Mixed cropping of barley *(Hordeum vulgare)* and wheat (*Triticum aestivum*) landraces in the central highlands of Eritrea

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Propositions

1. Mixed cropping of barley and wheat increases yield stability compared to barley or wheat sole crops.
   (this thesis)

2. The yield advantage of barley and wheat mixtures over their sole crops is due to niche differentiation, caused by differences in crop phenology and growth.
   (this thesis)

3. Mixed cropping can play a major role in the on-farm conservation of biodiversity.

4. In *hanfetz*, barley shows greater competitive ability than wheat; intra-specific competition is stronger than inter-specific competition for barley.

5. In subsistence farming, the main function of diversity of landraces is its buffering capacity against stress.

6. Where there's sweet, there's always bitter.

7. The man who removes a mountain begins by carrying away small stones.

8. Everything should be made as simple as possible, but not simpler.
   (Albert Einstein)

Propositions belonging to the PhD thesis of Woldeamlak A.
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Abstract

A common cropping system in the central highlands of Eritrea is mixed cropping of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)*; it is called *hanfetz* (Tigrigna word). Mixtures may give higher yield, better yield stability, better food quality and more animal feed. Factors affecting the productivity of mixtures include genotype combination, crop density and component crop ratio.

Grain yields differed significantly among genotype combinations in certain years. A combination of Ardu 12/60 + Kenya + Mana gave high mean grain yield (2009 kg ha^{-1}) and a relative yield advantage (RYT = 1.57) of 57% increase in grain yield over the sole crops. Harvest index, biomass, stand cover and thousand grain weight were well correlated with yield. Wheat plants were first suppressed by barley but later on grew taller than barley. The potential yield increase for mixtures over barley sole cropping may be associated with the relative height and higher light use (efficiency). Some genotype combinations also showed reasonable yield and resistance to stress with a drought susceptibility index < 1 such as IAR 485 + Mana (DSI=0.565).

Crop ratios of 100/50 (2275 kg ha^{-1}) and 100/25 (2241 kg ha^{-1}) were the best in grain yield when averaged over the three basic crop densities (100% = 100, 200 and 300 plants m^{-2}) and years. Barley showed greater competitive ability than wheat. For barley the intra-specific competition was more important than the inter-specific competition. In such studies, yield advantage can be either due to the density effect or complementary use of resources. The drawback of the additive design is that yield advantage may be partly due to increased density. However, niche differentiation showed that mixtures shared resources efficiently and the yield advantage was the result of complementary use of resources. In the study under drought stress, an additive ratio (higher density) did not result in higher total yield compared to that in replacement series. The niche differentiation in both years under drought stress also showed that the yield advantage was due to complementary use of resources among the crop species.

Stability analysis of barley and wheat mixtures on yield data from a large set of experiments showed that mixed cropping was significantly more stable than barley and wheat sole cropping. Some of the genotype combinations such as Ardu 12/60 + Kenya + Mana and Ardu 12/60 + Mana were more stable than others.

The most promising genotype combinations and crop ratios obtained from this study have to be verified on farm and demonstrated to farmers before the technology is released for use.

Key words: mixed cropping, genotype combinations, growth, light use efficiency, density, crop ratio, additive series, replacement series, drought stress, yield advantage, yield stability, competition, niche differentiation, barley, wheat.

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Contents

Chapter 1

General introduction

Overview of the agricultural systems in Eritrea, background of the project and justification

Eritrea

Eritrea is described below in terms of climate, soil, land use, water resources, agro-ecological zones, food production, production constraints and possible solutions.

Geographical location and climate

Eritrea is located in the Horn of Africa; it borders in the north to the Red Sea, in the south east to Djibouti, in the south to Ethiopia and in the west to Sudan.

The climate of Eritrea ranges from hot arid, adjacent to the Red Sea, to temperate sub-humid in isolated micro-catchments in the eastern escarpment. The mean annual temperature ranges from less than 19 °C in the highlands to more than 30 °C in the coastal areas. The Central Highlands Zone enjoys a cool semi-arid climate with lowest temperature occurring during December and January. The western lowlands of the country are relatively hot especially between April and June with temperatures up to 40 °C. The coastal areas have the highest temperatures of 25–40 °C between June and August. There are large temperature differences between day and night in the lowlands.

There are two rainy seasons namely the *short rainy season,* which is from March to April and the *main rainy season* from the end of June until the beginning of September. The total annual rainfall varies from less than 200 mm to more than 700 mm. There are even areas receiving higher rainfall above 1000 mm like the Green Belt Zone. These areas are located in the high elevated regions of the eastern escarpment of the central highlands. The coastal plains receive a small amount of rainfall below 150 mm per year. The rainy period for the northern coastal strip is from December to February (FAO, 1994).

The problem of inadequate total rainfall in some years is compounded by the variability in both total annual rainfall and its distribution. The intensity is also high in some years. This situation leads to stress periods affecting crop production.

Soils

There is limited information on the soils of Eritrea and they are described here in a generalised form (FAO, 1994; Azbaha et al., 1998).

Highlands

In the highlands, especially in the valleys, the soil is relatively deep, even though there are large areas that have either shallow or very shallow soil with stones on the surface. Such shallow soils are those where the top soil has been removed by erosion. According to the FAO soil classification system the major soils in the highlands are the Cambisols, Fluvisols, Luvisols, Nitosols and Vertisols. The soil reaction is mainly neutral to moderately alkaline. The organic matter content and nitrogen are described as low to medium; phosphorus and potassium are classified as low to high. Some of these soils are suitable for crop production apart from the fact that the top soil has been removed by erosion.

Lowlands
In the lowlands, the organic matter content and nitrogen are low to medium like in the highlands but the phosphorus is medium to high and potassium low to medium, thus quite different from the highlands. According to the FAO soil classification system, the soil orders found (Chromic luvisols, Eutric cambisols, Lithosols, Haplic xerosols) are different from those in the highlands. The soils are suitable for arable farming except in some pockets of lands that have a problem of salinity.

Coastal plains
The soils in the coastal plains are mainly characterised by the presence of sand dunes and loess materials. In many parts the soil is deep. The soils are different from those in the lowlands and the types are mostly Regosols or Lithosols. The alluvial soils of the coastal plain zone are deposited by streams and rivers from the highlands carrying enormous quantities of soil materials. The agricultural lands are thus mainly alluvial (fertile) because of the introduction of deposited soils together with irrigation water from rivers or streams. The soil reaction is mainly alkaline. If water for irrigation is available these soils are suitable for crop production.

Western plains
The western plains have primarily alluvial materials deposited either by rain or wind. There are also sand dunes accumulated in various places. The surface texture is loamy sand to sandy loam; silt loam; clay loam to sandy clay loam. Clay soils are also found in several pockets of the western plains. There is an increase of soluble salt deposits in some areas. The soil reaction is moderate alkaline even though there are areas, which are strong in alkalinity. The organic matter content and nitrogen are low; phosphorus and potassium are medium to high. Apart from the problem of salinity in some areas the soils are suitable for arable farming.

Land use

Out of the total area of 12,189,000 hectares of land only 3.42% is currently cultivated under rainfed conditions. The area utilised for irrigation is only 0.18% whereas the potential for irrigation is close to 4.92% out of the total area. There is still a potential for about 8.61% and 4.92% of the total area that can be utilised under rainfed and irrigated conditions respectively. The land use categories and the land area still to be utilised are shown in Table 1.1. This table shows the potential for expanding agricultural production both in terms of livestock (considering grassland areas) and crop production (Woldeamlak et al., 1994).

Water resources

There are potential drainage areas (which are the water source for rivers / streams) that can be used as a source of water for irrigation. For example the Mereb-Gash, Tekese-Setit and Anseba rivers that are seasonal but collect water from enormous catchment areas. There are a number of seasonal streams that can be used for irrigation. The ground water potential has not been systematically studied. Still, there are various bore holes and wells used for drinking and irrigation of mainly vegetables and fruits. The potential of bore holes and wells is extensive in alluvial and colluvial sediments which cover large areas of the plains of the central highlands, and south western lowlands zone. Small dams and reservoirs existing in different parts of the country could provide water to small scale irrigation schemes, which could be the source of substantial income from sales of vegetables and fruits.

Agro-ecological zones

FAO (1994) has classified Eritrea into six agro-ecological zones namely the Central Highland Zone (CHZ), Western Escarpment Zone (WEZ), South Western Lowland Zone (SWLZ), Green Belt Zone (GBZ), Coastal Plain Zone (CPZ) and North Western Lowlands Zone (NWLZ). The characteristics of selected potential

Table 1.1. Land resources in Eritrea 1998. The values in brackets are potential areas that could be utilised. Forest / woodlands include natural forest lands, plantations and woodlands.

Land use	Area ('000 ha)	Percentage
Cultivated land rainfed	417	3.42
Irrigated land	22	0.18
Forest / woodlands	736	6.03
Browsing / Grazing lands	6,967	57.16
Barren land	4,047	33.21
Potential rainfed land	(1,050)	(8.61)
Potential irrigated land	(600)	(4.92)
Total	12,189	100

Source: Ministry of Agriculture (1998)

zones are shown in Table 1.2. Most of the cultivated areas are found in the CHZ and SWLZ. Together these two zones account for 80% of the agricultural production. The Coastal Plain Zone is also one of the most important agricultural areas in the lowlands which has a potential for crop production mainly through irrigation.

Agricultural systems and crop production

Agriculture in Eritrea is the major occupation and source of income for about 80% of the population. Most people earn their living from arable farming, livestock rearing and fisheries (FAO, 1994). Crop production is mainly concentrated in the highlands (where 65% of the population lives) and in the lowlands. In Eritrea, the agricultural sector is given priority in order

- to increase the level of food security;
- to generate employment and increase income for the rural population;
- to supply raw materials to domestic agro-industries;
- to earn foreign exchange through export of high-value agricultural and agro-industrial products; and
- to protect and restore the environment.

Types of crops grown

Given the different altitudes and diverse agro-ecological conditions, a wide variety of cereals and horticultural crops is grown in Eritrea. In the highlands, typical crops are barley, *taff* (Tigrigna word for *Eragrostis teff*), wheat, oil seeds and legumes. In the lowlands, the main crops are sorghum, pearl millet, maize, sesame and groundnuts, and different types of fruits and vegetables (World Bank, 1992; CAAS, 1996). Out of the crops grown in Eritrea, sorghum is by far the most important crop in terms of total area followed by pearl millet, barley and *taff*. Maize and wheat are also among the important crops grown in the country.

Sesame is also important and is grown in the South-western lowlands. Cotton is another classical crop that can be produced using irrigation. These are high value crops both as a source of raw materials for industries and for export that deserve further attention.

Rainfed crop production is most likely to remain the main stay of Eritrea's agriculture but the role of irrigation is essential for the production of high value crops such as fruits and vegetables, cotton and sesame.

Level of production and yields

Statistics on total area cultivated and total production are approximate values from crop sampling surveys done by the Ministry of Agriculture, Eritrea. They are presented in Table 1.3.

Table 1.2. Characteristics of selected potential zones in relation to climate and production systems.

Zone	Type of production system	Rainfall mm	Altitude m	Main crops
Central Highland (CHZ)	Rainfed cereals / pulses based system	400-700	> 1500	barley, wheat, maize, sorghum, finger millet *taff* and grain legumes
South Western Lowland (SWLZ)	Crops/livestock mixed system, small scale irrigated horticultural system	> 400	600-700	sorghum, pearl millet and sesame, fruits, vegetables
Coastal Plain (CPZ)	Agropastoral spate irrigation, nomadic pastoralism	< 200	< 600 to sea level	sorghum, maize, pearl millet, vegetables

In general, the average yields of crops in the highlands are about 750 kg ha^{-1}. In the South western lowlands and coastal plains the yields reach on average 1,000 kg ha^{-1}. Generally yields are low and the yield of sorghum is highest with a mean of 1.04 t ha^{-1} followed by barley (0.99 t ha^{-1}) and *hanfetz* (Tigrigna word for barley and wheat mixtures) with a yield of 0.94 t ha^{-1}. The total area and production of crops in the different administrative zones and their production potential are given in Table 1.4.

Fruits and vegetables

Fruits and vegetables, both fresh and in processed form, have traditionally been part of Eritrean exports up to 1970s. This amounted to about 10% of the agro-industrial exports in which sesame (38%), dried lentils (18%), hides and skins and fish dominated. Exports were going to regional markets in Europe. Vegetables grown are mainly tomatoes, onions, sweet peppers (> 30,000 tons annually) and fruits include bananas, citrus, melons etc. (amounting to > 25,000 tons annually). The major problems in fruit and vegetable production are poor marketing channels, infrastructure, storage facilities etc. (FAO, 1994).

Food self sufficiency

In good years (i.e. years with above average rainfall (> 400 mm) and free from pests), the degree of food self sufficiency in Eritrea ranges from 50 to 75% (FAO, 1994). In 1991, only 10% of the national basic food needs was produced on 300,000 hectares of land (Appelton et al., 1992). In 1992, with heavy rain the production and total food supply were significantly higher and approximately

Table 1.3. Total area ('000 ha) and production ('000 t) and yield (t ha^{-1}) of cereals, pulses and oil seeds in Eritrea 1998-1999.

Crops	Total area			Total production			Yield		
	1998	1999	Mean	1998	1999	Mean	1998	1999	Mean
Taff	27.3	30.9	29.1	18.7	13.2	15.9	0.68	0.43	0.56
Wheat	25.2	24.7	25.0	23.0	19.0	21.0	0.91	0.77	0.84
Barley	45.6	43.4	44.5	56.6	31.8	44.2	1.24	0.73	0.99
Hanfetz	8.2	11.1	9.6	9.0	8.5	8.8	1.10	0.77	0.94
Maize	38.5	20.1	29.3	29	15.9	22.5	0.75	0.79	0.77
Sorghum	236.2	236.4	236.3	269.8	221.7	245.7	1.14	0.94	1.04
F. millet	13.0	15.5	14.3	7.6	5.4	6.5	0.58	0.35	0.47
P. millet	83.0	45.1	64.1	44.2	17.8	31.0	0.53	0.40	0.47
Pulses	6.9	15.0	11.0	3.3	7.7	5.5	0.47	0.51	0.49
Oil seeds	13.4	26.3	19.9	6.8	9.7	8.2	0.51	0.37	0.44
Total	497.4	468.4	482.9	467.9	350.7	409.3	----	-----	-----

Source: Ministry of Agriculture (1998-1999). Note: These are the latest data available; *hanfetz* (Tigrigna) means barley and wheat mixtures and *taff* is Tigrigna word for *Eragrostis teff*.

Table 1.4. Total area and production of crops grown by farmers in different administrative regions in Eritrea 1999. Note that this is the latest information available on crop area and production.

Administrative area	Total area		Total production		Yield
	'000 ha	%	'000 t	%	t ha^{-1}
Southern	128.1	27.4	63.0	18.0	0.49
Central	27.8	5.9	26.0	7.4	0.93
Gash-Barka	215.1	45.9	179.2	51.1	0.83
Southern Red Sea	39.3	8.4	51.2	14.6	1.30
Anseba	58.1	12.4	31.4	9.0	0.54
Total	468.4	100	350.7	100	----

Source: Ministry of Agriculture (1998-1999).

Table 1.5. Estimates of the total area ('000 ha) and production ('000 t) in Eritrea over time.

Year	Area	Production	Source
1975-86	239	188	Central Statistics Authority (1987)
1991	300	70 (10)*	Appleton et al. (1992)
1992	327	262 (30-40)	Ministry of Agriculture (1992)
1993-95	369	190 (25-30)	Ministry of Agriculture (1996)
1998	497	468 (85-90)	Ministry of Agriculture (1998)
1999	468	351 (60-65)	Ministry of Agriculture (1999)

*Note: The figures in parenthesis are percentages of the total food needs covered.

30–40% of the basic food needs was covered (Woldeamlak et al., 1994). However, in 1993-95 on average approximately 24–30% of the national food needs was produced locally. During the past few years agricultural production has increased. For example in the year 1998, it was estimated that up to about 85–90% of the national food needs was produced by local agriculture (Table 1.5).

Farming practices

Land preparation is mostly carried out with the traditional steel tipped plough drawn by a pair of oxen even though in some places camels are utilised for ploughing.

Usually the land is ploughed two to three times depending on the crop species and soil type. The frequency of ploughing for *taff* and fallowed land is higher. The last ploughing is carried out to cover the seed after planting which is done along the contour with a furrow for moisture conservation purpose. During the past 2–3 years machinery has been introduced into many potential farming areas where extensive lands have been ploughed. Seed is broadcasted by hand and chemical seed treatment or crop protection is not common. Chemical fertiliser and farm yard manure are mostly applied to cash crops. Cow dung is mainly dried as dung for fuel. Harvesting is by sickle and threshing is done by oxen trampling or by beating the grain using a stick as is the case with sorghum. Combine harvesters have been introduced to many potential areas during the past few years. Crops are mainly stored in large clay pots with a cover or in bags if the quantity is small. In hot areas, farmers store their products outside for aeration and sun drying to protect them against insect or fungus infestation. Single plants are selected by farmers from the field based on the physical characteristics of the seed and kept separately as seed for the next planting.

Livestock plays an important integral part in a farm household but the integration of livestock and crop production is not adequate. There are various breeds of livestock that have potential for meat and milk production. Oxen are used for draught, donkeys for transport and sheep, goats and poultry mainly for sale and domestic use. The lack of integration of livestock and crop production is mainly because of inadequate animal feed in terms of amount and quality; productivity and management of grasslands are poor.

Production constraints

Crop productivity has been low mainly due to drought stress, inappropriate crop management practices, occurrence of crop pests and diseases, lack of adequate farming technology and shortage of inputs. In some years, erratic rainfall is one of the most important constraints affecting crop production, which results in yield loss. The crop management practices are not adequate; inappropriate seeding rate (either high or low), lack of weeding and inadequate seed bed preparations are the most frequent errors. Insect pests attacking different crops also cause yield reductions or sometimes even crop failure. Shortage of inputs such as seeds, fertilisers, and crop protectants, and shortage of oxen for ploughing are major constraints for agricultural development.

There are several measures that can be implemented in order to solve these constraints. Some of them are:

- Improved protection against pests;
- Identification, testing and distribution of improved varieties or good quality landraces that are early maturing, high yielding, drought and pest resistance;
- Development of moisture conservation techniques such as the use of terraces in crop lands, ridges and furrows;
- Stimulation of dry planting so that crops can use even the first flush of rainfall and optimum amount of seeding rate for higher productivity; improved weeding practices;

- Enhancing cropping systems mainly intercropping / mixed cropping as a risk aversion mechanism, and agroforestry practices;
- Increased distribution of input such as chemicals (insects and weed control), seeds and fertilisers;
- Advancement of services such as machinery (ploughing and harvesting); transfer of technology and training.

Out of the above measures we will concentrate on cropping systems like mixed cropping. The common ones practised in Eritrea are *wahrer* (maize + beans; sorghum + beans; sorghum + millet), *sergen* (white + red *taff*) and *hanfetz* (barley and wheat mixtures). The statement of the problem will focus on barley and wheat mixed cropping.

Description of the problem

Mixed cropping of barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*) is practised under rainfed conditions in the Central highlands of Eritrea. The mixed cropping system has several advantages. Farmers can at least obtain a harvest of barley (the most drought resistant crop) if the season is dry and get a higher yield of both crops in mixtures if rainfall is normal. Mixtures show better resistance to biotic and abiotic stresses in adverse years. In years of adequate rainfall, the sole crop of barley does not make full use of the soil resources and of the potential offered by the growing season. So mixed cropping may result in higher yield stability and higher yield level as compared to sole cropping due to better utilisation of soil resources. The barley sole crop also provides low quality bread due to its low gluten content but when it is mixed with wheat the bread becomes tasteful, nutritious and more palatable. The crop residue is used for animal feed.

The most important factors that affect the productivity of barley and wheat mixed cropping in Eritrea are genotype combination, crop density, crop ratio and water use. Farmers use diverse landraces in barley and wheat mixed cropping, thus adding even more to the agro-biodiversity in the cropping system. The landraces used in mixtures differ in maturity, morphological characters (leaf area, plant height), drought resistance and yield potential. In some cases even mixtures of landraces for one of the two component crops or for both component crops are used. Farmers indicate that particular landraces or cultivars of barley and wheat combine better than others. The crop ratio commonly used is 67% barley and 33% wheat even though sometimes a crop ratio of 50% barley and 50% wheat is preferred. Additive crop combinations are not always desirable. Excessively dense plant stands can lead to weaker plants and can create a more adverse micro-environment.

There are very few scientific, analytical studies done on barley and wheat mixtures in Eritrea or elsewhere in Africa. Mixed cropping of these two crop species has not been addressed through appropriate field experimentation.

Performance of landrace combinations in mixtures has not been evaluated; optimum crop density and crop ratios have never been assessed; competition effects, yield advantage and stability have not been quantified. This thesis aims at filling this gap.

Objectives and hypotheses

Objectives

The objectives of the study are therefore:

- To identify varietal combinations of barley and wheat that produce high yields;
- To study the effect of population densities and proportions of component crops to optimise productivity of mixtures;
- To study the effect of drought stress on barley and wheat mixtures, testing various genotype combinations and component crop proportions so that the best genotype mixtures, crop densities and crop ratios may be identified under stress;
- To quantify and analyse yield stability and yield advantage of the mixtures; and
- To quantify competition effects in mixtures using descriptive crop modelling.

The hypotheses to be proved are listed below:

Hypotheses

- Mixed cropping is more stable than monocropping;
- Mixed cropping of barley and wheat results in a yield advantage;
- Specific genotype combinations give higher total yield than others under certain growing conditions based on optimal niche differentiation of the genotypes;
- Specific densities and crop ratios give optimal yield advantage;
- Specific crop ratios in additive series give more total biomass and grain yield than those in the replacement series under rainfed conditions;
- Barley is more competitive than wheat; niche differentiation in barley and wheat mixtures is due to complementary use of resources over time;
- Optimal genotype combinations and crop ratios depend on the sensitivity towards and timing of stress.

Approach of the study

A diagnostic farming systems survey was conducted in 1996 concentrating on parts of Eritrea where mixed cropping is important. After the survey, field experiments on genotype combinations, crop density and species proportions were conducted at two locations, (Halhale and Mendefera, both in Eritrea), in the rainy seasons of two years (1997 and 1998). Both research sites are south of Asmara. Moreover, during the off-season (dry period), drought stress trials including different genotype combinations and proportions of barley and wheat mixtures were conducted at one location (Halhale Research Station) for two years (1998 and 1999).

A brief description of the approaches used in this study is provided below.

Survey on mixed cropping of barley and wheat

A survey was performed using both a questionnaire and group discussions with farmers. The importance of mixed cropping, advantages of mixed cropping, farmers' practice in mixed cropping, biodiversity in relation to mixed cropping and constraints as well as future trends and research opportunities were identified.

Genotype combinations in barley and wheat mixtures

Three experiments were conducted at two sites (Halhale and Mendefera) under rainfed conditions for two seasons in 1997 and 1998 at Halhale and for one season in 1997 at Mendefera. Four barley and wheat landraces (or mixtures of landraces) were tested in all possible combinations with a total of 24 treatments out of which 16 were mixtures and 8 were sole crops.

Evaluation of crop densities and ratio in additive and replacement series in barley and wheat mixtures

Four experiments were done at two research sites (Halhale and Mendefera) during 1997 and 1998. Three densities and eleven proportions were tested in both additive and replacement series. A crop ratio of barley 67% / wheat 33%, farmers' practice, was included as a control.

Response of genotype combinations to drought stress in barley and wheat mixtures

Two experiments were conducted at Halhale Research Station during the off-seasons of 1998 and 1999 under irrigation. Halhale was taken as a site for such studies because of the availability of water and irrigation facilities. Three drought stress treatments and three genotypes of barley and of wheat in all possible combinations (nine mixtures and six sole crops) were tested.

Effect of drought stress on barley and wheat mixtures differing in crop ratio

Two experiments were laid out at Halhale Research Station, during the off-seasons of 1998 and 1999. Three drought stress treatments and eleven proportions in both additive and replacement series were evaluated.

Outline of the thesis

The general introductory chapter provided the general information on Eritrea, the background and justification of the experimental work, the outline of the problem, objectives and hypotheses of the research programme, and the approaches followed in the study.

In Chapter 2, the results of a diagnostic farming systems survey on barley and wheat mixtures (*hanfetz)* in the highlands of Eritrea are described. Several aspects of mixed farming are covered, including its importance, the arguments for mixed cropping, adaptation to stress conditions, production, uses of the crop and its residues, farmers' cultural practices, biodiversity in relation to the mixtures and future trends.

The productivity of the varietal mixtures in terms of total grain yield and total biomass is analysed in Chapter 3. Comparisons of sole cropping and mixed cropping are also included. Optimal genotype combinations are identified. A yield component analysis is carried out and the relationships of certain components with grain yield and biomass yield in mixtures are analysed.

Chapter 4 describes some crop ecological or crop physiological parameters related to growth and light use in barley and wheat mixtures. It explains the growth or behaviour of the genotypes as a sole crop or in mixtures in terms of leaf area, leaf area index, leaf area duration, and plant height. Moreover, it compares the light interception and light use efficiency of the two crop species in sole crop and in mixtures.

Relative yield advantage of mixtures in terms of biomass and grain yield was also quantified using the relative yield total (RYT) in Chapter 5. The chapter shows which varietal mixtures provide higher biomass or yield advantage relative to its sole crops. Competition relations as influenced by genotype combinations are quantified and dealt with in this chapter. The competition functions addressed include competition ratio and aggressivity values.

Chapter 6 covers the effect of drought stress on varietal mixtures. The productivity of the mixtures in biomass and grain yield grown under three drought stress situations is described. In addition, yield components and yield advantages in situations of drought stress are shown. A stress susceptibility index is assessed and yield losses due to drought stress are quantified for grain yield.

In Chapter 7, the effects of crop density on barley and wheat mixtures under additive and replacement designs are shown. The density and crop ratio that performs the best are identified. Yield advantage analyses based on land equivalent ratio (LER) for the additive series and on relative yield total (RYT) for replacement series are included. Niche differentiation and relative competitive ability of the two species analysed by the hyperbolic regression model are also part of this chapter.

In Chapter 8, the effect of drought stress under different additive and replacement series is analysed. The chapter shows the best yielding proportions under different irrigation regimes. The effects of crop ratio and drought stress on yield components, relative yield advantage, yield loss, competition and niche differentiation are also analysed.

Chapter 9 mainly deals with a yield stability test. It shows how mixed cropping of barley and wheat is stable and describes which genotype combinations are more stable than others. The aspect of genotype × environment interaction is also handled in this chapter. The stability performance of all the treatments in the mixed cropping experiments (such as genotype combinations, crop density and crop ratio both under rainfed and irrigation conditions) for the two locations are all combined in this chapter.

Finally, the results of the entire research project are discussed and summarised in a general discussion.

Biodiverse mixed cropping system of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* landraces in the highlands of Eritrea

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Abstract

Mixed cropping of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* is practised in the Central highlands of Eritrea. The grain yield is used for human consumption in the form of bread, kernels may also be roasted or used for the production of local beverages. The straw is used as animal feed. The mixtures are grown in a wide range of soils in areas where the rainfall ranges from 400 to 600 mm and maximum temperature is 27 °C. The advantages of growing the mixtures are higher total yield, better yield stability, better food quality, better animal feed and resistance to pests. Farmers in Eritrea have optimised crop proportions, landrace combinations and crop management of these mixtures of barley and wheat. The crop ratio commonly used is barley 67% and wheat 33%. Some landraces combine better than others and these combinations are most widely grown. Farmers sow the mixtures from mid June to mid July. Harvesting is done when barley is fully dried and when wheat becomes mature changing its canopy colour. Farmers in Eritrea will continue to grow mixtures as long as agriculture is characterised by low input and a high risk of drought. Mixed cropping can play a significant role in on farm conservation of landraces. The cropping system also provides a unique model for testing various relevant research questions relating to functionality of diversity.

Key words: biodiversity, mixed cropping, barley, wheat, Eritrea

Introduction

Mixed cropping is common practice in Africa, Asia and Latin America. It is defined as growing two or more crops simultaneously on the same land in the same growing season with an irregular broadcasting or mixing within a row (Andrews and Kassam, 1975; Chatterjee et al., 1993). A normal cropping system in the Central Highlands of Eritrea is mixed cropping of barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*); it is called *hanfetz* (Tigrigna word for any product with different racial backgrounds). This is a unique cropping system practised in very few locations in Africa but not elsewhere in the tropics. Other types of mixed cropping practised by farmers in Eritrea include *Wahrer*, a mixture of sorghum and pearl millet or sorghum and beans, and *Sergen*, a mixture of white and red *taff* (Tigrigna word for *Eragrostis teff*).

Most mixed cropping systems contain a legume, because in those cases there will be a clear benefit of mixing crops. In Eritrea, this is not always the case, as the prevailing stresses will condition the choice for crop mixtures. Andrews (1972) has mentioned that the benefits of mixed cropping can still be realised by growing mixtures of cereals.

The kernels from barley and wheat mixtures *(hanfetz)* are used for human consumption in the form of bread, locally known as *kitcha,* which is considered tasteful and nutritious. The kernels may also be roasted into a consumable product known as *kolo.* The kernels are also often used for the preparation of a local beverage, *sewa.* The straw is used for feed for animals, including cattle, sheep and goats.

This chapter analyses barley and wheat mixtures *(hanfetz)*, making use of (i) general information from literature; (ii) recent studies on Eritrean agriculture, (iii) information from recent surveys (which are partly unpublished); and (iv) own expertise with the system.

Production zones

Barley and wheat mixtures are mainly concentrated in the central highlands (Figure 2.1) in a rainfed cereal/pulse based land use system with annual rainfall ranging from 400 to 600 mm and in altitudes above 1500 m. The rainfall in July and August is the highest with a mean monthly rainfall of 146 mm and 111 mm, respectively (Figure 2.2A and B). The mixture is also produced in situations where rainfall is inadequate and is erratic both in amount and distribution. The potential evapotranspiration ranges between 1,300 and 1,800 mm per year. The mean temperature is around 18 °C (range 7 to 27 °C).

The mixture is grown in a wide range of soil types. However, the most important soils where the mixture is grown, are the brown clay soils with adequate water holding capacity. It is also grown in alluvial soils that are deposited on river basins occurring in the valley. Vertisols *(walaka)* or black clay soils, which are favourable especially during periods of lower rainfall because of their high water holding capacity, are utilised for mixed cropping as well. During periods of higher rainfall the sandy and non-stony soil types are suitable for growing the mixtures.

Advantages of *hanfetz*

In general, there are several advantages of mixed cropping in terms of yield, yield stability, quality of diet, animal feed from crop residues and control of biotic and abiotic stresses. In a number of surveys in Eritrea, farmers have indicated several advantages with respect to the cultivation of barley and wheat mixtures, like higher total yield, yield stability, preferred diet, animal feed, resistance to diseases, insects and weeds. These advantages are described below.

Yield advantage

The entire crop yield of *hanfetz* is usually higher than for barley or wheat monoculture. In addition, the flour quantity per unit of harvested product is higher than for a sole barley crop. Mixed cropping can result in a yield advantage as crop mixtures may allow each individual crop to exploit available resources of the niche to which it is adopted best. Mixtures may thus even yield nearly 50% higher than their component averages (Reddy and Reddy, 1981; Willey, 1979). This better exploitation of resources may be enhanced by mixing landraces or genotypes as is the case for *hanfetz*. Factors contributing to this yield advantage are:

- Better utilisation of soil borne resources by mixtures, due to niche differentiation;
- Better lodging resistance of barley due to the support given by the more sturdy wheat;
- Prolonged yielding ability since the early maturing barley may be overgrown by the later and taller wheat, thus lengthening the duration of the presence of a green canopy in the field;
- Better resistance of the mixture to drought and other (abiotic and biotic) stresses.

Yield stability

The barley/wheat mixture is grown as an insurance against drought. If one component crop fails or grows poorly, the other component makes use of the additional space and resources and may (partly) compensate for potential yield loss. This phenomenon depends on differences in either growth rate, duration of the growth cycle, resistance against drought or in timing of sensitive developmental stages. Barley is the most dependable cereal under extreme conditions of drought, because its precocity provides a mechanism to escape or avoid drought. It will also stand more frost or heat under semi-arid conditions.

However, a monoculture of barley provides low quality bread due to its low gluten content. Moreover, in years of adequate rains, the monoculture of barley does not make full use of the resources and potential offered by the growing season, therefore its mixture with wheat may produce higher yield.

Crop mixtures are not always successful as they can reduce yield stability if the component species are not complementary or if plant populations (especially component crop's proportions used) are not optimal.

Diet

Bread made out of the mixtures is preferable as it is more tasteful, palatable and digestible than that made of barley alone.

Animal feed

Crop residues are a major source of animal feed in Eritrea. The amount of straw of the mixtures is larger than that of barley alone. Barley straw, however, is considered to be more palatable as livestock feed.

Diseases, insect pests and weeds

The major diseases of the mixtures are fungal diseases (leaf spot, scald and rust). Their severity depends on the rainfall. Main insect pests include aphids (barley and wheat), barley fly (barley), army worm (barley and wheat), etc. About 60% of farmers claim that the severity of disease and insect problems in the mixture is lower than that in monocrops. This farmers' report requires confirmation through special field studies. Wolf (1985) has also suggested that the disease and insect resistance of mixtures is better. Midmore and Alcazar (1991) have shown that the leaf miner population in potato to be lower in mixed cropping than in the monocropping. The incidence of weeds, mainly wild oats, is also lower than in sole cropping, probably because mixed cropping provides a more competitive community of crop plants both in space and time as also suggested by Willey (1979a,b).

Production of barley and wheat mixtures

The details of total area, production and yield from 1994 to 1999 is shown in Figure 2.2C and D. In the period of 1994 until 1999, the mean area under barley and wheat mixtures was slightly above 7,160 hectares. This corresponded to 28% of the area under wheat and 16% of the area cultivated with barley (Table 2.1). The total area cultivated depends on the onset of seasonal rains. If the rain starts early, farmers plant maize and sorghum, if it starts late, wheat, barley or *hanfetz* will be sown. In the period 1994–99, the mean production reached around 6,200 tons annually. This is 30% and 14% of the production of wheat and barley respectively. Due to poor rainfall only approximately 2,300 tons were produced in 1995. During the year 1998, mixed cropping of barley and wheat was grown in 8,193 hectares of land with a total production of 8,992 tons. The annual area and production in both 1998 and 1999 were higher than in previous years. Especially in years with insufficient rainfall the production of mixtures was better than the production of a single crop of wheat or barley. On average, yields per hectare of *hanfetz* are estimated as 20% and 11% higher than the yields of monocultures of wheat and barley, respectively.

Factors affecting production of *hanfetz*

In any mixed cropping system various factors affect the productivity including genotype composition, crop density and component crop ratio, plant arrangement and spacing, availability of water, relative sowing date of component crops, etc. Out of these factors only a few are relevant for this chapter. Sowing dates for the component crops of barley and wheat mixtures are the same as the two crops are sown simultaneously on the same date. The plant arrangement is not critical as all farmers use broadcasting of seed. The other factors listed affecting productivity of barley and wheat mixtures are described below. They may contribute to increasing the productivity of the mixtures in Eritrea. We describe them here in general terms and in more detail later in this chapter.

Genotype composition

It is believed that some landraces in the mixtures combine better than others. Selecting the right varietal mixtures offers a wide scope for yield improvement as it does in sole cropping. The behaviour of mixed stands is not predictable from the behaviour of components in pure stands. According to Willey (1979a,b) a genotype should minimise intercrop competition and maximise complementary effects. These two demands, however, are not easy to comply with. The morphological characters of the varieties should stress their differential ability to exploit their own ecological niche for higher yield (Schoonhoven and Almekinders, 1995).

At the same time the barley and wheat mixed cropping system can be crucial for *in situ* conservation of biodiversity and genetic resources.

Crop ratio

Farmers in Eritrea use a ratio of 67% barley and 33% wheat and sometimes 50% barley and 50% wheat in a replacement series. Additive ratios are not known in practice. Determining the overall mixture densities and the relative ratio of component crops and those of their genotypes is important in analysing the yield advantages of mixtures (Willey and Osiru, 1972a,b; Willey, 1979a,b).

