-P_i) against GAI (Figure 6-5). Sole chickpea produced a *k* of 0.85 compared to about 0.4 for both sole wheat and the mixed crops.

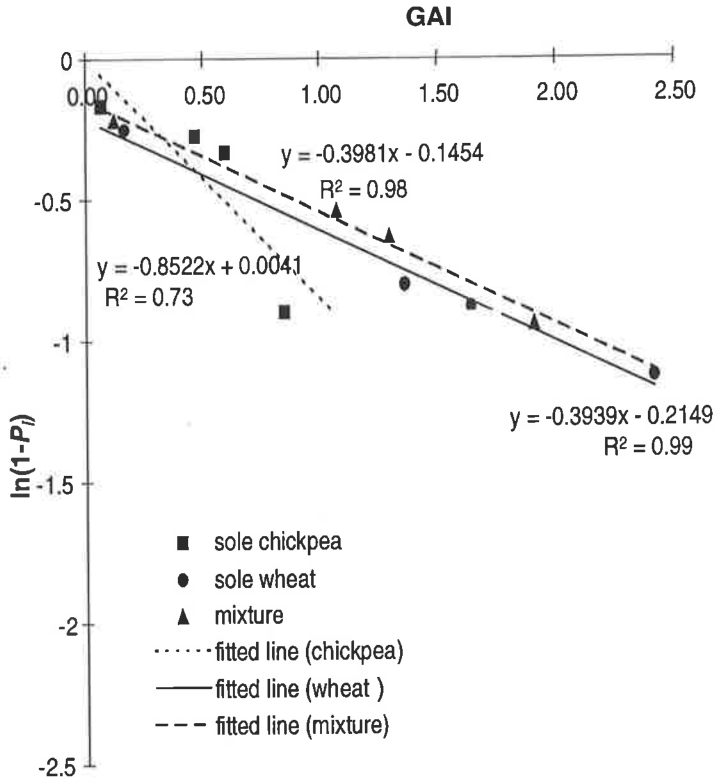


Figure 6-5 **Regression of ln(1-P_i) on corresponding GAI for the three cropping systems of wheat and chickpea. The slopes of the regressions were taken as the extinction coefficient (k)**

The amount of energy intercepted at all measurement dates was significantly higher for sole wheat than for the other cropping systems ($P<0.05$) (Figure 6-6a). At the end of the season total PAR intercepted was highest for sole wheat and least for sole chickpea. The quantity of PAR intercepted by wheat and chickpea in the mixture (Figure 6-6b) was estimated using their respective GAI values measured in the mixture and k values calculated for their sole crops, using Equation 6-8. Wheat intercepted greater PAR than chickpea in the mixed crop (Figure 6-6a). The total PAR intercepted in the mixed crop by chickpea was only 40% that of wheat during the entire season.

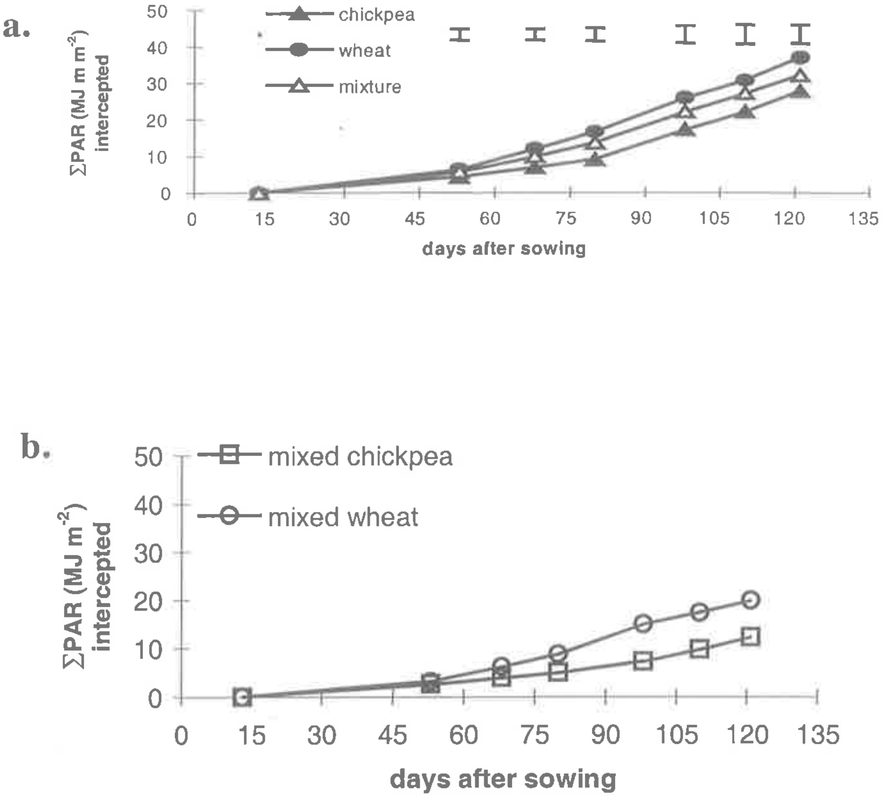


Figure 6-6 **Cumulative PAR intercepted by (a) sole wheat, sole chickpea and mixed crop, and by (b) wheat and by chickpea in mixed crop. The bars indicate the LSD values**

Radiation use efficiency (RUE). RUE for wheat grain production (RUE$_{grain}$) was similar to that of the mixture (P=0.05) and higher than that for sole chickpea (P<0.05) (Table 6-2).

In the mixed crop, wheat had higher RUE for total above-ground dry matter production (RUE$_{biomass}$) than chickpea. Overall, the RUE$_{biomass}$ values were in the order of wheat in mixture>mixed crop=wheat in sole crop>chickpea in sole crop>chickpea in mixture. The differences in RUE$_{grain}$ between the cropping systems followed a similar pattern to those in RUE$_{biomass.}$ The least efficient crop in using radiant energy was chickpea in both sole and mixed cropping systems (Table 6-2).

Table 6-2 **Radiation use efficiency (g MJ $^{-1}$ m^{-2}) for grain (RUE_{grain}) and for above-ground DM ($RUE_{biomass}$) yields for wheat and chickpea in sole and mixed crops. Analysis of variance was not performed on the data for chickpea in mixed crop and wheat in mixed crop**

Cropping system	RUE_{grain}	$RUE_{biomass}$
Sole chickpea	0.25b	0.87b
Sole wheat	0.73a	1.42a
Mixture	0.66a	1.59a
Chickpea in mixed crop	0.17	0.52
Wheat in mixed crop	0.95	2.43

Means with different letters are significantly different at (0.05%) HSD. The partitioning of RUE in the mixture was based on Equations 6-7 and 6-8

6.3.2.2 Soil water and evapotranspiration

Soil moisture. The volumetric moisture content (θ) in soil profiles at early tillering (53 DAS) was similar for the three cropping systems (Figure 6-7a). At this time the top 0.1 m of the profile was dry, averaging 10% moisture content. Below this depth, the soil moisture was approximately 30% at all depths down to 1.0 m, but increased to 35% at a depth of 1.4 m. On later dates, sole chickpea had the wettest profile while sole wheat had the driest. The differences in soil moisture for these treatments were especially evident between 0.3 to 0.8m depth. In this zone, the difference in θ between sole wheat and sole chickpea averaged 10% at 73 DAS (Figure 6-7b). This difference increased to a maximum of 15% at 103 DAS (Figure 6-7d), when wheat attained anthesis. Generally, θ between 0.2 and 1.2 m depths was always in the order sole chickpea>mixed crop>sole wheat. At 1.4 m depth, θ was not significantly affected by cropping systems throughout the season, probably because this is below the rooting depth of wheat and chickpea. At 116 DAS, the end of the season, chickpea had a wetter soil profile, or more unused water, than the other two treatments (Figure 6-7d).

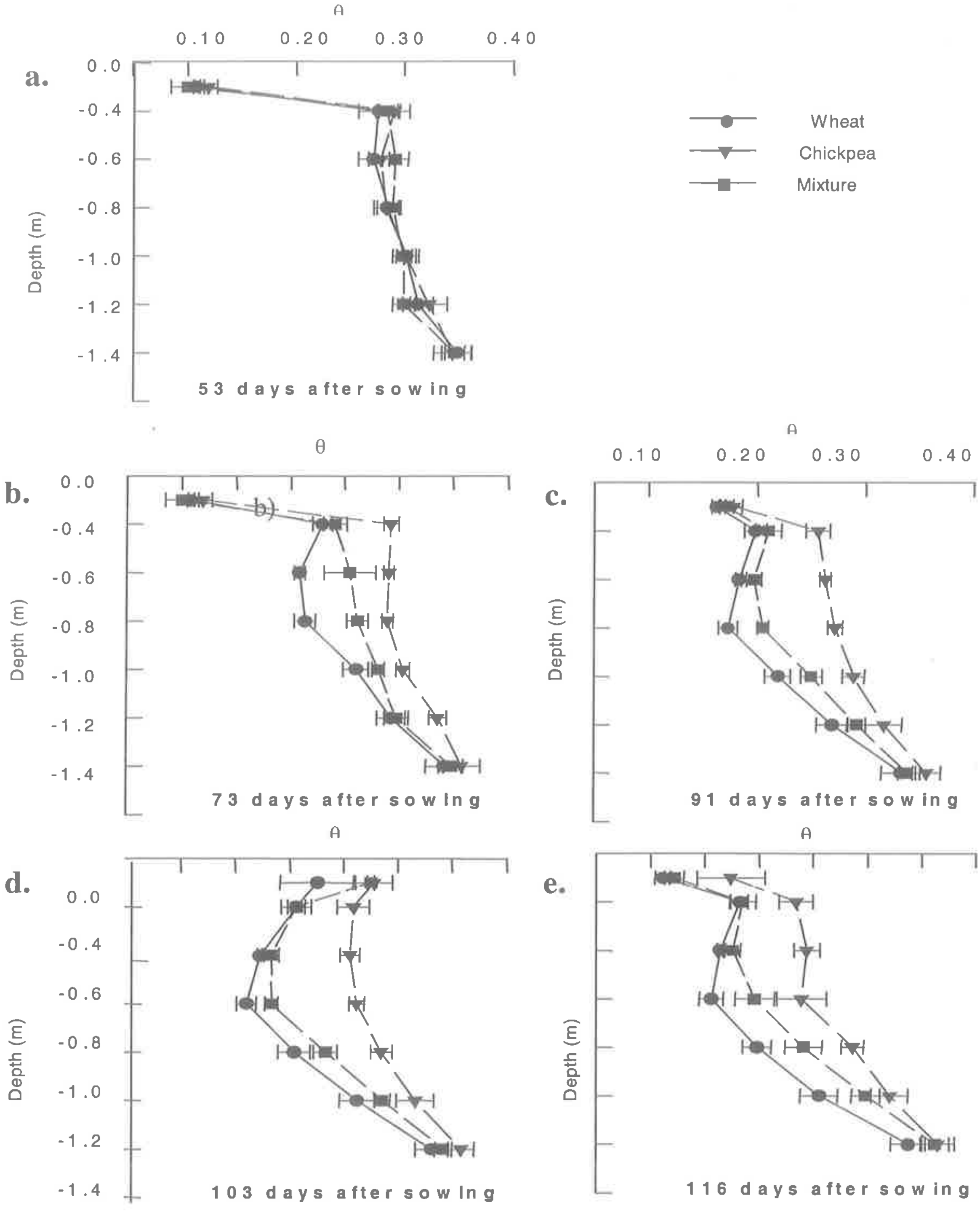


Figure 6-7 The volumetric soil moisture content (θ) in the 1.4m soil profile under sole wheat, sole chickpeas and mixed crops; the bars are standard errors of mean

The cumulative evapotranspiration (ΣET) was similar for the three cropping systems throughout the growing season (P=0.05) (Figure 6-8). However, from 70 DAS onwards, ΣET was always in the order of wheat>mixture>chickpea. The period of highest rates of ET was between 70 and 100 DAS, when daily ET was 5.6 mm for sole wheat as compared to 4.7 mm for the mixed crop and 3.8 mm for sole chickpea.

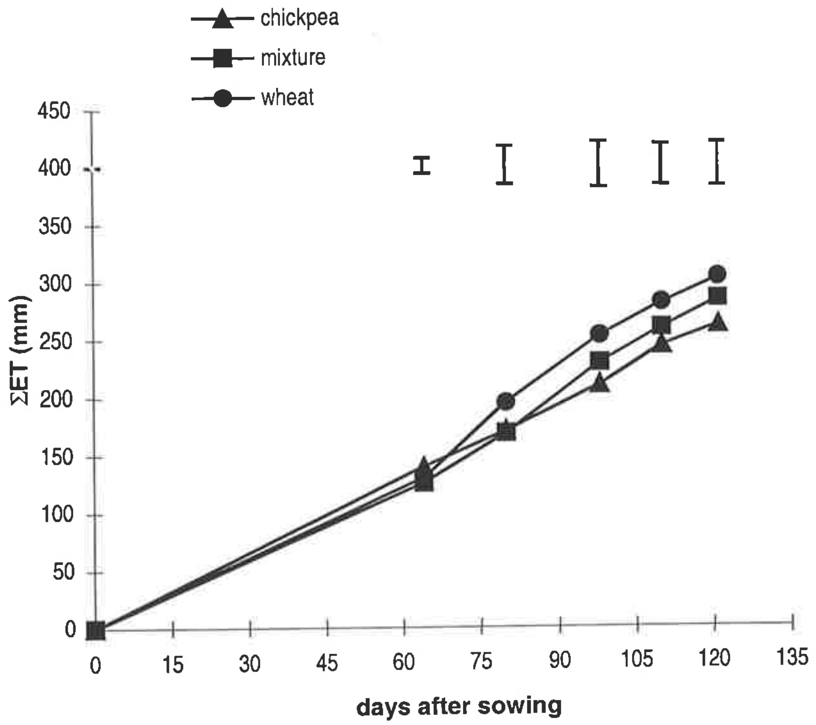


Figure 6-8 Cumulative evapotranspiration (ΣET) for sole wheat, sole chickpea and mixed crop. The bars indicate LSD (P=0.05) values

At the end of the season, total ET was similar for all the three treatments (Table 6-3).

Table 6-3 **Seasonal evapotranspiration (ET), soil evaporation under crop (E_S) and transpiration (T) for wheat, chickpea and the mixture; analysis of variance was not performed on the data in the last two columns**

Cropping system	ET (mm)	E_S (mm)	T(mm)
Wheat	302a	158	144
Chickpea	261a	170	91
Mixture	285a	148	137

Lower case letters in first column show statistically significant difference between means (P = 0.05) LSD

The daily values for ET were calculated and then partitioned into soil evaporation under crop (E_s) and transpiration (T) for the three cropping systems (Figure 6-9). In the first 16 DAS, E_s was the only component influencing ET in all cropping systems, averaging 1.5 mm per day for sole chickpea, 2.8 mm per day for sole wheat and 2.5 mm per day for the mixed crop. E_s continued to dominate ET for another 70 days, reaching maximum rates around 70 DAS. E_s was always higher for sole chickpea than for the other two cropping systems, which had similar rates.

In contrast to E_s, the rate of T (Figure 6-9) increased from an average of 0.25 mm per day for all treatments at 60 DAS to maxima of 3.5 mm per day for sole wheat, 2.5mm per day for the mixed crop and 1.5 mm per day for sole chickpea at 95 DAS. This phase was followed by a rapid decline in the rate of T after anthesis to less than 1 mm per day by 120 DAS in all treatments. For the entire growing season, T totaled 144 mm for sole wheat compared to 91 mm for sole chickpea (Table 6-3). There was a reciprocal relationship between the rates of E_s and T. E_s was almost completely suppressed in sole wheat and mixed crop when T rates in these treatments were at their peak.

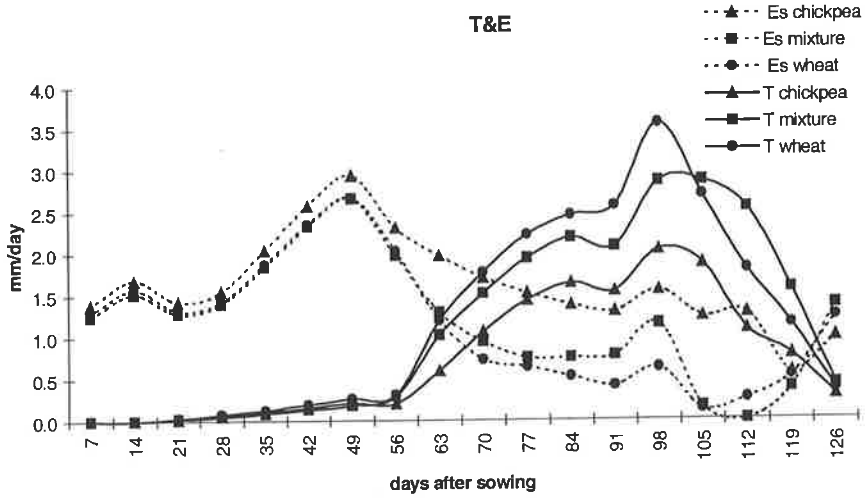


Figure 6-9 Daily rates of soil evaporation under crop (E_s) and transpiration (T) for sole wheat, sole chickpea and mixed crop.

In all three cropping systems, the majority of the water used was partitioned through E_s which averaged 52.3% of ET for sole wheat, 51.9% for the mixed crop and 64% for chickpea (Table 6-3).

The DM data in Figure 6-1 were used along with the respective transpiration data to calculate k_c (Equation 2-5 given on page 28). The results presented in Figure 6-10, produced k_c values of 2.9 P_a for wheat and 2.2 P_a for chickpea. These values were then used in Equation 2-4 to partition transpiration between the components of the mixture (i.e. wheat and chickpea). The T from mixed crop was partitioned between the components wheat and chickpea. The wheat canopy transpired (Figure 6-11) at least three times more water than the chickpea canopy.

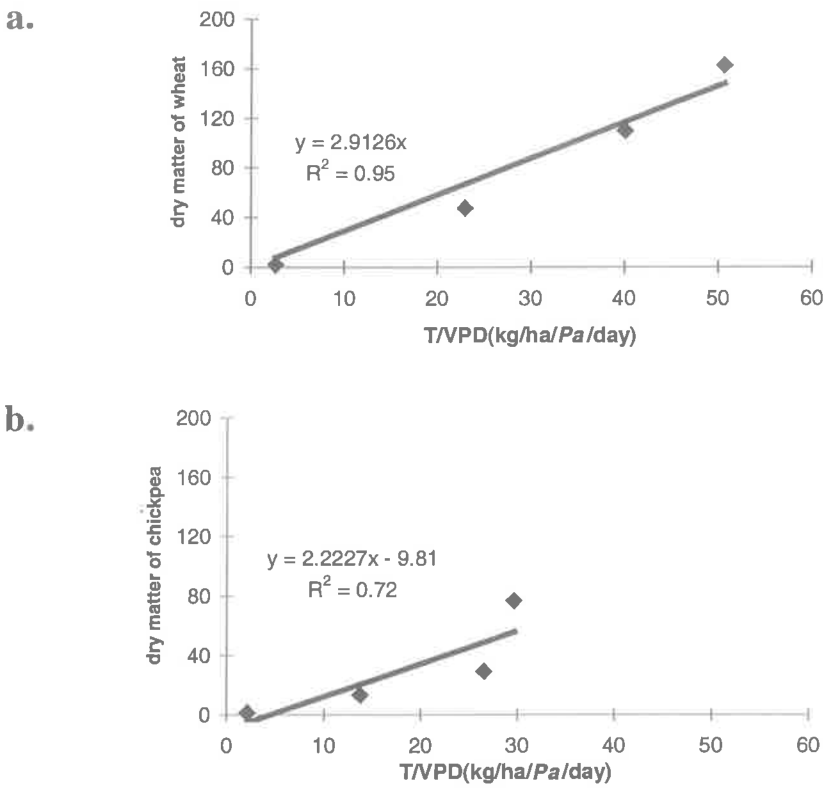


Figure 6-10 The relationship between above-ground dry matter produced (kg $ha^{-1}d^{-1}$) and the ratios of transpiration (T) to vapour pressure deficits (VPD) for (a) sole wheat and (b) sole chickpea; the slopes give the values for the transpiration efficiency constant (K)

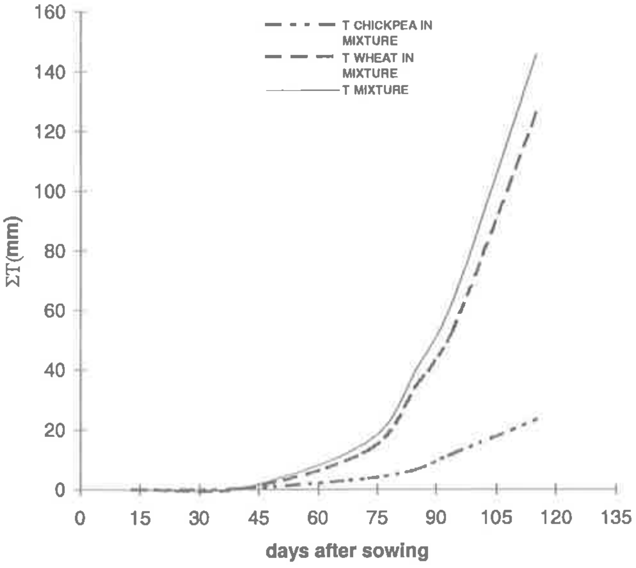


Figure 6-11 Cumulative transpiration (T) from the mixed crop and its partitioning between the component wheat and chickpea species

Water use efficiency (WUE) for the cropping systems

The WUE based on above ground DM produced ($WUE_{biomass}$) was similar for both the mixed crop and sole wheat, both of which had greater $WUE_{biomass}$ than the sole chickpea crop (Table 6-4). Water use efficiency based on grain yield (WUE_{grain}) for the mixed crop was similar to that for sole wheat. Both the $WUE_{biomass}$ and WUE_{grain} for chickpea were less than half those for the other two cropping systems.