Availability of water

Water is the most important limiting soil factor in rainfed semi-arid regions where mixed cropping is intensively practised. This is certainly also true in the highlands of Eritrea. Francis and Stern (1987) indicate that crops compete better for available water when their initial growth rate is fast, when they mature early and when they have a large root system. On the other hand they need to be able to save enough water to complete their growth cycle and mature. It is not known which mixtures are most productive under drought stress in Eritrea.

Genetic diversity and the mixtures

Landraces are still used extensively in subsistence agriculture in the tropics (van Hoof, 1987) and are widely used in mixed cropping. Even mixtures of landraces of the same species may be used. In barley and wheat mixtures, crop diversity is used to the maximum, even though both component crops are self-pollinators.

There is a genetic wealth of crop germplasm of barley and wheat in Eritrea (Table 2.2). The mixed cropping system *(hanfetz)*, may contribute to utilising and maintaining the existing diversity. Over time farmers in Eritrea have evaluated their mixtures and then composed the most favourable crop and landrace combination in the barley and wheat mixed cropping system. Farmers indicate that particular landraces of barley and wheat combine well, whereas others do not. A particular mixture of barley and wheat may be composed of for instance one barley and one wheat landrace or one barley and two wheat landraces. Table 2.3 gives an illustration of some of the landraces used in the cropping system. The cropping system in itself contributes to the maintenance of this functional diversity.

In subsistence farming stability in yield is more important than maximising yield. Diversity of landraces acts as a buffer against drought and is considered effective in order to obtain yield stability (ICARDA, 1995). In general the landraces used differ in maturity, drought resistance and yield potential. Within the crop species of *hanfetz*, genotypic differences among landraces indeed exist; the barley landrace, Yeha is early maturing (and thus drought avoiding) with high incidence of lodging; Kuunto is late maturing but high yielding. Similarly in wheat, Mana is early maturing as compared to other wheat genotypes whereas the landrace Itay/Kenya is late maturing. So the landraces used in the mixtures differ in maturity, drought resistance, yield potential and morphological characters (Table 2.3 and Figure 2.3).

Table 2.1. Estimates of mean total area, production and yield per hectare of the mixtures over the period 1994–99 in the highlands of Eritrea. The data estimates are based on the annual crop production assessment of the Ministry of Agriculture.

	Mixture	*Mixture* % of wheat	*Mixture* % of barley
Area	7,160 ha	28% of wheat area	16% of barley area
Production	6,200 t	30% of wheat production	14% of barley production
Yield	0.84 t ha^{-1}	20% > wheat monoculture	11% > barley monoculture

Source: Ministry of Agriculture (1994–1999)

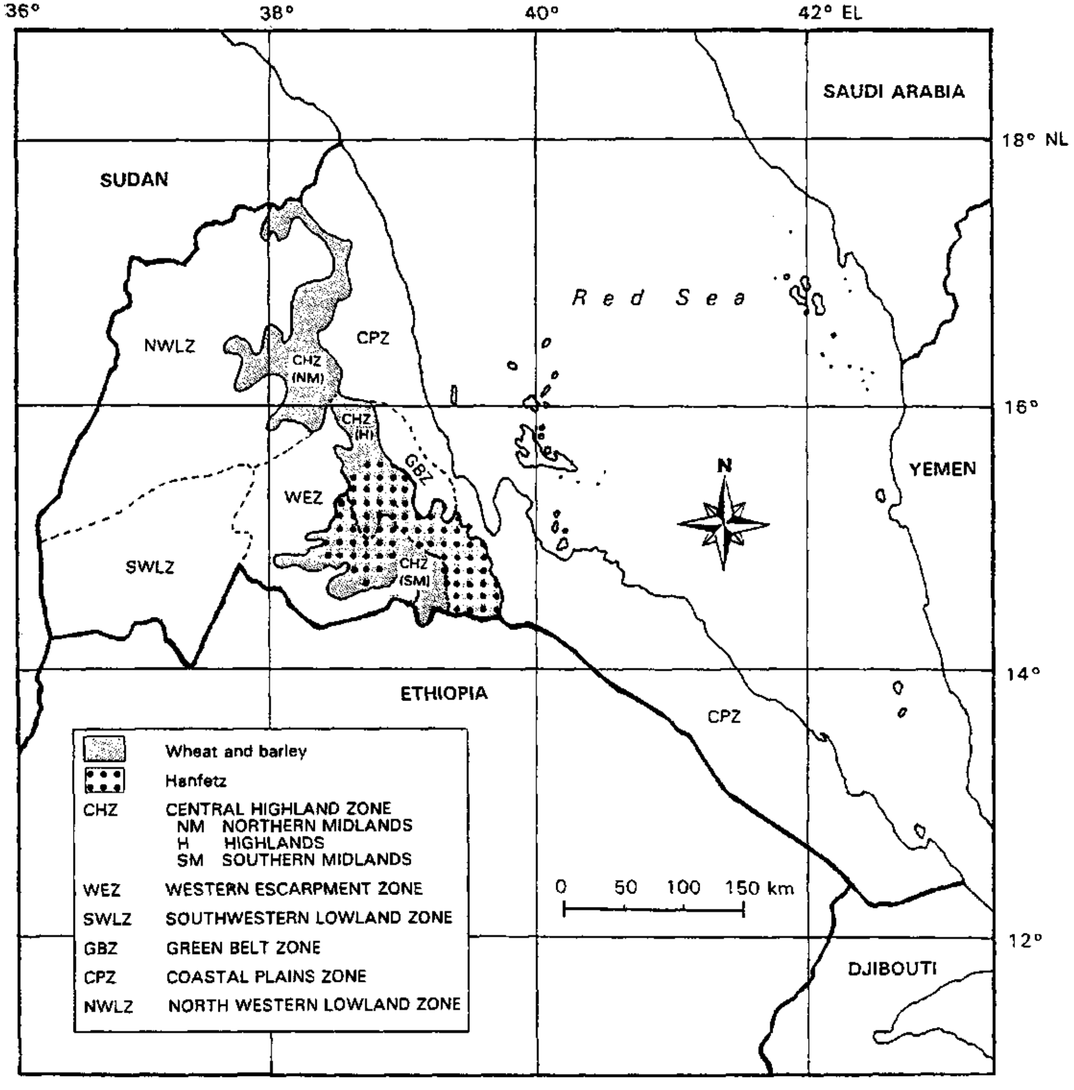

Figure 2.1. Major growing areas of *hanfetz* (barley and wheat mixtures) in Eritrea.

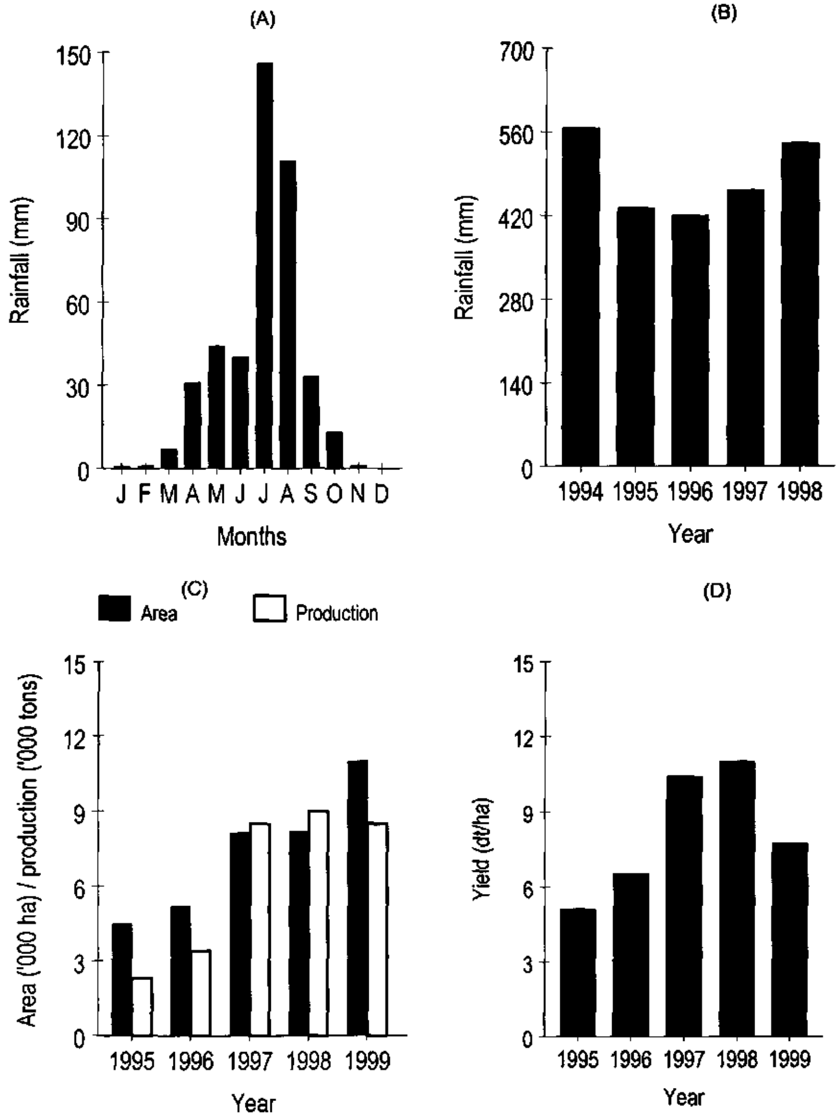

Figure 2.2. (A) Mean monthly rainfall in the *hanfetz* growing areas of Eritrea; (B) Mean annual rainfall in the *hanfetz* growing areas of Eritrea; (C) Trends in area ('000 hectare) and production ('000 tons) of barley and wheat mixtures in the highlands of Eritrea; (D) Trends in yield (dt ha^{-1}) in barley and wheat mixtures in the highlands of Eritrea. Along the y axis dt ha^{-1} is equivalent to quintals ha^{-1}.

Table 2.2. Diversity of crop species in Eritrea.

High diversity	**Medium diversity**
Taff *(Eragrostis teff)*	Grasspea *(Lathyrus sativus)*
Wheat *(Triticum aestivum)*	Chickpea *(Cicer arientinum)*
Barley *(Hordeum vulgare)*	Field pea *(Pisum sativum)*
Sorghum *(Sorghum bicolor)*	Finger milllet *(Eleusine coracana)*
Low diversity	**Traces of diversity**
Lentil *(Lens esculenta)*	Coffee *(Coffee arabica)*

Source: Melak (1975) and Melaku (1988)

Table 2.3. Landraces used in barley and wheat mixtures.

Crop	Landrace	Characteristics
Barley	Yeha	Early maturing, drought tolerant, two rows, white seeds, frost tolerant
	Kuunto	Late maturing, less drought tolerant, six rows, high yielding
Wheat	Itay/Kenya	Late maturing, no awns, white seeds, high yielding
	Mana	Early maturing, tall, white seeds
	Russo	Late maturing, long awns, flat heads, big seeds, high yielding, susceptible to rust

Table 2.4. Comparison of seeding rates and fertiliser rates (kg ha^{-1}) for barley, wheat and mixtures.

Crop	Seeding rate (kg ha^{-1})		Fertiliser rate (kg ha^{-1})
	Range	Mean	Mean
Wheat	80-200	120	76
Barley	160-280	200	92
Mixture	80-250	180	35

Cultural practices of the mixtures

Seed bed preparations

Basic cultivation is carried out with a wooden plough drawn by a pair of oxen. Ploughing is done three times for wheat and barley mixtures. The first ploughing is done in January after harvesting and the second one in May in order to eliminate some weeds that appear in the field. The third ploughing is done after sowing to cover the seed. When the land is left fallow for some years even 4–5 times ploughing may be required in order to avoid clods and to make the seed bed fine. The seed bed preparation is not much different from that practised in barley and wheat monocropping.

Sowing

The mixture is sown from mid June to mid July. Sorghum is sown earlier and if the rains are late or if sorghum fails to germinate it is replaced by either barley, wheat or mixtures. The seed is usually broadcasted by hand; row planting is not common.

Seeding rate

Farmers traditionally use a seeding rate for barley ranging from 160–280 kg ha^{-1} with a mean of 200 kg ha^{-1}, this can be considered as high. A relatively high seeding rate is used in order to get good stand to complete with weeds and to obtain high grain and straw yields.

The seeding rate for wheat used by farmers is relatively lower than for barley due to the higher proportion of tillers that successfully produce spikes (Table 2.4). The mixture requires a seeding rate from 80 to 250 kg ha^{-1}, the mean being 180 kg ha^{-1}. The amount of seed required for a mixed crop is lower than that of a barley monocrop because of the inclusion of wheat in the mixtures and farmers consider wheat to be stronger in tillering. The amount of seed provides a good groundcover to compete with weeds and results in adequate numbers of ears.

Fertilisers

Chemical fertilisers and farm yard manure are used in wheat and barley mixtures. Depending on the economic status about 57% of the farmers apply fertilisers, usually Di-Ammonium Phosphate (DAP) at the rate of 20 to 60 kg ha^{-1} with a mean rate of 35 kg ha^{-1}. A comparison of the fertiliser rates for the mixture and the other cereals is shown in Table 2.4. The fertiliser is broadcasted at sowing and incorporated in the soil with an oxen plough. Fertiliser application mainly occurs in areas with black soil because its adequate water holding capacity will enhance the use efficiency. Farm yard manure is not so often applied for barley and mixtures as priority is given to vegetables; moreover the limited amounts of animal waste available are often dried into a dung to be used for fuel, to solve the problem of firewood scarcity in most of the highlands.

Figure 2.3. Landraces of barley and wheat used for mixtures. In the figure from left to right are barley landraces Yeha and Kuunto and wheat landraces Kenya, Mana and Russo.

Rotation

The mixture of barley and wheat (hanfetz) is incorporated in various crop rotation cycles such as

In the cereal-based system with a four year cycle:
hanfetz → *taff* → linseed → barley or wheat → *hanfetz*

In the cereal/pulse-based system with a four year cycle:
hanfetz → wheat → fallow or pulses → pulses → *hanfetz*

In the cereal/ pulse-based system with a five year cycle:
hanfetz → sorghum → *taff* → linseed → beans or fallow → *hanfetz*

The rotation cycle is based on the need to conserve moisture, to improve soil fertility and to prevent soil erosion. Legumes in the rotation cycle contribute to the soil fertility through symbiotic nitrogen fixation.

Harvesting, threshing and storage

Farmers harvest the crop mixtures with a sickle by cutting the stems close to the groundlevel in order to maximise straw yield. The harvest period is from the end of October to mid November. Harvesting is done when barley is fully dried and when wheat becomes mature changing its canopy colour into yellowish. Farmers harvest early in the morning when it is humid in order to reduce shattering losses. If maturity is not uniform in the field then harvesting is performed patchwise; the mature patches are harvested and left to be threshed later when harvesting is complete. The harvested material is piled for two weeks if it is moist until it has lost moisture. It is threshed by trampling with oxen on a smoothed clay floor, it is then winnowed by hand. Farmers store the seed in bulk using traditional facilities made of earth mud. The seed to be used for the next planting is stored separately in a bag or in the traditional earth mud. Farmers also buy seeds of wheat and barley from the market and mix them in the ratio mentioned earlier.

Future trends

Farmers will continue to grow barley and wheat mixtures as long as the agriculture is a low input one with a high risk of drought. It currently acts as an emergency and an insurance crop and it is characterised by a relatively stable yield under potentially disastrous conditions. When irrigation and fertiliser become available, the advantage of the crop mixture in relation to yield and yield stability becomes less significant. The environment will be controlled to a higher degree and therefore become more uniform.

An increase in the market orientation of the production will favour monocropping over mixed cropping. At present, the mixture is used for home consumption; mixtures are rarely sold on the markets. When production levels would increase, surpluses become available for commercialisation and surplus of monocrop production may be fetching better prices. Mechanised harvesting would also favour monocropping; differences in plant height and differentiated maturity of the barley and wheat are disadvantageous in such a situation.

Maintaining the biological diversity of crop species is given much attention in Eritrea. In the effort to conserve plant genetic resources *in situ* conservation has become a major strategy. Mixed cropping may play a major role in on-farm conservation of landraces.

It may be concluded that the barley and wheat mixtures are well adopted to low input agriculture in complex, diverse and risk-prone environments. The mixed cropping will be replaced by monocropping of one of the component crops as the level of inputs is increased and thus the environmental variation is reduced. Therefore much attention in research concerns the agronomic background of the cropping system to support and strengthen farmers' management of landraces of barley and wheat under mixed cropping.

Opportunities for research

Apart from the research on mixed cropping described in this thesis, the cropping system provides a unique opportunity and model for testing other relevant research questions related to agro(bio)diversity. It may be researched further to allow scientists to answer questions such as:

- How much variation do we need to obtain yield stability in an agro-ecosystem?
- How does abiotic stress affect the frequencies of component crops and the genotype frequencies with component crops?
- Can we manipulate diversity to such an extent that it will serve as a tool to manage stress and abiotic variation in the agro-ecosystem?

Effect of genotype combination on the productivity of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* mixtures: Biomass, grain yield and yield component analysis

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Abstract

Mixed cropping experiments with barley and wheat genotypes were conducted at Halhale Research Station and a site near Mendefera, Eritrea, in two years, in order to identify the best genotype combinations of barley and wheat. Four barley and four wheat genotypes, landraces or combinations of landraces were tested in all possible combinations in a Randomised Complete Block Design with 4 replications and a plot size of 3.0 m^2. Data collected included biomass, grain yield, yield components, crop phenology, stand cover and harvest index. Regression analysis for the relationship between yield components and grain yield and biomass was carried out. Total grain yield differed significantly among the genotype combinations in both years. Kuunto (barley) and Mana (wheat) performed best in mixtures. The control mixture, Yeha + Mana, was surpassed by other varietal mixtures. Total grain yield was highest in a mixture of Ardu 12/60 + Kenya + Mana followed by Kuunto + Mana at Halhale. The crop characteristics with the best overall correlation with grain yield were harvest index (r=0.615**), biomass (r=0.641**), stand cover (r=0.441*) and thousand grain weight (r=0.578*). This set of experiments showed that the best genotype combinations differ from what farmers are currently using. Verification on farmers' fields of these results is advocated.

Key words: grain yield, biomass, yield components, mixed cropping, barley, wheat, landraces, genotypes, Eritrea

Introduction

Barley (*Hordeum vulgare*) is one of the most important cereal crops grown in the highlands of Eritrea. It is the most reliable cereal crop when drought or frost stress occurs. Barley matures earlier and is harvested earlier than other cereals thus escaping stress. Wheat (*Triticum aestivum*) is also grown in the highlands of Eritrea although it is not as important as barley in terms of total area and production. It is less drought tolerant and matures later than barley.

In mixed cropping, risk or failure due to adverse weather may be avoided. Mixed cropping is therefore considered as a tool to minimise risks in arable farming. Under mixed cropping resources are also better utilised and the prospects of obtaining good combined yields of the component crops are higher than in monocropping (Gill and Patil, 1983).

Genotype composition is one of the factors affecting productivity of barley and wheat mixtures. Farmers in Eritrea indicate that some genotypes of barley and wheat are better combiners than others (Woldeamlak and Struik, 2000). The component crops should exploit different ecological niches and complement each other in morphology, architecture, phenology and development, thus making better overall use of resources when growing together than when growing separately (Natarajan et al., 1980). Better exploitation of resources can also take place over time, by growing component crops differing in maturity. Indeed, Francis and Stern (1987) found that selecting component crops or genotypes differing in maturity may help the component crops to complement each other rather than compete for the same resources. Such a situation may also occur in barley and wheat mixtures.

Harper (1963) emphasised that the behaviour of a variety in mixed stands is not the same as its behaviour in pure stands but that this difference depended on the type of crop species. For example, Nielsen et al. (1981) observed yield reductions in oats and alfalfa mixtures due to the type of genotype combination. Several studies on mixed cropping have been able to identify suitable genotype combinations of various crop species. Other examples can be found for maize and soybean intercropping (Wiebe et al., 1963); for mustard and potato (Rathi et al., 1992); cowpea and pearl millet (Reddy et al., 1990); and pearl millet and cluster bean (Bhadoria et al., 1992).

This chapter is on the performance of barley and wheat genotypes in a mixed cropping system. It compares and analyses the behaviour of genotypes in sole crop and mixture in biomass and grain yield and identifies the genotype combinations that provide highest total biomass and grain yields.

Materials and Methods

Location

The study on mixed cropping of barley and wheat was conducted during the rainy seasons of 1997 and 1998. Three experiments were carried out at two sites and during two years. The first site (two experiments) was the Halhale Research Station, Eritrea, at an altitude of 1997 m above sea level on a silty clay soil, slightly alkaline in reaction, and free from salt. The annual rainfall during the two growing periods was 580 mm in 1997 and 656 mm in 1998. At the Halhale site, there was snow damage in 1998 during the knee height stage but crops were able to regenerate and grow very well. The second site (one experiment) was at a field station close to Mendefera (San Georgio) at an altitude of 1900 m above sea level; it has a black clay soil; rainfall was 710 mm in 1997.

Genotypes and genotype combinations

A total of 24 treatments were present in these three trials with 16 mixtures (4×4) and 8 sole crops (4×2). The genotypes (or genotype mixtures) tested were Yeha, Kuunto, Ardu 12/60 and IARH 485 (for barley) and Mana, Kenya + Mana, K

6290 and HAR 416 (for wheat) in all possible combinations. A mixture of Yeha + Mana (most common mixture in farmers' practice), was taken as a control. Seed was broadcasted at the end of June at both locations in the standard ratio of barley 67%: wheat 33%. A basal dressing of fertiliser at the rate 100 kg ha^{-1} Di-Ammonium Phosphate (46% P_2O_5 and 18% N) and 50 kg ha^{-1} Urea was applied and incorporated in the soil at planting.

Design and analysis

All experiments were laid out in a Randomised Complete Block Design with 4 replications and an individual plot size of 3.0 m^2. Data were analysed by a standard Analysis of Variance using MSTAT-C and by a Least Significant Difference test for comparing the means. The analysis was done for results of the sole crops separately, for the component yields of the two crop species, for the total mixture yields and also for the two years in the case of Halhale. Regression analysis between various parameters was also carried out.

Data collection

The plants of the component crops in the mixtures were harvested at physiological maturity and weighed at about 87.5% dry matter concentration as confirmed by sample analysis and drying. Data reported in this chapter are based on this dry matter concentration. The biomass of the component crops was added to get the total above-ground biomass of each mixture and was converted to kg ha^{-1}. For each genotype of each component crop, also the grains were harvested, threshed and weighed separately. Grain yield was converted into kg ha^{-1}. The grain yield of each genotype of the component crop in the mixture was added to get the total grain yield of the mixture.

Grain yield is the product of three yield components, namely number of ears per unit area, number of kernels ear^{-1} and grain weight. The number of ears m^{-2} is the total number of ears of the component mixtures counted in one m^2 using a quadrant. The numbers per component crop were added to obtain the total number of ears m^{-2} of the mixtures. The number of kernels ear^{-1} was counted from five ears of each of the component crops per plot. Ear size (cm ear^{-1}) was measured by taking five spikes of the component crop species in mixtures. Thousand grain weight was estimated by counting 200 seeds of each component crops, weighing them and multiplying the weight of 200 seeds by 5 to get the weight of 1000 seeds in grams.

Other relevant agronomic characters were recorded or calculated as well. These included stand cover, plant height, percentage lodging, crop phenology, and harvest index. Stand cover was estimated visually in % at seedling stage based on groundcover in the plots. Harvest index (%) was estimated as the ratio of the grain yield to the above-ground biomass.

Results

Biomass

The results on biomass of the experiments at the Halhale Research Station are given in Tables 3.1 and 3.2 and those at Mendefera (San Georgio) are shown in Tables 3.5 and 3.6. There were significant differences among the barley genotypes in biomass in the sole crop, in biomass of the barley component and in biomass of total mixtures (in both years) at Halhale while the genotype effect was not significant for the barley genotypes in the sole crop at Mendefera (Tables 3.1 and 3.5).

Kuunto gave the highest biomass in sole cropping at both sites, and for Halhale in both years (Tables 3.1 and 3.5). The average component biomass yield in mixtures and the average total mixture yield of barley genotypes were highest for Kuunto. Average total mixture biomass yields were higher than sole crop biomass in 1997 and 1998. Especially barley genotypes performed well as component crops in mixtures as compared to biomass yields in sole crops (Table 3.1).

No significant difference was obtained in the biomass of wheat genotypes in 1997 and 1998 in sole cropping at Halhale (Tables 3.1). Mana performed best as a component crop in mixtures and in total mixture biomass yields (Table 3.1). At the site Mendefera (San Georgio), wheat genotypes Mana (or Mana + Kenya) performed best in sole cropping, whereas wheat genotypes K 6290 and Mana performed best in mixtures (Table 3.5).

When considering the different genotype combinations separately, statistically significant differences in biomass were found among the genotype combinations. The results of the 16 different genotype combinations are shown in Tables 3.2 and 3.6 for Halhale and Mendefera, respectively. When averaged over two years at Halhale, the total biomass was highest for Kuunto + Mana (8800 kg ha^{-1}) and Kuunto + HAR 416 (8005 kg ha^{-1}). The classical combinations Yeha + Mana was surpassed by other genotype combinations (Table 3.2). At the Mendefera site, a mixture of Kuunto + K 6290 showed the highest biomass (9394 kg ha^{-1}), followed by Yeha + Mana (8093 kg ha^{-1}) and Kuunto + HAR 416 (8000 kg ha^{-1}) (Table 3.6). In all cases, a mixture of Yeha + Mana was one of the best performing combinations, with regards to biomass, but in all experiments it was surpassed by other combinations.

The barley genotypes showing higher biomass when grown as a sole crop did not show higher biomass in mixtures for both component crops in 1997. The genotypes that performed best as sole crop did not perform equally well as component crop. However, in 1998, the genotypes performing well in monocropping also performed well in mixtures for both component crops (Figure 3.1).

Grain yield

The results of the grain yield at Halhale are shown in Tables 3.3 and 3.4 and those of Mendefera are in Tables 3.5 and 3.6. There was significant variation in grain yield among the barley genotypes grown as sole crop and grown in mixtures at both locations in both years. The only exception was found for the genotypic differences in total mixture yields at Halhale in 1998. At Halhale, Kuunto was one of the best in grain yield, averaged over two years both in sole cropping and in mixtures (Table 3.3). At Mendefera, Kuunto also performed best as a sole crop, but Yeha was the best in grain yield as a component crop in mixtures, both for the component yield (2012 kg ha^{-1}) and for the total mixture yield (2179 kg ha^{-1}) (Table 3.5).

At Halhale, the standard genotype Yeha was outyielded by the other barley genotypes both in sole cropping and in mixtures. The grain yield for mixtures with Kuunto was higher than the grain yield of a sole crop of Kuunto. The same holds for all barley genotypes. They all had higher average total mixture yields than sole crop yields. With respect to grain yield, wheat genotypes were severely dominated by barley. This is especially visible from the component yields of the two crops. There was no variation in grain yield among the wheat genotypes either in sole cropping or in mixed cropping at Halhale except in 1998, when significant variation among the wheat genotypes was observed in the wheat component yields in the mixtures (Table 3.3).

At Mendefera, there were significant differences in grain yield for the crop component yields and the total mixture yields among the barley genotypes. There were no significant differences among wheat genotypes (Table 3.5). There was also significant variation among the genotype combinations in grain yield also at Halhale in 1997 and 1998. In 1997, a mixture of Ardu 12/60 + Kenya + Mana was the best yielding (2590 kg ha^{-1}). Also other combinations Ardu 12/60 + K 6290 (2143 kg ha^{-1}), and Kuunto + Mana (2044 kg ha^{-1}) gave relatively high grain yields at Halhale. In 1998, a mixture of Kuunto + K 6290 (1923 kg ha^{-1}) and Kuunto + HAR 416 (1883 kg ha^{-1}) were among the best yielding genotype combinations. When averaged over the two years, a mixture of Ardu 12/60 + Kenya + Mana was the best with a yield of 2009 kg ha^{-1} followed by Kuunto + Mana with 1837 kg ha^{-1} (Table 3.4).

There were significant yield differences among the genotype combinations at Mendefera. The total grain yield was highest for Yeha + Mana (2427 kg ha^{-1}) and Kuunto + K 6290 (2358 kg ha^{-1}). The genotype combinations that gave higher yields at Mendefera were different from those at Halhale (Tables 3.4 and 3.6). In Mendefera, mixtures containing the barley genotype IAR 485 generally

Table 3.1. Biomass yield (kg ha^{-1}) of barley and wheat genotypes grown as sole crop or in mixtures at Halhale Research Station, Eritrea, 1997 and 1998. Average component crop yield in mixtures (CCM) is the mean biomass of the genotypes as component crops, averaged over the different genotypes of the other crop. Average total biomass yield of the mixtures (T) is the mean biomass yield of the different genotypes in mixtures, averaged over the genotypes of the other component crop. The genotypes are listed in descending order based on the mean biomass of two cropping seasons under sole cropping. Means followed by the same letter are statistically not significantly different. Values without letters are statistically not significant.

Genotype	Sole crop			CCM			T		
	1997	1998	Mean	1997	1998	Mean	1997	1998	Mean
Barley									
Kuunto	8333	6833 a	7583 a	7083 a	6625 a	6969 a	7680 a	8179 a	7930 a
Yeha	5750	3917 b	4834 b	6792 a	2959 b	4876 b	7472 a	5375 b	6424 b
Ardu 12/60	5752	2668 b	4210 b	6657 a	1896 c	4277 b	8010 a	5033 b	6522 b
IAR485	4750	3667 b	4209 b	3656 b	3438 b	3547 c	4800 b	6437 b	5619 c
Mean	6146	4271	5209	6047	3729	4891	6991	6256	6624
LSD 5%	NS(*)	1550	1607	863	680	603	1477	1473	783
CV%	27.7	23.9	19.5	8.9	11.4	7.7	13	15.1	7.4
Wheat									
Mana	5500	8417	6959	1385 a	3791 a	2588 a	7822	6583	7203 a
K 6290	5667	6833	6250	780 b	2229 b	1505 b	6166	6458	6312 ab
Kenya+Mana	5560	6167	5864	940 ab	3192 a	2629 a	7565	6358	6962 a
HAR 416	4333	4583	4458	670 b	896 c	783 c	6410	5625	6018 b
Mean	5265	6500	5883	944	2527	1715	6991	6256	6624
LSD 5%	NS	NS	NS	490	970	433	NS	NS	733
CV%	34.0	33.8	38.7	32.3	23.8	15.6	14.7	11.8	7.0

(*) Significant at $P \leq 0.10$.

Table 3.2. Effect of genotype combinations on biomass (kg ha^{-1}) yield in barley and wheat mixtures at Halhale Research Station, Eritrea, 1997-1998. The combinations are listed in descending order based on the mean total biomass for two years. Means followed by the same letter are statistically not significantly different.

Genotypes		1997			1998			Mean
Barley	Wheat	Barley	Wheat	Total	Barley	Wheat	Total	1997-98
Kuunto	Mana	8333 a	917 bc	9250 a	5833 bc	2666 bc	8499 ab	8880 a
Kuunto	HAR 416	6250 bc	760 bc	7010 abcde	8000 a	1000 de	9000 a	8005 ab
Kuunto	Kenya+Mana	8167 ab	417 c	8584 ab	5417 cd	1300 cde	6717 bc	7651 abc
Ardu 12/60	Kenya+Mana	7083 abc	1332 b	8415 ab	1833 gh	4633 a	6466 bcd	7441 bc
Ardu 12/60	Mana	6583 abcde	2540 a	9123 a	1417 h	4333 a	5750 cdef	7437 bc
Kuunto	K 6290	5583 defg	293 c	5876 cdef	7250 ab	1250 cde	8500 ab	7188 bcd
Yeha	Kenya+Mana	7667 abcd	677 bc	8344 ab	2167 gh	3333 ab	5500 cdef	6922 bcde
Yeha	Mana	6917 abc	1083 bc	8000 abc	1917 gh	3417 ab	5334 cdef	6667 bcdef
Yeha	K 6290	6417 abc	583 bc	7000 abcde	3833 ef	2250 bcd	6083 cde	6542 cdef
IAR485	Kenya+Mana	3583 de	1333 b	4916 ef	3250 efg	3500 ab	6750 bc	5833 defg
IAR485	Mana	3915 de	1000 bc	4915 ef	2000 gh	4749 a	6749 bc	5832 defg
IAR485	K 6290	3040 e	1330 b	4370 f	4083 de	3083 b	7166 abc	5768 efg
Ardu 12/60	K 6290	6500 abc	915 bc	7415 abc	1750 h	2333 bcd	4083 ef	5749 efg
Yeha	HAR 416	6167 bc	377 c	6544 bcdef	3917 ef	667 e	4584 def	5564 efg
Ardu 12/60	HAR 416	6460 abc	627 bc	7087 abcde	2583 efg	1250 cde	3833 f	5460 fg
IAR485	HAR 416	4083 de	916 bc	4999 def	4417 cde	667 e	5084 cdef	5042 g
Mean		6047	944	6991	3729	2527	6256	6624
LSD 5%		2027	833	2410	1420	1503	2120	1377
CV%		23.5	22.0	24.9	26.7	34.5	24.4	14.7

Table 3.3. Grain yield (kg ha^{-1}) of barley and wheat genotypes grown in sole crop or mixtures at Halhale Research Station, Eritrea, 1997 and 1998. Average component crop yield in mixtures (CCM) is the mean grain yield of the genotypes as component crops, averaged over the different genotypes of the other crop. Average total grain yield in mixtures (T) is the mean grain yield of the different genotypes in mixtures, averaged over the genotypes of the component crop. The genotypes are listed in descending order of the mean grain yield of the two cropping seasons under sole cropping. Means followed by the same letter are statistically not significantly different. Values without letters are statistically not significant.

Genotype	Sole crop			CCM			T		
	1997	1998	Mean	1997	1998	Mean	1997	1998	Mean
Barley									
Kuunto	1250 a	1550 a	1400	1300 b	1370 a	1335 a	1439 b	1648	1544
Ardu 12/60	1393 a	717 b	1055	1540 a	439 c	990 b	1799 a	1193	1496
Yeha	727 b	1167 a	947	1365 ab	754 b	1060 b	1534 ab	1297	1416
IAR 485	1213 ab	647 b	930	531 c	716 b	624 c	918 c	1430	1174
Mean	1146	1020	1083	1184	820	1002	1424	1392	1408
LSD 5%	507	447	NS	230	173	170	347	NS	NS
CV%	36.4	27.4	30.3	12.1	13.3	10.5	15.6	18.8	12.7
Wheat									
Mana	607	1843	1225	334	851 a	593 a	1534	1437	1486
Kenya+Mana	1070	1627	1349	293	736 ab	515 a	1588	1352	1470
K 6290	893	1687	1290	163	527 b	345 ab	1282	1475	1379
HAR 416	997	837	917	171	176 c	174 b	1292	1304	1298
Mean	892	1499	1196	240	573	407	1424	1392	1408
LSD 5%	NS	NS	NS	NS	293	263	NS	NS	NS
CV%	38.9	35.2	27.6	32.9	31.1	37.4	26.4	18.5	12.8

Table 3.4. Effect of genotype combinations on grain yield (in kg ha^{-1}) in barley and wheat mixtures at Halhale Research Station, Eritrea, 1997-1998. Genotype combinations are listed in descending order based on the mean total grain yield of two years. Means followed by the same letter are statistically not significantly different.

Genotype combination		1997			1998			Mean
Barley	Wheat	Barley	Wheat	Total	Barley	Wheat	Total	1997-1998
Ardu 12/60	Kenya+Mana	2283 a	307 c	2590 a	420 f	1007 a	1427 abcd	2009 a
Kuunto	Mana	1787 ab	257 cd	2044 ab	1123 b	487 cde	1610 abc	1827 ab
Kuunto	HAR 416	1523 bcd	60 d	1583 bcde	1680 a	203 ef	1883 ab	1733 abc
Ardu 12/60	K 6290	1923 ab	220 cd	2143 ab	333 f	677 abcd	1010 cd	1577 abcd
Ardu 12/60	Mana	1490 bcd	187 cd	1677 bcd	320 f	1047 a	1367 abcd	1522 abcd
Yeha	Kenya+Mana	1537 bcd	150 cd	1687 bcd	517 ef	790 abc	1307 abcd	1497 abcd
Yeha	HAR 416	1607 abc	130 cd	1737 bc	1137 b	43 f	1180 cd	1459 bcd
Yeha	Mana	1273 bcde	297 cd	1570 bcde	493 ef	787 abc	1280 bcd	1425 bcd
Kuunto	K 6290	790 efg	97 cd	887 de	1723 a	200 ef	1923 a	1405 bcd
Yeha	K 6290	1043 cdef	120 cd	1163 cde	867 bcde	553 bcde	1420 abcd	1292 cde
IAR485	K 6290	720 efg	213 cd	933 cde	870 bcde	676 abcd	1546 abcd	1240 cde
Kuunto	Kenya+Mana	1100 cdef	143 cd	1243 bcde	953 bcd	223 ef	1176 cd	1210 de
IAR485	Mana	250 g	593 a	843 e	407 f	1083 a	1490 abcd	1167 de
IAR485	Kenya+Mana	260 g	573 ab	833 e	574 def	923 ab	1497 abcd	1165 de
IAR485	HAR 416	893 defg	170 cd	1063 cde	1013 bc	173 ef	1186 cd	1125 de
Ardu 12/60	HAR 416	463 fg	323 bc	786 e	683 cdef	283 def	966 d	876 e
Mean		1184	240	1424	820	572	1392	1408
LSD 5%		677	253	810	390	410	633	523
CV%		30.2	34.4	34.8	33.2	38.6	35.2	26.2

Table 3.5. Performance of barley and wheat genotypes in biomass yield (kg ha^{-1}) and grain yield (kg ha^{-1}) grown as sole crop and in mixtures at a site near Mendefera, Eritrea, in the growing season of 1997. Average component crop yield in mixtures (CCM) is the mean yield of the genotypes as component crops, averaged over the genotypes of the other component crop. Average total yield of mixtures (T) is the mean yield of the entire crop averaged for the genotype of the other component crop. The genotypes are listed in descending order on the average total mixtures (T) for grain yield. Means followed by the same letter are statistically not significantly different. Values without letters are statistically not significant.

Genotype	Biomass (kg ha^{-1})			Grain yield ((kg ha^{-1})		
	Sole crop	CCM	T	Sole	CCM	T
Barley						
Yeha	8250	6865 b	7391 b	2523 b	2012 a	2179 a
Ardu 12/60	7977	6354 c	7125 b	1997 c	1779 a	2022 a
Kuunto	8500	7459 a	7995 a	3053 a	1773 a	1940 a
IAR 485	6667	4417 d	5657 c	737 d	426 b	779 b
Mean	7849	6274	7042	2078	1497	1730
LSD5%	NS	492	558	361	304	346
CV%	15.6	7.0	7.1	15.6	18.3	17.9
Wheat						
K 6290	4417 b	709 b	7480 a	1117 bc	272	1935
Mana	6500 a	1232 a	7023 ab	1477 a	329	1739
HAR 416	4083 b	423 c	6903 ab	1047 c	130	1648
Kenya+Mana	6250 a	708 b	6761 b	1350 ab	200	1598
Mean	5313	768	7042	1248	233	1730
LSD5%	963	201	714	209	NS	NS
CV%	16.3	23.5	9.1	15.0	29.2	11.2

Table 3.6. Performance of genotype combinations of barley and wheat mixtures in biomass and grain yield at a site near Mendefera, Eritrea, 1997. The genotype combinations are listed in descending order based on the total grain yield. Means followed by the same letter are statistically not significantly different.

Genotype combination		Biomass (kg ha^{-1})			Grain yield (kg ha^{-1})		
Barley	Wheat	Barley	Wheat	Total	Barley	Wheat	Total
Yeha	Mana	7250 abc	843 bcde	8093 ab	2157 ab	267 bcd	2424 a
Kuunto	K 6290	8917 a	477 def	9394 a	2183 a	173 cde	2356 a
Ardu 12/60	K 6290	6750 bc	750 cdef	7500 abc	1990 ab	353 ab	2343 a
Yeha	K 6290	7167 bc	483 def	7650 abc	2127 ab	163 cde	2290 ab
Yeha	Kenya+Mana	6460 bcd	500 def	6960 bcd	1940 ab	170 cde	2110 ab
Ardu 12/60	HAR 416	6667 bcd	583 def	7250 bcd	1910 ab	150 cde	2060 ab
Kuunto	HAR 416	7667 ab	333 ef	8000 ab	1867 ab	113 de	1980 ab
Yeha	HAR 416	6583 bcd	277 f	6860 bcd	1823 ab	70 e	1893 ab
Ardu 12/60	Kenya+Mana	6083 bcde	583 def	6666 bcd	1673 ab	187 cde	1860 ab
Ardu 12/60	Mana	5917 cdef	1166 bc	7083 bcd	1543 ab	280 bc	1823 ab
Kuunto	Mana	6167 bcde	917 bcd	7084 bcd	1517 b	290 bc	1807 ab
Kuunto	Kenya+Mana	7083 bc	417 def	7500 abc	1523 b	93 e	1616 b
IAR 485	Mana	3833 g	2000 a	5833 cd	423 c	477 a	900 c
IAR 485	Kenya+Mana	4583 efg	1333 b	5916 cd	457 c	350 ab	807 c
IAR 485	K 6290	4250 fg	1127 bc	5377 d	353 c	397 ab	750 c
IAR 485	HAR 416	5000 defg	500 def	5500 cd	470 c	187 cde	657 c
Mean		6274	768	7042	1497	233	1730
LSD 5%		1707	533	1930	647	160	713
CV%		17.9	37.0	18.9	30.3	38.9	28.8

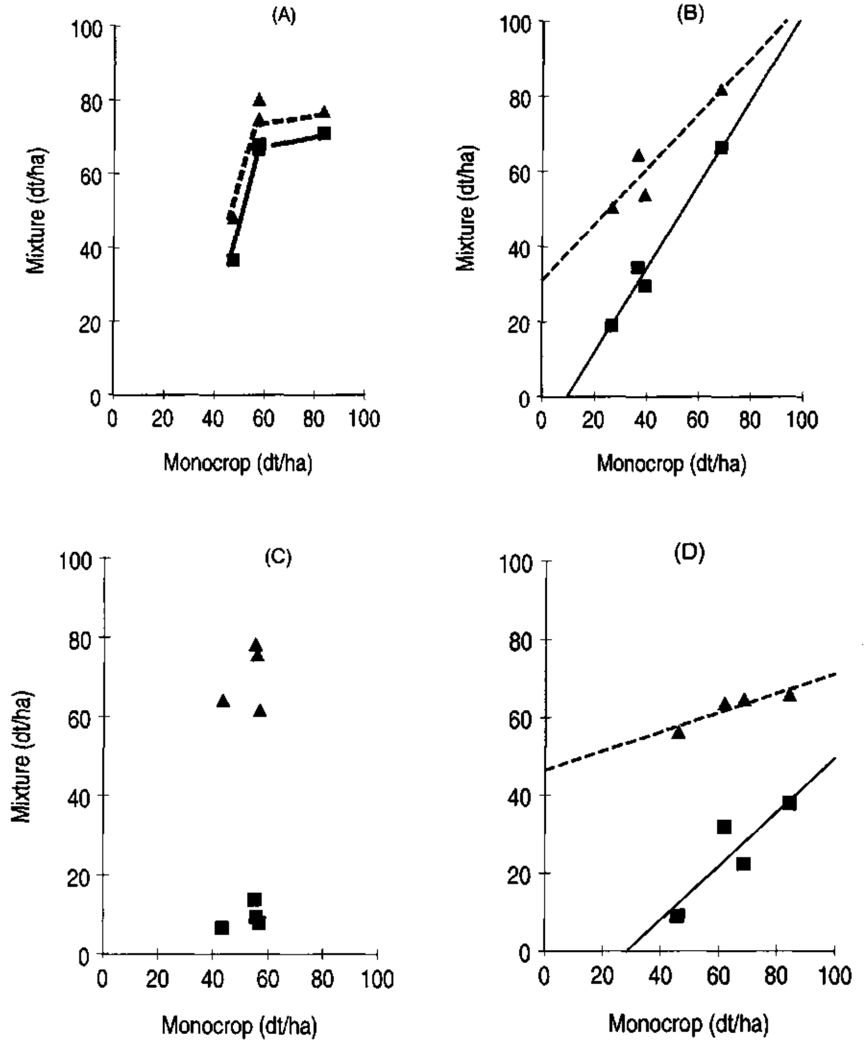

Figure 3.1. Relationship for Halhale (A) Between sole crop (SC), average component crop yield in mixtures (CCM) (r= 0.687) and average total mixtures (T) (r=0.585) barley biomass yield in 1997; (B) Between SC, CCM (r=0.988**) and T (r=0.921) in 1998, for barley biomass; (C) Between SC, CCM (r=–0.837) and T (r=0.372) in wheat biomass yield in 1997; (D) Between SC, CCM (r=0.846) and T (r=0.830) in wheat biomass yield in 1998. Note: ■- Average component of mixtures and ▲- Average total mixtures. Linear relations without asterisks are non significant. Note: in the graph dt ha^{-1} is the same as quintals ha^{-1}.

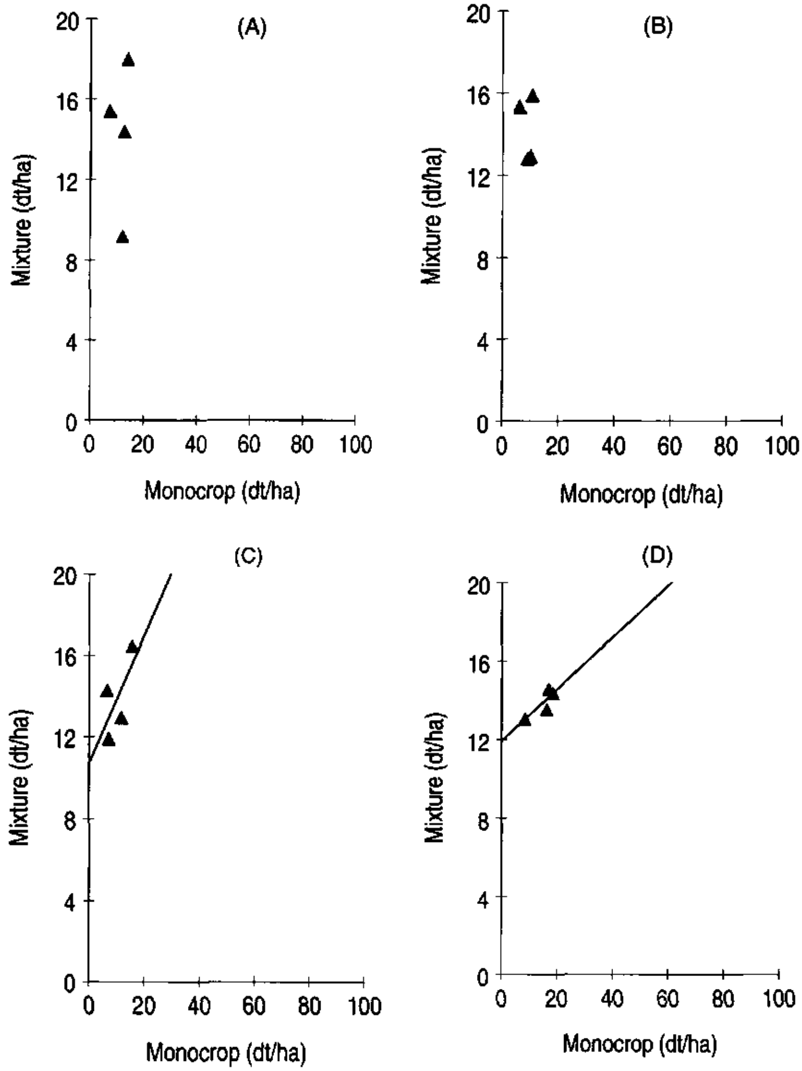

Figure 3.2. Relationship for Halhale (A) Between sole crop (SC) and T (average total mixtures) (r=–0.059) in barley grain yield in 1997; (B) Between SC and T (r=–0.166) in wheat grain yield in 1997; (C) Between SC and T (r=0.799) in barley grain yield in 1998; (D) Between SC and T (r=0.527) in wheat grain yield 1998. Note: in the graph dt ha^{-1} is the same as quintals ha^{-1}.

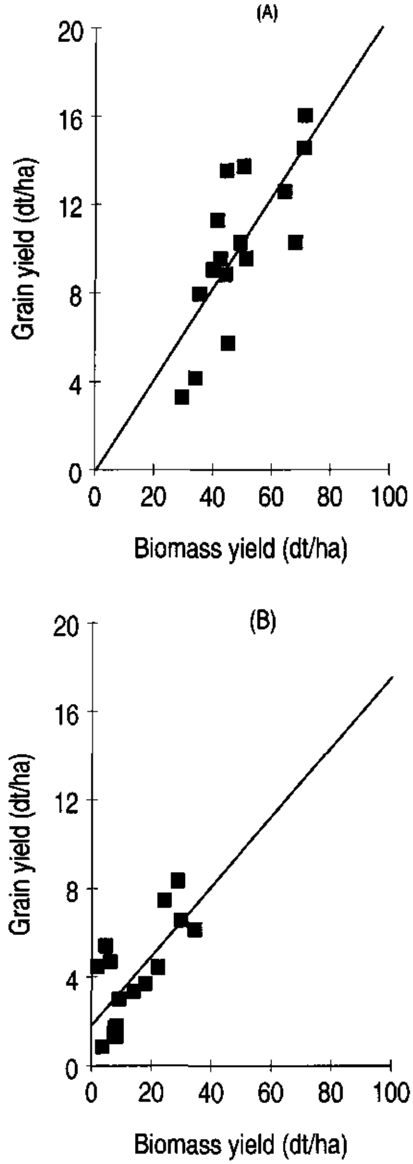

Figure 3.3. Relationship for Halhale between biomass and grain yields, with the regression coefficient reflecting the average harvest index for barley (A) and wheat (B). Linear correlations are significant for relations shown in A and B. Note: in the graph dt ha^{-1} is the same as quintals ha^{-1}.

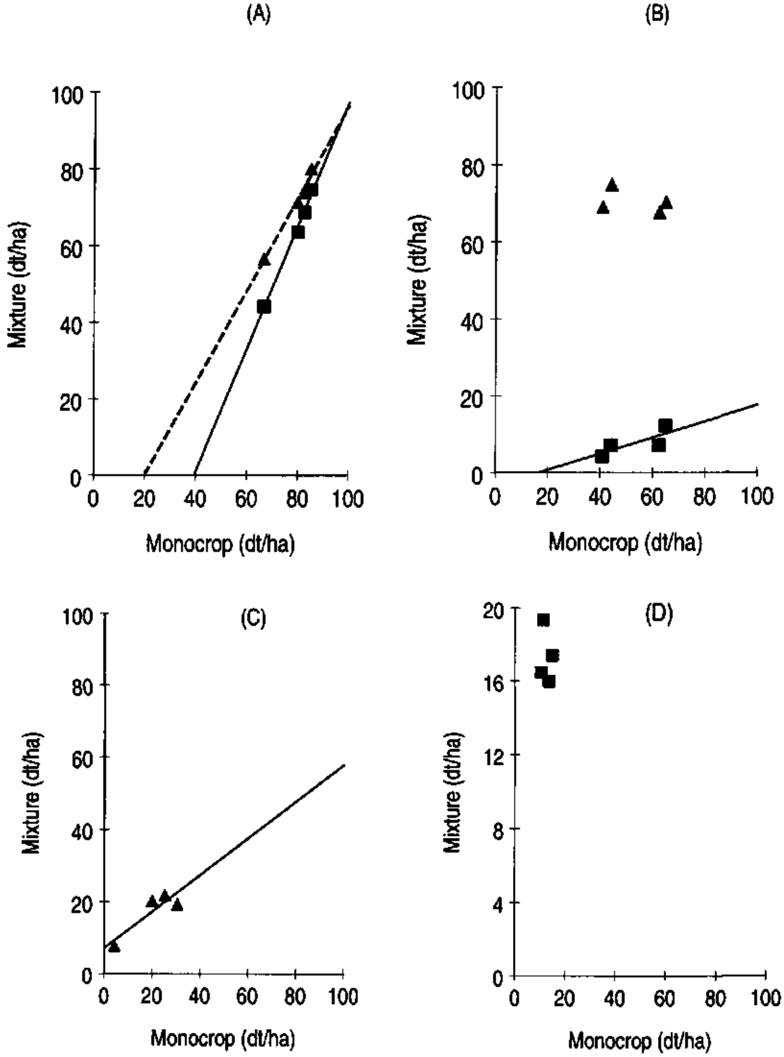

Figure 3.4. Relationship (A) Between sole crop (SC), average component crop yield in mixture (CCM) (r=0.996**) and average total mixture (T) (r=0.990**) for barley biomass; (B) between SC, CCM (r=0.775) and T (r=–0.396) for wheat biomass; (C) Between SC and T (0.894) for barley grain yield; (D) Between SC and T for wheat grain yield (r=–0.244) at Mendefera. Note: ■- Average component crop yield of mixtures and ▲- Average total mixtures. Note: in the graph dt ha^{-1} is the same as quintals ha^{-1}. **- significant at 1% level and *- significant at 5% level.

performed poorly, whereas mixtures that contained the wheat genotype K 6290 performed very well.

There was a negative correlation between grain yields under monocropping and those under mixed cropping in 1997. This was true both at Halhale (Figure 3.2) and at Mendefera (Figure 3.4). This means that the genotypes that did well under sole cropping did not perform similarly well under mixed cropping, especially with regard to grain yield. In 1998, the relation was different at Halhale, because the genotypes that performed well in grain yield as monocrops also did well in mixed cropping. This holds true for both crop species. In general, there was a positive correlation between biomass yield and grain yield among the genotypes in mixtures. Those genotypes with higher biomass yields also had higher grain yields at Halhale (Figure 3.3A for barley and 3.3B for wheat).

Yield components

The results of yield components and harvest index are shown in Table 3.7. The results of the regression analysis between yield components, biomass and grain yield are shown in Table 3.8 and Figures 3.5 and 3.6.

Although differences were not significant, Yeha (317 ears m^{-2}) and Ardu 12/60 (300 ears m^{-2}) showed more ears as a component crop than in sole cropping. All wheat genotypes except Mana also showed this effect (Table 3.7). There was no relationship between number of ears averaged over two years and grain yield (r=0.055) or biomass (r=–0.028) (Figure 3.5 and Table 3.8).

Kuunto was the only barley genotype that showed more kernels ear^{-1} as a component crop compared to a sole crop; among the wheat genotypes, Mana (34 kernels per ear) and K 6290 (30 kernels per ear) also had more kernels ear^{-1} as a component crop than as a sole crop (Table 3.7), but differences were never significant. Mean number of kernels ear^{-1} were not significantly correlated with either biomass (r=0.148) or grain yield (r=–0.179) (Figure 3.5 and Table 3.8).

Kuunto showed higher TGW (32 g 1000 $seeds^{-1}$) as a component crop than as a sole crop. All barley genotypes showed this effect which was statistically significant. Among wheat genotypes, Kenya + Mana and Mana showed an increased TGW as a component crop compared to a sole crop (Table 3.7) but this effect was not significant. There was a positive correlation between TGW and biomass or grain yield. The correlation between TGW and grain yield was significant, but not between TGW and biomass (Figure 3.6 and Table 3.8).

In barley, there was no difference in spike size between monocropping and mixed cropping. In wheat, all genotypes had lower values in mixtures than as sole crop (Table 3.7). Mean ear size averaged over the two years did not significantly correlate with grain yield (r=0.31) or biomass (r=0.30) (Table 3.8).

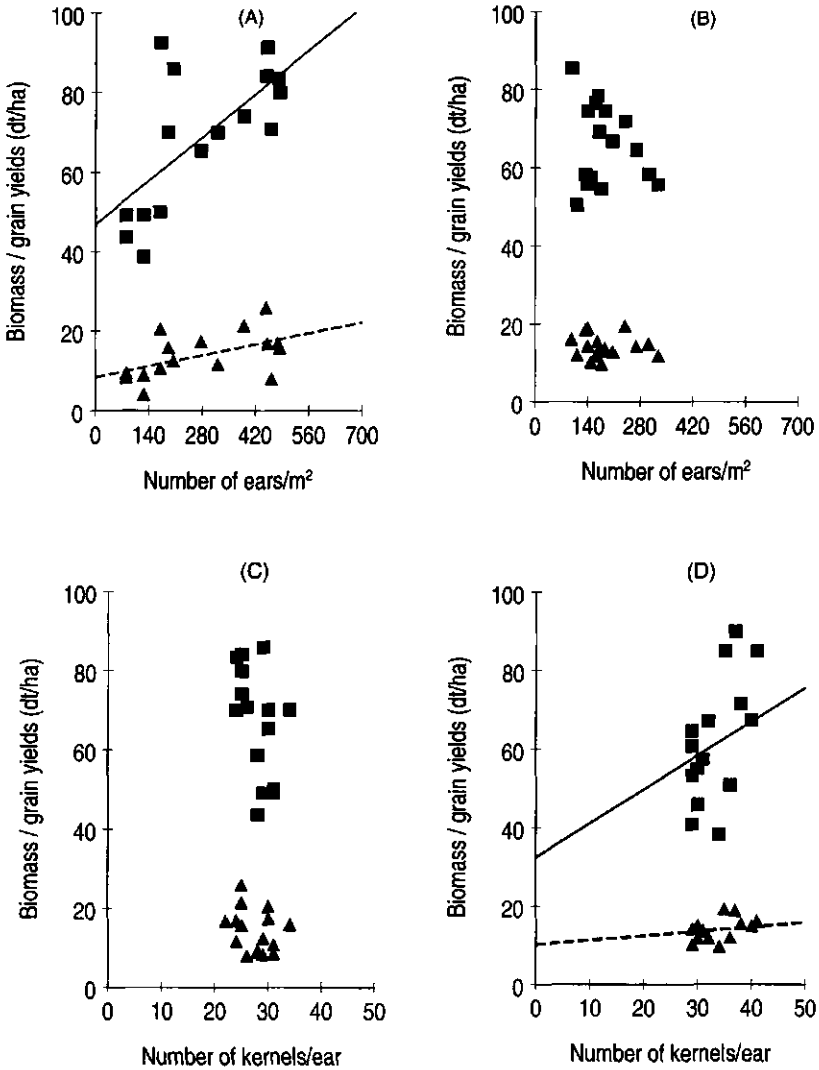

Figure 3.5. Relationship for Halhale between (A) Number of ears m^{-2}, biomass and grain yields in 1997; (B) Number of ears m^{-2}, biomass and grain yields in 1998; (C) Number of kernels ear^{-1}, biomass and grain yields in 1997; (D) Number of kernels ear^{-1}, biomass and grain yields in 1998. Note: ■- Total biomass yield and ▲- Total grain yield of mixtures. In the graph dt ha^{-1} is the same as quintals ha^{-1}.

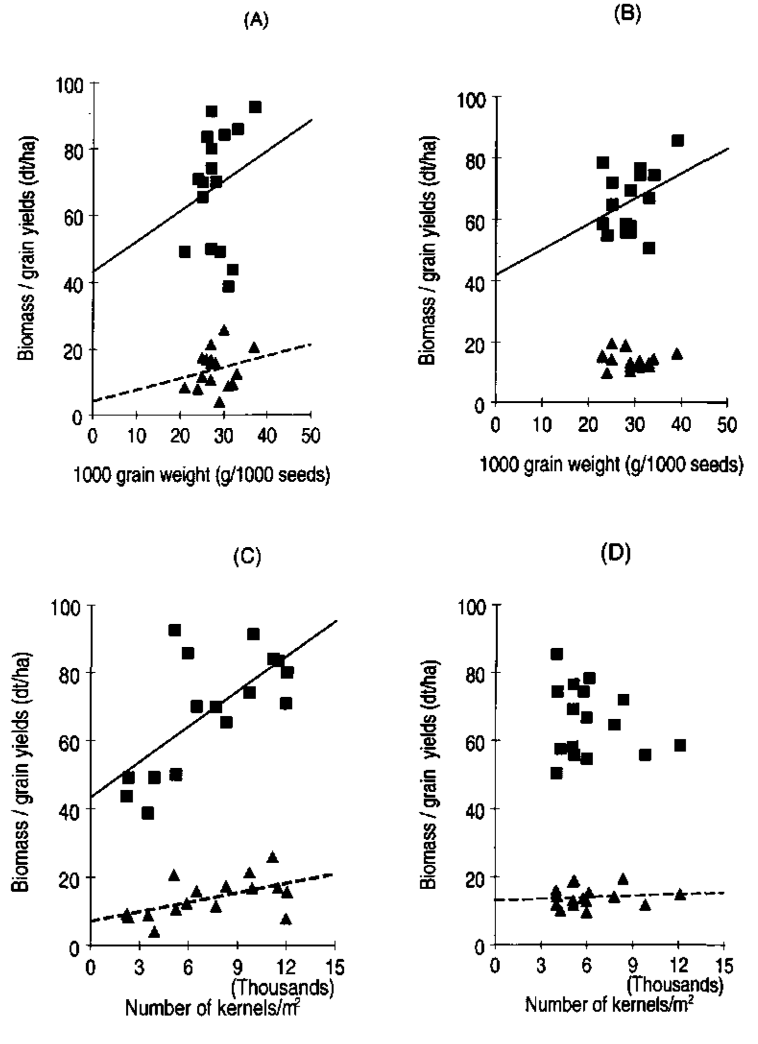

Figure 3.6. Relationship for Halhale between (A) Thousand grain weight, biomass and grain yields in 1997; (B) Thousand grain weight, biomass and grain yields in 1998; (C) Number of kernels m^{-2}, biomass and grain yields in 1997; (D) Number of kernels m^{-2}, biomass and grain yields in 1998. Note: ■- Total biomass yield and ▲- Total grain yield of mixtures. In the graph dt ha^{-1} is the same as quintals ha^{-1}.

Table 3.7. Yield components and harvest index averaged over the two years (1997–1998) for barley and wheat genotypes grown in monocropping and as component crops in mixtures at Halhale, Eritrea. Means followed by different letters are statistically significantly different. Values without letters are statistically not significant.

	Ear m^{-2}		Kernels ear^{-1}		TGW (g)		Ear size (m)		Kernels m^{-2}		Harvest index (%)	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Barley												
Kuunto	207	166	32	34	24	32	9.8	8.8	6624	5644	13.3	19.5
Yeha	275	317	35	28	22	27	9.5	9.1	9625	8876	19.5	21.7
Ardu 12/60	196	300	34	28	22	28	8.4	9.0	6664	8400	25.1	23.1
IAR 485	145	146	41	34	23	27	8.5	8.9	5945	4964	23.0	17.7
Mean	206	232	36	31	22.8 a	28.5 b	9.0	9.0	7215	6971	20.2	20.5
LSD 5%	NS		NS		2.7		NS		NS		NS	
Wheat												
Mana	314	253	22	34	20	31	9.9	9.2	6908	8602	17.6	23.4
K 6290	161	214	23	30	28	28	9.6	8.4	3703	6420	20.6	25.9
Kenya + Mana	204	230	41	30	24	28	9.9	9.3	8364	6930	23.0	24.9
HAR 416	90	232	43	23	30	27	10.5	8.9	3870	5336	20.6	21.6
Mean	192	232	32	29	25.5	28.5	10.0 a	9.0 b	5711	6822	20.5	24.0
LSD 5%	NS		NS		NS		0.74		NS		NS	

Note: (1) = Monocrop, (2) = average of component crop in mixtures for all characters, except for Ear m^{-2} which is the average of the total mixtures; TGW– thousand grain weight.

Table 3.8. Regression analysis for the relationship between mean agronomic characters, biomass and grain yield of the mixtures of barley and wheat genotypes at Halhale Research Station, Eritrea, 1997-1998.

Parameter	Biomass yield			Grain yield		
	1997	1998	Pooled	1997	1998	Pooled
Stand cover	0.62*	0.63*	0.72*	0.26	0.55*	0.44*
Plant height	0.56*	0.57*	0.60*	0.21	0.50*	0.10
Lodging	0.33	-----	0.33	0.39	-----	0.39
Days to heading	–0.29	0.12	0.29	–0.52*	0.63*	0.22
Days to maturity	–0.13	–0.11	0.09	–0.17	0.46*	–0.07
Ear size	0.46*	0.47*	0.30	0.49*	–0.01	0.31
Ear m^{-2}	0.68*	–0.23	–0.22	0.53*	–0.06	0.05
Kernels ear^{-1}	–0.43*	0.03	0.15	–0.30	0.10	–0.18
TGW	0.20	0.35	0.39	0.23	–0.10	0.58*
Kernels m^{-2}	0.68*	–0.13	–0.30	0.54*	0.11	0.18
Biomass	-----	----	-----	0.71*	0.24	0.64*
Harvest index	0.33	–0.50*	–0.039	0.75*	–0.23	0.62*

Note: The lodging incidence in 1998 at Halhale was almost nil, hence values not shown. Those values without asterisks are non significant.

Yeha and Ardu 12/60 were the best in number of kernels m^{-2} as component crops. All wheat genotypes had more kernels m^{-2} as a component crop than as a sole crop except Kenya + Mana (Table 3.7), but in both crops differences were not significant. Also correlations between mean number of kernels m^{-2} and grain yield or biomass were not significant (Figure 3.6 and Table 3.8).

Harvest index was highest for Ardu 12/60 among the barley genotypes (25.1%). Kuunto had lower harvest index (13.3%) in sole cropping but showed much higher harvest indices in mixtures (19.5%). All wheat genotypes had higher harvest indices in mixtures than as sole crops (Table 3.7). There was a positive relationship between mean harvest index averaged over two years and grain yield (r=0.62*). The correlation between mean harvest index of two years and biomass (r=–0.039) was negative but not significant (Table 3.8).

Discussion

Morphological aspects

The aim of selecting appropriate landrace combinations is to minimise or reduce intercrop competition and maximise complementary effects. Attention should be given to differences in morphological characters when identifying complementary genotypes. Taller cultivars are highly competitive but lodging could be a problem. Reducing the height of dominant cultivars in mixed cropping has resulted in higher yields of associated crops (Andrews and Kassam, 1975). In cowpea, erect and dwarf genotypes had less competitive effect in maize intercropping than taller ones (Wien and Nangju, 1976). In barley, vigorous genotypes in mixtures had competitive advantage over less vigorous ones resulting in higher biomass and grain yield (Hamblin and Donald, 1974). Kuunto was one of the leafy and relatively tall barley genotypes with higher biomass in sole crop and in mixtures at Halhale. IAR 485 was also was one of the leafy barley genotypes but relatively shorter in height than Kuunto. Mana was one of the tall wheat genotypes showing higher biomass in mixtures.

Phenological aspects

In this study barley genotypes matured within 90 to 95 while the wheat genotypes matured within 100 to 105 days at Halhale. Barley matured earlier than wheat. The same trend was observed at Mendefera. When barley matures earlier than wheat it leaves the soil resources for wheat to continue growth. Willey (1979a,b) and Francis and Stern (1987) indicated that in maize, short duration cultivars gave higher yields in mixtures. Furthermore, Willey and Osiru (1972a,b) believed that early maturing crop species as one of the component crops in mixtures can complement late maturing component crops rather than compete for the same resources.

Value of specific genotype combinations

The present traditional practice in *hanfetz* is to combine Yeha and Mana. This combination has shown its ability to perform relatively well in mixed cropping, even though other combinations have outyielded this classical combination in total grain yield. At Halhale, a mixture of Kuunto and Mana was one of the best in biomass and also in grain yield. The average total yield of the mixture was consistently higher than the yield of the component crops. This was true for biomass and grain yield. In most cases biomass and grain yield were higher for mixtures than for comparable sole crops.

Several research workers confirmed that the genotype composition affects the yields of the mixtures. For example, the performance of a certain maize genotypes (Gango-S) was better than the performance of other maize genotypes when grown with soybeans (Wiebe et al., 1963). Higher yields were obtained for a landrace of mustard in association with potato than for a released mustard variety (Rathi et al., 1992). Certain maize genotypes produced higher yields than others in mixed cropping (Fischer, 1977a,b). In pearl millet and cluster bean mixtures, some genotype combinations (for example HG72 + P21) gave higher total yields than others (Bhadoria et al., 1992). Cowpea genotypes in mixtures with dwarf pearl millet gave higher yields as opposed to tall ones (Reddy et al., 1990).

There was a positive correlation for the mixtures between biomass and grain yield (r=0.641*) when averaged over the two years. The combinations with highest total biomass were also among the best yielding in grain yield. For example a mixture of Kuunto + Mana or of Ardu 12/60 + Kenya + Mana showed a good performance in biomass and also in grain yield.

Yield components

The number of ears per unit area depends on the number of plants per unit area and on the number of fertile tillers per plant. The number of grains per ear depends on the number of spikelets per ear and number of fertile florets per spikelet (Peter et al., 1988). Some of the yield components are better related to grain yield than others. Yield components are responsible for the compensation mechanism of grain yield which helps to fully optimise the yield potential. Based on this, Langer and Liew (1973) considered number of ears m^{-2} as an important factor in determining the number of kernels m^{-2} and grain yield in cereals. The mean number of ears m^{-2} was higher for wheat than for barley due to better tillering capacity.

More kernels m^{-2} for some wheat genotypes (e.g. Mana) was caused by more ears m^{-2} and more kernels ear^{-1}. The lower harvest index in some genotypes, such as Kuunto, as a sole crop probably was due to higher biomass yield. In contrast, higher harvest index for some genotypes (IAR 485 and Ardu 12/60) was due to relatively low biomass. Ardu 12/60 showed higher harvest index as a component crop than as a sole crop, because it produced less biomass and less grain yield as a component crop.

The number of ears m^{-2} for Kuunto as a component crop was lower than for Kuunto as a sole crop but grain yield was compensated by more kernels ear^{-1} and higher TGW. Yeha as a component crop had more ears m^{-2} than the sole crop (or even than other barley cultivars), resulting in more kernels m^{-2} but the lower number of kernels per spike could have reduced the grain weight m^{-2}. Mana as a component crop showed more kernels $ears^{-1}$ and relatively more ears m^{-2} than the sole crop (or the other wheat genotypes) and this contributed to more kernels m^{-2}. Mahon (1983) and Rekunen (1988) confirmed that these characters are affected by heritability and that there is a variation between cultivars and genotypes.

In this present work, the plant characteristics providing the best prediction for yielding ability were harvest index, biomass, stand cover and thousand grain weight. Johnson et al. (1983), Rosielle and Frey (1975) and Wych and Struthman (1983) suggested that a high harvest index results in a higher yielding ability in cereals. Plant height and biomass were also strongly and positively correlated. Harvest index did not positively correlated with biomass in mixtures. This is in agreement with Sanio (1990) who mentioned the strong and positive correlation of plant height with biomass in oats.

In the present study other characters such as lodging, ear size, number of ears m^{-2} and days to heading showed a positive but non significant correlation with yielding ability when values averaged over two years were used. Sanio (1990) indicated that lodging, days to heading and thousand grain weight shows a correlation ($P \leq 0.10$) with yield in oats.

Conclusion

The genotype combinations such as Ardu 12/60 + Kenya + Mana (2009 kg ha^{-1}) and Kuunto + Mana (1827 kg ha^{-1}) were the best in grain yield when rainfall was normal. The experiments showed that the best genotype combinations differ from what farmers currently use. Two of the best mixtures including the control (Yeha + Mana) need to be tested in on-farm verification trials at a diversity of locations before they can be released to be used by farmers.