Table 6-4 **Water use efficiency of grain yield (WUE_{grain}) and above-ground DM ($WUE_{biomass}$) for sole wheat, sole chickpea and the mixed crop**

Cropping system	$WUE_{biomass}$ (kg $ha^{-1}mm^{-1}$)	WUE_{grain} (kg $ha^{-1}mm^{-1}$)
Sole chickpea	9.4 b	2.6 b
Mixed crop	20.8 a	10.3 a
Sole wheat	20.4 a	8.6 a

Means with different letters are significantly different (P=0.05)

Transpiration efficiency (TE)

Transpiration efficiency (TE) was calculated either as the ratio of DM ($TE_{biomass}$) or grain yield (TE_{grain}) produced to the amount of water transpired by the crop. $TE_{biomass}$ (Table 6-5) was highest for sole wheat, being 28% and 60% higher than for mixed crop and for sole chickpea respectively. The response of TE_{grain} to cropping systems followed a similar trend to that of $TE_{biomass}$. Thus, in both sole and mixed crops, chickpea were less efficient in T than wheat.

Table 6-5 **Transpiration efficiency for grain (TE_{grain}) and above-ground DM ($TE_{biomass}$) yields by sole wheat, sole chickpea and mixed crop**

Cropping system	TE_{biomss}	TE_{grain}
Sole chickpea	9.2	32.4
Sole wheat	22.6	44.6
Mixed crop	17.6	42.5

6.3.2.3 Soil nitrogen uptake and utilisation

N taken up by the crop per unit of land area and partitioned into the shoot was in the order sole chickpea<mixture<sole wheat during most of the growing season (Figure 6-12a). At grain harvest, total N accumulated in the shoot was similar for sole wheat and mixed crop, while sole chickpea contained the least N. In the mixed crop shoot N was always significantly higher for wheat than for chickpea (Figure 6-12b). The difference between the two species in the mixture reached its maximum at maturity, when wheat had about 6 times the shoot N of chickpea.

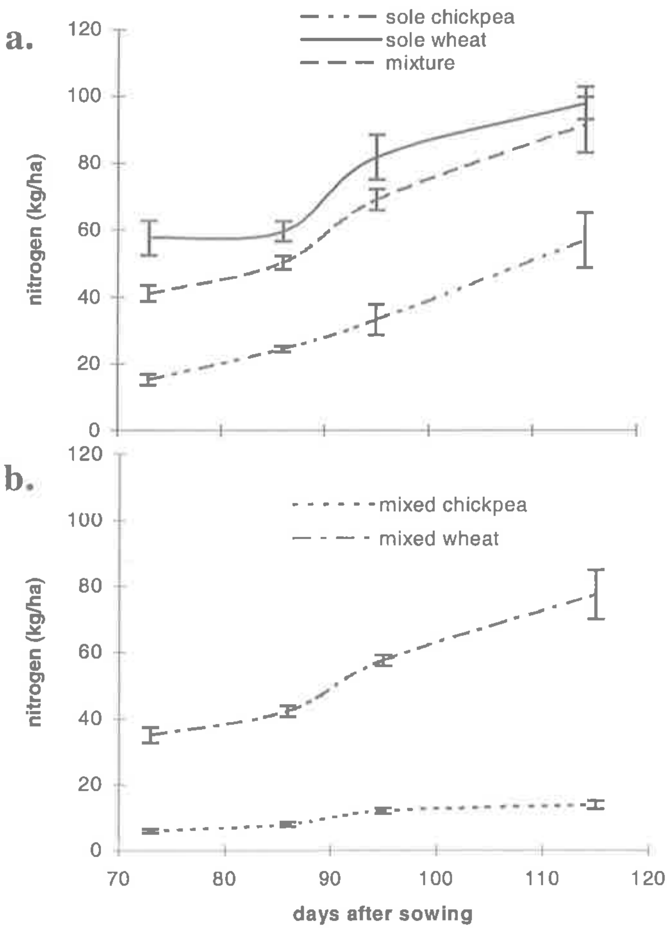


Figure 6-12 Total shoot nitrogen per unit area by (a) sole wheat, sole chickpea and mixed crop, and (b) by wheat and by chickpea in the mixed crop at grain harvest; bars indicate standard error of mean

At grain harvest, nitrogen concentration in the grain of wheat was not significantly affected by intercropping, although the N content in the grain and leaves of wheat was appreciably higher in the mixture than in the sole crop (Figure 6-13a). For chickpea, N distribution was not significantly affected by the cropping system (Figure 6-13b). For both crops, either in the sole or mixed crop, grain accounted for at least 60% of the total shoot N at grain harvest.

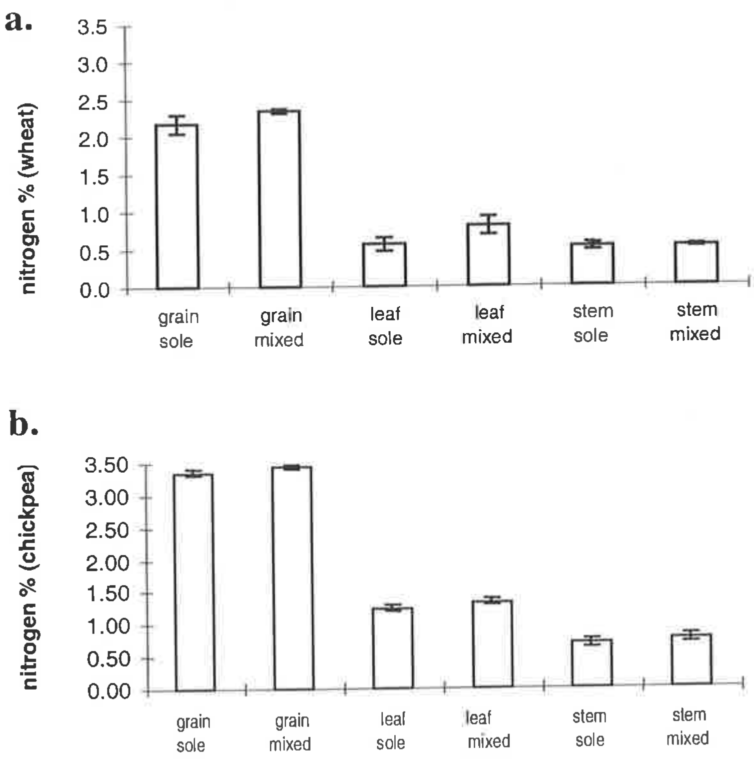


Figure 6-13 **Nitrogen concentration (%) in various plant parts of (a) wheat and (b) chickpea in sole or mixed crops; bars indicate standard error of means**

Nitrogen fixation and transfer

Calculations using equation 6-9 showed that chickpea growing in mixture was more reliant on nitrogen fixed from the atmosphere (89%) than sole chickpea which was only 73% reliant on atmospheric N (Figure 6-14). However, since the N yield of sole chickpea was greater than that of the mixture (Figure 6-14) it follows that the quantity of shoot N_2 fixed by sole chickpea was greater (42 kgN ha^{-1}) than for mixed chickpea (12 kgN ha^{-1}).

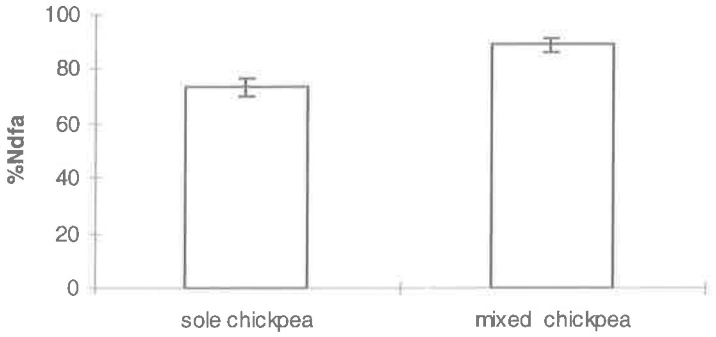


Figure 6-14 Percentage of shoot nitrogen derived from the atmosphere (%Ndfa) in sole and mixed chickpea; error bars show standard error of means

As can be seen from Figure 6-15 the $\delta^{15}N$ of wheat shoots in intercropping with chickpea was markedly less than that for wheat shoots in sole crop. Using equation 6-10 it can be calculated that 31% of shoot N in the wheat growing in the mixture was apparently derived from the chickpea, and this equates to 24 kg N ha^{-1} transferred from chickpea to wheat (Figure 6-16).

Figure 6-15 $\delta^{15}N$ of shoots in sole and mixed wheat; error bars show standard error of means

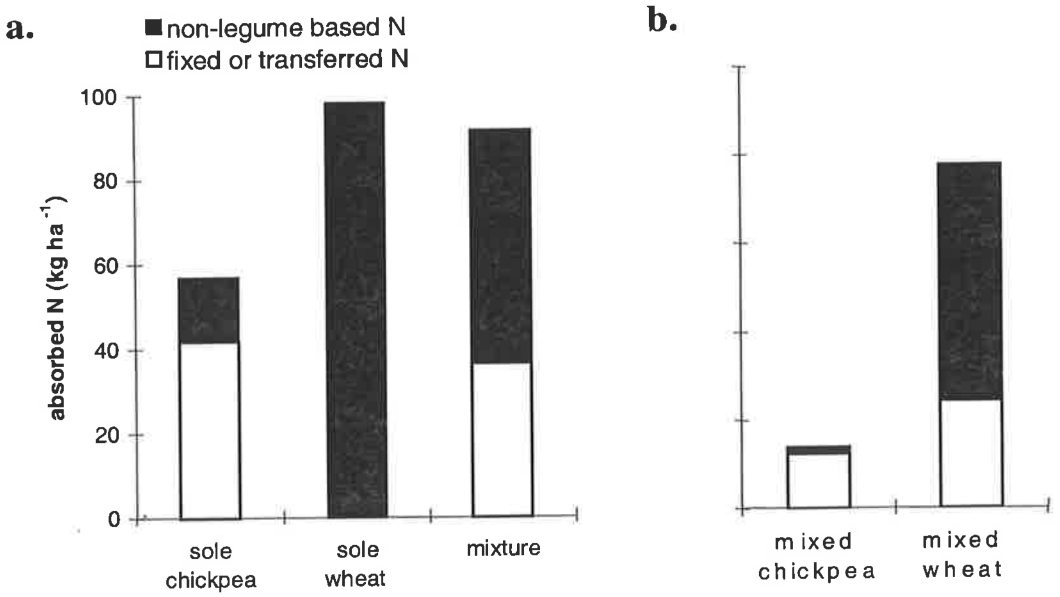


Figure 6-16 Sources of shoot N (a) in the three different cropping systems, and (b) partitioned in the two separate components of the mixture

N-fertiliser use efficiency (N-FUE)

Overall N-FUE was extremely poor for all the cropping treatments (Table 6-6) with the maximum recovery being less than 4%. N-FUE was higher for chickpea in sole crop than chickpea in the mixture when calculated either at flowering time or from the grain at maturity. However, N-FUE calculated at flowering or using grain remained similar for chickpea, but decreased between the two periods for wheat (Table 6-6). Sole chickpea had the highest recovery of N fertiliser measured either at flowering time or in grain. The lowest recoveries were in wheat grain in both monoculture and mixture (Table 6-6).

Some higher levels of LER with application of higher levels of N were obtained.

Table 6-6 **N fertiliser use efficiency (N-FUE) and recovered N Fertiliser (kg ha^{-1}) for the cropping systems, given 40 kgN ha $^{-1}$as ammonium sulfate at early tillering**

Cropping system	N-FUE (at flowering)	Recovered N (at flowering)	N-FUE (grain)	Recovered N (grain)
Sole chickpea	3.94 ±0.36	1.6	3.79±0.31	1.5
Chickpea in mixture	2.50 ±0.41	1.0	2.93±0.25	1.2
Sole wheat	3.69 ±0.42	1.5	1.97±0.55	0.79
Wheat in mixture	3.05 ±0.38	1.2	1.91±0.33	0.76

(± values) show standard error of means

6.3.2.4 Biological efficiency and competition

The land equivalent ratio (LER) for this experiment was about one (1.01), which shows neither advantage nor disadvantage of mixed cropping. Wheat was 2.4 times more aggressive than chickpea.

6.4 Discussion

6.4.1 Growth in sole crops and mixtures

Crop dry matter production is determined by capture and use of resources. In the experiment reported in this chapter (Table 6-1), mixture (6239 kg per ha) and sole wheat (6618 kg per ha) had greater dry matter than sole chickpea (2962 kg per ha). The DM produced in mixture was similar to that produced by sole wheat throughout the season (Figure 6-1a). Dry matter production of the mixture during the season was more than of the sole chickpea crop. The main reason for low chickpea DM would be the lower growth rate for chickpea (maximum of 70.25 kg ha^{-1} d^{-1}) in comparison with the total mixture (maximum of 123.80 kg ha^{-1} d^{-1}), and sole wheat (144.57 kg ha^{-1} d^{-1}).

In an intercrop with a similar growth cycle, the ability of each component crop to capture limiting resources is the key factor in determining the competitive ability of each intercrop. The wheat biomass produced in the mixture at the end of the season was only 84% of sole wheat (Figure 6-1b). Chickpea in mixture performed poorly compared to its sole crop, producing only 26% of the DM produced by its sole crop. In the mixture wheat grew faster early in the season, which enabled it to dominate resource capture and use (Fukai and Trenbath, 1993). A more vigorous root system of cereals may have been responsible for the wheat absorbing more water from the system. The results of resource partitioning clearly indicate that mixed wheat had better access to resources, especially water, compared to mixed chickpea. This disproportionate sharing resulted in less DM and grain yield for chickpea. There was also a temporal trend in the dominance of wheat. At 41 DAS wheat produced 2.7 times greater biomass than chickpea, and at the end of the season wheat had 7 times greater dry biomass than chickpea. The maximum growth rate of mixed chickpea was 15.5 kg per ha per day, which was about 7 times less than mixed wheat at 108.2 per ha per day (Table 6-1).

6.4.2 Resource use and capture in sole crops and mixtures

Water

Water is the most limiting resource in dryland farming areas of South Australia. Considering the volumetric moisture content of the soil (θ), at early tillering stages of growth, sole wheat, sole chickpea and the mixture had similar moisture content at all measured depths. However, the soil profile under sole wheat around 40 to 80 centimetres became significantly drier than that of the mixture, between 73 - 91 days after sowing (DAS). The θ value of the mixture was significantly lower than that for sole chickpea up to the 103 DAS. Thereafter sole chickpea started to absorb more water from the profile. Since chickpea had a lower growth rate than wheat at the beginning of the season, chickpea used less water, resulting in the wettest profile amongst the three cropping systems under sole chickpea. The θ for the mixture lies between sole wheat and sole chickpea (Figure 6-7). Similarly, Kushwaha and de R. (1987) in a mustard-chickpea mixture found that chickpea had the wettest soil profile. Perhaps chickpea is generically less vigorous and use less water than the non-legume component of the cropping system. In contrast Morris *et al.* (1990) and Shackel and Hall

(1984) found similarities in the pattern and quantities of soil water use for sorghum and cowpea in their respective sole crop and mixture. Shackel and Hall (1984) suggested that this similarity in water depletion could be the reason for the successful use of these species for intercropping under semi-arid conditions.

Generally, ET was statistically similar for the cropping systems (Table 6-3), a pattern consistent with an earlier report by Morris and Garrity (1993). However, there was a tendency for a difference between ET of different cropping systems as evidenced by an ET for sole chickpea 16 % less than sole wheat (Table 6-3). The important difference between the treatments was in the character of ET. Figure 6-9 shows that while most ET was lost by E_s, mainly due to a poor canopy cover, both sole wheat and the mixture had a GAI greater than 2 during most of the season (Figure 6-2), and this ensured a significant portion of ET through T. These differences in the magnitudes of T for the various treatments were reflected in both the dry matter and grains produced (Figures 6-1a and 6-3). When T in the mixture was partitioned between the two components, the T for wheat in mixture was 4.9 times more than that of mixed chickpea. This suggests that chickpea had less opportunity to absorb water, probably because of the very vigorous rooting system and higher GAI of wheat. Mixed wheat was also more efficient in using the transpired water, and this was reflected in higher grain yield and DM. The TE of mixed wheat was close to that of the sole crop, while TE for DM was much less in sole chickpea than wheat. This clearly shows that competition had an adverse effect on TE of the dominated crop (chickpea).

However, ET of the mixture was only slightly different from both sole wheat (6%) and sole chickpea (8%). Morris and Garrity (1993) also concluded that ET of intercropping systems was generally 6-7% greater than their respective sole crops. Similar results have been reported by Grema and Hess (1994) who found that intercropping of cowpea with millet did not increase ET over sole cowpea, perhaps because increased T in the intercrop was equivalent in magnitude to E_S in the sole crop. However, the results of the current study are contrary to those of Singh and Singh (1983) and Mandal *et al.* (1986b). Singh and Singh (1983) found that the mixture used more water than sole crop chickpea. Similarly, Mandal *et al.* (1986b) computed ET by wheat, chickpea and mustard grown either as sole crops or intercrops and found seasonal ET to be in the order of chickpea<wheat< wheat-chickpea mixture.

It appears that the mixed crop used water, the most limiting factor for growth in this dryland area, almost as well as the dominant and well adapted crop, wheat. The mixture and sole wheat had similar water use efficiency for grain (WUE_{grain}) and for dry matter $WUE_{biomass}$. WUE_{grain} and $WUE_{biomass}$ were the least in sole chickpea (Table 6-4). Ahalawat *et al.* (1985) observed a similar result in a wheat-lentil mixture, with similarities between WUE of wheat sole crop and mixture and a lower WUE for sole lentil. Mandal *et al.* (1986b) found that the WUE was the greatest for sole wheat, followed by wheat-chickpea mixture, with the chickpea sole crop producing the lowest WUE.

T is the component of ET which is directly linked to biomass production, so WUE largely depends on the proportion of T (Singh and Sri Rama, 1989). T and TE for grain and biomass for sole wheat and mixture were similar, although $TE_{biomass}$ was lower in the mixture (Table 6-5). The E_S for chickpea was higher than mixture due the poorer ground cover by chickpea. T, which normally determines DM production, was also higher in mixture than sole chickpea.

Radiation

The productivity of any plant community depends on RU and RUE. Better interception of radiation in the canopy is expected in mixtures due to temporal differences in growth (Table 6-2). However, crops with similar growth cycles can also differ in radiation interception because of differences in canopy architecture, or because of planting patterns (Keating and Carberry, 1993).

In the current experiment, P_i values (Figure 6-4) of sole wheat and mixture were generally similar except between 60-90 DAS which was a fast growth period for wheat. In the same period sole chickpea had a very poor P_i, which seems to be due to a significantly lower GAI compared with other treatments during its vegetative growth. This resulted in the cumulative PAR intercepted (Figure 6-6a) being lowest for sole chickpea.

Differences in PAR intercepted during the season provide further explanation for the yield differences between the treatments (Figure 6-3). Previous studies by Ali (1993) of a wheat-chickpea mixture and Marshall and Willey (1983) of a millet-groundnut mixture found higher yields for mixtures in comparison to pure stands, which was attributed to greater interception of radiation by the mixed crop canopies. Reductions in the yield of the dominated species, mostly legumes in cereal-legume mixtures, are often associated with impaired light interception. This was demonstrated in the studies of Cruz and Sinoquet (1994) with a (*Digitaria decumbens*)-legume (*Arachis pintoi*) mixture and Stirling *et al.* (1990) with groundnut based intercropping. They suggested that yield losses in intercropped groundnut may be largely explained by the reduced PAR interception by short-statured legume crops.

Better RUE has been reported as the main reason for better productivity of intercropping systems, rather than higher radiation interception (Table 6-2). Both mixture and sole wheat were similar in RUE for biomass and grain. Again RUE for both grain and biomass was higher in mixture and sole wheat than sole chickpea, which could be another reason for higher DM production in the mixture. In fact including a crop such as wheat with higher RUE may improve the productivity of the system, compared to sole chickpea. According to Keating and Carberry (1993) a large number of intercropping systems have benefited from the addition of a high photosynthetic rate crop to a legume which generally has a lower photosynthetic rate. In a groundnut-millet intercropping situation, Marshall and Willey (1983) found that the sole cereal had similar RUE to the mixture but higher RUE than the sole legume component, which is consistent with the results of this experiment.

With a grass-legume mixture Faurie *et al.* (1996) found that the mixture had higher RUE than sole crops. This might be because radiation saturated photosynthesis was avoided in the mixture. In contrast, Cruz and Sinoquet

(1994) found that a *Digitaria decumbens-Arachis pintoi* mixture did not allow for improved utilisation of radiation.

Wallace *et al.* (1990) partitioned water and radiation use in a cane-maize intercrop, and found that the comparatively slow growth of sugar cane as the dominated crop led to less T and lower radiation interception for this species. Faurie *et al.* (1996) also partitioned radiation interception in a grass-clover mixture and similarly found lower RUE for the legume in the mixture. Conversely, Reddy and Willey (1981) showed better resource use efficiency for millet-groundnut in mixture.

Nitrogen

N absorption. The ability of an intercrop to absorb and make more efficient use of soil nutrients depends on different factors such as the extent of root growth of the mixture, soil water level, and how the entire root zone is explored by the roots (Francis, 1989). N absorption of sole wheat was higher than the mixture until flowering time (Figure 6-12). At the end of the season both mixture and wheat had a similar amount of nitrogen in their above ground dry matter. Total N content of mixture was higher than sole chickpea throughout the season. By flowering, the mixture had absorbed more N than chickpea. Reddy and Willey (1981) reported that in an intercrop of pearl millet-groundnut, because of little changes in the percentage of N of each component of the mixture, the total nitrogen uptake was largely reflected by the biomass of each crop. Therefore, the N uptake of the mixture was higher than that of sole crops.

In the current investigation, the lowest amount of N absorption was seen in mixed chickpea. A decline in leaf N concentration at low N supply could affect the RUE by limiting radiation saturated rates of photosynthesis (Faurie *et al.*, 1996). Similar results were seen in a faba bean-barley intercrop (Danso *et al.*, 1987). In this case the total N in intercropped faba beans was less than mixed barley. In contrast, Kushwaha and De (1987) reported better N uptake in a chickpea-mustard intercrop because chickpea nodulated better and had larger nodules when grown in mixture. There was also a higher uptake of N for mustard in the mixture.

N fixation and transfer. N fixation and transfer in intercropping is of a great importance prompting Stern (1993) to state that: "The success of intercrop farming systems depends initially on effective nitrogen fixation and more importantly, on subsequent transfer of nitrogen to the non-legume."