Growth and light use in barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* grown as sole crops and in mixtures

Woldeamlak A. and P. C. Struik

Abstract

Eight sole crops (4 barley + 4 wheat) and sixteen mixtures (4 barley × 4 wheat) were evaluated in a Completely Randomised Design at Halhale, Eritrea in order to analyse the growth and light use of barley and wheat grown as sole crops and in mixtures. The seed was broadcasted in a plot size of 3.0 m^2. Plant height followed a sigmoid curve. The results showed that initially, barley was taller than wheat, but at the end wheat became taller, both in the case of the sole crop and in the mixtures. Therefore wheat was able to use resources becoming available at the end of the growing season. Leaf area was maximum at about 50 days after sowing (DAS) for barley as a sole crop and for total mixtures. For sole crops of wheat maximum leaf area was reached at about 30 DAS. The dry weight of wheat as a sole crop was higher than that of the mixtures. Wheat as a sole crop showed higher light use efficiency (1.73 g MJ^{-1}) than either barley or mixtures when averaged over the growing season but this value could be overestimated by an overestimation of the number of plants m^{-2}. A significant and positive correlation was found between plant height and biomass (r=0.55*) or grain yield (r=0.68*) at Halhale when averaged over the two years and between leaf area and biomass (r=0.56*) at Halhale in 1997. The study shows that component crops had different growth (plant height) patterns suggesting that they had different demands for resources over time. Indeed, wheat was more efficient in use of resources at the end of the growing season when barley lost many tillers and had lodged. We could not prove a significant benefit of mixed cropping by increased light interception or improved light use efficiency of the mixtures. Yet, temporal difference in growth patterns of the component crops may enable mixtures to utilise resources in a complementary way. Thus crops / varieties of barley and wheat selected for different growth patterns over time can increase productivity at least over the barley sole crop under favourable conditions.

Key words: leaf area, light use, dry weight, plant height, barley, wheat, mixed cropping, Eritrea

Introduction

Crop growth of barley and wheat in the highlands of Eritrea takes place from the end of June to mid October in areas at an elevation above 1500 m above sea level and with an annual rainfall between 400–700 mm. Barley and wheat mixtures are frequently grown in an agro-ecosystem of cereals and pulses based system under rainfed conditions.

The rate of growth determines the time of canopy closure and full light interception thus affecting both the biomass and grain yield. In mixtures, crop species with a high growth rate at early stages are expected to compete well and get a larger share of resources as compared to those that grow slowly. Sibma (1977) and Spitters and Kramer (1986) indicated that the knowledge on the differences in growth characteristics contributes to a better understanding of the competitive differences or complementarity between cultivars or crop species in mixtures. Progress in selecting better crops / varieties with high combined crop yield will also require a better understanding of the physiological mechanisms underlying intercropping compatibility (Mutsaers et al., 1993). Growth rate of crop plants is governed by a number of factors among which are the type of crops / cultivars used in mixtures (Harris, 1990). For example, depending on the crop species, leafy crop / varieties have the capacity to capture more light resulting in higher dry weight as compared to non leafy ones (Hamblin and Donald, 1974).

Therefore, growth characteristics such as plant height, leaf area and dry weight are important in identifying the underlying mechanisms of crop compatibility.

Light is probably one of the most important aerial resources where better temporal use of resources is achieved in mixed cropping (Baker and Yusuf, 1976). The temporal difference in growth patterns of barley and wheat as component crops is expected to provide wheat the opportunity to utilise light resources after the maturity of barley. Crop phenology of barley and wheat as component crops in mixtures has already been described in Chapter 3.

Total biomass production of a crop is a function of the amount of solar radiation intercepted by the canopy and the efficiency by which this radiation is converted into dry matter (Monteith, 1977). If crops are grown under favourable conditions biomass yield is positively correlated with solar radiation intercepted during the growing season. This implies that the amount of radiation intercepted by a crop primarily determines the biomass or grain yield (Monteith, 1977; Galagher and Biscoe, 1978). However, there could be important differences between sole crops and mixtures in the efficiency of converting solar radiation in to biomass and the distribution of light within the plant canopy (Allen and Scott, 1980).

Research on mixtures has concentrated on the competition for resources between species; the emphasis in the case of competition for light has been placed on the ability of one species to compete with the other. An effective competitor captures resources quickly, but this does not necessarily result in the most efficient use of light energy (Caldwell, 1987). No study has been done up to now on the growth and light use of barley and wheat mixtures elsewhere and in Eritrea. This present chapter describes research that aimed at characterising barley and wheat grown as a sole crop and in mixtures, by analysing their growth pattern and light use.

Materials and Methods

The field site, experimental design and experimental details in the present study have been described in Chapter 3. To avoid repetition it is described only briefly here.

Cropping system

Four barley and four wheat genotypes were grown as sole crops (4 barley and 4 wheat) and in mixtures (all 16 possible combinations) at Halhale Research Station, Eritrea. A mixture of Yeha + Mana, a classical combination used by farmers, was included as a standard. Crops were sown at the end of June. The seeds were weighed and based on a pre-determined thousand grain weight a crop ratio of barley 67% and wheat 33% was set assuming that the germination rate of the seed was 100%. The seed was broadcasted over the entire plot. A fertiliser rate of 100 kg ha^{-1} Di-Ammonium Phosphate (DAP; 18% N and 46% P_2O_5) and 50 kg ha^{-1} Urea was applied and incorporated in the soil at planting. The trial was hand-weeded twice to remove some of the common weeds in the area.

Design

The data from eight sole crops and sixteen mixtures grown in a Completely Randomised Design was used for the growth analysis. The genotypes as sole crops and mixtures were randomly assigned in each plot with a net plot size of 3.0 m^2. Linear regression analysis was performed to analyse the relationships among some growth parameters (leaf area, plant height), biomass and grain yield. The data for dry weight and leaf area index was converted into values per m^2 based on the number of plants established in the plots. Plant height for each component crop was measured and compiled per plant basis.

Sampling

Sampling for leaf area and dry weight of the above-ground parts were done starting from 20 days after sowing. Plant samples were collected at 10 days intervals during the early crop growth stages but later on samples were taken at about every 20 days. Barley and wheat plants were collected separately from the plots with mixtures and the values were averaged for the mixtures, especially those for leaf area and dry weight determination (of the above-ground parts). Individual plant samples were also taken from the plots in sole crops for growth analysis.

Data collected

Some of the types of data collected are described below:

Morphological characters

Plant height (cm $plant^{-1}$) was measured from the groundlevel up to the top of the plant or ear.

Total dry weight (g $plant^{-1}$) of the above-ground parts was estimated after oven drying at 110 °C for 17 hours and weighing after drying. The dry weight per plant was converted into values per m^2 (assuming 200, 233 or 300 plants m^{-2} in the plots). The ear was also included at the period of maturity for the total dry weight.

Leaf Area (LA in cm^2 $plant^{-1}$) was determined as the product of length (L), width (W) and a leaf shape factor (K).

$$LA = L \times W \times K \qquad (4.1)$$

where L= length of the leaf; W= maximum width of the leaf and K= a constant. K was set at 0.8, a normal value for small cereals like barley and wheat.

Leaf Area Index (LAI in m^2 m^{-2}) was estimated by dividing the leaf area of the sampled plants by the area they occupied. The leaf area index was estimated based on 200, 233 or 300 plants m^{-2} in the plot for barley, mixtures and wheat respectively.

Leaf Area Duration (LAD in m^2 m^{-2} $\times$ days) over a certain time interval was estimated as the product of LAI and the duration of the time between respective samplings in days as shown below:

$$LAD= \sum(LAI_1+ LAI_2)/ 2)) \times dT \qquad (4.2)$$

where LAD is leaf area duration, dT is time interval in days between the sampling periods; LAI_1 is leaf area index at T_1 and LAI_2 is leaf area index at T_2.

Light interception

The amount of incoming solar radiation in MJ m^{-2} per day was assessed on the basis of global radiation for the monthly periods during the growing season of one of the sites in Eritrea. The fraction of incoming light intercepted by the crop (*f*, MJ MJ^{-1} or dimensionless) was calculated based on LAI. The formula was used to estimate light fraction intercepted in several crops (Versteeg and van Keulen, 1986). The formula is described also by Goudriaan and van Laar (1994).

$$f= 1-e^{-k \times LAI} \qquad (4.3)$$

where *f* is the fraction of the incoming radiation intercepted by a crop, k is the extinction coefficient and LAI ($m^2\ m^{-2}$) is leaf area index; e is the base of the natural logarithm and is equal to 2.718. The extinction coefficient (*k*) in wheat is high shortly after emergence, declines rapidly to a minimum of 0.45 and later becomes constant with a value of 0.5 (Meinke, 1996). A *k* value may be greater, equal or less than 1 depending on the leaf distribution of a crop (Trenbath, 1979). Considering all the variations as mentioned above, the *k* value here was taken on average as 0.7. Furthermore, the active radiation which is utilised by the green leaves, makes up about 50% of global radiation which was taken into account when calculating the light interception used by the crop.

Light use efficiency (LUE in g MJ^{-1}) was calculated as the ratio of the dry weight accumulation (DW in g m^{-2}) to the accumulated photosynthetically active light intercepted by the crop (AL in MJ m^{-2}).

$$LUE = DW / AL \qquad (4.4)$$

Results

Plant height

The results on plant height are shown in Table 4.1 and Figure 4.1. The trend of plant height over time followed a sigmoid curve. A rapid increase in plant height was observed for barley as a sole crop and as a component crop in mixtures up to 70 DAS, when it reached maximum height; plant height decreased from 70 DAS onwards when barley matured. Wheat plants in mixtures were at first suppressed but later on grew taller than barley. Wheat as a sole crop and as a component crop in mixtures was tallest between 70 and 100 DAS (Figure 4.1) when barley reached maturity stage. Final plant height was higher for wheat than for barley.

The differences in plant height between component crops are also shown in Table 4.1. Wheat as a sole crop was tallest (74 cm) followed by wheat as component in mixtures. Barley in mixtures grew taller than barley as sole crop when averaged over the growing period, suggesting an interaction between species and cropping system.

There was a positive and significant correlation between mean plant height at maturity averaged over two years (1997 and 1998) and biomass (r=0.55*) or grain yield (0.68*) at Halhale considering the biomass and grain yield data of genotype combinations from Chapter 3.

Leaf area

The results of the leaf area measurements are shown in Table 4.2 and Figure 4.2. Maximum leaf area for the barley sole crop was reached at about 50 days after

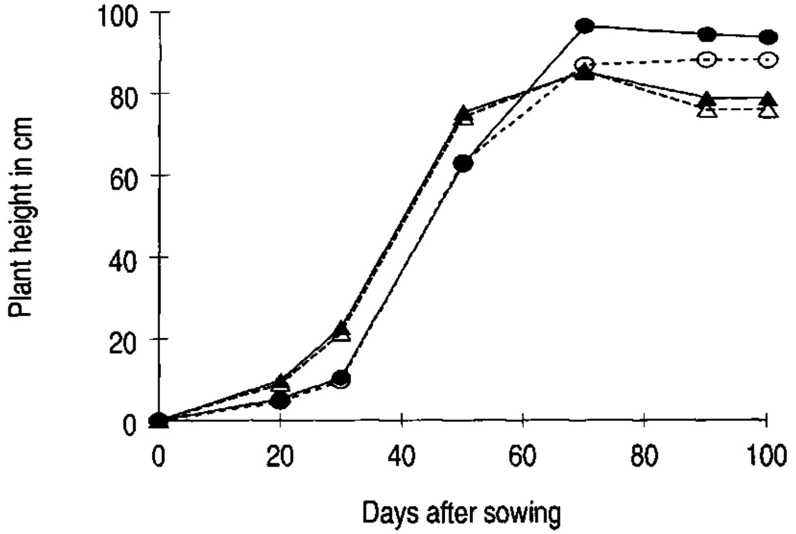

Figure 4.1. Changes over time of plant height (cm) for barley and wheat as sole crops and component crops in mixtures at Halhale Research Station, Eritrea in 1997. Δ- Barley sole crop, ▲- Barley as component mixtures, O- Wheat sole crop, ●- Wheat as component crop in mixtures.

Table 4.1. Plant height (cm) at maturity of barley and wheat as sole crop and as component mixtures at Halhale station averaged over two years (1997 and 1998).

Cropping systems	Range	Mean
Barley sole crop	56–69	64
Wheat sole crop	66–80	74
Barley component mixtures	60–73	67
Wheat component mixtures	62–78	69
Average total mixtures	61–76	69

LSD5%: sole cropping versus mixed cropping–NS
barley versus wheat–6.1

CV%: 10%

sowing and was 205 cm^2 $plant^{-1}$. The mixtures also reached maximum leaf area at 50 DAS (maximum at total leaf area 234 cm^2 $plant^{-1}$). The leaf area for wheat as a sole crop developed poorly and was lower per plant than for both the barley sole crop and mixtures, but there were more plants m^{-2}. The barley sole crop showed higher leaf area values in the second half of the growing season than both the mixtures and the wheat sole crop.

The maximum leaf area index was 4.10 and 5.45 m^2 m^{-2} at about 50 DAS for barley sole crops and mixtures respectively and 3.24 m^2 m^{-2} at about 30 DAS for the wheat sole crop. The average leaf area index over the whole season was higher for mixtures (2.75 m^2 m^{-2}) than for barley (2.58 m^2 m^{-2}) or wheat (2.14 m^2 m^{-2}) (Figure 4.2 and Table 4.2).

The total leaf area duration was highest for the mixtures (239 m^2 m^{-2} × days) followed by barley sole crop (217 m^2 m^{-2} × days). The wheat sole crop had the lowest leaf area duration (Table 4.2).

There was a positive correlation in mixtures between leaf area and biomass yield (r=0.56*) or grain yield (r=0.40) at Halhale in 1997 considering the biomass and grain yield from Chapter 3.

Dry matter (g m^{-2})

The mean total dry matter weight (g m^{-2}) for the above-ground parts in the sole crops and the mixtures throughout the growing period is shown in Table 4.2. Barley established easily and initially had a faster growth rate than the slower growing wheat sole crop. The wheat sole crop was better in dry weight increase than barley sole crop starting 70 DAS.

The mean total dry weight of the above-ground parts averaged over the growing period was the highest for wheat sole crop (1103 g m^{-2}) followed by barley sole crop (800 g m^{-2}) (Table 4.2). The development of dry weight over time can be derived from Figure 4.3.

Light use efficiency (LUE)

The results on light interception and light use efficiency are shown in Figure 4.3.

Light interception and accumulation

The fractions of light intercepted by the crop types were similar for barley sole crop and mixtures and slightly lower for wheat sole crop in the middle of the growing season. Light accumulation showed an exponential response during the growing period (Figure 4.3). There was a positive and significant relationship between the accumulated light (MJ m^{-2}) and the dry weight of the above-ground parts (g m^{-2}) for barley sole crop (r= 0.939), wheat sole crop (r=0.974*) and the mixtures (r=0.994*) (Figure 4.3).

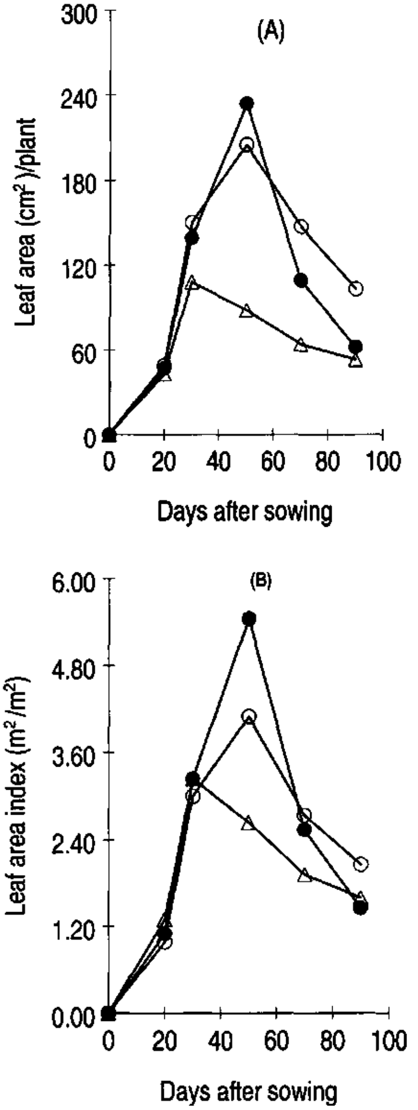

Figure 4.2. Changes over time of (A) Leaf area (LA, cm^2 $plant^{-1}$); (B) Leaf area index (LAI, m^2 m^{-2}) at Halhale Research Station, Eritrea, 1997. O- Barley sole crop, Δ- Wheat as a sole crop ●- Barley & Wheat as mixtures.

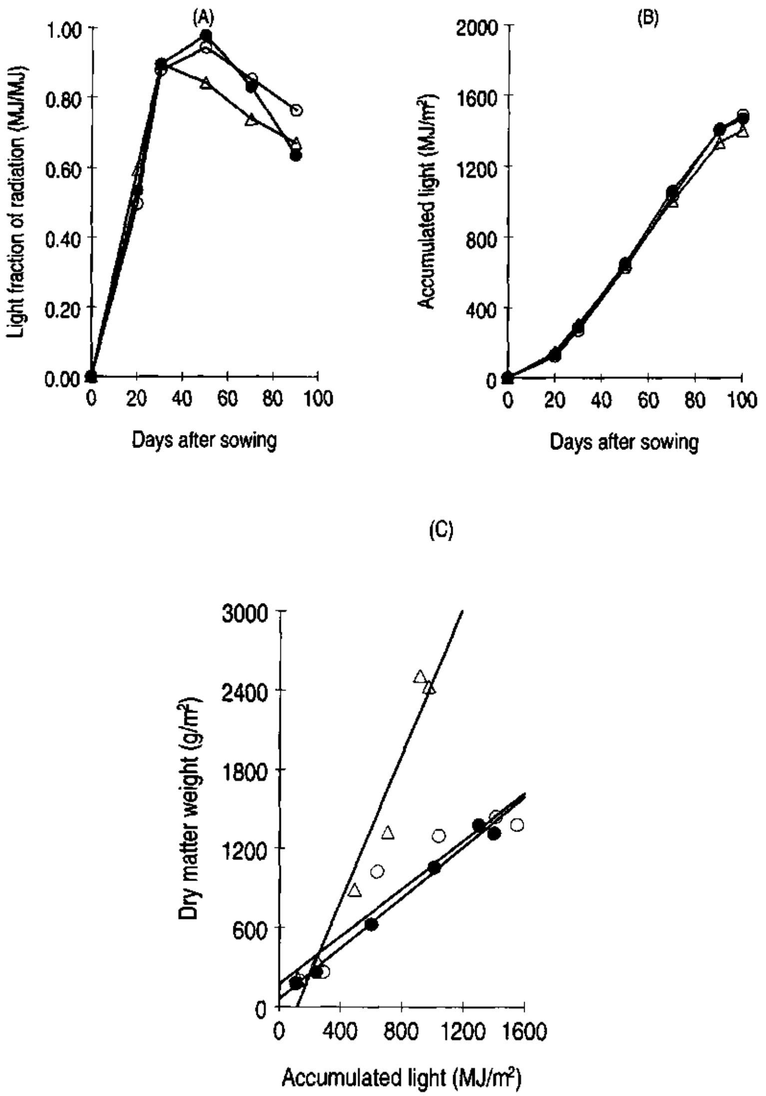

Figure 4.3. Light interception and light use in barley and wheat as sole crop and as component crops in mixtures. (A) The fraction of incoming light intercepted by the crop canopy; (B) Light accumulated by the canopy; (C) Relationship between accumulated light (MJ m^{-2}) and dry weight (g m^{-2}) based on global radiation. Note: ○- Barley as a sole crop, Δ- Wheat as a sole crop and ●- Barley & Wheat as mixtures.

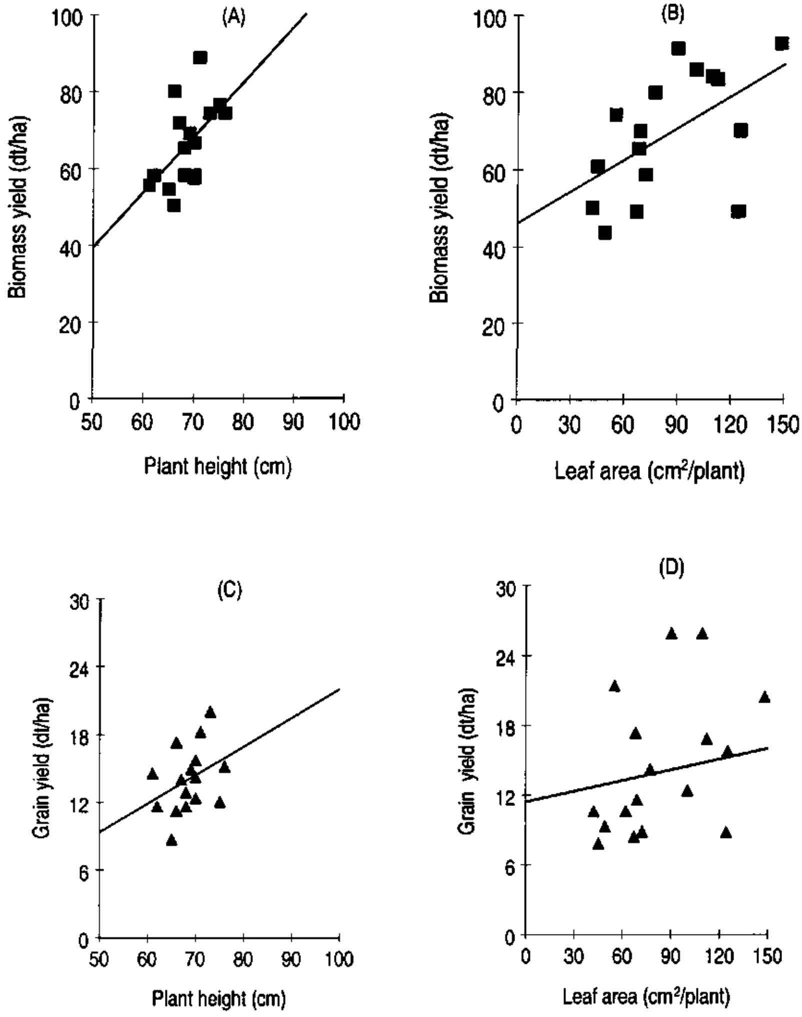

Figure 4.4. Relationship between (A) Mean plant height and biomass yield (r=0.550*) at Halhale (mean of 2 years); (B) Mean leaf area and biomass yield (r=0.564*) at Halhale in 1997; (C) Mean plant height and grain yield (r=0.545*) at Halhale (mean of 2 years); (D) Mean leaf area and grain yield (r= 0.397) at Halhale in 1997. ■- Biomass yield; ▲- Grain yield. The biomass yield and grain yield data are from Chapter 3 and dt ha^{-1} above is the same as quintals ha^{-1}.

Table 4.2. Growth parameters and light use efficiency in barley and wheat sole crops and mixtures at Halhale, averaged over the growing season.

Characters	Barley sole crop	Wheat sole crop	Mixtures
Leaf area (cm^2 $plant^{-1}$)	129	71	118
Leaf area index (m^2 m^{-2})	2.58	2.14	2.75
Leaf area duration (m^2 $m^{-2}\times$ days)	217	175	239
Dry weight (g m^{-2})	800	1103	833
Light use efficiency (g MJ^{-1})	0.93	1.73	0.90

Light use efficiency

The light use efficiency was the highest for wheat as a sole crop followed by barley as a sole crop (Figure 4.3 and Table 4.2). This may be due to an overestimation of the final number of plants in the calculations of the wheat sole crop yield. See also Chapter 3. Figure 4.3C also suggests that the light use efficiency of the barley sole crop dropped severely at the end of the season probably due to the loss of tillers and due to lodging.

Discussion

The potential quantities of light intercepted by each component in mixtures could be affected by the relative heights of the canopies of the components and by the efficiency with which they intercept and absorb light. Mixing crop species or cultivars of both shorter and taller components can greatly affect light penetration especially for undersown species unless there is a temporal difference in resource use. The difference in phenological development such as maturity periods and plant height in barley and wheat mixtures may improve the use of resources use in time during the growing period. When the growth of the major component crops differ in time, the crops make their major demands on resources at different times and become complementary to each other. Jenings and Aquine (1968) and Olasantous (1985) have reported on the importance of plant height in complementary use of resources when grown in mixtures. For example in tomato and okra intercropping increased plant height of okra was observed as tomato approached fruit picking stage which contributed to niche differentiation.

The total leaf area for all crops reached a maximum and declined at some point due to leaf ageing. Prior and Russel (1976), Hunter (1980) and Aase (1978) have reported positive and significant (r=0.95**) relationships between leaf area and dry weight which might change depending on plant growth and environmental conditions. Better photosynthesis of crops can be achieved from LAI of 2-3 or even higher. However, photosynthesis of a plant stand is practically independent of the orientation of leaves especially at LAI values of 3 or less (Peter et al., 1988). The average value of LAI during the growing period for the mixtures was the highest which contributed to better photosynthesis and relatively better dry weight than the barley sole crop. If a crop has low LAI the photosynthetic response to increasing incident light is similar to that of a single leaf. If the LAI is higher, shaded leaves at the bottom of the canopy can continue to respond to an increase in incident light even if the leaves in the upper canopy are light saturated. Barley grows fast at early stage and the plant canopy becomes thicker, the whole shoot system responds to increasing light flux up to higher levels intercepting a greater proportion of incident light than wheat sole crop especially between 50 to 90 DAS. An effective competitor like barley captures resources quickly but it does not necessarily result in efficient use of light.

Wheat as a sole crop achieved more dry matter accumulation than barley as a sole crop due to the higher number of plants m^{-2} and taller plant height compared to barley as a sole crop. Moreover, especially during the second half of the growing season the LUE appeared to be high. At early stages in the growing season soil moisture conditions were favourable and vapour pressure deficits were low which was to the benefit of barley in terms of growth either in sole cropping or in mixtures. Wheat as a sole crop developed dry matter slowly even though it increased faster later during the growing period. The early development of growth rate for barley has laid a foundation for the dry weight during the early growth stage even though not higher than the wheat sole crop. In mixtures, slow growth of wheat as a component mixture can decrease its ability to compete with barley as a component mixture. Similar findings were reported in legumes in Australia in which dry matter accumulation was associated with growth rate during the growing period (Siddique and Sedgley, 1986; Thomas, 1995).

The mean light use efficiency averaged over the growing period was much higher for the wheat sole crops. The light use efficiency for the wheat sole crop was probably overestimated but may also have been partly due to water saving by lower LAD, less lodging and less tiller death. Galagher and Biscoe (1978) have mentioned that biomass is correlated with intercepted radiation during the growing season. This study also showed a significant positive relationship between light accumulation and dry weight.

Light use efficiency can vary with cultivar or crop species (Blum, 1990), with stress such as diseases and drought (Green et al., 1985; Madeira et al., 1994) and with season and management practices (Gregory et al., 1992). In this study it was assumed that the soil conditions were favourable, that there was no drought; diseases and insect incidence were not prevalent. The management factors used were mostly similar to those practised under farmers conditions such as the type of landraces, crop ratio or density, weeding, planting method used, etc.

Conclusion

Wheat became taller than barley. Light use efficiency averaged over the growing season was higher for the wheat sole crop compared to the barley sole crop. The higher light use efficiency for the wheat sole crop was due to lower light accumulation and higher dry weight. The potential yield increase for mixtures over barley sole cropping may be associated with the relative height and a higher light use (efficiency) of wheat. In this limited data set the yield advantage of barley and wheat mixtures could not be related to simple crop ecological parameters, such as light interception or light use efficiency.

Yield advantage in genotype combinations of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* mixtures

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Abstract

Barley and wheat genotypes grown in mixtures were evaluated at Halhale and Mendefera, Eritrea, in 1997-1998, in order to identify genotype combinations with yield advantage and component crops with better competitive ability. Relative Yield Total (RYT) was quantified as an indicator of yield advantage and competition functions such as Competition Ratio (CR) and Aggressivity value (A) were estimated as a measure of competitive ability of the genotypes. Regression analysis on the relationship between RYT and grain yield and biomass and between CR and grain yield were carried out. There were significant differences in RYT based on grain yield averaged over the two years at Halhale. A combination of Yeha+ Kenya + Mana (RYT=2.22) and Yeha + HAR 416 (RYT=1.68) showed considerable yield increases relative to their sole crops. The grain yield and RYT (r=0.700**) were positively and significantly correlated. The classical combination of Yeha + Mana (RYT=1.55) also showed a yield advantage but was surpassed by other combinations. At Mendefera, Kuunto + K 6290 gave the highest yield advantage (RYT=1.15) which was higher than that of the control, Yeha + Mana (RYT=1.01). Barley was more competitive than wheat. Kuunto (CR=3.52) was most competitive among barley genotypes and Kenya +Mana (CR=1.68) among the wheat genotypes. There were positive and significant relations between competition ratio and grain yield of component crops in mixtures. This study indicated that some genotype combinations may show a yield advantage, which implies that they are complementary in resource use.

Key words: yield advantage, relative yield total, aggressivity, competition ratio, barley, wheat, mixed cropping, genotype, Eritrea

Introduction

One of the reasons of growing barley and wheat mixtures is a possible yield advantage. The mixtures can result in a yield advantage because of a more efficient exploitation of available resources. This better exploitation of resources might be enhanced by mixing genotypes or landraces that are maximum in their complementarity (Woldeamlak and Struik, 2000). The success of any mixed cropping system therefore depends on the proper choice of genotypes.

The main mechanisms of complementarity are related to the difference in growth pattern of the component crops. When growth patterns differ in time, component crops make their major demands of resources at different times (Chapter 4; Willey, 1979). This type of complementarity gives better use of resources over time. Temporal differences are also beneficial when there is a difference in maturity between component crops. In this situation the early component crop (barley) can ensure efficient early use of resources while the later maturing components (wheat) can ensure efficient use of any residual resource (Chapter 3; Willey, 1979a,b).

Competition occurs when the use of some resources by one species is at the expense of the use of the same resources by another. However, when crop species show a yield advantage in mixed cropping it implies that they are complementary. In terms of competition, the effect of mutual inhibition is smaller than the advantage. The competitive relationship of barley and wheat genotypes or landraces as component crops in mixtures has not been quantified through field studies. Such quantification would help in selecting genotype combinations for maximum utilisation of growth resources and higher yield advantage.

This study involves various genotype combinations using a crop ratio of barley 67% and wheat 33%. The hyperbolic regression approach to describe competition (Spitters, 1983a) cannot be applied in this study because the model deals with data sets of populations varying in crop ratio and total density (cf. Chapter 7). Therefore, in this chapter, competitive functions like competition ratio and aggressivity values are considered in order to estimate competition in barley and wheat genotype combinations. Trenbath (1974), Willey (1979a,b), Holkar et al. (1991), Chatterjee et al. (1993), Rew et al. (1996) and Banik (1996) have successfully used these competitive relations in order to estimate competition in intercropping as affected by variations in genotype composition.

The main objective of this study were therefore (i) to quantify yield advantage of barley and wheat genotypes in mixtures using relative yield total and (ii) to identify component genotypes having better competitive ability than the standard ones.

Materials and Methods

In three experiments at different sites and in different years, four barley and four wheat genotypes were grown in all possible combinations in a Randomised Complete Block Design in four replications. The experiments included 16 genotype combinations and 8 sole crops. Individual plot size was 3.0 m^2. Details on the experiments have been described in Chapter 3. Here we will focus on the relative advantages in biomass and grain yield of the genotype combinations and methods of estimating competitive functions.

Yield advantage

Relative yield total (RYT)

RYT was used in order to estimate the yield advantage. The details of the method can be found in Chapter 7 of this thesis. The relative yield advantage was estimated as:

$$RYT = RY_1 + RY_2 = Y_{12} / Y_{11} + Y_{21} / Y_{22} \qquad (5.1)$$

where species 1 is barley and species 2 is wheat; Y_{12} and Y_{21} are biomass yields or grain yields of component crops in mixtures; Y_{11} and Y_{22} are the biomass yields or grain yields of the sole crops. When RYT is equal to 1, the same yield of the mixtures of each species may be obtained from the sole crop. When RYT > than 1, the genotypes of the two crops are complementary in resource use which implies that they have collected and shared their resources in such a way that a yield advantage occurred relative to their sole crops. When RYT < 1, the genotype combination in mixtures is disadvantageous (Trenbath, 1974; Mead and Willey, 1980; Martin and Snaydon, 1982; Natarajan and Willey, 1986; Francis and Stern, 1987; Mehta et al., 1990; Chatterjee et al., 1993; Natarajan and Zharare, 1994). The drawback of using the relative yield total (RYT) is that the yield advantage is only valid for a specific crop ratio used in this case barley 67% and wheat 33%.

Competitive relations

Competition ratio (CR)
The competition ratio was computed for the genotypes as component crops in mixtures as:

$$CR_1 = RY_1 / RY_2 \times Z_2 / Z_1 ; \qquad (5.2)$$
$$CR_2 = RY_2 / RY_1 \times Z_1 / Z_2$$

where species 1 is barley and species 2 is wheat; CR_1 and CR_2 are the competitive ratios for the crop species; RY_1 and RY_2 are the relative yields of barley and wheat, respectively; Z_1 is the proportion of barley in mixtures; Z_2 is the proportion of wheat in mixtures. Higher competition ratios indicate that the competitive ability of the component crop is high and equal competition ratios between component genotypes in mixtures show equal competitive ability.

Aggressivity
Aggressivity was estimated as:

$$A_1 = Y_{12}/(Y_{11} \times Z_1) - Y_{21}/(Y_{22} \times Z_2); \qquad (5.3)$$
$$A_2 = Y_{21}/(Y_{22} \times Z_2) - Y_{12}/(Y_{11} \times Z_1)$$

where species 1 is barley and species 2 is wheat; A_1 and A_2 are the aggressivity values of the crops; Y_{12} and Y_{21} are the yields of the genotypes as a component crop in mixtures; Y_{11} and Y_{22} are the yields of the genotypes in sole crops; Z_1 and Z_2 are proportions of the crops in mixtures. An aggressivity value of zero indicates that the component species are equally competitive. For any other situation both species will have the same numerical value but the sign of the dominant species will be positive (+) and of the dominated ones negative (–) (Gilchrist, 1965; Willey, 1979a,b; Willey and Rao, 1980; Chatterjee et al., 1993; Banik, 1996; Rew et al., 1996).

Results

Relative Yield Total (RYT)

RYT biomass yield

The results for RYT for biomass for the genotype combinations at Halhale Research Station and at Mendefera, Eritrea 1997-1998, are shown in Table 5.1. There were significant differences in biomass among the mixtures in 1997 at both locations. In the year 1997, Ardu 12/60 + Mana (RYT=1.60) gave the highest RYT value followed by Ardu 12/60 + Kenya + Mana (RYT=1.47). Yeha + Mana, the standard combination, also showed an increase of 40% in biomass yield relative to the sole crops. Some of the other high yielding genotype combinations (Chapter 3) such as Kuunto + Mana also showed a yield advantage, with 17% increase relative to the sole crops.

In 1998, at the same location (Halhale), the RYT based on biomass yield again significantly differed among the combinations. The highest increase in RYT was for the mixtures of IAR 485 + K 6290 (RYT=1.56), IAR 485 + Kenya + Mana (RYT=1.44) and Ardu 12/60 + Kenya + Mana (RYT= 1.44). When averaged over the two years at the same location (Halhale) there were also significant differences in RYT based on biomass yield among mixtures. A combination of Ardu 12/60 + Kenya + Mana (RYT=1.46) and Ardu 12/60 + Mana (RYT=1.32) showed the highest yield advantages. Kuunto + Mana (RYT=1.17) that was one of the best genotype combinations in terms of total biomass yield (Chapter 3) also showed a high yield advantage (Table 5.2) relative to their sole crops. There was a positive correlation between RYT and biomass yield at Halhale (Figure 5.1).

The results of RYT based on biomass yield for the Mendefera site are also shown in Table 5.1. There were significant differences in RYT based on biomass yield among the genotype combinations at Mendefera. The relative advantage in biomass yield at this location (Mendefera) strongly depended on the type of genotype combinations. The genotype combination that showed the highest advantage in biomass at Mendefera was Kuunto + K 6290 (RYT=1.15). The genotype combinations performing poorly in biomass advantage at Halhale performed better at Mendefera (Table 5.1). There was a positive correlation

Table 5.1. RYT for biomass yield for different genotype combinations in barley and wheat mixtures at Halhale Research Station and Mendefera, Eritrea 1997 and 1998. Combinations are listed in descending order of the mean value for two years (Halhale). Means followed by the same letter are statistically not significantly different.