Decreased availability of soil N due to its depletion by companion non-legume species may increase fixation of N by the legume in a mixture (Davis and Woolley (1986), Midmore (1993)). In the current study it seems that wheat had a more vigorous rooting system, and therefore absorbed more N than chickpea from soil. This could have promoted N fixation in chickpea which was reflected in 17% more symbiotic N fixation in the mixture as compared to the sole chickpea. Danso *et al.* (1987) found that faba bean intercropped with barley resulted in higher proportion of Ndfa in mixture than sole crop. In their experiment the higher %Ndfa came from a higher competition for N caused by an increase in the barley population in the mixture. A higher proportion of N fixation from the atmosphere does not necessarily mean a higher N yield production for the legume in mixture, as is demonstrated in this study where total N yield for sole chickpea was 57 kg ha^{-1} compared with only 12 kg ha^{-1} for chickpea in mixture (Figure 6-16). In the work by Danso *et al.* (1987) also a lower absorption of N for mixed faba bean was seen in the mixture than sole crop.

It was evident in the current study that a proportion of N in the wheat in the mixture was apparently transferred from the legume (Figure 6-15). Hardarson *et al.* (1988) also found that in lucerne-ryegrass the atom % ^{15}N excess in the grass from the mixture was slightly lower than in the pure grass stand, suggesting possible transfer of N from lucerne to ryegrass. The amount of transferred N from chickpea to wheat in the mixture was estimated at 21 kg ha^{-1}, while total N fixation was estimated at only 12 kg from shoots of chickpea in the mixture. This large difference between the estimated amount of N fixed in mixed chickpea, and that amount transferred to wheat might be because a large proportion of fixed N could have remained in the root and rhizosphere zone of chickpea. It has recently been reported that roots of chickpea might contain up to 70% of the total fixed N in a sole crop chickpea (Khan, pers. comm.). Senaratne and Ratnasinghe (1993) quantified the percentage of N derived by maize from intercropped groundnuts to be from 17% (cultivar X-14) to 39% (cultivar Red Spanish), indicating a marked genotypic variability in N-supplying ability. Transfer of N from phaseolus bean to maize was also observed by Giller *et al.* (1991). However, they indicated that because of little benefit under conditions of severe N limitation, many careful field experiments are required to conclude that N transfer from phaseolus to intercropped cereals is significant in agriculture. Stern (1993) indicates that most of the transfer occurs at the end of growth cycle of the legume, and generally transfer is relatively small. However, in this study, because of significantly higher $\delta^{15}N$ of wheat shoot in monoculture than in the mixture under the dryland conditions of South Australia it seems that N transfer may be important. As cited by Giller *et al.* (1991) from Vandermeer (1989) "The transfer of fixed N from the cereal may be viewed as a facultative benefit, which may have the potential for further manipulation to increase cereal yields."

N-FUE. Surprisingly, chickpea showed a higher N-FUE than wheat in both sole and intercropping situations, indicating that 40 kg N ha^{-1} may have decreased the capacity of chickpea to fix atmospheric nitrogen and encouraged uptake of soil or transfer N (Table 6-6). In addition, overall, low fertiliser use efficiency of the cropping systems under dryland conditions may have contributed to this effect (McNeill, pers. comm.). McNeill *et al.* (1996) investigating the seasonal variation in the suitability of different methods for estimating biological nitrogen fixation by grain legumes under rainfed conditions, reported in one year, that when 30 kg of N was applied the proportion of N recovered was greater in chickpea than in wheat.

Sole and mixed wheat showed similar N-FUEs, indicating that intercropping did not improve N-FUE in wheat. However, N-FUE of chickpea in the intercropping was less than sole chickpea which is due to its greater efficiency in fixing atmospheric N. This might indicate that application of N in a wheat-chickpea intercrop under low input not only maintains N-FUE for wheat but also does not have a great effect on nitrogen fixation of the mixed chickpea. This phenomena might help to increase the N pool of the soil. Pilbeam *et al.* (1997) found that from 30 kg ha^{-1} ^{15}N- labelled ammonium sulfate only 8% was recovered in shoot biomass. 50% remained in the soil N pool, and 38% was lost probably due to volatilisation of N fertiliser. Cowell *et al.* (1989) in some pea and lentil based intercrop experiments conducted at five sites, reported that where the growing conditions were poor, intercropping had a higher N-FUE than sole crops. However at the other sites intercropping systems had similar to intermediate N-FUE.

Normally, in an intercropping situation of crops with similar growth rates, LER values are close to 1 (Fukai and Trenbath, 1993). LER for this experiment was 1.01. However, Figure 6-16 clearly shows that the total amount of N in shoots for the mixture is very similar to that of sole wheat, of which only 55 kg ha^{-1} was non-legume based and therefore results in benefits for any subsequent crop. These findings show that intercropping might have a potential for improving overall N availability in the agricultural systems of South Australia.

Grain yield and biological efficiency

There was a reduction of 74% in the grain yield of chickpea in mixture (Figure 6-3) through reduction in most of the yield components such as number of seeds per m^2, weight of seeds per plant plant and 100 grain weight (Table 5-13). A lower HI was another reason for yield reduction. A 50% reduction in plant density only resulted in a 30% reduction in grain yield in wheat (Figure 6-3). Wheat partly compensated for the lower plant density in the mixture by producing more heads per plant, spikelet heads and grains per head (Table 5-12). The LER for the cropping system was about 1.

A richer N pool, with a lower water uptake from soil profile under intercropping in comparison with sole wheat, may have a positive effect on the growth of the subsequent crop. On the other hand wheat-chickpea intercropping was more efficient in use of the resources, and therefore more successful than sole chickpea in biomass and grain production. These findings present scope for further improvement of cropping systems under the dryland conditions of South Australia.

6.5 Summary and conclusions

Growth and grain yield. The biomass of the mixture (6618 kg ha^{-1}) was more than chickpea (2962 kg ha^{-1}) but similar to that of wheat (6239 kg ha^{-1}). The main reason for low biomass in chickpea could be a lower growth rate (maximum of 70.3 kg ha^{-1} d^{-1}) in comparison with the mixture (maximum of 123.8 kg ha^{-1} d^{-1}), and sole wheat (144.6 kg ha^{-1} d^{-1}) (Table 6-1). Wheat in the mixture produced 5449 kg per ha biomass at the end of the season, which was much higher than chickpea in mixture (771 kg ha^{-1}). The maximum growth rate of mixed chickpea was 15.2 kg ha^{-1} day^{-1}, and it was 108.2 kg ha^{-1} day^{-1} for mixed wheat (Table 6-1). There was a reduction of 74% in the grain yield of chickpea in the mixture (Figure 6-3) through reduction in most of the yield components; a lower HI was another reason for this yield reduction. A 50% reduction in plant density only resulted in a 30% reduction in grain yield in wheat in compare to sole wheat (Figure 6-3).

Water. The sole chickpea crop had the wettest profile i.e. the most unused water of the three systems at maturity. The final moisture content of the soil under the mixture was between that for the sole wheat and sole chickpea crops (Figure 6-7). The ET values were not statistically different throughout the season (Table 6-3), probably because of high variability in the experimental data. The mixture was only slightly different from both sole wheat (6%) and sole chickpea (8%). The mixture and sole wheat had similar water use efficiency for WUE_{grain} and $WUE_{biomass}$. The WUE_{grain} and $WUE_{biomass}$ were lowest for sole chickpea (Table 6-4). The T, which normally determines the DM, was also higher in the mixture than sole chickpea.

Light. The P_i of sole wheat and mixture was mostly similar except between 60-90 DAS. In the 60-96 DAS period the sole chickpea had a very poor P_i, which seems to be due to a significantly lower GAI during its vegetative growth. This also resulted in a lower absorption of total radiation energy in the sole chickpea as compared to sole wheat. The cumulative PAR was also similar for sole crops and mixture. Both mixture and sole wheat were similar in RUE for biomass and grain. The RUE for both grain and biomass was higher in mixture and sole wheat than sole chickpea, which could be another reason for higher DM production in the mixture. The highest RUE of all other cropping systems was obtained in the mixed wheat.

Nitrogen. The total N content of the mixture was higher than for sole chickpea throughout the season. The lowest amount of N absorption was seen in mixed chickpea. Chickpea in intercrop was 17% more reliant on nitrogen fixed from the atmosphere than the sole chickpea. However, total N yield for sole chickpea was 57 kg ha^{-1} compared with only 14 kg ha^{-1} for chickpea in mixture (Figure 6-16). It was also evident in this experiment that a proportion of N in the wheat in the mixture was apparently transferred from the legume (Figure 6-15). Chickpea showed a higher N-FUE than wheat in both sole and intercropping situations, which indicates that the fertiliser applied to the crop (40 kg N ha^{-1}) may have decreased the capacity for fixing atmospheric nitrogen in chickpea, and encouraged uptake of soil N. The sole and mixed wheat crops had similar N-FUEs, indicating that intercropping did improve N-FUE in wheat. However, N-FUE of chickpea in the intercropping was less than sole chickpea which is due to its greater efficiency in fixing atmospheric N.

LER for this experiment was about 1, indicating no advantage or disadvantage of intercropping over sole cropping.

Conclusions

In mixtures wheat by means of its prolific root system absorbs most of the soil resources, and because of the fast growth early in the season suppresses the legume part of the mixture. At the same time reduced N content of the soil promotes N_2 fixation in the chickpea in the intercropping system. Some of the fixed nitrogen appears to have been transferred to wheat in the mixture. Given this access to most of the available resources (water and nitrogen) the mixed wheat produced a similar DM to sole wheat, and almost compensated for the reduction in plant population. In the mixture chickpea was not able to utilise resources on offer efficiently. The overall use of the soil resources was less in intercropping systems, but based on the LER data it would appear that there was no advantage or disadvantage of intercropping to grain yield. Given a richer N pool, and a wetter soil profile with intercropping in comparison with sole wheat the intercropping may have positive rotational effects on the growth of a subsequent crop. Therefore, it is possible that resource use efficiency is an important key to the productivity of intercropping systems, and there is a potential to increase the productivity of the agricultural system by inclusion of intercropping in a crop rotation. To promote a more holistic approach to the outcomes of this study, the findings given in preceding chapters should also be considered. Therefore in the final chapter the results and findings of all the experiments undertaken will be discussed and some suggestions for further research presented.

7. GENERAL DISCUSSION

7.1 Introduction

Water and N often limit crop yield under dryland farming conditions in South Australia (Squires, 1991). Sowing time may be delayed due to lateness of the beginning of the rainfall season in autumn or winter, and rainfall variability may affect productivity. A drought period at the end of the growing season can also impair productivity (White, 1991). Potential benefits of intercropping systems are enhanced efficiency and yield stability of the cropping system, and this may suit the low input dryland agricultural systems of South Australia. The aim of the study discussed in this thesis was to quantify yield performance, competition effects and the capture and utilisation of resources of some important winter cereals and legumes as intercrops. To address this aim a series of field experiments were conducted to evaluate species and varieties, population density, plant arrangement, irrigation and N fertiliser effects on intercrops and corresponding sole crops. Prior to this project, there had been little research on intercropping in this region. Because of the complex interactions which occur in intercropping systems, statistical analysis in intercropping is much more complex than the univariate data analysis for monocultures (Federer, 1993). Therefore a number of different methods (i.e. univariate analysis, bivariate analysis, regression analysis, CR and LER indices and graphical methods) were used to analyse the results of intercrop performance. Moreover, adaptation of intercropping to extensive farming systems such as that practised in the wheatbelt of Australia can be quite difficult because of a lack of appropriate seeding equipment, harvesters and weed control methods. Therefore undertaking this research project required a lot of care, caution and effort. The extent of achievements in the study of species and varietal interactions, agronomic practices and resource capture and use, and also some limitations and further research needs will be addressed and discussed in this chapter.

7.2 Species and varietal aspects

Based on a common assumption that the best varieties for sole cropping can be used for intercropping systems as well (Davis and Woolley, 1993), and the recommendation of Francis (1986) to consider what farmers are growing in the region, species and cultivars were selected for the first experiment. Binary mixtures of two cereal species (wheat and barley) in combination with three legume species (faba bean, field pea and chickpea) were compared to their sole crops. LER was slightly higher in the barley-based intercrops than wheat-based intercrops. However, barley was much more aggressive and caused a large reduction in the growth of the intercropped legumes. The chickpea-wheat intercrop had slightly higher LER than other wheat based mixtures. Despite the fact that LER for grain was less than 1 showing no benefit from intercropping, the LER for biomass showed gains in biological efficiency in intercropping over sole cropping. Thus, for the remainder of the research, wheat and chickpea was chosen as the species for intercropping studies. By conducting a varietal experiment, it was found that Excalibur wheat and Semsen chickpea were preferable to Machete wheat and Desavic chickpea. Generally the yield of legumes in mixtures was dramatically reduced. In these experiments competition for water appeared to be the main reason for the reduction of legume yield. This could be because the currently grown wheat and barley cultivars have been selected after appropriate selection programs to suit the dryland conditions of the region, having strong root systems and being well adapted to adverse conditions. In contrast, most of the common cultivars of grain legumes especially chickpea have not been locally bred for drought tolerance. Therefore, the best varieties for sole cropping may not be suited for intercropping systems under the dryland conditions of South Australia. However, the observed differences between different species and varieties leaves scope for a more judicious selection of species and varieties.

Ideally, for intercropping to be successful one should select for characteristics which, without being associated with low yield, reduce competition against the second crop and one should choose a dominated crop which grows well in the environment which is altered by the dominant crop. This may minimise inter-crop competition and maximise complementarity, which can be obtained in time (temporal dimension) or space (spatial dimension) or both (Francis, 1986a). According to the published literature complementarity effects mainly occur in a temporal dimension; these complementarity effects are less likely to occur in a spatial dimension (Willey, 1979a; Ofori and Stern, 1987a; Francis, 1989 and Fukai and Trenbath, 1993). The major source of temporal complementarity is the differences between the growth cycles of component crops. An example of intercropping with temporal difference is the intercropping of pigeonpea and sorghum in India (Rao, 1986). Sorghum is harvested after 3.5 to 4.5 months while pigeonpea matures 3 to 6 month laters. Since they capture the resources partly at different times the productivity of this system has been reported to be 66% higher than that of sole cropping. Temporal complementarity similar to that reported in India, appears impractical for the short and often unreliable growing seasons of South Australian dryland conditions. However, it is possible to find species and cultivars with some differences in their growth cycle. For example, Baker and Yusuf (1976) believed that for some cereal mixtures advantage might occur if there was at least a 30 day difference in maturity. Hollamby (pers.comm., 1998) has recorded a 20 day difference in maturity between wheat cultivars and breeding lines available in South Australia. He has indicated that even greater differences in maturity are possible through breeding. A survey of different species and cultivars grown in the region might lead to the selection of varieties with relatively different growth cycles. This would enable optimisation of complementary effects under dryland conditions from growing appropriate crop species and cultivars.

Selection for improved spatial complementarity is another way to increase the productivity of intercropping systems. Canopy architecture and root characteristics are the main factors affecting mixture productivity. As mentioned before, the majority of popular wheat and barley cultivars under rainfed conditions have strong root systems and are well adapted to adverse environmental conditions. In contrast, common varieties of grain legumes grown in South Australia are not well adapted to local conditions. Choosing legumes with better adaptation and vigorous root systems could be a solution to this problem.

Many of the desired characteristics such as growth cycle differences can be obtained from early generation testing of available species and varieties (Davis and Woolley, 1993). Then the selected cultivars must be evaluated as intercrops. For example, in the breeding programs for pigeonpea at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), pigeonpea genotypes for intercropping systems are selected by adding a cereal between their rows (Willey, 1979b). It is suggested that the intercropping research programs need to work closely with legume breeding programs, and genotypes may need to be evaluated under conditions that include competition with a companion crop experienced in farmers' fields.

7.3 Agronomic Practices

From the experiments on species and cultivars reported in this thesis, it was evident that legumes perform poorly in mixtures under the harsh conditions of South Australia. LERs were mostly close to 1, and the share of the cereal component in the final yield was much greater than that of the legume component. However, both legumes and cereals have a bearing on the calculation of LER. Therefore, attempts to increase the legume yield in mixtures without affecting the relative yield of the cereal component, would improve the efficiency of the system. Moreover, the legume component has a higher nutritional and economic value than wheat. Therefore one of the main aims of intercropping cereals and legumes should be increasing the final yield of the legume in the mixture. Agronomic practices can have a positive effect on yield performance of field crops by permitting optimal sharing of natural resources. Manipulating plant population density and row arrangement of crops might offer a practical way to maximise inter-specific complementarity especially under low input agricultural systems (Midmore, 1993). In three field experiments the effect of different agronomic practices, namely seeding rate, row arrangement, fertiliser and irrigation, on grain yield, competition and efficiency of some intercropping systems were studied.

Generally, minimum plant populations of wheat (W50), and maximum plant populations of chickpea (C100) reduced the aggressivity of wheat in the mixture, thereby improving the performance of the legume component of the mixture. Another strategy to improve the legume component in a mixture involved manipulating row arrangements. The main finding was that the greater the proximity of the rows of wheat, the poorer the chickpea yield in the mixture. Using competition ratio of wheat with respect to chickpea, wheat in the 'mixed in a row' arrangement was 85 times more competitive than chickpea, while in the 'double alternate rows' wheat was 13 times more competitive than chickpea. When chickpea was planted with wheat in a row chickpea was completely eliminated from the system. However, widening the rows of wheat by replacing rows of wheat with chickpea decreased the productivity of the cropping system. It was found that, for both dry and wet conditions, double alternate rows of both crops was the best planting arrangement.

A common assumption concerning intercropping is that this practice is suitable for low input areas. In South Australia both water and nitrogen are often the most limiting factors for agricultural production (Webber *et al.*, 1976). Consequently interactions between N and water supply were also investigated in this project. Addition of water under irrigated conditions had a positive effect on yields of both sole crops and mixtures. It also decreased the competition between wheat and chickpea. However, there was a trend towards lower LER under irrigation. Under dryland conditions N application did not affect the yield of the component crops, but with irrigation the addition of N decreased the yield of chickpea. This clearly shows that when water is available, addition of N can also increase competition for light due to shading. The other result to emerge was that under irrigation chickpea (C100:W50) became slightly more competitive against wheat. Under irrigation the CR values of wheat with respect to chickpea are smaller (Table 5-2), because chickpea becomes more competitive when irrigated than under dryland conditions where the wheat is more competitive (Table 4-11). However, under dryland conditions, wheat in a mixture absorbed most of the resources, and caused severe depression of chickpea growth and yield.

Another agronomic practice that might enable the legume to have a greater share in the final yield is "staggered cropping". The legume component of the mixture is planted a little earlier than the cereal component, thus allowing the legume to absorb resources more successfully than if both crops were planted at the same time. Therefore, agronomic practices offer an opportunity to reduce the intensity of inter-specific competition and thereby increase the productivity of the intercrops.

7.4 Resource capture and use

The ability to capture and use resources mainly depends on the genetic characteristics of a crop, and this should be taken into account when choosing appropriate crops and species. In the two previous sections, choosing species and agronomic practices were discussed. In this section discussion on resource capture and use, which is necessary for understanding the performance of intercrop components, is presented.

The dominance of cereals because of their fast growth and root characteristics has already been reported by many researchers (e.g. Rao, 1986; Ofori, 1986; Ofori and Stern, 1987a). In different mixtures investigated, intercropped wheat had faster growth than intercropped chickpeas early in the growing season. This early advantage enabled wheat to become the dominant crop. Further into the season interspecific competition reduced the availability of resources for chickpeas. Despite the primary assumption that the typically deeper rooting system of legumes gives them the advantage of better access to water and nutrient uptake (Fukai and Trenbath, 1993), and despite the ability of legumes to absorb nitrogen from the atmosphere (Ofori and Stern, 1987a) allowing chickpeas to become more competitive under the low nitrogen conditions of this study, the supply of resources to chickpeas was denied by wheat with its greater competitive ability. As mentioned before, the reason for wheat's strong competitive ability might be its selection for drought tolerance, while chickpea is a new crop in the region and thus varieties are not as well adapted as wheat. In contrast, under irrigated conditions chickpea showed a slightly greater competitiveness against wheat in the C100:W50 combination. However under dryland farming conditions, chickpeas were totally out-competed by wheat in mixtures in some cases. The reason for this phenomenon was stated clearly by Fukai and Trenbath, (1993): "Once a particular component develops better access to the limiting resource and begins to deny supply to the other, there is a tendency for a positive feedback mechanism to operate, so that the other component tends to become progressively more dominant while the growth of the other component may be suppressed almost completely". Using some of the theoretical framework, the amount of captured radiation energy for chickpea in mixture was estimated to be 12 MJm^{-2}, which is 43% of its sole crop and 38% of the total radiation intercepted by the mixture canopy. The radiation energy intercepted by wheat in mixture was 20 MJm^{-2}. Radiation use efficiency (RUE) of chickpeas in mixtures was 0.17 g MJm^{-2}, which is 68% of sole chickpea, while it was 0.95 g MJm^{-2} for wheat. Transpiration for chickpeas in mixtures was 17% of the total transpiration of the mixture, suggesting reduced DM production of chickpeas in mixtures. The transpiration use efficiency (TE) of chickpeas in mixtures was 13 kg ha^{-1} mm^{-1} as compared to 20 kg ha^{-1} mm^{-1} TE for wheat in mixtures. The mixture left more moisture in the soil profile than sole wheat. Wheat in the mixtures absorbed most of the available water and nitrogen and, probably because of fast vegetative growth early in the season, suppressed the legume component of the mixture. At the same time this use of N by the wheat crop appeared to promote additional N_2 fixation in the intercropping systems, with evidence of some nitrogen transferring to the wheat crop in the mixture.

Legumes in mixtures received the smaller share of resources. The Harvest Index (HI) for wheat remained almost the same in mixtures and sole crops. However for chickpeas the HI for mixtures was 8% lower than for the sole crop, showing poorer assimilate partitioning to grain for chickpeas in mixtures than in sole crops. The relative yield for chickpeas in the C100:W50 treatment was 0.30 while it was 0.71 for wheat, showing a greater share for wheat than chickpeas in mixtures, and indicating no advantage or disadvantage of intercropping. However, the overall impact of mixture on N pool of soil, was less than sole wheat. Moreover, the moisture remaining in the soil under mixture was also greater than sole wheat. Thus, having more resources in the soil after a mixture of wheat and chickpea than wheat alone might have a positive effect on the growth of the subsequent crop.