		Halhale			Mendefera
Barley	Wheat	1997	1998	Mean	1997
Ardu 12/60	Kenya + Mana	1.47 ab	1.44 ab	1.46 a	0.85 c
Ardu 12/60	Mana	1.60 a	1.04 efg	1.32 ab	0.92 bc
Yeha	Kenya + Mana	1.45 ab	1.09 defg	1.27 b	0.86 bc
Yeha	K 6290	1.22 bcde	1.31 abcde	1.27 b	0.98 bc
Ardu 12/60	HAR 416	1.26 abcd	1.25 bcdef	1.26 b	0.98 bc
IAR 485	Kenya + Mana	0.99 def	1.44 ab	1.22 bc	0.90 bc
IAR 485	K 6290	0.87 ef	1.56 a	1.22 bc	0.90 bc
IAR 485	HAR 416	1.07 cdef	1.35 abcd	1.21 bcd	0.87 bc
Kuunto	Mana	1.17 bcde	1.17 bcdefg	1.17 bcd	0.87 bc
Kuunto	HAR 416	0.93 def	1.39 abc	1.16 bcde	0.98 bc
Yeha	HAR 416	1.16 bcde	1.15 bcdefg	1.16 bcde	0.87 bc
Yeha	Mana	1.40 abc	0.90 g	1.15 bcde	1.01 ab
Ardu 12/60	K 6290	1.29 abcd	1.00 fg	1.15 bcde	1.02 ab
IAR 485	Mana	1.00 def	1.11 cdefg	1.06 cde	0.88 bc
Kuunto	Kenya + Mana	1.06 cdef	1.00 fg	1.03 de	0.90 bc
Kuunto	K 6290	0.72 f	1.24 bcdef	0.98 e	1.15 a
Mean		1.17	1.21	1.19	0.93
LSD5%		0.37	0.30	0.18	0.16
CV		22.4	17.5	10.5	12.3

between RYT and total biomass yield (r=0.798**) at Mendefera (Figure 5.1).

RYT in grain yield

The results of RYT of the genotype combinations based on grain yield at Halhale Station, 1997-1998, are shown in Table 5.2.

In 1997, highest yield advantages were from a mixture of Yeha + Kenya + Mana (RYT=3.51) and Yeha + HAR 416 (RYT=2.34). The best combination in grain yield (Chapter 3; Kuunto + Mana) had a yield advantage of 85% increase over the sole crops. In general, the RYT value averaged over all mixtures suggested a yield advantage of mixed cropping (49% increase) (RYT=1.49; Table 5.2).

Table 5.2. RYT based on grain yield for genotype combinations in barley and wheat mixtures at Halhale Research Station and Mendefera, Eritrea, 1997 and 1998. The combinations are listed in descending order of the mean value of Halhale for two years (Halhale). Means followed by the same letter are statistically not significantly different.

Genotype combination		Halhale			Mendefera
Barley	Wheat	1997	1998	Mean	1997
Yeha	Kenya + Mana	3.51 a	0.93 defg	2.22 a	0.90 cdef
Yeha	HAR 416	2.34 b	1.02 cdefg	1.68 b	0.79 efg
Ardu 12/60	Kenya + Mana	1.93 bcd	1.21 bcdef	1.57 bc	0.98 bcde
Yeha	Mana	2.24 bc	0.85 fg	1.55 bc	1.03 bc
Kuunto	Mana	1.85 bcde	0.98 cdefg	1.42 bcde	0.70 gh
IAR 485	HAR 416	0.91 ghi	1.78 a	1.35 bcdef	0.82 defg
Yeha	K 6290	1.56 defg	1.07 cdefg	1.32 bcdef	0.99 bcd
Kuunto	HAR 416	1.28 defghi	1.32 bc	1.30 bcdefg	0.72 fgh
IAR 485	K 6290	0.83 hi	1.74 a	1.29 bcdefg	0.84 cdefg
Ardu 12/60	K 6290	1.63 cdef	0.88 efg	1.26 bcdefg	1.32 a
IAR 485	Mana	1.19 efghi	1.22 bcdef	1.21 cdefg	0.89 cdefg
Ardu 12/60	Mana	1.38 defgh	1.02 cdefg	1.20 cdefg	0.96 bcde
IAR 485	Kenya + Mana	0.75 hi	1.46 ab	1.11 defg	0.88 cdefg
Kuunto	K 6290	0.74 hi	1.23 bcde	0.99 efg	0.87 cdefg
Ardu 12/60	HAR 416	0.65 i	1.29 bcd	0.97 fg	1.10 b
Kuunto	Kenya + Mana	1.01 fghi	0.75 g	0.88 g	0.57 h
Mean		1.49	1.17	1.33	0.90
LSD5%		0.67	0.37	0.44	0.20
CV (%)		31.9	21.9	22.9	15.9

In 1998 (Halhale), there were significant differences among genotype combinations in RYT based on grain yield. A combination of IAR 485 + HAR 416 (RYT=1.78) or IAR 485 + K 6290 (RYT=1.74) showed the highest advantage in grain yield relative to the sole crops (Table 5.3). In 1998 also, there was an advantage of mixed cropping in grain yield with 17% increase (RYT= 1.17; Table 5.2). When averaged over the two years there were significant differences in RYT based on grain yield. A combination of Yeha + Kenya + Mana (RYT=2.22) and Yeha + HAR 416 (RYT=1.68) showed very high increases in grain yield relative to the sole crops. The standard, Yeha + Mana, also showed a yield advantage of 55% increase over the sole crops (Table 5.2), even though the value was surpassed by other combinations. Grain yield and RYT (r=0.700**) were positively and highly correlated (Figure 5.1).

Table 5.3. Effect of genotype on relative yield total (RYT) based on biomass yield or grain yield, in barley and wheat, averaged over genotypes of the other component crops at Halhale 1997-1998. The RYT of the average component of mixtures is the mean RYT value of the genotypes as component crops, averaged over the different genotypes of the other crop. The list is based on descending order of the mean RYT in grain yield. Values without letters are statistically not different. Means followed by the same letter are not significantly different.

Genotype	RYT in biomass yield			RYT in grain yield		
	1997	1998	Mean	1997	1998	Mean
Barley						
Yeha	1.31 a	1.11	1.21 ab	2.41 a	0.97 b	1.69 a
Ardu 12/60	1.41 a	1.18	1.30 a	1.40 b	1.10 b	1.25 ab
IAR 485	0.99 b	1.37	1.18 ab	0.90 b	1.55 a	1.24 ab
Kuunto	0.97 b	1.20	1.09 b	1.22 b	1.07 b	1.15 b
Mean	1.17	1.22	1.20	1.49	1.17	1.33
LSD5%	0.16	NS	0.16	0.86	0.28	0.46
CV (%)	8.4	13.9	8.4	36.3	14.7	21.5
Wheat						
Kenya + Mana	1.24 ab	1.24	1.24	1.80 a	1.09 ab	1.45
Mana	1.30 a	1.06	1.18	1.67 ab	1.02 b	1.35
HAR 416	1.11 bc	1.29	1.20	1.19 ab	1.35 a	1.27
K 6290	1.03 c	1.28	1.16	1.19 ab	1.23 ab	1.22
Mean	1.17	1.22	1.20	1.49	1.17	1.33
LSD5%	0.16	NS	NS	0.86	0.29	NS
CV (%)	8.4	13.9	8.4	36.3	14.7	21.5

The results of the Mendefera site are also shown in Table 5.2. There was a significant difference in RYT and in grain yield. Like the biomass, the yield advantage in grain yield depended on the type of genotype combination. Out of all genotype combinations tested at Mendefera, only Ardu 12/60 + K 6290 (RYT=1.32); Ardu 12/60 + HAR 416 (RYT=1.10) and Yeha + Mana (RYT=1.03) showed yield advantage for grain yield relative to the sole crops (Table 5.2). There was a positive but non-significant relationship between RYT and grain yield (r=0.336) at Mendefera (Figure 5.1).

The RYT of the genotypes as component crops for the Halhale experiment is shown in Table 5.3. For RYT biomass yield, Ardu 12/60 (RYT= 1.30) was the highest among the barley genotypes with a 30% increase, whereas Kenya + Mana (RYT= 1.24) was the highest among the wheat genotypes with a 24% increase averaged over the two years. For RYT grain yield, Yeha (RYT=1.69) showed the highest increase among the barley genotypes, whereas Kenya + Mana (RYT=

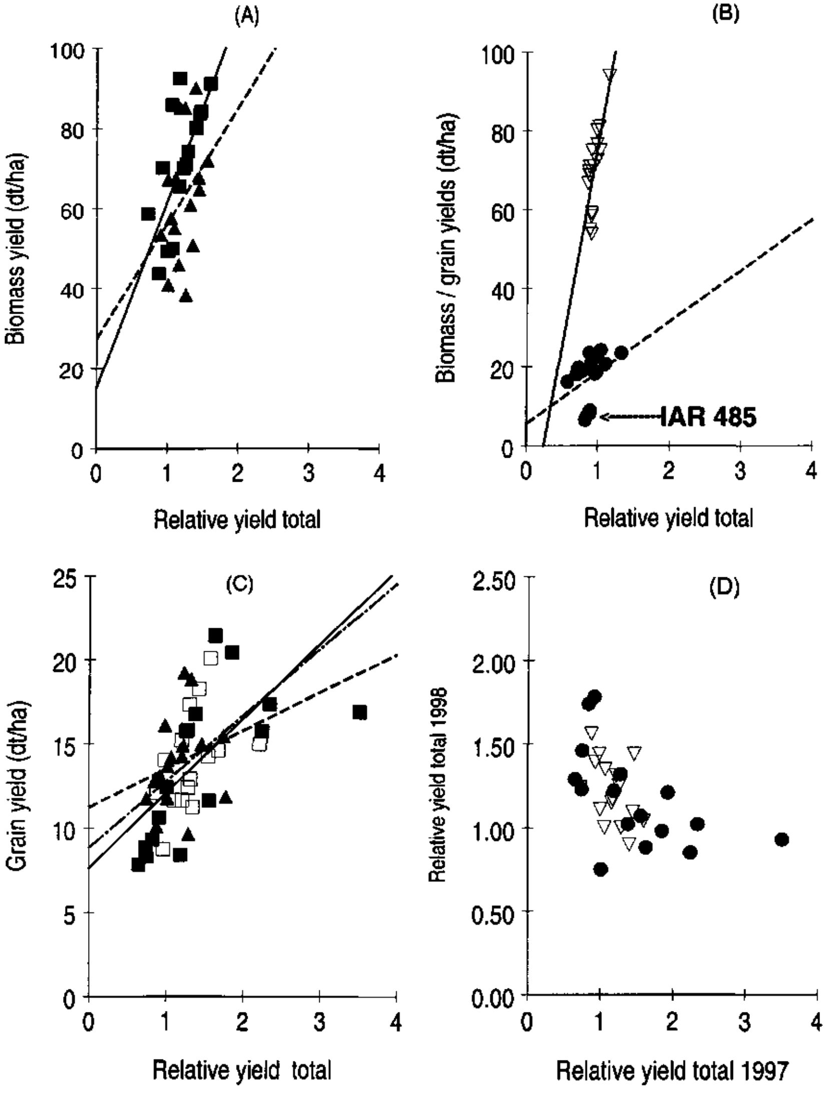

Figure 5.1. (A) RYT vs biomass yield in 1997 (r=0.706**) and RYT vs biomass yield in 1998 (r=0.354) at Halhale; (B) RYT vs biomass yield (r=0.798**); RYT vs grain yield (r=0.336) 1997 at Mendefera in 1997; (C) RYT vs grain yield in 1997 (r=0.621**) and RYT vs grain yield in 1998 (r=0.249) and mean RYT vs grain yield (r=0.437) averaged over 2 years at Halhale; (D) RYT biomass yield 1997 vs RYT biomass yield 1998 (r=–0.444); RYT grain yield 1997 vs RYT grain yield in 1998 (r=–0.549*) at Halhale. Note: In all the graphs ∇- Biomass yield and ●- Grain yield, ■- 1997, ▲- 1998; and □- Mean of 2 years; **- significant at 1% level. In the graph dt ha^{-1} is the same as quintals ha^{-1}.

1.45) was the highest among the wheat genotypes with a 45% increase when averaged over the two years.

Competitive relations

Competition Ratio (CR)

In the year 1997, barley (CR=2.85) was more competitive than wheat (CR=0.88). The average competition ratio of the genotypes of component crops in mixtures was highest for Kuunto (CR=4.46) and Yeha (CR=4.08) showing the better competitive ability of the genotypes. IAR 485 (CR=0.91) was poorly competitive among the barley genotypes as shown from the competition ratio. Among the wheat genotypes, Kenya + Mana were better in competition (CR=1.81), whereas K 6290 had a relatively poor competitive ability in mixtures (CR=0.44) (Table 5.4).

In 1998, barley (CR=1.96) had a higher competition ratio than wheat (CR=1.16). Again, Yeha (CR=2.89) and Kuunto (CR=2.57) were better in competitive ability than the other barley and wheat genotypes. This time the

Table 5.4. Average competition ratio of the component crops in mixtures at Halhale, 1997–1998. CR- the mean competition ratio of genotypes as components crops, CR^{-1}- the reciprocal of CR. Average competition ratio of components in mixtures (CR) is the mean value of the genotypes as component crops, averaged over the different genotypes of the other crop. Results are listed in descending order of the mean competition ratio of CR- averaged over two years.

Crops/genotypes	1997		1998		Mean	
	CR	CR^{-1}	CR	CR^{-1}	CR	CR^{-1}
Barley						
Kuunto	4.46	0.34	2.57	0.96	3.52	0.65
Yeha	4.08	0.56	2.89	0.69	3.49	0.63
Ardu 12/60	1.93	0.36	0.70	0.89	1.32	0.63
IAR 485	0.91	1.78	1.66	0.39	1.29	1.09
Mean	2.85	0.76	1.96	0.73	2.41	0.75
Wheat						
Kenya + Mana	1.81	1.76	1.54	0.47	1.68	1.12
Mana	0.59	1.31	1.82	1.34	1.21	1.33
HAR416	0.67	5.27	0.39	1.64	0.53	3.46
K 6290	0.44	3.04	0.89	1.81	0.67	2.43
Mean	0.88	2.85	1.16	1.32	1.02	2.09

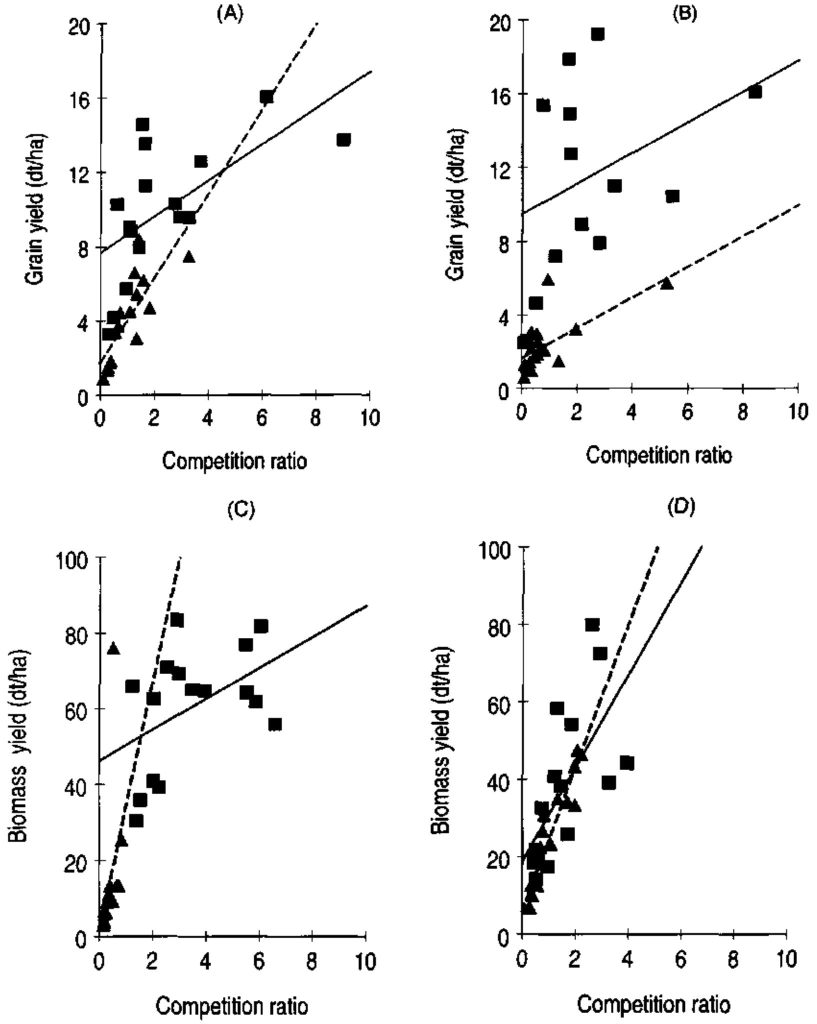

Figure 5.2. Competition ratio (CR) vs grain yield and biomass yield of component crops in mixtures at Halhale. (A) CR vs grain yield of barley (r=0.393) and grain yield of wheat (r=0.675**) in 1997; (B) CR vs grain yield of barley (r=0.582*) and grain yield of wheat (r=0.888**) in 1998; (C) CR vs biomass of barley (r=0.468) and biomass of wheat (r=0.861**) in 1997; (D) CR vs biomass yield of barley (r=0.660*) and biomass yield of wheat (r=0.936**) in 1998. Note: ■- Barley ; ▲- Wheat. Note: in the graph dt ha^{-1} is the same as quintals ha^{-1}; **- significant at $P \leq 0.01$; *- significant at $P \leq 0.05$.

Table 5.5. Aggressivity values of average components in mixtures in barley and wheat genotype combinations at Halhale in 1997-1998, listed based on the descending order of mean aggressivity value averaged over the two years. Average values of components in mixtures are the mean values of the genotypes as component crops, averaged over the different genotypes of the other crop.

Crop/genotype	1997	1998	Mean
Barley			
Yeha	2.12	–0.13	1.00
Kuunto	1.00	0.74	0.87
Ardu 12/60	0.77	–0.55	0.11
IAR 485	–0.80	0.32	–0.24
Mean	0.77	0.13	0.45
Wheat			
Mana	0.003	0.57	0.29
Kenya + Mana	–0.98	0.43	–0.28
K 6290	–0.95	–0.42	–0.69
HAR416	–1.16	–1.07	–1.12
Mean	–0.77	–0.13	–0.45

barley genotype Ardu 12/60, (CR=0.70), was poor as shown by the competition ratio. Among the wheat genotypes, HAR 416 had the lowest competition ratio. There was usually a positive and significant relationship between competition ratio, and grain yield of the component crop (Figure 5.2).

Aggressivity

The aggressivity values of the component crop in mixtures are shown in Table 5.5. The mean aggressivity values for the wheat genotypes in both years were negative.

In 1997, the mean value for barley was positive. The aggressivity values were higher for Yeha (A=2.12) and Kuunto (A=1.00) than for the other barley genotypes. All wheat genotypes, except Mana showed a negative value of aggressivity in mixtures. In 1998, two barley genotypes showed a negative value, namely Yeha (A= –0.13) and Ardu 12/60 (A= –0.55), whereas the wheat genotypes Kenya + Mana and Mana showed positive (but very small) values.

Discussion

In addition to the concept of yield advantage based on the relative yield total, the competition functions used can describe the competition relationships in genotype combinations thus providing some indication of possible yield advantage. For any given combination, all functions show which component is dominant and which component is dominated. However, the functions do not show the magnitude of yield advantage. For this the RYT values are preferable as they show relative yield advantage better than the competitive relations. The competitive relations and the yield advantage estimates are discussed further below.

Yield advantage

There were only few genotype combinations, especially at Halhale, that did not show a yield advantage in mixtures. The standard combination Yeha + Mana (RYT=1.55) showed a yield advantage in mixtures at Halhale, but was surpassed by other combinations. This implies that there were combinations with better yield advantage than this standard. There was also a difference in RYT between the locations. This could be due to the poorer performance of the sole crops compared to the mixtures at Halhale than at Mendefera, which resulted in a higher yield advantage. At Mendefera, the sole crops performed better and hence the yield advantage for the mixtures was absent or small. There were also variations of RYT between years on the same location (Halhale), which could be due to the difference in rainfall between the two years that contributed to the variation in yield of the sole crops or mixtures and thereby resulted in variations in the magnitude of the yield advantage.

Regardless of the absence of yield advantage averaged over the genotype combinations in mixtures at Mendefera, mixed cropping could still be useful in that location because of the other benefits such as insurance mechanism for periods of drought, and the improved diet, straw yield and yield stability, that are also beneficial (Chapter 2). The yield advantage gives a clue that the genotypes of the crop species in mixtures were able to utilise the available resources in the niche to which they are grown best. This means that the efficiency of the mixtures in utilising the ecosystem in the soil is larger relative to the sole crops (Willey and Osiru, 1972a,b; Osiru and Kibra, 1979; Willey, 1979a,b; Reddy and Reddy, 1981; Natarajan and Willey, 1986; Reddy et al., 1986). This study indicated that the efficient use of resources may be enhanced by mixing compatible landraces or cultivars.

The RYT was extremely high for certain genotype combinations and this is based on relatively very poor performance of the sole crops. The lower the yield of the sole crop or the higher the yield in mixtures, the higher will be yield advantage.

Competition ratio

The component crops in mixtures that showed higher competition ratios yielded better. Some genotypes were more competitive than others. Similar trends were observed in an intercropping system of mustard + chickpea with some genotypes being more competitive than others (Gangasaran and Giri, 1985; Kushwaha and De, 1987).

Competition ratio (CR) is simply the ratio of the individual RYT's of the two component crops but corrected for the proportions in which the crops were initially sown. Competitive ratios can give the exact degree of competition by indicating the number of times one crop is more competitive than the other. Although the CR concept may provide a way of defining relations between competitive ability, it does not eliminate some of the problems of interpreting these relations in biological terms.

The higher the competitive ability, the higher the grain yield and yield advantage. On the other hand, RYT puts yields on a relative basis to respective sole crops so that the magnitude of yield advantage of the two component crops can be added together. However, this measure (RYT) alone cannot define quantitatively the degrees of competition in any given situation. So CR helps to identify the balance of competition and describes the competition situation between component crops that is most likely to give maximum yield advantage even though it cannot quantify the magnitude of the yield advantage.

Aggressivity

The aggressivity values of barley were generally positive showing its dominance over wheat in mixtures. The aggressivity values of wheat were generally negative indicating that it was dominated by barley. For those cases where both were positive, the values were also larger for barley than where showing the difference in the degree of dominance. Barley grows very fast at early growth stages utilising the resources, which could be the reason for its dominance (Chapter 3). Willey (1979a,b), Singh et al. (1984) and Rai (1986) have mentioned the dominance of one component crop over the other in grass–legume mixtures using aggressivity value.

Aggressivity value is a function which attempts to measure the intercrop competition by relating the yield changes in mixtures of component crops (Equation 5.2 this chapter). The aggressivity value can be used not only in genotype combinations but also in the evaluation of various crop ratios. However, it is not a suitable measure in intercrop competition when evaluating different crop ratios of additive and replacement series.

Conclusion

In general, this study suggested that barley was highly competitive and dominant as a component crop over wheat. Furthermore there was a difference in competitive ability depending on the type of genotypes used as component crops. The competitive relations, especially the competition ratio, were able to describe competition of genotype combinations but cannot measure the degree of yield advantage. RYT can estimate the yield advantage in mixtures relative to the sole crops. So the competition ratio and RYT together can describe what is going on in a mixed cropping experiment as affected by genotype combinations. Mixed cropping showed a yield advantage compared to sole cropping but this was not the case at Mendefera even though there were two or three genotype combinations that showed some yield advantage. The best yielding genotype combinations (Chapter 3) like Ardu 12/60 + Kenya + Mana (mean RYT=1.57) showed a considerable yield increase over the sole crops at Halhale. Kuunto + Mana which was also one of the best yielding mixtures (Chapter 3) showed 55% increase. Yeha + HAR 416 gave the highest yield advantage of all (RYT=1.68) and surpassed the standard, Yeha + Mana, used by farmers.

Response of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* genotype combinations to drought stress under mixed cropping

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Abstract

Two field trials on the response of mixtures of barley and wheat to drought stress were conducted at Halhale Research Station during the off-seasons of 1998 and 1999. Objectives were to assess whether mixtures were less affected by drought stress than sole crops and to identify genotype combinations in which grain yield was reduced the least. Three barley and three wheat genotypes in all nine possible combinations together with the six sole crops were grown without or with early or late drought stress in a split plot design with four replications. Drought stress treatments were assigned to the main plots, and genotype combinations to the subplots. The differences in grain yield among genotype combinations were statistically significant in both years and the effect of drought stress on grain yield at $P \leq 0.10$ in 1999 and at $P \leq 0.05$ when averaged over the two years. The interaction drought stress × genotype combination was not significant at $P \leq 0.05$ There was a significant and positive relationship between yield loss and drought susceptibility index (DSI). Some high yielding genotype combinations showed DSI > 1 namely Ardu 12/60 + K 6290 (2804 kg ha^{-1}), Yeha + K 6290 (2738 kg ha^{-1}) and IAR 485 + Mana (2728 kg ha–1). On the other hand, IAR 485 + Kenya + Mana (2728 kg ha^{-1}; DSI=0.960), Yeha + Kenya + Mana (2499 kg ha^{-1}; DSI=0.958) and Yeha + Mana (2220 kg ha^{-1}; DSI=0.447) showed reasonable grain yield and better resistance to stress than the other types of genotype combinations. The promising genotype combinations need to be tested in on-farm trials and demonstrated to farmers on a wide scale before release.

Key words: agro-biodiversity, mixed cropping, barley, wheat, genotype combination, drought stress, drought susceptibility index, yield loss, Eritrea

Introduction

Shortage of water is limiting to crop production in arid and semiarid regions of the tropics (Kozlowski, 1968). About 64% of the tropics' cropped land suffers from drought during the growing season (Rowland, 1993). Some arid and semiarid areas have become disaster areas due to drought resulting in food shortages and famine.

In Eritrea, the amount of rainfall in the highlands ranges from 400 to 650 mm which is enough for crop production. However, sometimes the distribution is erratic and the intensity is high, meaning that a large proportion of the total amount may fall in a short period of time. Furthermore, the rainfall situation is erratic in its distribution, that the rainfall may stop during critical stages of crop growth thus significantly lowering yield.

Among the primary strategies of crop adaptation in situations of erratic rainfall are the use of drought resistant crop species (barley, sorghum, millet) or cultivars; crop management practices (dry planting, optimum seeding rate); moisture conservation practices (cultivation in ridges and furrows, terraces in crop lands, water harvesting); supplementary irrigation (from rivers, wells, reservoirs, ponds and streams) and adaptation of cropping systems (intercropping or mixed cropping).

Mixed cropping of barley and wheat *(hanfetz)* is one of the cropping systems adopted in the highlands of Eritrea. Barley is adaptable to adverse weather conditions. It matures earlier than wheat escaping drought that may affect crops at the heading stage. Wheat is more drought susceptible. Mixed cropping is a risk aversion mechanism or insurance in case of drought because if wheat fails then a harvest of barley can still be obtained. The other reasons of growing barley and wheat mixtures are fully described in Chapter 2. Natarajan and Willey (1986) emphasised that total yields or component yield in mixed cropping can be relatively stable in stress situations because the component crops can complement each other and make better overall use of resources over time when grown together than when grown separately. This may definitely be the case for the resource water, but use of other resources (such as nutrients) also depends on the level of soil moisture available.

Wheat is sensitive to drought stress reducing productivity (Arnon, 1972; Acland, 1973). Water demand of wheat during the seedling stage is less although stress at that stage retards growth permanently and thereby reduces production severely (Acland, 1973). Elnadi (1969) revealed that water shortages during maturation phases affect the productivity of wheat. Barley is better adopted to drought conditions (Cecarelli and Mekni, 1985) and is superior in its water use efficiency over wheat (Christodoulou, 1974; Mekni, 1981). Barley tends to mature earlier than other crops thus escaping drought. However, drought stress during its crop cycle can reduce seed set and yield considerably (Levit, 1972; Simane et al., 1988). Drought stress in barley genotypes also results in shrivelled grains (Levit, 1972).

Varietal differences in drought resistance within crop species are often large. This is also true for barley (Martinez et al., 1995) and wheat (Passioura, 1977; Simane et al., 1988; Dencic et al., 2000) with variation in growth and yield response among cultivars. Difference in drought resistance among genotypes was also found in sorghum (Yilma et al., 1990) and grain legumes (ICARDA, 1993).

Utilising genotypes resistant to drought stress in a mixed cropping system could serve as a means of raising the low yields in situations of rainfall shortage and improving yield stability by minimising yield losses. Natarajan and Willey (1986) showed that total dry matter production tends to decline as the degree of drought stress increased in sorghum and groundnut mixed cropping. Intercropping outperformed sole cropping in sorghum + cowpea (Botswana), without reducing sorghum yield under dryland farming conditions (Lightfoot and Tayler, 1987). No study has been done elsewhere to examine the effect of genotype combination to drought stress in a mixed cropping of barley and wheat. This chapter focuses on the response of barley and wheat genotype combinations to drought stress and assesses the drought susceptibility index (DSI) and yield loss (YL).

Materials and Methods

Site and season

The study on moisture or drought stress effects in barley and wheat mixtures was conducted at Halhale Research Station, Eritrea, during the off-seasons of 1998 and 1999. The site has a clay loam soil and facilities for irrigation. The normal rainy season is from June to September but in order to be able to impose drought stress regimes, the experiment was conducted from January to May when rain is not expected.

Moisture regimes

Three moisture or drought stress treatments were imposed, namely

1. MS_1– Control, no stress by maintaining soil moisture content at 60–70% of maximum soil moisture;
2. MS_2– Stress at seedling stage, early stress with a soil moisture content maintained at 10–20% soil moisture content, followed by irrigation after two weeks of stress;
3. MS_3– Stress at heading stage, a late stress of two weeks with a soil moisture content maintained at 10–20% soil moistures, preceded and followed by irrigation.

The top 10 cm was wetted just prior to sowing in order to ensure proper germination. The moisture content was monitored using a moisture meter with a gypsum block and the soil was irrigated when the moisture level was below the standard already stated. The watering was done using flood irrigation hence much attention was given to prevent water flow from one plot to another.

Cropping systems

The cropping systems studied included a total of fifteen treatments with six sole crops and nine mixtures. A mixture of Yeha + Mana was used as standard. The barley genotypes tested were Yeha, IAR 485 and Ardu 12/60 and wheat genotypes were Mana, Kenya + Mana and K 6290 in all possible combinations. All plots were sown on December 10, 1998 and December 15, 1999.

Crop management practices

The mixtures were hand sown with a broadcasting method. The amount of seed was prepared based on thousand grain weight in a proportion of barley 67% and wheat 33%. A basal dressing of fertiliser at the rate of 100 kg ha^{-1} Di-Ammonium Phosphate (DAP, 18% N and 46% P_2O_5) and 50 kg ha^{-1} (46% N) Urea was applied to the whole experimental unit before sowing. The plots were weeded twice during the cropping period. Harvesting was done for both crop species separately; the crops were also threshed and weighed separately. Yields reported are based on 12.5% moisture content.

Design and analysis

Two-factor factorial experiments were carried out in a split-plot design in 4 replications and an individual plot size of 2.0 m^2. There were three main plots in each replication with drought stress levels assigned to the main plot and variety or varietal mixtures assigned to the subplots. The number of subplots per main plot was 15. The data were analysed by standard Analysis of Variance. The correlations between various agronomic parameters were also assessed by linear regression.

Data collected

The type of data collected were similar to previous experiments which are fully explained in Chapter 3. To avoid repetition we limit ourselves to listing the types of data collected such as grain yield, biomass yield, plant height and yield components (ear size, number of ears m^{-2}, number of kernels per ear and thousand grain weight). However, additional measurements or calculations relevant to this chapter were:

Yield loss (%) was computed as

$$(GY_1 - GY_2) / GY_1 \times 100 \qquad (6.1)$$

where GY_1 is grain yield under stress-free conditions and GY_2 is grain yield under stress conditions.

Drought Susceptibility Index (DSI) was estimated using the formula described by Fischer and Maurer (1978):

$$DSI = (1 - Y_2 / Y_1) / (1 - X_2 / X_1) \qquad (6.2)$$

where Y_1 is the yield of genotype combinations without stress; Y_2 is the yield of genotype combinations under stress; X_1 is the grand mean yield of all genotype combinations (of both crops) without stress; X_2 is the grand mean yield of all genotype combinations (of both crops) under stress.

A DSI less than 1 indicates low stress susceptibility, which means better drought resistance. A DSI greater than 1 indicates that the stress susceptibility is high.

Yield advantage was estimated using the Relative Yield Total on the basis of grain yield (see also Chapters 5 and 7). The formula to estimate RYT is:

$$RYT = RY_1 + RY_2 = (Y_{12} / Y_{11}) + (Y_{21} + Y_{22}) \quad (6.3)$$

where Y_{12} and Y_{21} are the grain yields of the mixtures of barley and wheat, respectively; Y_{11} and Y_{22} are the grain yields of the sole crops of barley and wheat, respectively.

Results

Total biomass yield

The response of genotype combinations to stress with regard to total biomass yield (kg ha^{-1}) is shown in Table 6.1. There was a statistically significant effect of drought stress in 1998 but not in 1999. The biomass yield was highest in MS_1 (control), whereas MS_3 (stress at heading) produced more biomass than MS_2 (stress early in the crop cycle), in both years. There was a significant difference among the genotype combinations in biomass yield in 1998 and when averaged over the years. A combination of Ardu 12/60 + Kenya + Mana (8875 kg ha^{-1}), Yeha + K 6290 (8832 kg ha^{-1}) or Ardu 12/60 + K 6290 (8510 kg ha^{-1}) gave highest total biomass yield in 1998. The lowest biomass yield was obtained from a combination of IAR 485 + Mana (5418 kg ha^{-1}). In 1999, a combination of Yeha + Mana (7501 kg ha^{-1}) was the best yielding followed by Yeha + Kenya + Mana (7342 kg ha^{-1}). When averaged over the two years, there was also a significant difference among the genotype combinations at $P \leq 0.10$. A mixture of Yeha + Mana (7640 kg ha^{-1}) and Yeha + Kenya + Mana (7613 kg ha^{-1}) were the best in total biomass. Mixtures with IAR 485 performed poorly.

The total biomass (kg ha^{-1}) for the drought stress and selected genotype combinations is shown in Figure 6.1. For each stress type, the best mixtures were Yeha + K 6290 in MS_1 (8625 kg ha^{-1}) and MS_2 (7238 kg ha^{-1}) and Yeha + Mana in MS_3 (7756 kg ha^{-1}) with highest total biomass yield when averaged over the two years. Some of the genotype combinations that performed best in total biomass yield under stress at seedling (MS_2) did not perform similarly well under stress at heading (MS_3).

The biomass averaged over the total mixtures (T) of each genotypes are shown in Table 6.3. In 1998, among the barley genotypes, IAR 485 (8192 kg ha^{-1})

Table 6.1. Response of crops differing in genotype composition to drought stress (MS) in total biomass yield (kg ha^{-1}) in mixtures of barley and wheat averaged over the genotypes or stress types at Halhale 1998–1999. MS_1= no stress; MS_2= stress at seedling stage; and MS_3= stress at heading stage. The asterisk in parenthesis (*) below shows a significance at $P \leq 0.10$. The list is in descending order of mean grain yield averaged over two years. Means followed by the same letter are statistically not significantly different. Values without letters are statistically the same.

Treatments		1998	1999	Mean
Drought stress				
MS_1		8169 a	7641	7905
MS_2		6695 b	6064	6380
MS_3		6994 b	6090	6542
Mean drought stress		7286	6598	6942
Barley	**Wheat**			
Yeha	Mana	7778 bc	7501	7640 a
Yeha	Kenya + Mana	7882 bc	7342	7613 a
Ardu 12/60	Kenya + Mana	8875 a	6130	7503 a
Yeha	K 6290	8832 a	6077	7455 a
Ardu 12/60	K 6290	8510 ab	5835	7173 a
Ardu 12/60	Mana	7192 c	6839	7016 a
IAR 485	Mana	5418 d	6743	6081 b
IAR 485	Kenya + Mana	5610 d	6542	6076 b
IAR 485	K 6290	5473 d	6376	5925 b
Mean		7286	6598	6942
LSD 5%				
Drought stress		527	NS	NS(*)
Genotype		892	NS	728
Genotype × drought stress		NS	NS	NS
CV%		15.1	25.5	12.8

and Yeha (8164 kg ha^{-1}) showed higher biomass yield in average total of mixtures in 1998. In the same year, among the wheat genotypes, K 6290 (7605 kg ha^{-1}) showed maximum yield. In 1999, Yeha gave higher biomass yield among the barley genotypes in average total of the mixtures. In the same year, Mana (8028 kg ha^{-1}) contributed to higher biomass yield among the wheat genotypes. When averaged over the two years, Yeha (7569 kg ha^{-1}) and Kenya + Mana (7064 kg ha^{-1}) contributed to the higher yield in mixtures among the barley and wheat genotypes, respectively.