7.5 Productivity in relation to growing season water supply

Efficiency of intercropping systems is less likely to be improved when the component crops are planted at the same time and have a similar growth cycle. As an overall assessment of the productivity of the intercropping system, Relative Yield (RY) of wheat and chickpea, LER, and CR rates of wheat to chickpea, under six different environments (1993, 1994, 1995 dry, 1995 wet and two out-of-season experiments in 1993 and 1994) are now reviewed.

The relative yield of chickpea shows a very strong linear increase with the increase in the amount of available water (Figure 7-1). As mentioned previously, the greater nutritive and monetary value of the legume portion of a mixture is one of the important aspects of intercropping cereals with legumes.

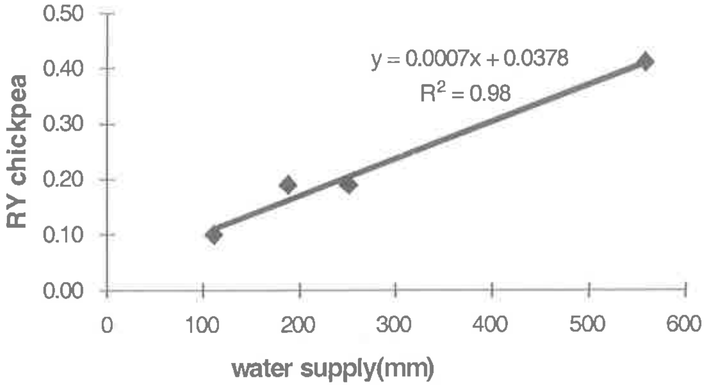


Figure 7-1 Regression between the relative yield (RY) of chickpea, in a C50:W50 mixture with wheat, and water supply; each point on the graph represents a separate experiment

The regression curve of available water and RY of wheat in a mixture with chickpea (Figure 7-2) shows that with increasing water supply in the system the relative yield of wheat decreased. However, under dryland conditions wheat had a greater share in the yield of the mixture. This could have been due to greater absorption and utilisation of water by the wheat component of the mixture, making it the dominant crop under dryland conditions.

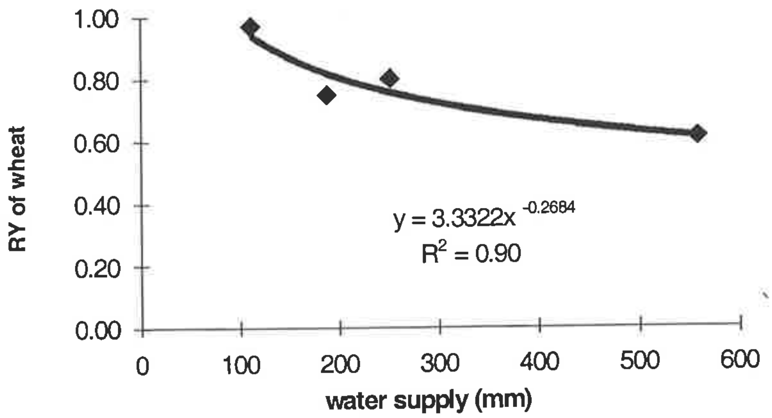


Figure 7-2 **Regression between the relative yield (RY) of wheat in a C50:W50 mixture with chickpea, and water supply**

CR values (Figure 7-3) also show a trend of decreasing competitive ability (aggressivity) of wheat against chickpea with increasing amounts of available water. The CR decreased from 12 under dryland conditions to less than 2 under irrigated conditions.

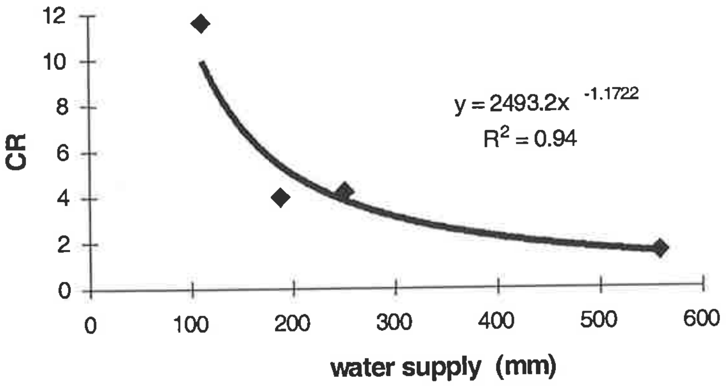


Figure 7-3 **Regression between competition ratio (CR) of wheat against chickpea in a C50:W50 mixture and water supply**

There is no relationship between LER and the amount of available water (Figure 7-4). This was also confirmed by other details presented in Chapter 5. In a competitive situation, the increase in relative yield of one component is offset by an equivalent decrease in the amount of RY of the other component. Therefore LER, which is the total of the relative yields of the two crops, did not show any deviation from unity.

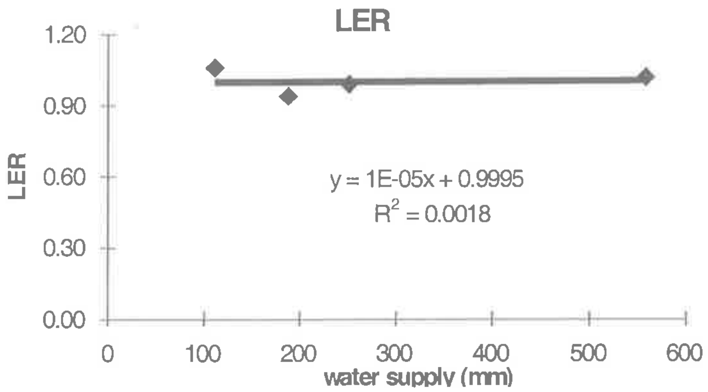


Figure 7-4 **Regression between land equivalent ratio (LER) in a C50:W50 mixture of wheat and chickpea and water supply**

Fukai and Trenbath (1993) also found that when two plants with the same duration of growth grew in an area, the LER rarely exceeds 1. They argued that the reason farmers practise intercropping of two crops with similar growth duration was to enhance the stability of their system. To demonstrate this point, two out of season experiments were carried out to show the effect of intercropping under extreme environmental conditions (Table 7-1).

The first was planted on 16 September 1993, and therefore experienced heat stress and photoperiodic reactions. The high temperatures and long photoperiod resulted in shortening of the vegetative phase for wheat with sole crop wheat yielding less than the average for the region. However, chickpea performed normally and therefore the reduction of grain yield of wheat was compensated for by the gains in chickpea. This resulted in the highest LER of all experiments undertaken.

The second out of season experiment was undertaken in Iran with the same cultivars (Appendix 6). The time of planting was the second month of spring, which was two months later than the normal time of planting for that region. The delay was largely due to exceptionally wet conditions, which on that heavy soil type held up seeding for an extended period. Thereafter, reproductive development of wheat in both sole crop and mixture was severely affected by heat stress. Lack of vernalisation for wheat could have also affected its reproductive development. Consequently, wheat produced no grain yield, however chickpea managed to produce a relative yield of 0.48. This example illustrates the buffering or insurance effect of intercropping, under harsh growing conditions.

Table 7-1 Relative yield (RY), land equivalent ratio (LER) and competition ratio (CR) of wheat against chickpea

Location	Year	RY wheat	RY chickpea	LER	CR
Roseworthy	1993	0.85	0.40	1.25	2.12
Kermanshah (Iran)	1994	—	0.48	0.48	—

7.6 Conclusion

From the results of the whole study it can be concluded that under most situations the $\text{LER}_{\text{grain}}$ was close to 1, showing no clear advantage or disadvantage of intercropping. However, in some circumstances the $\text{LER}_{\text{biomass}}$ was greater than 1. Moreover, it seems that overall resource use is less in intercropping of wheat and chickpea than sole wheat. Therefore there is the possibility of improving productivity and stability of the cropping rotation by intercropping. However, a thorough study of plant breeding for legumes is necessary to find appropriate species and cultivars with a high degree of compatibility in mixtures. The findings of this study also support the idea that agronomic practices such as row arrangement (preferably a 2-2 arrangement) and seeding rates in favour of the legume component can improve the productivity of the legume component and sometimes of the whole intercropping system. Therefore, this study leaves scope for the improvement of cropping systems for rainfed areas of southern Australia through the use of appropriate intercropping systems.

Appendix 1: Plan of Experiment 1, Chapter 4

Yield performance and competition in intercrops of two cereal species and three species of legume under rainfed conditions

⇑
North

PB	CO	PA	PO	AO	BO	FA	FB	CB	CA	FO

rep 1

PA	FO	CB	FB	CO	PB	OB	FA	OA	CA	PO

rep 2

PA	PO	CB	FA	CO	FB	BO	CA	FO	PB	AO

rep 3

CA	FO	BO	PO	FA	PA	CO	PB	AO	CB	FB

rep 4

BO	PB	PA	PO	FO	FB	CO	CB	AO	CA	FA

rep 5

Experimental design: randomised complete block design with 5 replicates

Plot size: 2.25 m x 12 m

Distance between replications: 8 m

Treatments: non legumes: A: wheat, B: barley

legumes: C: chickpea, F: faba bean, P: pea

O: sole crop

Appendix 2: Plan of Experiment 2, Chapter 4

The effect of varietal selection on intercropping of wheat and chickpea

⇑
North

REP 1	C2W2	C1W2	C2	W2	C1W2	C2	C1W1	C1W1	C2W1	C2W1	C1	C2W2	W2	C1
REP 2	C2W2	C1W1	C1W1	C2	C2	C1W2	W1	C2W2	C1W2	C2W1	W2	C1	C2W1	C1
REP 3	C1W2	C1	W1	C2W2	C2	W2	C2W2	C2W1	C2W1	C1	C2	C1W1	C1W2	C1W1
REP 4	C2	C1	C1W1	W2	C2W2	C2W1	C1W1	C1	C2W1	C1W2	C2	W1	C1W2	C2W2

Experimental design: randomised complete block design with 4 replicates and factorial treatment structure (W x C)

Plot size: 10 m x 2.5 m

Distance between replications: 1 m

Treatments: chickpea varieties: Desavic (C1) and Semsen (C2)

wheat varieties: Excalibur (W1) and Machete(W2)

Appendix 3: Plan of Experiment 1, Chapter 5

The effect of seeding rates on yield of wheat and chickpea intercrops

⇑
North

C100-W100	C100	C75-W75	C50W50	C50W100	W100

rep 1

C75-W75	C50W100	C100	C100-W100	W100	C50W50

rep 2

C75-W75	C50W50	C100	W100	C100-W100	C50W100

rep 3

Plot size: 5 m x 1.2 m

Distance between replications: 1 m

Treatments: C = chickpea, W = wheat; the first number in each set is the percentage density of chickpea and the second number is the percentage of wheat in mixtures; C100 and W100 show the percentage density of sole crops of chickpea or wheat according to their recommended densities

Appendix 4: Plan of Experiment 2, Chapter 5

The effects of seeding rates and row arrangements on wheat-chickpea intercropping systems