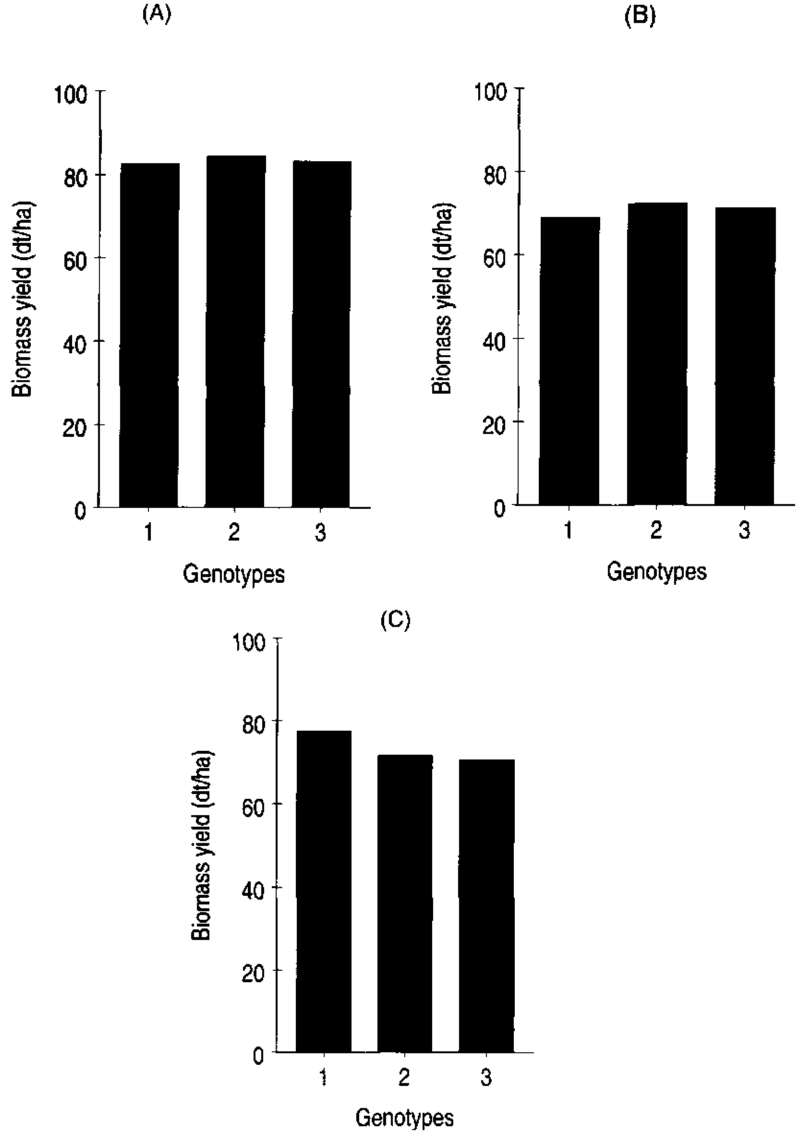

Figure 6.1. Genotype × drought stress interaction of some selected barley and wheat genotype combinations in biomass yield averaged over two years. (A) MS_1= Control (no drought stress); (B) MS_2= stress at seedling stage; (C) MS_3= stress at heading stage. The legend is the same for all graphs. Along the x axis, 1- Yeha + Mana, 2- Yeha + Kenya + Mana, 3- Ardu 12/60 + Kenya + Mana.
Note: in the y axis dt ha^{-1} is the same as quintals ha^{-1}.

Table 6.2. Response of crops differing in genotype combinations to drought stress (MS) as expressed by their combined grain yield (kg ha^{-1}) in mixtures of barley and wheat averaged over the genotypes or stress types at Halhale, 1998-1999. MS_1= no stress; MS_2= stress at seedling stage, and MS_3= stress at heading stage. The asterisk in parenthesis (*) below indicate a significance at $P \leq 0.10$. The list is in descending order of the mean grain yield averaged over two years. Means followed by the same letter are statistically not significantly different. Values without letters are statistically the same.

Treatments		1998	1999	Mean
Drought stress				
MS_1		3078	2337	2708
MS_2		2342	1765	2054
MS_3		2651	1836	2244
Mean drought stress		2690	1980	2335
Barley	**Wheat**			
Ardu 12/60	K 6290	3682 a	1927 ab	2804 a
Yeha	K 6290	3839 a	2300 a	2738 a
IAR 485	Mana	1041 c	2245 a	2728 a
IAR 485	Kenya + Mana	1334 c	1592 b	2715 ab
Yeha	Kenya + Mana	3211 ab	1662 b	2499 ab
Yeha	Mana	3176 ab	1670 b	2220 bc
IAR 485	K 6290	1824 c	1901 ab	1863 cd
Ardu 12/60	Mana	2770 b	2186 a	1760 cd
Ardu 12/60	Kenya + Mana	3335 ab	2334 a	1688 d
Mean		2690	1980	2335
LSD 5%				
Drought stress		NS	NS(*)	NS(*)
Genotypes		793	515	464
Genotypes × Drought stress		NS	NS	NS
CV		36.2	31.5	24.0

The agronomic characters having relationship with biomass yield when pooled over the two years are shown in Table 6.4. None of the characters had a positive and significant relationship with biomass yield.

Total grain yield

There was a statistical significant difference among the genotype combinations in total grain yield in both years at $P \leq 0.05$. The drought stress effect was not

Table 6.3. Differences in biomass yield (kg ha^{-1}) or grain yield (kg ha^{-1}) for average combined yields of mixtures among barley and wheat genotype combinations exposed to different types of drought stress, averaged over stress types at Halhale, 1998–1999. The list is in descending order based on the mean biomass yield averaged over the two years. Means followed by the same letter are statistically not significantly different. Values without letters are statistically the same.

Genotype	Biomass yield			Grain yield		
	1998	1999	Mean	1998	1999	Mean
Barley						
Yeha	8164 a	6973	7569 a	3409 a	1877	2643 a
IAR 485	8192 a	6268	7230 a	1400 b	1913	1657 b
Ardu 12/60	5500 b	6554	6027 b	3262 a	2149	2706 a
Mean	7286	6598	6942	2690	1980	2335
LSD5%	1589	NS	465	301	NS	351
CV%	9.3	10.7	5.9	8.3	14.1	6.7
Wheat						
K 6290	7605	6096	6851	3115 a	2043	2579
Kenya + Mana	7456	6671	7064	2627 b	1863	2245
Mana	6796	7028	6912	2329 b	2034	2182
Mean	7286	6598	6942	2690	1980	2335
LSD	NS	NS	NS	302	NS	NS
CV%	7.0	9.0	10.2	8.2	14.2	6.8

significant in 1998 but significant in 1999 and also when averaged over the two years at $P \leq 0.10$. But there was no effect of drought stress and the interaction between drought stress and genotype combination was not significant either. The total grain yield was higher for the control (MS_1) in both years when averaged over the genotypes. The order in grain yield was $MS_1 > MS_3 > MS_2$ even though not statistically significant. In 1998, a combination of Yeha + K 6290 (3839 kg ha^{-1}) and Ardu 12/60 + K 6290 (3682 kg ha^{-1}) were the best yielding when averaged over the stress types. The standard mixture, Yeha + Mana (3176 kg ha^{-1}), was outyielded by other genotype combinations. In 1999, a combination of Ardu 12/60 + Kenya + Mana (2334 kg ha^{-1}) and Yeha + K 6290 (2300 kg ha^{-1}) were the best in grain yield. When averaged over the two years, Ardu 12/60 + K 6290 (2804 kg ha^{-1}), Yeha + K 6290 (2738 kg ha^{-1}), and IAR 485 + Mana (2728 kg ha^{-1}) were the best yielding (Table 6.2).

The total grain yield (kg ha^{-1}) of some selected genotype combinations of each drought stress treatment is shown in Figure 6.2. A combination of Yeha + K 6290 (3189 kg ha^{-1}) in MS_1, Yeha + Mana (2510 kg ha^{-1}) in MS_2 and MS_3

Table 6.4. Relationship between agronomic characters biomass yield and grain yield for different drought stress treatments for crops differing in genotype combinations at Halhale (1998 and 1999) when pooled over the two years. MS_1 is the control with no drought stress, MS_2 is stress at seedling stage and MS_3 is stress at heading. The asterisk shows significance at $P \leq 0.10$.

Characters	Pooled					
	Biomass yield			Grain yield		
	MS_1	MS_2	MS_3	MS_1	MS_2	MS_3
Stand cover	0.14	–0.25	–0.27	–0.23	–0.45	–0.23
Plant height	–0.50	–0.04	–0.36	–0.65	–0.31	–0.31
Days to heading	–0.64	–0.85*	–0.34	–0.56	–0.69*	–0.44
Days to maturity	–0.59*	–0.57	–0.67*	–0.56	–0.18	–0.69*
Ear size	–0.13	–0.36	–0.49	0.08	0.55	0.46
Ear m^{-2}	0.13	–0.19	0.12	0.63*	0.23	0.17
Kernels ear^{-1}	–0.44	–0.25	–0.65*	–0.00	–0.37	–0.43
TGW	0.23	0.14	–0.23	0.60*	0.19	0.13
Kernels m^{-2}	0.25	0.42	0.48	0.55	0.46	0.39
Biomass yield	--------	-----	-----	0.74*	0.75*	0.59*
Harvest index	0.57	0.45	0.22	0.97*	0.93*	0.85*

(2780 kg ha^{-1}) were the best in total grain yield when averaged over the two years.

When the combined yield of mixtures (T) were averaged, Yeha (3409 kg ha^{-1}) contributed to a better grain yield (3409 kg ha^{-1}) in 1998. In contrast, IAR 485 showed poorer grain yield (1400 kg ha^{-1}) in the same year. In 1999, Ardu 12/60 (2149 kg ha^{-1}) among the barley genotypes and K 6290 (2043 kg ha^{-1}) among the wheat genotypes gave best combined grain yields. IAR 485 was poorly yielding among the barley genotypes whereas Mana was the poorest among the wheat genotypes (Table 6.3).

The agronomic characters and their relationships with biomass or grain yield when pooled over the two years are shown in Table 6.4. Biomass yield (r=0.74*), ears m^{-2} (r=0.63*) and harvest index (0.97*) in MS_1 and days to heading (r=–0.69*), biomass yield (r=0.75*) and harvest index (r=0.93**) in MS_2 showed a positive and significant relationships with grain yield. Biomass yield (r=0.59*) and harvest index (r= 0.85*) also showed significant relationships with grain yield in MS_3.

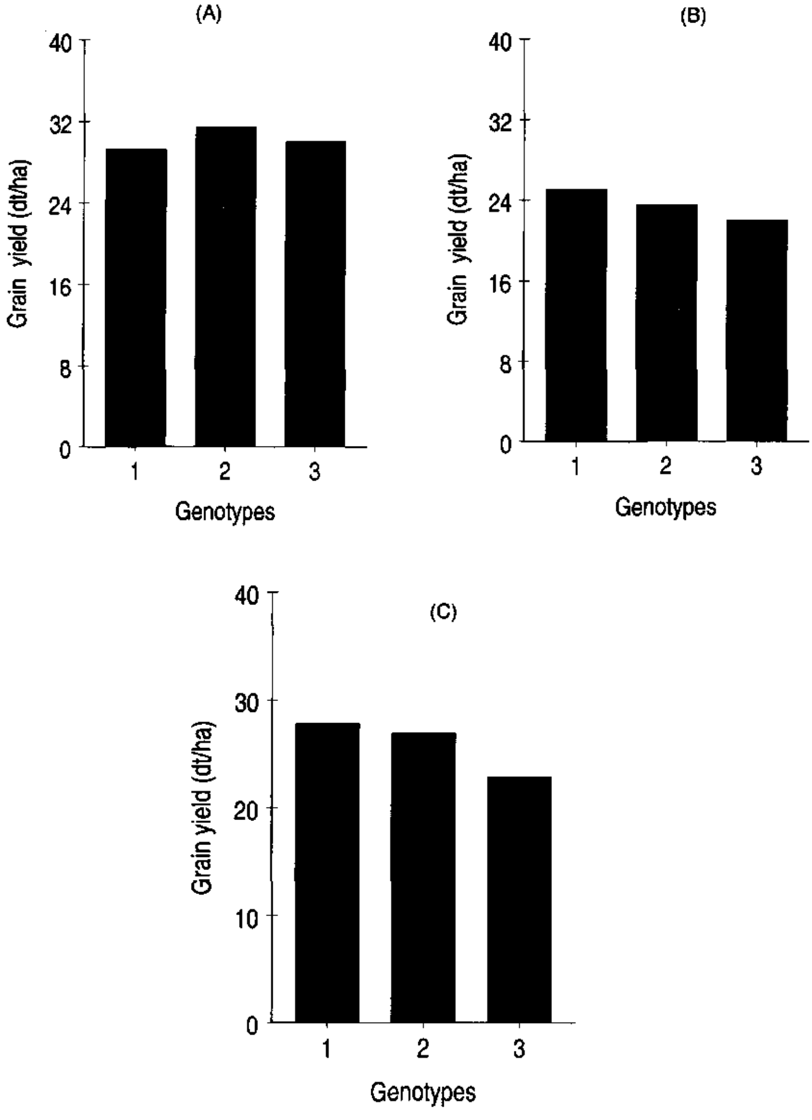

Figure 6.2. Genotype × drought stress interaction of some selected barley and wheat genotype combinations in grain yield averaged over two years. (A) MS_1= Control (no drought stress); (B) MS_2= stress at seedling stage; (C) MS_3= stress at heading stage. The legend is the same for all graphs. Along the x axis, 1- Yeha + Mana, 2- Yeha + Kenya + Mana, 3- Ardu 12/60 + Kenya + Mana.
Note: in the y axis dt ha^{-1} is the same as quintals ha^{-1}.

Drought Susceptibility Index (DSI)

The drought susceptibility index of genotype combinations is shown in Table 6.5. Genotype combinations with better resistance to drought based on the drought susceptibility index (for grain yield) were Yeha + Mana (DSI=0.511), Yeha + Kenya + Mana (DSI=0.564) in 1998 when stress was induced at seedling stage (MS_2). Yeha + Mana (DSI= 0.332), Yeha + Kenya + Mana (DSI=0.644) and IAR 485 + Kenya + Mana (DSI=0.657) showed resistance against stress in the heading stage (MS_3). When averaged over the stress types, Yeha + Mana (DSI=0.422), Yeha + Kenya + Mana (DSI=0.604) and IAR 485 + K 6290 (DSI=0.769) showed the best resistance to stress. In 1999, Ardu 12/60 + Mana (DSI=0.027), IAR 485 + Mana (DSI=0.225) and Yeha + Mana (DSI=0.691) were resistant to stress at seedling stage (MS_2). Yeha + Mana (DSI=0.253) and Yeha + K 6290 (DSI=0.691) showed lower DSI values at stress in heading stage (MS_3). There were also other genotype combinations with DSI < 1 showing some resistance to stress. When averaged over the stress types, Yeha + Mana (DSI=0.472), IAR 485+ Mana (DSI=0.565) and Ardu 12/60 + Mana (DSI=0.631) showed the lowest index values. On the other hand, when averaged over the two years, Yeha + Mana (DSI=0.447) showed the lowest index but there were other combinations with DSI < 1 showing resistance to stress (Table 6.5).

Differences among genotypes in DSI when averaged over the total values of each genotype in mixtures (based on grain yield) are shown in Table 6.7. In 1998, both Yeha (barley) and K 6290 (wheat) showed DSI < 1. In 1999, all barley genotypes showed DSI < 1 except Ardu 12/60. When averaged over the two years Yeha (barley) and Mana (wheat) were most resistant to stress.

Some of the combinations with better resistance to stress at seedling (MS_2) did not show the same behaviour when stressed at heading stage (MS_3). Some genotype combinations that were susceptible to stress at seedling (MS_2) were resistant to stress at heading stage (MS_3). There were also combinations that showed resistance to both stresses, especially in 1998 and in some cases in 1999.

There was a negative relationship between DSI (based on grain yield) and grain yield in total mixtures in both years; this relationship was significant in 1999. The lower the DSI, the higher the grain yield and the higher the DSI, the lower the grain yield (Figure 6.3).

Yield Loss (YL%)

The yield losses based on grain yield of the genotype combinations are shown in Table 6.6. The yield loss was relatively less in stress at heading stage (MS_3) compared to stress at seedling stage (MS_2). The combinations with lower yield losses were Yeha + Mana (11.2%), IAR 485 + Mana (12.5%) and Ardu 12/60 + Mana (13.6%) when averaged over the stress types. When averaged over the two

Table 6.5. Drought Susceptibility Index (DSI) based on grain yield in barley and wheat mixtures in stress at seedling stage (MS_2) or in stress at heading stage (MS_3) at Halhale, 1998-1999. The list is in ascending order based on the DSI averaged over the two years. The asterisk in parenthesis (*) below indicates a significance at $P \leq 0.10$. Means followed by a different letter are statistically significantly different. Means without letters are statistically the same.

Genotype combination		1998		Mean	1999		Mean	2 years
		MS_2	MS_3		MS_2	MS_3		Mean
Yeha	Mana	0.511	0.332	0.422	0.691	0.253	0.472	0.447
Ardu 12/60	Mana	0.842	1.627	1.235	0.027	1.235	0.631	0933
IAR 485	K 6290	0.974	0.563	0.769	0.979	1.285	1.132	0.951
Yeha	Kenya + Mana	0.564	0.644	0.604	1.615	1.009	1.312	0.958
IAR 485	Mana	0.909	1.801	1.355	0.225	0.904	0.565	0.960
Yeha	K 6290	1.148	1.001	1.075	1.518	0.691	1.105	1.090
Ardu 12/60	K 6290	1.157	1.115	1.136	1.27	1.215	1.243	1.190
Ardu 12/60	Kenya + Mana	1.093	1.37	1.232	1.116	1.538	1.327	1.280
IAR 485	Kenya + Mana	2.264	0.657	1.461	1.363	0.987	1.175	1.318
Mean		1.051	1.012	1.032	0.978 b	1.013 a	0.996	1.014
				1998			1999	Mean
LSD 5%								
Drought stress				NS			0.010	NS
Genotype				(*)			NS	NS
Genotype × drought stress				NS			NS	NS
CV%				40.3			41.2	39.7

Table 6.6. Yield loss (%) based on grain yield in mixtures of barley and wheat in stress at seedling stage (MS_2) and in stress at heading stage (MS_3) at Halhale, 1998–1999. The list is in ascending order based on the yield loss (%) averaged over the two years. The asterisk in parenthesis (*) below indicates a significance at $P \leq 0.10$.

Genotype combination		1998		Mean	1999		Mean	1998-99
		MS_2	MS_3		MS_2	MS_3		Mean
Yeha	Mana	12.2	4.6	8.4	16.9	5.4	11.2	9.8
Ardu 12/60	Mana	20.1	22.6	21.4	0.7	26.5	13.6	17.5
IAR 485	Mana	21.7	25.0	23.4	5.5	19.4	12.5	18.0
IAR 485	K 6290	23.3	7.8	15.6	24.0	27.5	25.8	20.7
Yeha	Kenya + Mana	13.5	8.9	11.2	39.5	21.6	30.6	20.9
Yeha	K 6290	27.5	13.9	20.7	37.1	14.8	26.0	23.4
Ardu 12/60	K 6290	27.7	15.5	21.6	31.1	26.1	28.6	25.1
Ardu 12/60	Kenya + Mana	26.1	19.0	22.6	27.3	33.0	30.2	26.4
IAR 485	Kenya + Mana	54.1	9.1	31.6	33.4	21.2	27.3	29.5
Mean		25.1	14.0	19.6	23.9	21.4	22.7	21.2
				1998			1999	Mean
LSD 5%								
Drought stress				NS			NS	NS
Genotype				(*)			NS	NS
Genotype × drought stress				NS			NS	NS
CV%				40.6			41.0	39.1

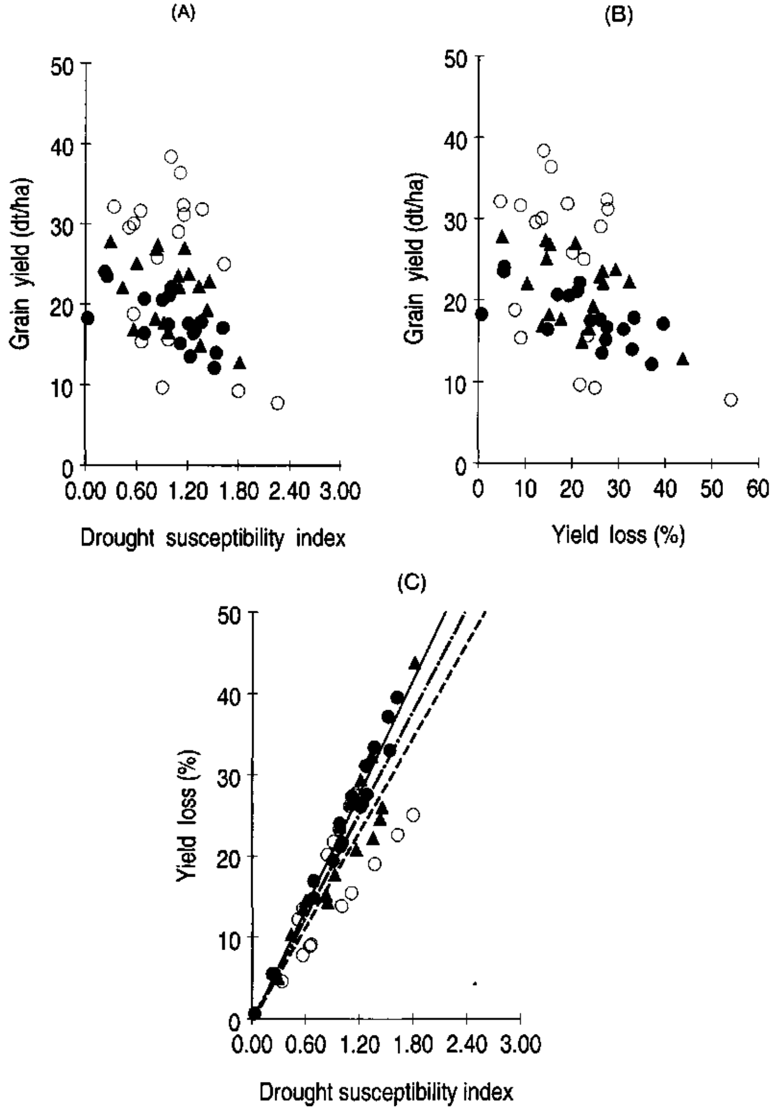

Figure 6.3. Relationship between (A) Drought susceptibility index and grain yield of mixtures under stress in 1998 (r=–0.393) in 1999; (r=–0.668*), mean of 2 years (r=–0.423); (B) Yield loss and grain yield in 1998 (r=–0.436), 1999 (r=–0.765*) and mean of 2 years (r=–0.443); (C) Drought susceptibility index and yield loss in 1998 (r=0.853*), in 1999 (r=0.988**) and mean of 2 years (0.912**). ○- 1998; ●- 1999 and ▲- mean of 2 years. Note: in the graph dt ha^{-1} is the same as quintals ha^{-1}.

years, the yield loss was between 9.8 to 29.5% (although non significant). A combination of Yeha + Mana (YL=9.8%), Ardu 12/60 + Mana (YL=17.5%) and IAR 485 + Mana (YL=17.9%) showed lowest yield loss.

The difference among genotypes in yield loss are shown in Table 6.8. When averaged over the two years, Yeha (YL=18.0%) and Mana (YL=15.1%) gave minimum yield losses.

There was a negative correlation between yield loss and grain yield (r=−0.393) but it was not significant. The lower the yield loss, the higher the grain yield. The mixtures with higher yield loss were the ones with low yield under drought stress (Figure 6.3). Furthermore, there was a significantly positive correlation between yield loss and drought susceptibility index. Those mixtures with low DSI had lower yield loss and those with higher DSI showed higher yield loss (based on grain yield).

Yield advantage

The RYT in grain yield ranged from 1.8 to 3.2 in 1998. A combination of Yeha + K 6290 gave the highest yield advantage (RYT=3.2) over its sole crop when averaged over all stress types in 1998. The yield advantage was higher in 1998 than in 1999. In 1999, Yeha + Mana (RYT=1.2), IAR 485 + Mana (RYT=1.2) and Ardu 12/60 + K 6290 (RYT=1.2) gave 20% increase in grain over the sole crop. When averaged over the two years RYT was between 1.9 and 2.1. The highest yield advantage was obtained for Yeha + Mana (RYT=2.1) and Ardu 12/60 + K 6290 (RYT=2.1). All genotype combinations showed a yield advantage in mixtures when RYT was averaged over the years and stress types. Averaged over the two years, there was a yield advantage of the mixtures (Table 6.7).

The average value of each genotype based on total RYT is shown in Table 6.8. Among the barley genotypes, Yeha (RYT=3.0) contributed to the highest yield advantage in 1998. Among the wheat genotypes, K 6290 (RYT=2.8) contributed to highest advantage in grain yield. In 1999, all barley genotypes showed an increase of 10% over their own sole crops; there was no yield advantage for K 6290 (RYT=1.0). When averaged over two years, Yeha (RYT=2.1) among the barley genotypes and both Kenya + Mana (RYT=1.9) and K 6290 (RYT=1.9) among the wheat genotypes showed highest yield advantages.

Discussion

Productivity

Stress can retard growth permanently and thereby production. Barley grows fast during early growing stages. Drought stress at that stage could have affected its

Table 6.7. Relative Yield Total (RYT) averaged over the stress types for combined grain yield in response of the genotype combinations to drought stress of barley and wheat genotype combinations at Halhale, 1998–1999. The list is listed in descending order averaged over the two years. The asterisks in parenthesis (*) below indicate a significance at P ≤ 0.10.

Genotype combination		RYT		
		1998	1999	Mean
Yeha	Mana	3.0	1.2	2.1
Ardu 12/60	K 6290	3.0	1.2	2.1
Yeha	Kenya+ Mana	2.8	1.2	2.0
Yeha	K 6290	3.2	0.8	2.0
Ardu 12/60	Kenya+ Mana	2.8	1.0	1.9
Ardu 12/60	Mana	2.3	1.0	1.7
IAR 485	Kenya+ Mana	2.1	1.1	1.6
IAR 485	K 6290	2.2	0.9	1.6
IAR 485	Mana	1.8	1.2	1.5
Mean		2.6	1.1	1.8
LSD 5%				
Stress		NS	NS	(*)
Genotype		NS	(*)	0.599
Genotype × stress		NS	NS	NS
CV%		31.9	40.7	25.0

Table 6.8. Drought susceptibility index (DSI), yield loss (YL%) and relative yield total (RYT) when each genotype is averaged over the total values in mixtures with any other genotype of the other component crop at Halhale, 1998–1999. The list is in descending order based on mean DSI over two years.

Genotypes	DSI		Mean	YL		Mean	RYT		Mean
	1998	1999		1998	1999		1998	1999	
Barley									
Yeha	0.700	0.963	0.832	13.4	22.6	18.0	3.0	1.1	2.1
IAR 485	1.195	0.957	1.076	23.5	21.9	22.7	2.0	1.1	1.6
Ardu 12/60	1.201	1.067	1.134	21.9	24.1	23.0	2.7	1.1	1.9
Mean	1.032	0.996	1.014	19.6	22.9	21.3	2.6	1.1	1.9
Wheat									
Mana	1.004	1.556	0.780	17.7	12.4	15.1	2.4	1.1	1.8
K 6290	0.993	1.160	1.077	19.3	26.8	23.1	2.8	1.0	1.9
Kenya+Mana	1.099	1.271	1.185	21.8	29.4	25.6	2.6	1.1	1.9
Mean	1.032	0.996	1.014	19.6	22.9	21.3	2.6	1.1	1.9

growth and finally the productivity. Elnadi (1969) and Acland (1973) revealed that water shortage during grain filling and maturation phases could affect the productivity of wheat severely. Simane et al. (1988) mentioned that drought stress at anthesis can also affect the productivity of barley by reducing seed set and seed size. Most probably wheat is more sensitive to water shortages than barley during grain filling and maturation phases.

A degree of susceptibility to drought stress exists at all stages of the life cycle of a plant. However, it appears that there are critical stages when drought stress affects productivity most. Stress at heading stage may reduce the number of spikelets by suppressing the tillering capacity and spikelet formation of crops as compared to no stress. Davidson and Chavalier (1987), Kezer and Robertson (1972) and Duwayri (1984) revealed that in wheat reduced biomass and grain yield at seedling stage were due to less vegetative growth as a result of limited water supply. Stress at seedling stage may also be detrimental for the growth of the later emerged tillers, which consequently do not contribute to grain or straw yield.

The reason for lack of consistency in effects on biomass yield and grain yield between years could be due to aphid infestation that was more prevalent in 1998 than in 1999. Some plots were infested more than others, which could have affected the yield of some genotypes more either in sole crops or in some of the component mixtures. Secondly, gravity irrigation was used to conduct the trial and the actual water applied in each plot could not be measured. The above reasons could have contributed to the variation in biomass or grain yield among the two years.

Drought susceptibility index (DSI)

Genotypes with high yield potential and low stress index are desirable under stress situations. In sorghum, certain genotypes with low DSI had higher yield under stress conditions (Yilma et al., 1990; Reddy and Kidane, 1993). In mixtures, the genotype combination producing highest yields but showing poor resistance to stress is probably due to better yielding ability of the genotypes under favourable conditions rather than to drought resistance.

Drought susceptibility index gives a clue about the difference between yield of the genotypes under non stress and under stress conditions. DSI was used as a measure of drought resistance in minimising reduction in yield caused by unfavourable compared to the favourable environment. This parameter was used as a measure of drought resistance in various crop species such as in wheat (Fischer and Maurer, 1978; Dencic et al., 2000), in sorghum (Yilma et al., 1990) and in grain legumes (ICARDA, 1993).

The negative relationship between DSI and grain yield showed that the higher the resistance to drought, the better the grain yield. This is in agreement with Hamdi and Erskine (1986) who reported a negative correlation between grain yield and DSI in lentil genotypes grown under drought stress. Dencic et al. (2000) mentioned a low drought susceptibility index in some wheat landraces ranging from 0.72 to 0.75, whereas other genotypes showed high susceptibility index between 1.24 to 1.25 (DSI > 1). Bruckner and Frohberg (1987) explained that genotypes with low DSI values can be considered as drought resistant because they exhibit a smaller than average reduction in yield under stress compared with favourable conditions. However, using DSI as a parameter alone has its limitation for the quantification of the response of a genotype to drought conditions because the conclusion is based on yield reduction under stress compared to non stress conditions. DSI combined with grain yield or yield components can be helpful in suggesting genotypes favourable under stress conditions.

Water Use Efficiency

Water use efficiency is the ratio of biomass yield or grain yield to unit mass of water uptake. Water use is commonly defined as ET or the evapo-transpiration component of water balance. The formula used to determine the water balance is $I = S_1 - S_2 + R + D + ET$ where I= irrigation water applied, S_1= initial stored soil water and S_2= final stored soil moisture are always measured. Run off (R) and drainage (D) are occasionally measured or with valid reason regarded as zero (Morris and Garrity, 1993). In this study it was not possible to measure the amount of water applied during irrigation and hence it was not possible to quantify the water use. In several studies water use in sole crops and intercrops differed slightly. Mandal et al. (1986) showed an increase in water use efficiency in wheat *(Triticum aestivum)* + mustard *(Brassica juncea)* and wheat *(Triticum aestivum)* + chickpea *(Cicer arientinum)* intercropping by 3 to 7% compared to sole crop. Reddy and Willey (1981) reported intercropping to increase water use by 25% compared to sole crop. Natarjan and Willey (1980) indicated that the water use of intercropping and sole crop were similar. Even though the magnitude of water use efficiency was not quantified, based on the yield advantage of mixed cropping over sole cropping, we can summarise that the mixed cropping was efficient in water use, otherwise there might not have been a yield advantage or yield increase over the sole crops. The water use advantage could only be realised because of continued water uptake by the component crop, in this case wheat, that remained active after barley got matured.

Conclusion

Genotypes with lower DSI showed higher yield ($r=-0.410$) suggesting that those with higher resistance to drought stress gave higher total yield in mixtures even though it was not significant. Some of the high yielding genotype combinations showed DSI > 1; these included Ardu 12/60 + K 6290 (GY=2804 kg ha^{-1}), Yeha + K 6290 (GY=2738 kg ha^{-1}) and IAR 485 + Mana (GY=2728 kg ha^{-1}). However, IAR 485 + Kenya + Mana (GY=2728 kg ha^{-1}; DSI=0.960), Yeha + Kenya + Mana (GY=2499 kg ha^{-1}; DSI=0.958) and Yeha + Mana (GY=2220 kg ha^{-1}; DSI=0.447) were mixtures with reasonable grain yield and better resistance to stress. Some of these genotype combinations should be verified in on-farm trials and demonstrated to farmers on a larger scale before release.

Evaluation of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* mixed cropping in additive and replacement series: Competition, yield advantage and niche differentiation

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Abstract

Four field trials evaluating mixed cropping of barley and wheat using both additive and replacement series were conducted under rainfed conditions at two locations (Halhale and Mendefera) in Eritrea, during the 1997 and 1998 seasons. The aim was to assess the optimum sowing density and the optimal crop ratio for maximum productivity, to assess the yield advantage, and to analyse competition in more detail. Competition and niche differentiation were estimated by a mathematical approach based on non linear regression analysis. Higher yields (although not significantly different) were obtained in additive ratios, especially at a basic sowing density of 200 plants m^{-2}. The effect of crop ratio was significant for grain yield at both locations in the replacement series. There was no significant interaction between sowing density and crop ratio. The traditional crop ratio of 67/33% proved indeed optimal in the replacement series. The analysis showed that it was advantageous to grow barley and wheat in mixtures because more land area was required to obtain the same yield in sole crops. The drawback of the additive design is that the crop ratio and increased plant density are confounded making it impossible to identify the real cause of yield advantage. However, a hyperbolic regression approach showed that barley and wheat grown in mixtures had yield advantages as a result of complementary use of resources. Barley showed greater competitive ability than wheat; for wheat, inter-specific competition was larger than the intra-specific while for barley the intra-specific competition was greater than the inter-specific. From this study it can be concluded that mixtures gave higher yields probably because they were able to use resources more efficiently.

Key words: competition, niche differentiation, yield advantage, additive series, replacement series, crop density, crop ratio, barley, wheat, mixed cropping, Eritrea

Introduction

The cropping system *hanfetz* is practised in the highlands of Eritrea. *Hanfetz* is the Tigrigna word for mixed cropping of barley and wheat. The mixtures are sown under rainfed conditions from the end of June until the first week of July. Farmers traditionally broadcast the mixtures in a replacement ratio of barley 67% and wheat 33%. Barley 50% and wheat 50% is also used rarely.

Factors affecting the productivity of barley and wheat mixtures include the density and the crop ratio (Woldeamlak and Struik, 2000). Excessively dense plant stands can result in misuse of limiting resources and may lead to weaker plants and lower productivity (Willey and Osiru, 1972a,b; Lal et al., 1974; Martin and Snaydon, 1982). Sowing density below the optimum leads to inefficient utilisation of soil resources by the plants resulting in inadequate yield. Optimum plant density and proportion in mixed cropping may generally help to facilitate and ensure penetration of more solar radiation towards the undergrowing component crop of the system (Singh and Chauhan, 1991).

In additive series, the total population density (and thus the population pressure) is higher. The total proportion is greater than 100%. When the crop ratio of component crops increases the total density also increases (Willey and Osiru, 1972a,b). The disadvantage is that it is difficult to identify whether competition between component crops is due to component crop ratios or total density. In replacement series, the mixing ratio varies but the total density remains constant. The total proportion adds up to 100% (Harper, 1964; Willey and Osiru, 1972a,b; Trenbath, 1974; Fischer, 1976).

Optimum crop density needed for higher yield has been well determined in the intercropping of other crop species (Chinwuba, 1967; Egharevba, 1977; Bartlet, 1980 and Remison and Luca, 1982). Additive proportions have resulted in higher productivity (Evans, 1960; Evans and Greedharm, 1962; Agboola and Fayemi, 1971; Lal et al., 1974; Singh and Chauhan, 1991; Singh and Singh, 1992) than the replacement series. For example, 75/75 in sunflower + soybean (Lal et al., 1974); 100/75 in pearl millet and green gram (Singh and Chauhan, 1991); 100/75 in pigeon pea and sesame (Singh and Singh, 1992). A difference in grain yield was also obtained among the ratios in the replacement series in which a ratio of 67/33 gave more yield than 50/50 such as in maize–bean mixtures (Willey and Osiru, 1972a,b); in sorghum–bean mixtures (Osiru and Willey, 1972); in sunflower–radish intercropping (Lakhami, 1976); and in field pea varietal mixtures (Schouls and Lengelaan, 1994). On the other hand in wheat–chickpea mixtures a crop ratio of 50/50 resulted in higher grain yield than 67/33 (Reddy and Rajendra, 1980; Singh and Ram, 1972).

Up to now there are no concrete, science-based recommendations for sowing densities or proportions in barley and wheat mixtures. The objective of this study was to identify optimum sowing density and crop ratio of the *hanfetz* system; to assess the yield advantage of mixed cropping of barley and wheat and to analyse competition between these crops quantitatively, using a mathematical model based on hyperbolic non linear regression.

Materials and Methods

Location

Four field experiments were conducted at two locations in the highlands of Eritrea, namely at the Halhale Research Station and at a site near Mendefera (San Georgio), during the rainy periods of 1997 and 1998. July, August and October were the months with the highest rainfall at both locations. There was also unexpected prolonged rainfall in November in 1997 at both sites, due to the El Niño phenomenon in that year. The rainfall amount was higher at Mendefera than at Halhale. The details of the locations in terms of elevation, amount of rainfall, soil type etc., are given in Chapter 3.

Design and treatments

The genotypes of barley (Yeha) and wheat (Mana) were grown at three basic sowing densities (100% =100, 200 or 300 plants m^{-2}) in crop ratios with additive and replacement series. In additive design, the crop ratio in % included were 25/100; 50/100; 75/100; 100/25; 100/50; 100/75. In the replacement series, the barley and wheat crop ratios evaluated were in % 100/0 (barley sole crop), 0/100 (wheat sole crop), 33/67, 50/50, 67/33. The amounts of seed needed to obtain these ratios were assessed based on the thousand grain weight of both crops. The thousand grain weight for Yeha (barley) was 38 grams and for Mana (wheat) 22 grams. The amount of seed planted was assumed to have 100% germination based on the germination test conducted before planting.

The treatments were arranged in two-factor factorial experiments in a Randomised Complete Block Design in 4 replications and an individual plot size of 3.75 m^2. The sowing densities and crop ratios were factorially combined to give 27 mixed cropping treatments and 6 sole crops. The sowing densities and crop ratios were randomly assigned to the plots.

Agronomic practice

Seed was broadcasted during the end of June at both locations and both years. Dry planting was practised so that the crop could use the first flush of rainfall for emergence. Crop emergence was on average 5 days after sowing for barley and 8 days after sowing for wheat. The emergence was faster at Mendefera than at Halhale due to earlier sufficient rainfall for germination.

A basal dressing of fertiliser was applied to all plots at a rate of 100 kg ha^{-1} Di-Ammonium Phosphate (DAP, 18% N and 46% P_2O_5) and 50 kg ha^{-1} Urea (46% N). The fertiliser was incorporated into the soil at planting. This is a blanket fertiliser recommendation for cereals in the highlands of Eritrea and by applying such an amount it was assumed that there would not be any limitation of nitrogen in the soil. No irrigation or pest control was carried out. Weeds were removed manually twice at 30 and 45 days after sowing the crop. Wild oat is one of the most important weeds in barley and wheat; it was removed regularly whenever it appeared in the plots. Wild oat is difficult to recognise especially at earlier stage so removing wild oats was not easy. Wild oat removal becomes easier when it produces heads.

The varieties used in the study were Yeha (barley landrace) and Mana (wheat landrace) which form a combination popular among farmers for mixed cropping. The characters of the landraces are described in Chapter 2. Crops were harvested at about 88 days after sowing for barley and 100 days for wheat at Halhale, 91 days for barley and 103 days for wheat at Mendefera, in both years.

Data collected

The types of data collected were similar to those in Chapter 3. To avoid repetition the methods are here only described briefly.

The plants of the component crops in the mixture were harvested at physiological maturity and weighed separately. Subsamples were dried to assess the proportion of dry matter content and to convert results into data with the same moisture content. All data in the paper are based on 12.5% moisture content reflecting practical conditions. The biomasses of the two component crops were added to get the total above-ground biomass of each mixture and this sum was converted into kg ha^{-1}. The grain yield of each component crops in each treatment was added to get the total grain yield of the mixture.

During crop growth characters recorded were plant height, lodging (%), crop phenology, ear size (cm), number of ears m^{-2}, number of kernels ear^{-1}, stand cover (%) and thousand grain weight (g/1000 seeds).

Yield advantage analysis

Relative yield total (RYT)

RYT was used to estimate the yield advantage in the replacement series (Willey and Osiru, 1972a,b). The restrictions in using RYT are that it only provides information on the yield advantage relative to a particular crop density. The yield advantage was estimated by adding the relative yield of the component crops to get the relative yield total as shown below:

$$RYT = RY_1 + RY_2 = (Y_{12}/Y_{11}) + (Y_{21} / Y_{22}) \quad (7.1)$$

where Y_{12} and Y_{21} are the yields of barley and wheat mixtures respectively. Y_{11} and Y_{22} are the yields of the sole crops of barley and wheat, respectively.

The biomass or grain yield of the mixture was divided by the corresponding total density of the monocrop. RYT values greater than 1 indicates that there is at least to some extent complementarity in resource use. RYT values less or equal to 1 indicate that the species fully share the common limiting resources, i.e. they compete fully and show no resource complementarity.

Land equivalent ratio

LER was used to assess the yield advantage in mixed cropping in the additive series. The LER expresses the relative land area under sole cropping that is required to give the same yield of each species in mixtures (Trenbath, 1976; Natarajan and Willey, 1980; Spitters and Kropff, 1989; Singh and Chauhan, 1991; Nkrumah et al., 1995; Banik, 1996). The formula used is the same as the one for the relative yield total except that some of the designations are different.

$$LER = L_1 + L_2 = (Y_{12} / Y_{11}) + (Y_{21} / Y_{22}) \quad (7.2)$$

where L_1 and L_2 are the land equivalent ratios of barley and wheat respectively; Y_{11} and Y_{22} are the yields of the sole crops of barley and wheat at the relevant plant density in the sole crop, respectively; Y_{12} and Y_{21} are the yields in mixtures of barley and wheat, respectively. Hyperbolic regression analysis (Equation 7.3) was used to estimate the reference yields for the specific densities used in the additive design. When LER > 1, a larger area of land is required to produce the same yield of the mixtures in sole cropping at the recommended density which means that there is a yield advantage in mixed cropping. For instance if LER= 1.57, then 57% more land area is required for the monocrops to give the same yield as in the mixtures. When LER = 1, it does not make any difference to grow either a mixture or the sole crops, because the yield obtained in mixed cropping can be obtained by growing the same area of land in monocropping. Even though very rare, when LER < 1, the yields that may be obtained in mixtures are lower than those in monocropping. It implies that larger area under mixed cropping gives the same yield as smaller land area planted with monocultures. It means that mixtures are not advantegous in terms of land area required. The major drawback of the additive design is the interpretation of the outcome because it remains unresolved whether LER > 1 results from an increased total density or is caused by resource complementarity.

Model description

When two or more crops are simultaneously grown on the same land, they compete for the resources such as light water and nutrients. Multispecies competition can be analysed by a non linear regression approach (Spitters, 1983) There have been several applications of this approach. Among these are the description of competition between crops and weeds, and of intercropping situations (Spitters and van den Bergh, 1982; Spitters, 1983a; Spitters and Kropff, 1989).

Intra-specific competition

The competition between plants of the same species is the intra-specific competition. This competition expresses itself in the response of individual plant biomass to plant density, but has also consequences for crop yield. Crop biomass yield is related to plant density according to the equation below (Spitters, 1983a):

$$Y_1 = N_1 / (b_{10} + b_{11} N_1) \qquad (7.3)$$

in which Y_1 is the yield (g m^{-2}) of the crop in monoculture; N_1 is the plant density of the crop (plants m^{-2}); and b_{10} and b_{11} are constants.

From Equation 7.3 the average weight per plant (W_1; g $plant^{-1}$) can be derived as:

$$W_1 = Y_1/N_1 = 1/(b_{10} + b_{11}N_1) \qquad (7.4)$$

To estimate b_{10} and b_{11} this expression can be rewritten in a linear regression form as:

$$1/W_1 = b_{10} + b_{11}N_1 \qquad (7.5)$$

where b_{10} is the intercept and b_{11} is the slope of the linear relationship between $1/W_1$ and N_1.

The intercept b_{10} is the reciprocal of the biomass or yield of an isolated plant ($W_1=1/b_{10}$). The slope (b_{11}) measures how $1/W_1$ increases and hence how the per plant weight (W_1) decreases with any plant added to the population. The coefficient b_{11} is the reciprocal of the maximum yield per unit area achieved at infinite density. The parameter $1/b_{10}$ is the apparent weight of an isolated plant and $1/b_{11}$ measures the maximum attainable weight or yield per unit area. The ratio b_{11}/b_{10} is the measure of intra-specific competition. At low plant density there is no inter-plant competition so that the per plant weight remains constant with decreasing density.

Inter-specific competition

The competition of plants of different species when they are growing in the same field is the inter-specific competition. If plants of the same species affect $1/W_1$ additively, then it is likely that adding plants of another species will also have an additional effect on the value of $1/W_1$. Based on this assumption the reciprocal of the per plant weight of species 1 (barley) in a mixture with species 2 (wheat) can be calculated as:

$$1/W_1 = b_{10} + b_{11}N_1 + b_{12}N_2 \qquad (7.6)$$

where the first subscript of the regression coefficients denotes the species in which the biomass or yield is considered and the second subscript is that of species grown together with it.

The coefficient b_{11} measures the effect of intra-specific competition whereas b_{12} measures the effect of inter-specific competition. The ratio b_{11}/b_{12} measures the relative competitive ability to derive niche differentiation (Spitters, 1983a;b; Spitters and Kropff, 1989; Spitters et al., 1989).

Niche differentiation index

The above parameters can also be used to derive a niche differentiation index (NDI). This index can be estimated as:

$$NDI = (b_{11} / b_{12}) \times (b_{22} / b_{21}) \quad (7.7)$$

If this ratio exceeds unity, there is niche differentiation, indicating that the species in the mixtures together capture more resources and are utilising resources probably better than they do as sole crops, which means that the species are not only competing for the same resources. A ratio less than unity suggests some kind of inhibition caused by competition for the same resources and that the species are eliminating one another. It means that the species are restricted in their growth by the requirement of the same resources and that they are avoiding each other. If the NDI is unity, then the two species are competing equally for the same resources (Spitters, 1983 a, b; Connoly, 1987; Spitters et al., 1989) without any additional negative effect of this competition.

Analysis

The data on biomass and grain yield were analysed using a standard Analysis of Variance; the Least Significant Difference was calculated to compare the means and the means were ranked accordingly. The analysis of variance for biomass yield, grain yield, relative yield total and land equivalent ratio were computed for locations and years. The analysis for the additive and replacement series were done separately. The data of the sole cropping were analysed together with the replacement series. The total biomass and total yield of the mixtures of 4 environments (2 locations and 2 years) were analysed together to assess the variation over years and locations. Correlations between selected agronomic parameters and biomass and grain yield were calculated. The biomass and grain yields were averaged over sowing densities and crop ratios.

The biomass and grain yields for the component crops were analysed using a non linear regression analysis so that competition and niche differentiation could be estimated. The model can deal with data sets of populations varying in crop ratio and total density. It can also be used for mixed cropping experiments regardless of the density design. Analysis was performed using the following equations, which were fit into the model for species 1.

$$Y_{12}= N_1/(b_{10} + b_{11}N_1 + b_{12} N_2) \quad (7.8)$$

$$Y_{12}= (N_1/b_{10})/(b_{12}/b_{10}) + (b_{11}/b_{10}\times N_1) \times (b_{12}/b_{10} \times N_2) \quad (7.9)$$

$$Y_{12}= (N_1 \times W_1)/ [1+(b_{11}/b_{10}\times N_1) + (b_{12}/b_{11} +b_{11}/b_{10}) \times N_2] \quad (7.10)$$

which can be re-written as

$$Y_{12}= N_1 \times W_1/ (1+a_1 \times (N_1+\in \times N_2)) \quad (7.11)$$

in which $a_1= b_{11}/b_{10}$ and $\in = b_{12}/b_{11}$; $1/\in = c = b_{11}/b_{12}$
For species 1

$$Y_1= N_1 \times W_1/ (1+a_1 (N_1+(1/c_1) \times N_2)) \quad (7.12a)$$

in which W_1 is the apparent weight of an isolated plant ($1/b_{10}$) in g plant^{-1}; a_1 is a parameter characterising inter-specific competition (b_{11}/b_{10}) and c_1 ($1/\in$) is the relative competitive ability (b_{11}/b_{12}) describing how many individuals of species 2 are equivalent to each individual of species 1. The maximum attainable yield can be estimated as the reciprocal of b_{11} ($1/b_{11}$) (Watkinson, 1981). Alike for species 2:

$$Y_2= N_2\times W_2/ (1+a_2 (N_2+(1/c_2) \times N_1)) \quad (7.12b)$$

Results

Additive series

Biomass yield

There was no significant effect of the additive crop ratio on biomass yield in both locations and years. There was a density effect in Halhale in 1997, and averaged over the two years for both locations, significant with S_3 giving the highest biomass yields. The interactions between the two factors were not significant. The biomass yield was higher in 1998 than in 1997 at both locations. The biomass yield was higher at Mendefera than at Halhale, particularly in 1998 (Table 7.1).

The mean biomass values for the different sowing density × crop ratio combinations are shown in Figure 7.1. The mean biomass yield was higher in the additive crop ratios as compared to that in the replacement series. At Halhale, when averaged over the two years, S_3 (300 plants m^{-2}) at 50/100 (9172 kg ha^{-1}) and 75/100 (9154 kg ha^{-1}) gave maximum biomass yield beyond which there was

Table 7.1. Biomass yield (kg ha^{-1}) in additive crop ratios at three basic sowing densities (S_1-100; S_2-200 and S_3-300 plants m^{-2}) on barley and wheat mixed cropping at Halhale and Mendefera, Eritrea 1997-1998. The results are averaged over the densities and crop ratios. The asterisk in parenthesis (*) below shows that the effect was significant at $P \leq 0.10$. Means followed by the same letter are not statistically significantly different. Values not followed by a letter are not significantly different.

Treatments	Halhale			Mendefera		
	1997	1998	Mean	1997	1998	Mean
Density						
S_1-100	6194 b	8875	7535	5665	9147	7406 b
S_2-200	6667 b	8521	7594	6290	9239	7765 ab
S_3-300	8340 a	8846	8593	6437	9475	7956 a
Mean	7067	8747	7907	6131	9287	7709
Crop ratio B/W						
25/100	7046	8826	7936	5911	9973	7942
50/100	7833	8972	8403	6177	9533	7855
75/100	7322	8851	8087	5974	9356	7665
100/25	6953	8469	7711	5848	8935	7392
100/50	6400	8421	7411	6301	9622	7962
100/75	6827	9023	7925	6355	8989	7672
Mean	7067	8747	7907	6131	9287	7709
LSD 5%						
Density	869	NS	NS(*)	NS	NS	477
Crop ratio	NS	NS	NS	NS	NS	NS
Density × crop ratio	NS	NS	NS	NS	NS	NS
CV%	21.4	15.6	14.9	22.6	9.6	10.6

a decline (Figure 7.1). At Mendefera, S_3 at 25/100 (8552 kg ha^{-1}) and 100/50 (8303 kg ha^{-1}) gave maximum biomass yields when averaged over the two years (Figure 7.1).

Grain yield

There was no significant effect of sowing densities, crop ratios or the interaction between these two factors in grain yield at both locations. Grain yields were higher in 1998 than in 1999 (Table 7.2). In barley additive series, yields were higher at 50/100 and in wheat additive series at 100/50 when averaged over the two years at Halhale. This phenomenon was not statistically significant. Grain yields were closely associated with biomass yield, although at the same grain yield more biomass was regained when crop densities increased.

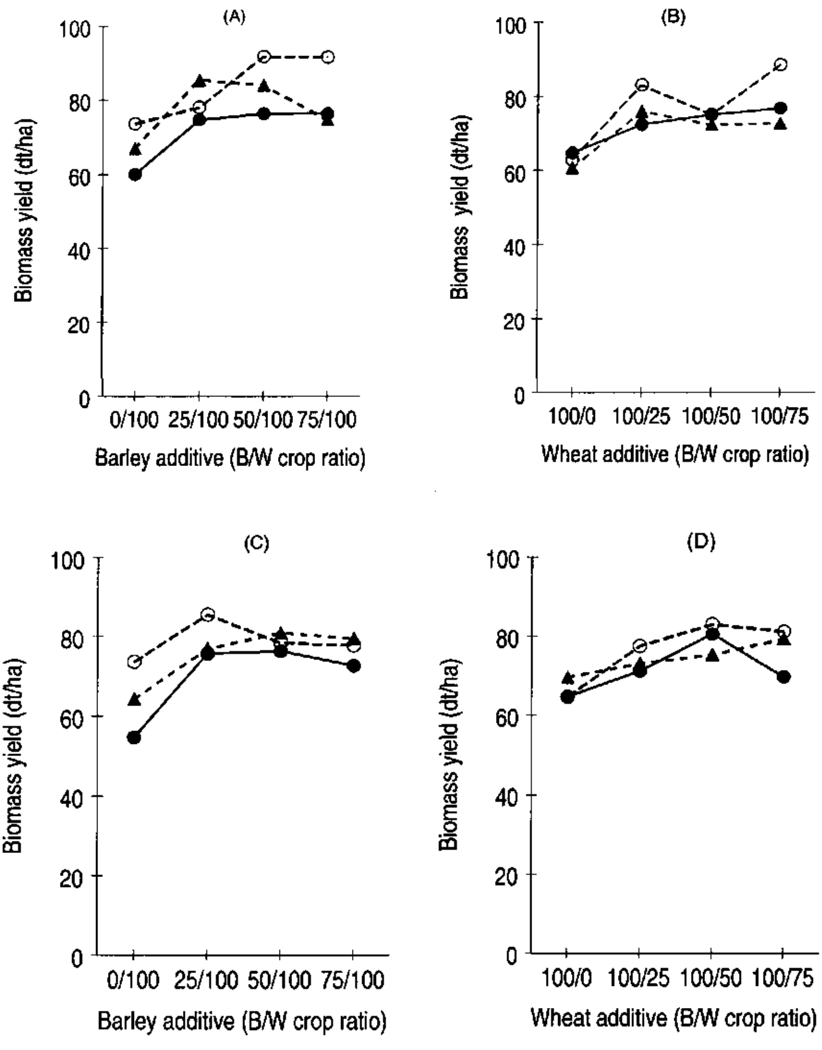

Figure 7.1. Effect of density and crop ratio (B/W) in the additive series on the mean biomass yield of mixed cropping of barley and wheat at two locations. (A) Barley additive mean of 2 years at Halhale; (B) Wheat additive mean of 2 years at Halhale; (C) Barley additive mean of 2 years at Mendefera; (D) Wheat additive mean of 2 years at Mendefera. ●- S_1 (100%=100 plants m^{-2}), ▲- S_2 (100%=200 plants m^{-2}) and ○- S_3 (100%=300 plants m^{-2}). In the graph along the y axis dt ha^{-1} is the same as quintals ha^{-1}.

Table 7.2. Grain yield (kg ha^{-1}) in a crop ratio of additive series at three basic sowing densities (S_1-100; S_2-200 and S_3-300 plants m^{-2}) on barley and wheat mixed cropping at Halhale and Mendefera, Eritrea 1997-1998. The asterisk in parenthesis (*) below shows that the effect was significant at $P \leq 0.10$. Values without a letter are statistically not significant.

Treatments	Halhale			Mendefera		
	1997	1998	Mean	1997	1998	Mean
Density						
S_1-100	1874	2514	2194	1614	1968	1791
S_2-200	2119	2192	2156	1502	2196	1849
S_3-300	2086	2177	2132	1644	2030	1837
Mean	2026	2294	2161	1586	2065	1826
Crop ratio B/W						
25/100	1780	2445	2113	1736	2391	2064
50/100	1953	2343	2148	1470	2017	1744
75/100	1800	2106	1954	1718	1964	1841
100/25	2145	2336	2241	1655	2067	1861
100/50	2176	2372	2275	1541	2270	1906
100/75	2058	2314	2186	1548	2005	1777
Mean	2026	2294	2161	1586	2065	1826
LSD 5%						
Density	NS	NS	NS	NS(*)	NS	NS
Crop ratio	NS	NS	NS	NS	NS	NS
Density × crop ratio	NS	NS	NS	NS	NS	NS
CV%	28.0	20.4	15.8	31.6	22.2	17.8

The grain yields (kg ha^{-1}) of all sowing density × crop ratio combinations averaged over the two years are shown in Figure 7.2. At Halhale, when averaged over the two years, S_2 at 100/25 (2457 kg ha^{-1}) and S_1 at 100/50 (2425 kg ha^{-1}) gave highest grain yields but not significantly different. At Mendefera, S_3 at 25/100 (2306 kg ha^{-1}) showed the best grain yield followed by 100/50 when averaged over the two years.

Replacement series

Biomass yield

The biomass yields (kg ha^{-1}) in the replacement series at Halhale and Mendefera in 1997 and 1998 are shown in Table 7.3. Sowing density had an effect on biomass yield in both years at Halhale. The effects of crop ratios and the

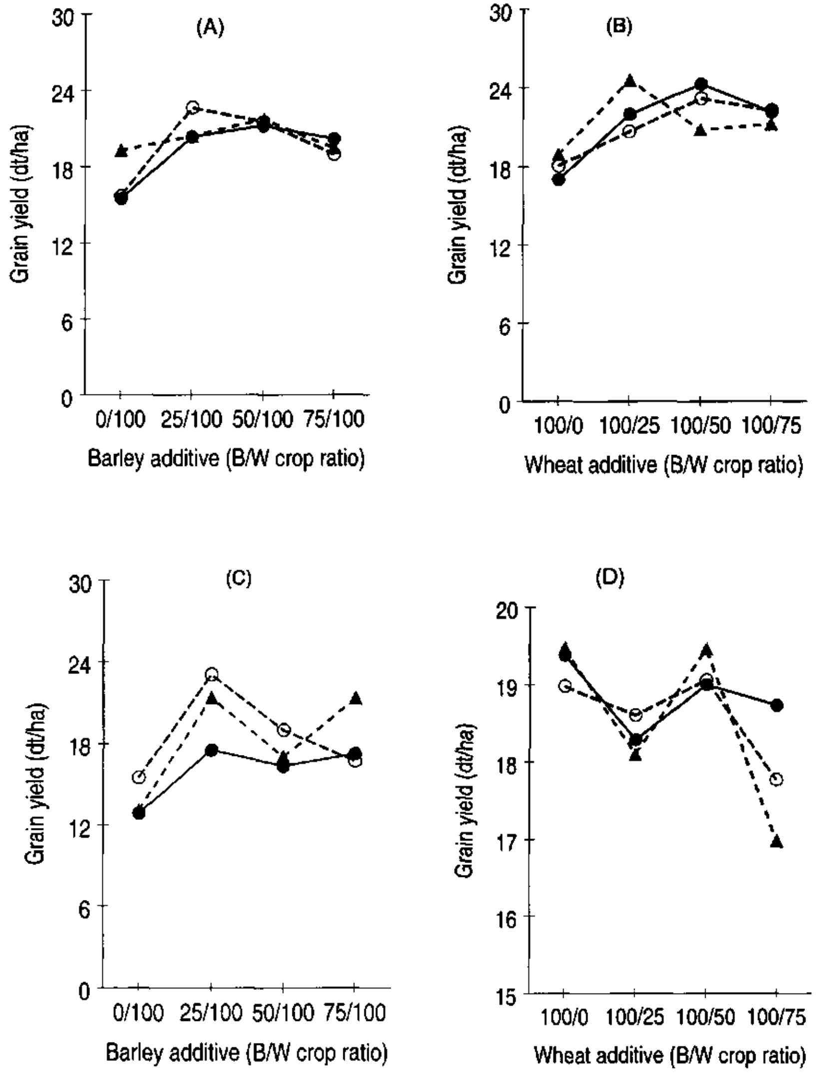

Figure 7.2. Effect of density and crop ratio (B/W) in the additive series on the mean grain yield of mixed cropping of barley and wheat at two locations. (A) Barley additive mean of 2 years at Halhale; (B) Wheat additive mean of 2 years at Halhale; (C) Barley additive mean of 2 years at Mendefera; (D) Wheat additive mean of 2 years at Mendefera. ●- S_1 (100%=100 plants m^{-2}), ▲- S_2 (100%=200 plants m^{-2}) and ○- S_3 (100%=300 plants m^{-2}) and along the y axis dt ha^{-1} is the same as quintals ha^{-1}.

Table 7.3. Biomass yield (kg ha^{-1}) in a replacement series of crop ratios at three sowing densities (S_1-100; S_2-200 and S_3-300 plants m^{-2}) for barley and wheat mixed cropping at Halhale and Mendefera, Eritrea 1997-1998. The results are averaged over the densities or crop ratios. The asterisk in parenthesis (*) below show that the effect was significant at $P \leq 0.10$. Means followed by the same letter are not significantly different. Values without a letter are statistically not significant.

Treatments	Halhale			Mendefera		
	1997	1998	Mean	1997	1998	Mean
Density						
S_1-100	4653 b	6892 b	5772 b	4499	8174	6337 b
S_2-200	6256 a	7834 a	7045 a	5700	8784	7242 a
S_3-300	6679 a	8336 a	7508 a	6238	8033	7136 a
Mean	5862	7687	6775	5479	8331	6905
Crop ratio B/W						
0/100	4778	8601	6689	4550 b	8286 b	6418 c
33/67	5824	8179	7002	5290 ab	8123 b	6707 bc
50/50	6223	8134	7179	5558 a	8823 ab	7191 ab
67/33	6099	7368	6734	6022 a	9133 a	7578 a
100/0	6388	6156	6272	5976 a	7287 c	6632 bc
Mean	5862	7687	6775	5479	8331	6905
LSD 5%						
Density	962	812	621	NS(*)	NS	547
Crop ratio	NS(*)	NS	NS	770	770	706
Density × crop ratio	NS	NS	NS	NS	NS	NS
CV%	26.3	16.4	14.3	17.1	12.7	12.1

interaction between sowing density and crop ratio were not significant. At Mendefera, crop ratio had an effect on biomass yield in both years but the sowing density did not.

Again the interaction between the two factors was not significant statistically. When averaged over crops/crop ratios and years, a density of 100 plants m^{-2} (S_1) showed reduced biomass yield (5772 kg ha^{-1}) whereas 300 plants m^{-2} (S_3) gave higher biomass yield (7508 kg ha^{-1}) at Halhale. A similar trend was observed at Mendefera, although the intermediate density, 200 plants m^{-2} (S_2), seemed to show highest mean biomass yield (7242 kg ha^{-1}). There was no significant difference between S_3 and S_2 in biomass yield at Mendefera when averaged over the two years. Mixtures did not outyield the barley sole crop in biomass yield but were always higher than the wheat sole crop. In 1998, the sole

Table 7.4. Grain yield (kg ha^{-1}) in a replacement crop ratio at three sowing densities (S_1-100; S_2-200 and S_3-300 plants m^{-2}) for barley and wheat mixed cropping at Halhale and Mendefera, Eritrea 1997-1998. The asterisk in parenthesis (*) below shows that the effect was significant at $P \leq 0.10$. Means followed by the same letter are not significantly different. Values with out letter are statistically not significant.

Treatments	Halhale			Mendefera		
	1997	1998	Mean	1997	1998	Mean
Density						
S_1-100	1398	2108	1753	1474 b	1940	1707 b
S_2-200	1697	2084	1891	1801 a	2010	1906 a
S_3-300	1420	2191	1806	1899 a	2031	1965 a
Mean	1505	2128	1817	1725	1994	1859
Crop ratio						
0/100	1281 c	2084 b	1683 b	1261 c	1502 c	1382 b
33/67	1329 bc	2361 a	1846 ab	1605 b	2456 a	2031 a
50/50	1531 abc	2411 a	1971 a	1794 ab	2117 ab	1955 a
67/33	1638 ab	2009 bc	1824 ab	1956 a	2047 ab	2001 a
100/0	1744 a	1773 c	1759 b	2007 a	1848 bc	1928 a
Mean	1505	2128	1817	1725	1994	1859
LSD 5%						
Density	NS	NS (*)	NS	222	NS	196
Crop ratio	359	278	212	286	392	253
Density × crop ratio	NS	NS	NS	NS	NS	NS (*)
CV%	28.1	16.5	14.3	20.1	23.9	16.5

crop of wheat outyielded the barley sole crop, but there were also positive effects of mixing the two. This was consistent across the two locations. The crop ratios with highest biomass yield at Mendefera were not the same as those in Halhale. A ratio of 67/33 showed highest biomass yield (7578 kg ha^{-1}) at Mendefera when averaged over the two years, but also for each individual year. Biomass yield was more in 1998 than in 1997 due to more rainfall in 1998 and the mean biomass yield was higher at Mendefera than at Halhale.

The mean biomass yields for each density × crop ratio combination in the replacement series at Halhale and Mendefera averaged over two years are given in Figure 7.3. At Halhale, when averaged over the two years, S_3 (300 plants m^{-2}) at a ratio of 33/67 (8105 kg ha^{-1}) showed highest biomass yield. At Mendefera, when averaged over the two years, S_3 at 67/33 (8282 kg ha^{-1}) and the same density at 50/50 (7952 kg ha^{-1}) gave highest biomass yields.

Grain yield

The grain yields for the replacement series of both locations for the year 1997 and 1998 are shown in Table 7.4. Crop ratio in the replacement series had a significant effect on grain yield at both locations and in both years. Furthermore there was a significant effect of sowing density in grain yield in 1997 at Mendefera, but not in 1998. A sowing density of 100 plants m^{-2} (S_1) gave lowest mean grain yield over the years whereas at Mendefera, a density of 300 plants m^{-2} (S_3) was superior in yield (1965 kg ha^{-1}). The wheat monocrop was outyielded by the barley monocrop in 1997 in grain yield and there were no effects of mixtures which was consistent over locations. Averaged over sowing densities, mixtures did not outyield the barley sole crop in grain yield but were always higher than the wheat sole crop. All mixtures performed better than expected based on their proportions of the two crops and there was a complementary effect of the barley in the replacement series. In 1998, the contrary happened because the wheat monocrop outyielded the barley monocrop in grain yield with positive effects of mixtures. The same result was also obtained for biomass yield. When averaged over the two years, a crop ratio of 50/50 showed highest grain yield (1971 kg ha^{-1}) at Halhale and at Mendefera crop ratios 33/67 (2031 kg ha^{-1}) and 67/33 (2001 kg ha^{-1}) were superior in grain yield even though these effects were not statistically significant. Grain yield was higher in 1998 than in 1997 due to more rainfall.

The grain yields for all density × crop ratio combinations at Halhale and Mendefera in the replacement series averaged over two years are given in Figure 7.3. At Halhale, a sowing density of S_2 at 67/33 (2043 kg ha^{-1}) and 50/50 (2032 kg ha^{-1}) showed maximum grain yield when averaged over the two years. At Mendefera, a sowing density of S_2 (200 plants m^{-2}) at 67/33 (2314 kg ha^{-1}) was the best in grain yield beyond which the grain yield declined when averaged over the two years.

The overall analysis of variance of the densities and crop ratios is given in Table 7.5. It shows the statistical difference among the crop ratios (both additive and replacement series). The combined analysis of variance over locations and years indicated that there was an effect of the treatments (crop ratio and density) and years in biomass yield. The location × year interaction was also significant. The effects of treatments, locations and years were significant for total grain yield. The treatment × year and location × year interactions were significant for grain yield (Table 7.6).

Agronomic characters

Number of ears m^{-2} (Figure 7.4) and number of kernels m^{-2} showed a positive and significant relationship with biomass yield in 1997 at Halhale but not so at Mendefera (Figure 7.6). Harvest index was negatively (significantly) correlated

Table 7.5. Mean square of the analysis of variance for biomass yield and grain yield on the effect of density and crop ratio (additive and replacement series) at two locations and years. Mean square values without asterisk are non significant; ** shows significance at 1% and * significance at 5% level.

Source of variation	Biomass				Grain yield			
	1997		1998		1997		1998	
	Halhale	Mendefera	Halhale	Mendefera	Halhale	Mendefera	Halhale	Mendefera
Density	3.195**	3.168**	0.260	0.840*	0.093**	0.157	0.113**	0.720
Crop ratio	0.502**	0.499**	0.962**	0.772**	0.135**	0.111**	0.127**	0.148**
Density × crop ratio	0.182	0.182	0.400	0.320	0.051**	0.022	0.053	0.706
CV%	19.7	19.8	18.9	16.5	17.5	26.0	22.8	23.9

Table 7.6. Mean squares and level of significance for total biomass yield and grain yield for the mixtures for 2 locations and 2 years. One asterisk (*) shows the significance at $P \leq 0.10$ and two asterisks (**) the significance at $P \leq 0.05$.

Factor	Mean square	
	Total biomass yield	Total grain yield
Treatment	64945 **	2322
Location	6572	52646 *
Year	7368817 *	256132 *
Treatment × location	28025	3481
Treatment × year	22367	6586 *
Location × year	813021 *	16539 *
Treatment × location × year	12241	1100

Table 7.7. Relationship between selected agronomic characters and biomass yield or grain yield on the evaluation of crop density and crop ratios for barley and wheat mixtures at two locations and two years, Eritrea. (* = significant at $P \leq 0.05$; n= 33).

Characters	1997		1998		Pooled	
	Biomass yield	Grain yield	Biomass yield	Grain yield	Biomass yield	Grain yield
Halhale						
Biomass	-----	0.33	-----	0.19	-----	0.32
Plant height	0.44	0.03	0.24	0.58*	0.20	0.24
Harvest index	–0.55 *	0.59 *	–0.71 *	0.55*	–0.78 *	0.34
Ears m^{-2}	0.62 *	0.33	–0.20	0.39	0.39	0.34
Kernels ear^{-1}	–0.38	–0.51 *	0.11	0.19	–0.31	–0.23
Kernels m^{-2}	0.53 *	0.18	–0.20	0.36	0.35	0.27
TGW	–0.18	0.58	0.13	0.32	–0.09	0.52*
Mendefera						
Biomass	-----	0.29	-----	–0.01	----	0.25
Plant height	–0.14	0.03	0.07	0.25	0.03	0.30
Harvest index	–0.57 *	0.61 *	–0.73 *	0.65 *	–0.54 *	0.66*
Ears m^{-2}	0.12	0.15	0.02	0.29	0.18	0.33
Kernels ear^{-1}	–0.26	–0.03	0.08	0.19	–0.33	0.18
Kernels m^{-2}	–0.01	0.14	0.06	0.39	0.14	0.15
TGW	0.03	0.38	–0.05	0.68*	–0.01	0.46

with biomass yield in both locations and years. On the other hand, harvest index contributed positively and significantly to grain yield at both locations and years (Table 7.7). Number of kernels m^{-2} was also positively related with grain yield at both locations although not significantly so (Table 7.7). Thousand grain weight was positively correlated with grain yield in 1998 at both locations (Figures 7.5 and 7.7) but was significant at Mendefera only. When pooled over the two years, harvest index was negatively and significantly correlated with biomass yield at both locations while TGW had a positive and significant correlation with grain yield at both locations (Table 7.7).