⇑
North

cw 32	cw 12	cw 23	cw 21	cw 25	w03	cw 24	cw 31	cw 35	cw 11	cw 13	cw 33	c01	cw 22	c02	c03	cw 14	cw 15	w01	w02	cw 34

rep1

cw 23	cw 33	w02	cw 21	cw 13	cw 12	cw 24	w03	cw 34	cw 32	w01	c01	cw 35	cw 14	cw 25	cw 22	cw 15	cw 11	c03	c02	cw 31

rep 2

cw 33	cw 13	cw 24	cw 22	c02	w02	cw 23	cw 35	cw 14	cw 15	c01	cw 31	w03	cw 25	cw 21	w01	cw 12	c03	cw 32	cw 11	cw 34

rep3

w 01	w 03	cw 22	cw 32	cw 12	cw 35	w02	c03	c01	cw 14	cw 21	c02	cw 25	cw 13	cw 31	cw 11	cw 23	cw 33	cw 34	cw 15	cw 24

rep4

Experimental design: randomised complete block design with 4 replicates

Plot size: 10m X 2.5m

Distance between replications: 1 m

Treatments: W = wheat, C = chickpea, C-W = chickpea=wheat;

first set of numbers: 0 = sole crop (not different rows), 1 = single alternate rows, 2 = double alternate rows and 3 = mixed in a row;

second set of numbers: for intercrops, c-w1=50% of the recommended seed rate per plot (r/p), 2 = 75% (r/p), 3 = 100% (r/p), 4 = 50% chickpea-100% wheat and 5 = 100%chickpea-50% wheat for sole crops i.e. c and w 1 = 100% (r/p), 2 = 150% (r/p), 3 = 200% (r/p)

Appendix 5: Plan of Experiment 3, Chapter 5

The effect of nitrogen fertiliser and combinations of different densities and row ratios on wheat-chickpea intercrops and their soil crops under irrigated and rainfed conditions

a) Rainfed conditions

⇐
North

C-W 50-50 4-2	C=100	C-W 100-50	C-W 50-50	C-W 100-100	C=200	C-W 50-50 3-2	W=200	W=100
C-W 50-50 4-2	C=100	C-W 100-50	C-W 50-50	C-W 100-100	C=200	C-W 50-50 3-2	W=200	W=100

REP1

C-W 50-50 4-2	C=200	W=100	C-W 100-50	W=200	C=100	C-W 50-50	C-W 50-50 3-2	C-W 100-100
C-W 50-50 4-2	C=200	W=100	C-W 100-50	W=200	C=100	C-W 50-50	C-W 50-50 3-2	C-W 100-100

REP2

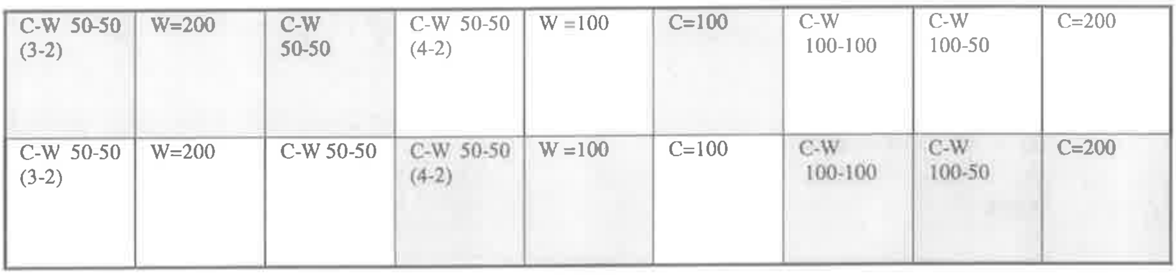
C-W 100-50	W=100	C-W 50-50 3-2	W=200	C=100	C=200	C-W 50-50	C-W 100-100	C-W 50-50 4-2
C-W 100-50	W=100	C-W 50-50 3-2	W=200	C=100	C=200	C-W 50-50	C-W 100-100	C-W 50-50 4-2

REP3

C-W 100-100	C-W 50-50 3-2	W=200	C-W 50-50	C=100	W=100	C-W 50-50 4-2	C-W 100-50	C=200
C-W 100-100	C-W 50-50 3-2	W=200	C-W 50-50	C=100	W=100	C-W 50-50 4-2	C-W 100-50	C=200

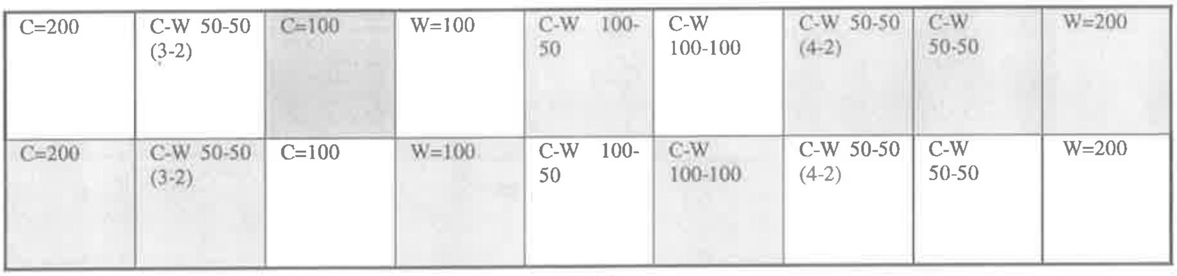
REP4

b) Irrigated conditions



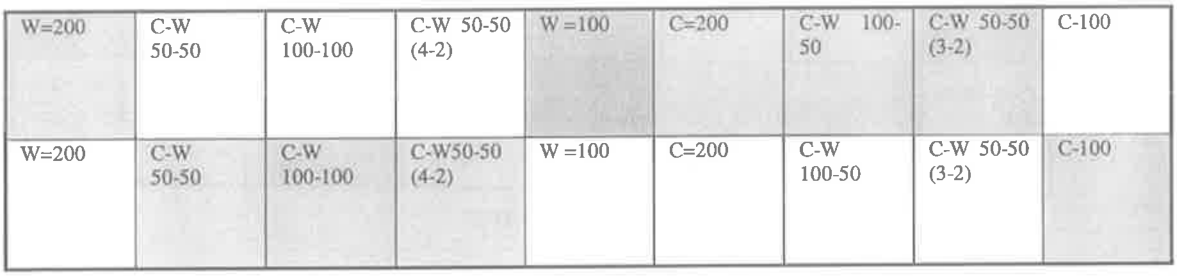
C-W 50-50 (3-2)	W=200	C-W 50-50	C-W 50-50 (4-2)	W =100	C=100	C-W 100-100	C-W 100-50	C=200
C-W 50-50 (3-2)	W=200	C-W 50-50	C-W 50-50 (4-2)	W =100	C=100	C-W 100-100	C-W 100-50	C=200

REP1



C=200	C-W 50-50 (3-2)	C=100	W=100	C-W 100-50	C-W 100-100	C-W 50-50 (4-2)	C-W 50-50	W=200
C=200	C-W 50-50 (3-2)	C=100	W=100	C-W 100-50	C-W 100-100	C-W 50-50 (4-2)	C-W 50-50	W=200

REP2



W=200	C-W 50-50	C-W 100-100	C-W 50-50 (4-2)	W =100	C=200	C-W 100-50	C-W 50-50 (3-2)	C-100
W=200	C-W 50-50	C-W 100-100	C-W50-50 (4-2)	W =100	C=200	C-W 100-50	C-W 50-50 (3-2)	C-100

REP3

Experimental design: randomised complete block design with 4 replicates and split plot treatment structure

plot size: 2.5 m x 10 m

sub plot: 2.5 m x 5 m

Distance between replications: 1 m

Treatments: C = chickpea, W = wheat;

the first number in each set is the percentage density of chickpea and the second number is the percentage of wheat in mixtures; W100, W200, C100 and C200 show the percentage density for sole crops according to their recommended densities;

N0 = no fertiliser was applied; 40 kg ha^{-1} of N was applied to shaded area

Appendix 6 Information about the experiment in Iran (1994)

The data is taken from an experiment which was carried out to investigate the effect of different densities on wheat-chickpea intercrops and their sole crops at Sararood experimental station, Kermanshah, Iran from April to August 1994. Excalibur wheat and Semsen chickpea were hand sown in sole crop and mixtures at various seeding rates with a double alternate row arrangement. The plots were 3 x 5 m, consisting of 12 rows spaced 0.25 m apart. The average rainfall of the area is about 480 mm. The experiment was planted two months later than the normal time of sowing chickpea, therefore crops were affected by heat stress. To maintain the experiment, three supplementary irrigations were applied. The treatment which is used for the present study is taken from a C50:W50 seeding rate. The yield of chickpea in the mixture averaged about 223 kg per ha, while average yield of sole chickpea was 466 kg per ha.

Appendix 7: Land equivalent ratio and competition ratio

Land equivalent ratio (LER) and competition ratio (CR) of wheat with respect to chickpea calculated using non-standardised values of sole crops for different experiments

Chapter 4, trial 1

Cropping system	wheat-chickpea	wheat-pea	wheat-faba bean	barley-chickpea	barley-pea	barley-faba bean
LER	0.97	0.8	0.95	1.05	0.9	0.9

Chapter 4, trial 2

Cropping system	LER	CR
ExcaliburDesavic	0.95	23.3638
ExcaliburSemsen	0.93	9.487478
MacheteDesavic	0.98	21.64619
MacheteSemsen	1.03	10.63464

Chapter 5 trial 1

Cropping system	LER	CR
Wheat-chickpea	1.230456	2.083207

Chapter 5, trial 2

Row arrangement	Density	LER	CR
SAR	C100:W100	1.00	18
DAR	C100:W100	1.01	11
MIR	C100:W100	1.00	112
SAR	C100:W50	0.98	11
DAR	C100:W50	1.03	6
MIR	C100:W50	1.07	19
SAR	C50:W100	1.00	30
DAR	C50:W100	1.04	11
MIR	C50:W100	0.79	130
SAR	C50:W50	0.98	25
DAR	C50:W50	1.06	9
MIR	C50:W50	1.00	60
SAR	C75:W75	0.98	16
DAR	C75:W75	0.93	10
MIR	C75:W75	0.95	68

Single alternate rows (SAR); double alternate rows (DAR); mixed in a row (MIR); C = chickpea, W= wheat, the first number in each set is the percentage density of chickpea and the second number is the percentage of wheat in mixtures

Chapter 5, trial 3a under rainfed conditions

N	Treatment	LER	CR
0	c--w 100-50	1.01	2.3
1	c--w 100-50	0.95	3.2
0	c--w 50-50	0.94	3.9
1	c--w 50-50	0.97	4.0
0	c-w 100-100	0.96	3.2
1	c-w 100-100	0.96	3.9
0	c-w 3-2	0.93	2.1
1	c-w 3-2	0.90	1.8
0	c-w 4-2	0.70	0.6
1	c-w 4-2	0.81	0.7

Treatments: C = chickpea, W = wheat;

the first number in each set is the percentage density of chickpea and the second number is the percentage of wheat in mixtures;

0 = no fertiliser was applied; 1 = 40 kg ha^{-1} of N

Chapter 5, trial 3b under rainfed conditions

Nitrogen	Treatment	LER	CR
0	c-w 100-50	0.86	1.0
1	c-w 100-50	0.89	1.1
0	c-w 50-50	1.02	1.5
1	c-w 50-50	0.96	1.3
0	c-w 100-100	0.98	1.2
1	c-w 100-100	0.88	1.3
0	c-w 3-2	1.02	0.8
1	c-w 3-2	0.90	0.6
0	c-w 4-2	0.87	0.5
1	c-w 4-2	0.73	0.4

Treatments: C = chickpea, W= wheat;

the first number in each set is the percentage density of chickpea and the second number is the percentage of wheat in mixtures;

0 = no fertiliser was applied; 1= 40 kg ha^{-1} of N

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