Yield advantage

Relative yield total (RYT)

The results of RYT based on biomass yield for Halhale and Mendefera are shown in Table 7.8. An example of the trend of relative biomass yield in component crops and mixtures is shown in Figure 7.8. The RYT in biomass was significantly different among the sowing densities at Halhale in 1998 and at Mendefera in 1997. There was no significant difference in RYT based on biomass among the crop ratios and the interaction between the two experimental factors was also not significant at both locations and years. At Halhale, a density of 200 plants m^{-2} (S_2) showed a yield advantage of 30% (RYT=1.30) in 1997 and a density of 300 plants m^{-2} (S_3) had more yield (RYT=1.32) in 1998. At Mendefera a density of 300 plants m^{-2} showed a yield advantage of 14% (RYT=1.14) in 1997 and 37% (RYT=1.37) in 1998. The mean RYT averaged over the two years was also higher for S_3 (RYT= 1.26) than for the other densities. Comparing the crop ratios, 50/50 gave the highest RYT based on biomass at Halhale in 1997 (RYT=1.15) and in 1998 (RYT=1.16) and also when averaged over the two years (RYT=1.16). At Mendefera, a crop ratio of 33/67 showed the best yield in 1997 (RYT=1.07) and in 1998 (RYT=1.34) and also when averaged over the two years (RYT=1.21). There was a yield advantage at all locations and years in biomass yield. The increase in yield advantage in biomass yield was higher at Mendefera (RYT=1.17) compared to Halhale (RYT=1.11) when averaged over the two years.

The RYT based on grain yield at both locations is given in Table 7.9. There was a significant difference among the sowing densities in RYT based on grain yield in both years at Halhale but not at Mendefera. The differences among the crop ratios in RYT based on grain yield in 1998 were significant at Halhale but not at Mendefera. A sowing density of 200 plants m^{-2} (S_2) showed 68% increase in grain yield in 1997 and 300 plants m^{-2} (S_3) a 55% increase in 1998 at Halhale. When averaged over the two years, S_2 (200 plants m^{-2}) showed 42% increase over the sole crop density. Considering the crop ratios, at Halhale a ratio of 67/33 (RYT=1.36) in 1997 and 50/50 (RYT=1.41) in 1998 gave the best yield

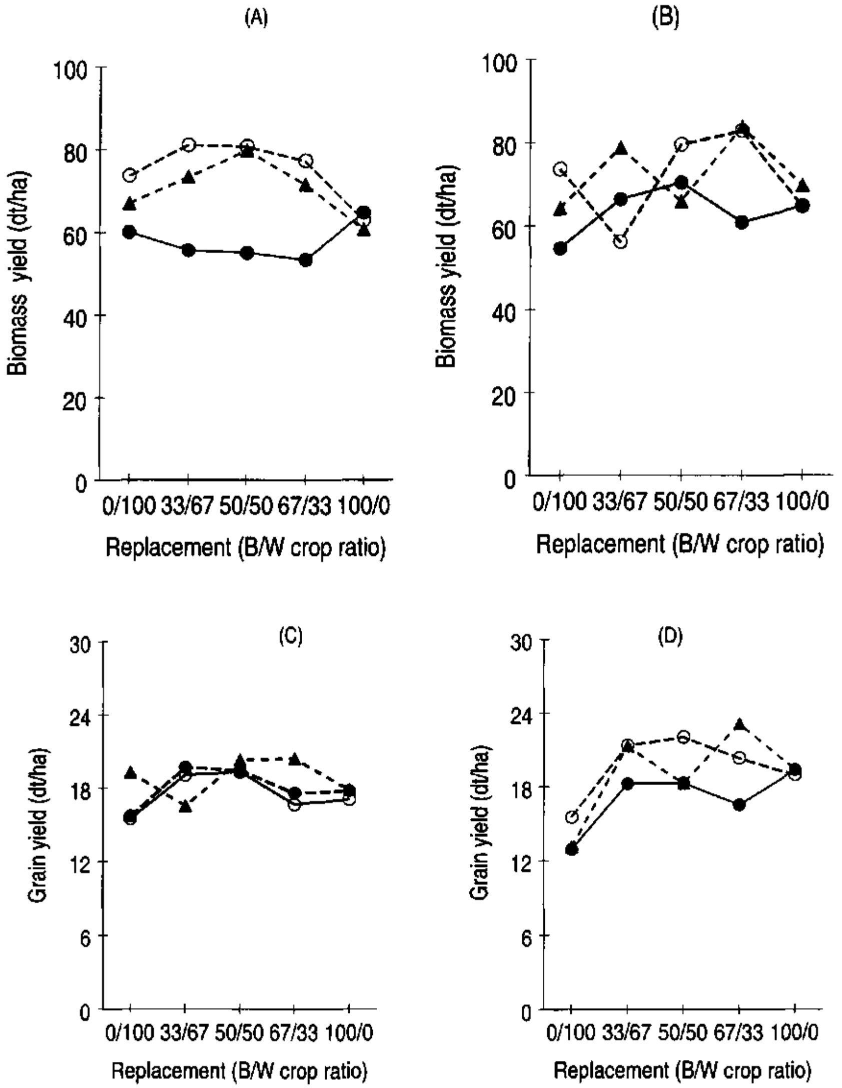

Figure 7.3. Biomass yield and grain yield averaged over the two years in the replacement series. (A) Mean biomass yield at Halhale; (B) Mean grain yield at Mendefera; (C) Mean grain yield at Halhale; (D) Mean grain yield at Mendefera; ●- S_1 (100%=100 plants m^{-2}), ▲- S_2 (100%=200 plants m^{-2}) and O- S_3 (100%=300 plants m^{-2}). Along the y axis dt ha^{-1} is the same as quintals ha^{-1}.

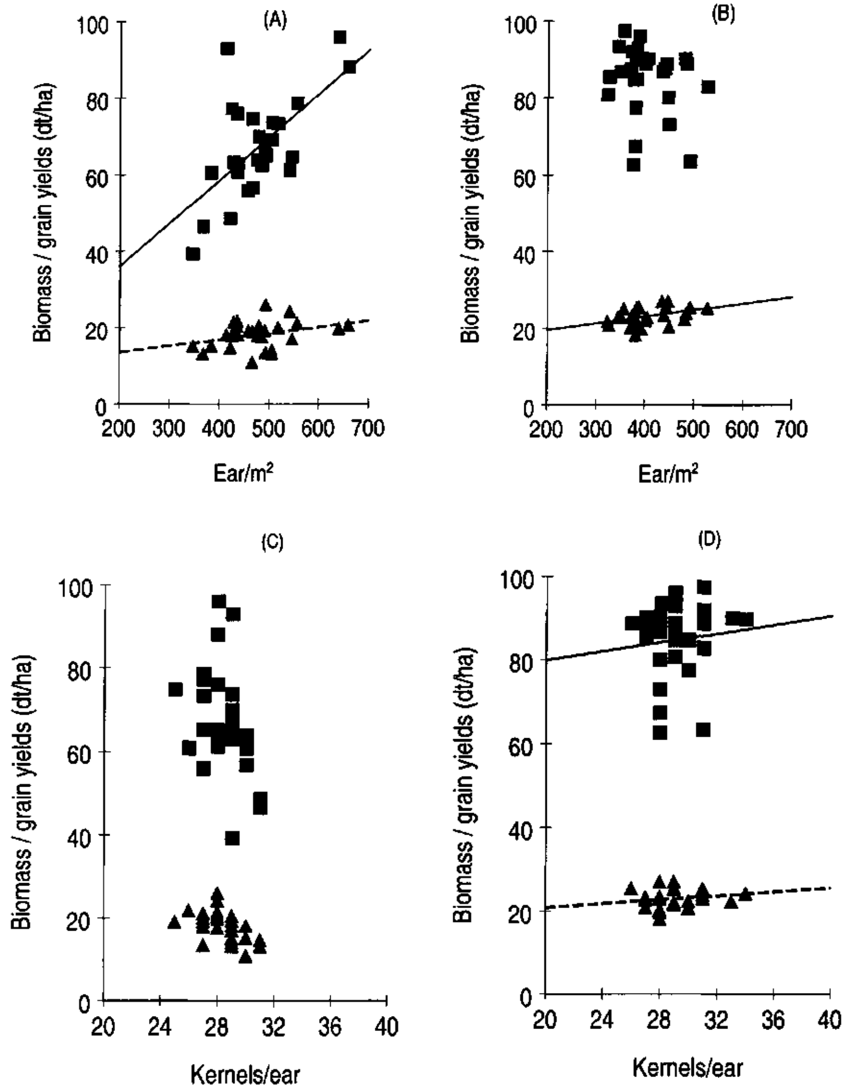

Figure 7.4. Relationship between yield components and biomass yield or grain yield at Halhale, Eritrea, 1997 and 1998. (A) Number of ears m^{-2} in 1997; (B) Number of ears m^{-2} in 1998; (C) Number of kernels ear^{-1} in 1997; (D) Number of kernels ear^{-1} in 1998. Note: ■- Total biomass yield and ▲- Total grain yield. Along the y axis dt ha^{-1} is the same as quintals ha^{-1}.

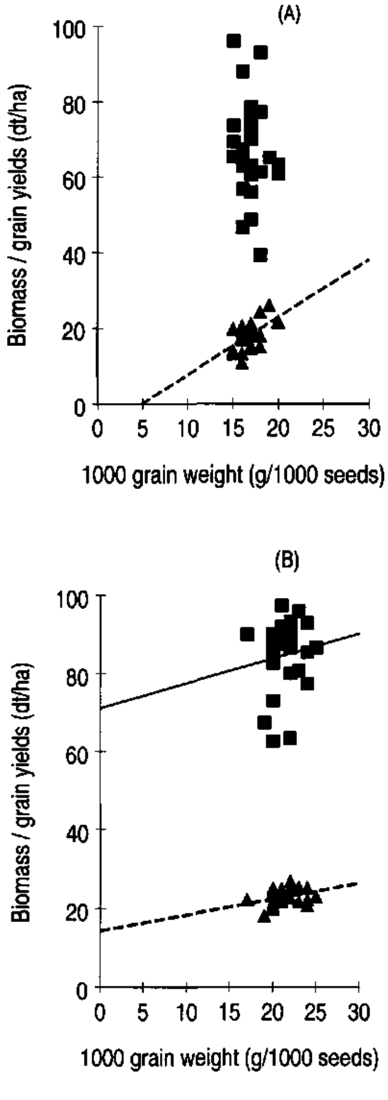

Figure 7.5. Relationship between yield components and biomass yield or grain yield at Halhale, Eritrea, 1997 and 1998. (A) Thousand grain weight (TGW, g/1000 seeds), 1997; (B) Thousand grain weight (TGW, g/1000 seeds) 1998. Note: ■- Total biomass yield and ▲- Total grain yield. Along the y axis dt ha^{-1} is the same as quintals ha^{-1}.

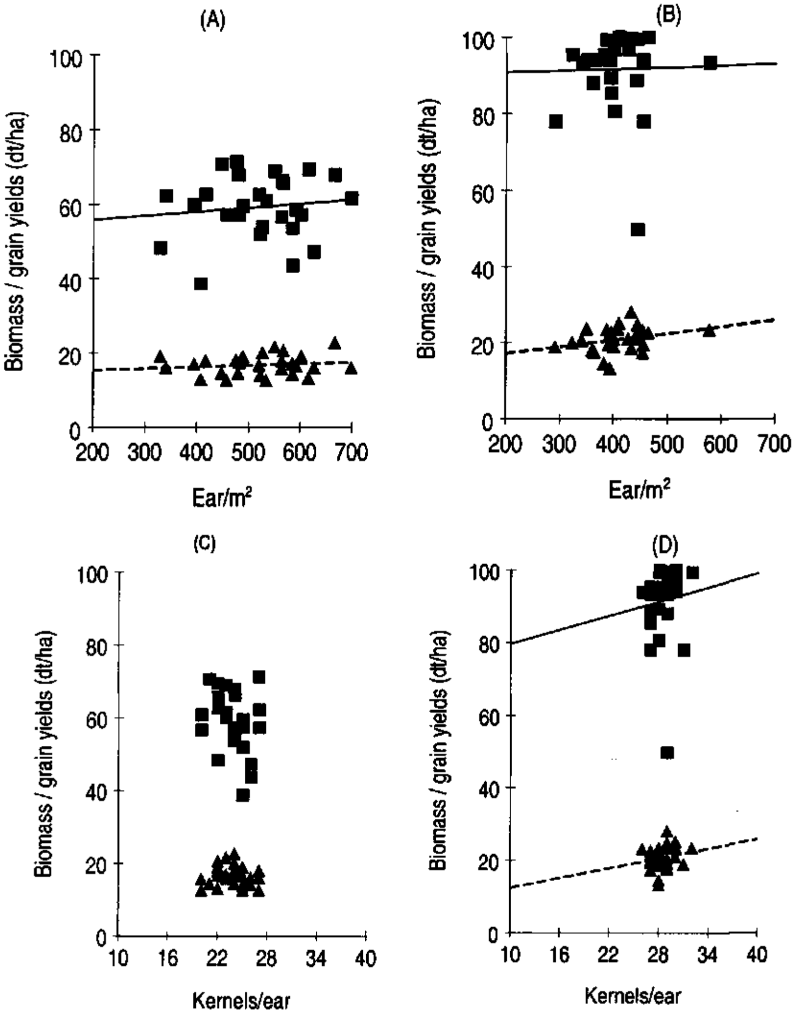

Figure 7.6. Relationship between yield components and biomass yield or grain yield at Mendefera, Eritrea, 1997 and 1998. (A) Number of ears m^{-2}, biomass yield and grain yield in 1997; (B) Number of ears m^{-2}, biomass yield and grain yield in 1998; (C) Number of kernels ear^{-1}, biomass yield and grain yield in 1997; (D) Number of kernels ear^{-1}, biomass yield and grain yield, 1998. Note: ■- Total biomass yield and ▲- Total grain yield. Along the y axis dt ha^{-1} is the same as quintals ha^{-1}.

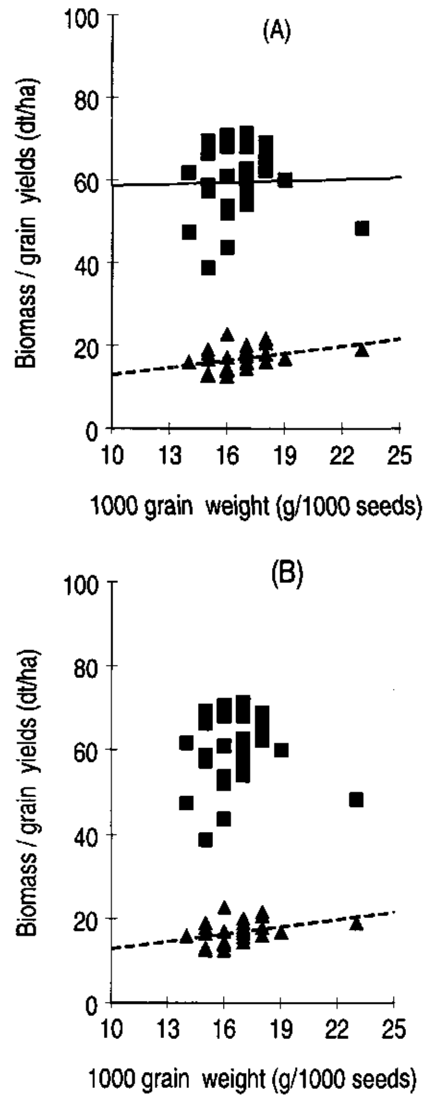

Figure 7.7. Relationship between yield components and biomass yield or grain yield at Mendefera, Eritrea, 1997 and 1998. (A) Thousand grain weight (TGW), biomass yield and grain yield in 1997; (B) Thousand grain weight (TGW), biomass yield and grain yield in 1998. Note: ■- Total biomass yield and ▲- Total grain yield. Along the y axis dt ha^{-1} is the same as quintals ha^{-1}.

Table 7.8. Relative yield total (RYT) for biomass yield in a replacement series of crop ratios at three total densities of 100 (S_1), 200 (S_2) and 300 (S_3) plants m^{-2} at Halhale and Mendefera, Eritrea 1997-1998. The results are averaged over the densities or crop ratios. Means followed by the same letter are not significantly different. Values without a letter are statistically not significant.

Treatments	Halhale			Mendefera		
	1997	1998	Mean	1997	1998	Mean
Density						
S_1-100	0.93	0.87 b	0.90 b	0.92 b	1.24	1.08 b
S_2-200	1.30	1.16 a	1.22 a	1.08 ab	1.23	1.16 ab
S_3-300	1.09	1.32 a	1.21 a	1.14 a	1.37	1.26 a
Mean	1.11	1.12	1.11	1.05	1.28	1.17
Crop ratio						
33/67	1.11	1.08	1.10	1.07	1.34	1.21
50/50	1.15	1.16	1.16	1.02	1.22	1.12
67/33	1.06	1.11	1.09	1.06	1.28	1.17
Mean	1.11	1.12	1.12	1.05	1.28	1.17
LSD 5%						
Density	NS	0.23	0.18	0.17	NS	0.14
Crop ratio	NS	NS	NS	NS	NS	NS
Density × crop ratio	NS	NS	NS	NS	NS	NS
CV%	29.5	23.7	18.9	18.9	22.5	14.6

advantage. A crop ratio of 50/50 (RYT=1.35) was the best in yield advantage with 35% over the monocrop when averaged over the two years. The yield advantage was much higher at Halhale (RYT=1.30) than at Mendefera (RYT=1.16) when averaged over crop ratios and years.

Land Equivalent Ratio
The LER values based on grain yield are shown in Table 7.10. There were significant effects of density and crop ratio at both locations and years, but the effect of the interaction was not significant. The LER was > 1 in both locations and years indicating a yield advantage when mixtures were grown compared to the sole crops. The land area required in sole crops at Mendefera (32%) was higher than at Halhale (23%) when averaged over the two years. Higher density in mixtures showed lower yield advantage in terms of land area in both years and when averaged over the years. This was consistent at both locations.

Considering the crop ratios when averaged over the densities, the lowest ratio of 100/25 and 25/100 showed a yield advantage in land area required. A crop ratio of 100/75 showed the smallest advantage in land area required. The

Table 7.9. Relative yield total (RYT) for grain yield in a replacement series of crop ratios at three densities of 100 (S_1), 200 (S_1) and 300 (S_3) plants m^{-2} at Halhale and Mendefera, Eritrea 1997-1998. The results are averaged over the densities or crop ratios. Means followed by the same letter are not significantly different. Values without letters are statistically not significant.

Treatments	Halhale			Mendefera		
	1997	1998	Mean	1997	1998	Mean
Crop density						
S_1-100	1.13 b	1.21 b	1.18	0.93	1.19	1.06 b
S_2-200	1.68 a	1.16 b	1.42	1.05	1.35	1.20 ab
S_3-300	1.04 b	1.55 a	1.30	1.14	1.31	1.23 a
Mean	1.28	1.31	1.30	1.04	1.28	1.16
Crop ratio B/W						
33/67	1.20	1.35 a	1.28	1.08	1.45	1.27
50/50	1.30	1.41 a	1.35	1.04	1.21	1.13
67/33	1.36	1.17 b	1.27	1.00	1.18	1.09
Mean	1.28	1.31	1.30	1.04	1.28	1.16
LSD 5%						
Density	0.41	0.14	NS	NS	NS	0.16
Crop ratio	NS	0.13	NS	NS	NS	NS
Density × crop ratio	NS	NS	NS	NS	NS	NS
CV%	32.9	12.9	20.6	23.9	28.7	16.2

yield advantage at Mendefera was higher than at Halhale.

Competition and Niche differentiation

The results for the estimates of the intra- and inter-specific competition and niche differentiation indices in mixtures of barley and wheat at Halhale and Mendefera, 1997–1998, are shown in Tables 7.11 and 7.12. The lower the value of b_0, the higher the apparent weight of an isolated plant. The weight of an isolated plant (g $plant^{-1}$) of barley was relatively higher than that of a wheat plant for total biomass or total grain yield at both locations and years (Table 7.11). The maximum attainable yield ($1/b_1$, $1/a$) was also relatively higher for barley as a component crop than for wheat in both years and locations. The maximum attainable yield for barley was higher in 1998 than in 1997, for total biomass and total grain yield at Mendefera. The maximum attainable yield for wheat in biomass was higher in 1997 than in 1998 at Mendefera. On the other hand at Halhale the maximum attainable yield for biomass in wheat was higher in 1998 than in 1997. Even

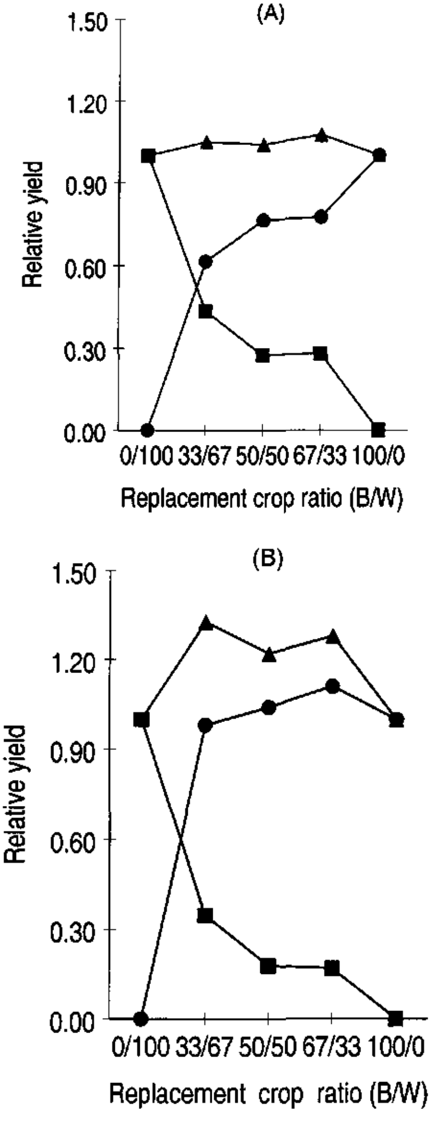

Figure 7.8. Example of relative yield in biomass of component crops barley and wheat and of total mixtures in replacement series at Mendefera. (A) Relative yield of biomass in 1997; (B) Relative yield in biomass in 1998. ●- Barley as a component crop; ■- Wheat as a component crop and ▲- Mixtures.

Table 7.10. Land Equivalent Ratio (LER) in grain yield in additive crop ratios at three basic densities (S_1- 100%=100; S_2- 100%=200 and S_3- 100%=300 plants m^{-2}) on barley and wheat mixed cropping at Halhale and Mendefera, Eritrea, 1997-1998. Means followed by the same letter are statistically not significantly different. Values followed by the same letter are statistically not significant.

	Halhale			Mendefera		
Treatments	1997	1998	Mean	1997	1998	Mean
Density						
S_1-100	1.42 a	1.32 a	1.37 a	1.36 a	1.54 a	1.45 a
S_2-200	1.27 b	1.13 b	1.20 b	1.27 b	1.31 b	1.29 b
S_3-300	1.15 c	1.07 b	1.11 c	1.16 c	1.25 b	1.21 c
Mean	1.28	1.17	1.23	1.26	1.37	1.32
Crop ratio B/W						
25/100	1.58 a	1.37 a	1.48 a	1.44 a	1.62 a	1.53 a
50/100	1.30 b	1.11 bc	1.21 b	1.24 b	1.31 bc	1.28 b
75/100	1.10 cd	1.03 c	1.07 c	1.17 bc	1.19 c	1.18 c
100/25	1.39 b	1.34 a	1.37 a	1.38 a	1.55 a	1.47 a
100/50	1.25 bc	1.18 b	1.22 b	1.24 b	1.36 b	1.30 b
100/75	1.06 d	1.01 c	1.04 c	1.12 c	1.18 c	1.15 c
Mean	1.28	1.17	1.23	1.26	1.37	1.32
LSD 5%						
Density	0.113	0.090	0.082	0.080	0.112	0.055
Crop ratio	0.159	0.127	0.116	0.113	0.158	0.078
Density × crop ratio	NS	NS	NS	NS	NS	NS
CV%	15.2	13.2	11.6	11.0	14.1	7.3

though maximum attainable yield for wheat was higher in 1997, the per plant weight of an isolated plant was lower for wheat in 1997.

The relative competitive ability was higher for barley than for wheat in both years and locations. The competition was greater at Mendefera in 1998 for both total grain yield and total biomass for barley as a component crop. The competition received from barley was relatively greater than wheat at Mendefera in 1998 for total grain yield and total biomass than at Halhale. At Halhale, the competitive ability for barley was higher in biomass during the year 1997 as compared to 1998. Grain yield for Mendfera in 1998 can be taken as an example inorder to explain the competitive ability of barley in mixtures. For barley, one barley plant was able to compete equally with about eight (7.81) wheat plants. For barley, the presence of one barley plant feels as strong as the presence of eight wheat plants. For wheat, four wheat plants were equal to about one barley plant (0.240; 1/4th). The influence of barley plants relative to the influence of wheat was at least four times greater.

There was niche differentiation for both total biomass and grain yield at both locations and years. The degree of niche differentiation was higher for grain yield than for biomass at both locations. Niche differentiation was higher at Halhale than at Mendefera in 1998 for both total biomass and grain yield (Table 7.12).

Discussion

Productivity

The total biomass and grain yields were higher in additive series as compared to replacement series at both locations in both years. This is in agreement with several workers who obtained similar results in mixed cropping of other crop species. For example, Rew et al. (1995) confirmed that the total biomass in grass mixtures was maximum in the additive series. Singh and Chauhan (1991) showed that grain yield was influenced significantly by the additive series giving high total yield in mixtures. A crop ratio of pearl millet 100% and green gram 75% in additive series gave higher total grain yield. Banik (1996) confirmed a higher yield potential in the additive series of 100% pigeon pea and sesame 75%. Fischer (1977a,b) obtained a better yield at higher density in mixtures of maize–beans even though the effects were not significant.

The total grain yield and total biomass for the mixtures was higher in 1998 than in 1997 at both locations. For barley both the apparent weight of a plant (g $plant^{-1}$) and maximum attainable yield (g m^{-2}) were consistently higher in 1998 than in 1997. However, for wheat these characters were not consistent because the maximum attainable yield (g m^{-2}) was higher while the weight of an isolated plant was lower (g $plant^{-1}$) in 1997. On the other hand, the maximum attainable yield was lower while the weight of an isolated plant was higher in the year 1998. Since the apparent weight of an isolated plant and maximum attainable yield per m^{-2} was higher for barley this could have compensated for the higher total yield in 1998 despite the lower attainable yield of wheat per m^{-2} in the same year.

Harvest index was positively related with grain yield while it was negatively correlated with biomass. The higher biomass resulted in higher number of ears m^{-2} and hence higher grain yield with some yield penalties.

Yield advantage

Land equivalent ratio and relative yield total do not describe the nature of intra- and inter-specific competition. Furthermore these parameters do not quantify the relative competitive ability of the crop species but only show the extent of yield

Table 7.11. Estimates of parameters b_0 (1/W), b_1(1/a) and b_2 (c/b_1) in total biomass yield and grain yield for barley and wheat for both the replacement and additive series at Halhale and Mendefera sites, Eritrea, 1997-1998.

Characters / locations	Barley			Wheat		
	b_{10}	b_{11}	b_{12}	b_{20}	b_{21}	b_{22}
Total biomass yield						
Halhale 1997	0.0610	0.00125	0.00041	0.1560	0.0020	0.00066
Halhale 1998	0.0100	0.00150	0.00076	0.0070	0.0012	0.00120
Mendefera 1997	0.0578	0.00130	0.00044	0.1178	0.0029	0.00100
Mendefera 1998	0.0200	0.00100	0.00015	0.0060	0.0039	0.00110
Total grain yield						
Halhale 1997	0.0891	0.00590	0.00248	0.213	0.0116	0.00630
Halhale 1998	0.0600	0.00580	0.00288	0.130	0.0036	0.00350
Mendefera 1997	0.1400	0.00400	0.00186	0.140	0.0111	0.00550
Mendefera 1998	0.0200	0.00250	0.00032	0.020	0.0304	0.00730

Table 7.12. Inter-specific competition and niche differentiation indices (NDI) in mixtures of barley and wheat at Halhale and Mendefera, 1997 and1998. The number of observations for each character / location is n=132. The asterisks (*) show a level of significance $P \leq 0.05$.

Characters/location	Barley			Wheat			NDI
	b_{11}/b_{12}	SE	r^2	b_{22}/b_{21}	SE	r^2	
Total biomass yield							
Halhale 1997	3.049	±0.102	0.550*	0.330	±0.117	0.699*	1.010
Halhale 1998	1.970	±0.290	0.770*	0.998	± 0.200	0.560*	1.970
Mendefera 1997	2.955	±0.377	0.777*	0.345	± 0.092	0.757*	1.020
Mendefera 1998	6.670	±2.100	0.720*	0.282	±0.080	0.840*	1.880
Total grain yield							
Halhale 1997	2.379	± 0.228	0.362*	0.543	±0.170	0.511*	1.292
Halhale 1998	2.010	±0.460	0.460*	0.986	±0.250	0.490*	1.990
Mendefera 1997	2.150	±0.460	0.580*	0.495	±0.130	0.630*	1.060
Mendefera 1998	7.810	±2.510	0.310*	0.240	±0.110	0.200*	1.880

advantage in a particular density which could be the result of sharing or not sharing resources in harmony with one another. It is believed that yield advantage analysis together with the nonlinear regression approach can describe what is happening in a mixed cropping experiment. In this study the nature of the conclusions based on LER or RYT corresponded with the result of niche differentiation index in most of the situations.

The analysis showed that it was advantageous to grow barley and wheat in mixtures because more land area is required to obtain a yield in sole crops similar to that in mixtures. In this study the yield advantage might result because the two crop species are complementary in resource use or from the density effect. The analysis in the additive design showed that the yield advantage of the mixtures could be due to increased plant density. The question is why not achieve a benefit of higher yield in the sole crop by using higher density rather than growing mixtures. Indeed, a part of the benefit of higher total yield might be achieved by growing the sole crop at higher density but this is not always true.

The replacement approach is more suitable to address the issue of yield advantage of mixed cropping. In the replacement approach the ratios vary but the total density are the same in mixtures as in sole crops. In Eritrea, mixed cropping is grown as an insurance mechanism in case of drought so growing sole crops of wheat means taking a risk of stress especially if a high density is used in sole crops. However, the hyperbolic regression approach has confirmed that barley and wheat grown together in mixtures have promoted each other so that yield advantage was the result of complementary use of resources. Mkamilo (1998) have found similar results in the yield advantage analysis of barley and oats intercropping. Nevertheless, it is important to realise that barley and wheat mixtures have other advantages and benefits apart from higher total yield. In Eritrea, farmers grow mixed crops as an insurance mechanism against drought but also because of preferred diet, need for animal feed, etc. The advantage of growing mixtures is fully described in Chapter 2 of the thesis.

Niche differentiation

The NDI > 1 was related to RYT > 1 showing that the yield advantage was due to complementary use of resources. In general, the niche differentiation in barley and wheat mixtures can be explained in time and in resource use. Barley is early maturing and can escape periods of moisture deficit by maturing before the onset of the period with low rainfall. Difference in height could help the crops to utilise resources at different times in a better way. Barley is sensitive to lodging under sole cropping but in mixtures it is physically supported by the more robust wheat allowing it to get enough solar resources.

Competitive ability

The relative competitive ability was higher for barley than for wheat. Inter-specific competition was higher than intra-specific for barley and intra-specific competition was greater than inter-specific for wheat. Any wheat plant suffered less competition from other wheat plants than from the barley plant while barley plants suffered more from barley than from wheat. Willey and Osiru (1972a,b) have mentioned that, in a mixture, the more competitive species will actually utilise a greater proportion of the environment than is allocated to it at sowing time. Thus if the more competitive species has a higher yield potential, the comparison of a mixture with pure stands will be in favour of the mixtures. In addition, the fact that competition among the same plant species in monocropping was higher for barley than for wheat suggests that the density for barley should be relatively less than that of wheat due to higher competitive ability among the barley plants.

Descriptive model

The nonlinear regression approach proved a useful tool in estimating the yield density relationship in mixed cropping because it described the interaction between the two crop species accurately. The product of the competitive ability of the crop species helps to estimate the niche differentiation among crop species, explaining whether the two crop species when grown together are maximising soil resources for optimum productivity in mixtures. Such description is much more difficult to get using only RYT or LER values. However, it should be noted also that the hyperbolic regression approach is a descriptive one and explains what is happening in a location during that specific season by describing the competitive interactions between species in mixed cropping.

The model is applicable for any data set of populations varying in crop ratio and total density. The descriptive regression approach is very suitable when a range of densities are used, as it is the case in this study. It has been used in intercropping experiments regardless of the density design whether additive or replacement (Spitters, 1983a; Spitters et al., 1989). The time course of competition can be described by the help of this model in experiments where both monocrops and mixed crops are harvested at intervals. For each harvest the competition parameters can be estimated as well (Spitters and Kropff, 1989).

Conclusion

This set of experiments indicated that in the replacement series at a basic density of 200 (S_2) plants m^{-2} at 67/33 at Halhale and Mendefera improved total grain yield. However, at Halhale, the total grain yield in the additive series was much higher with S_2 at 100/25 or S_1 at 100/50 when averaged over the two years. At Mendefera, the total biomass was much higher in the additive series at S_3 and a ratio of 25/100. The standard density and crop ratio currently in use by farmers, 200 plants m^{-2} at 67/33 (replacement series), was outyielded by the additive densities in total grain yield. Mixtures probably gave higher yields because they were able to use environmental resources more efficiently. This could occur due to differences in growth and difference in height of the two crops for better light utilisation. The promising densities and crop ratios including the current standard need to be verified at a larger scale under on farm conditions and demonstrated to farmers before the technology is released for use.

Effect of drought stress on the yield advantage and competition in barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* mixtures differing in crop ratios

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Abstract

The effects of drought or moisture stress (MS_1– no stress; MS_2– stress at seedling stage and MS_3– stress at heading stage) on the performance of a mixed crop of barley and wheat was studied at different crop ratios in additive and replacement series at Halhale (Eritrea) during the off-seasons of 1998 and 1999. The objective was to identify crop ratios with minimum yield loss under stress and to quantify competition and niche differentiation of component crops in mixtures grown under stress. Yield loss and yield advantage were estimated; competition and niche differentiation were assessed by analysing the data using a hyperbolic competition model. The drought stress × crop ratio interactions were not statistically significant. When averaged over years, drought stress during seedling stage reduced yield stronger than drought stress during heading. The best yields were found for the crop ratios 50% barley / 50% wheat (1152 kg ha^{-1}), 25% barley / 100% wheat (1151 kg ha^{-1}) and 100% barley / 25% wheat (1114 kg ha^{-1}). Plants stressed at seedling stage showed reduced height compared to those stressed at heading stage and in general, drought stress reduced plant height and all yield components. Barley was more competitive than wheat. One barley plant was as competitive as about seven wheat plants (for example for grain yield 1998 and 1999). The Niche Differentiation was higher than 1 in all years confirming the significant yield advantage of mixtures over sole cropping and illustrating that the crop species did not just compete for the same resources. Additive crop ratios (for example ratios 100% / 75% or 75% / 100%) did not result in higher total grain yield compared to those in replacement ratios.

Key words: competition, crop ratio, barley, wheat, mixed cropping, drought stress, niche differentiation, Eritrea

Introduction

Shortage of water is seriously limiting crop production in arid and semi arid areas of the tropics. In Eritrea, rainfall in the highlands ranges from 400-700 mm but the rainfall distribution is erratic, resulting periods of severe drought stress. Mixed cropping of barley and wheat is practised as one of the risk aversion strategies in case of drought. To maximise productivity with the least risk, optimum ratios of the component crops have to be defined.

Several workers have stressed the importance of crop ratio or crop density when soil resources are limiting. The success of mixed cropping systems relative to pure stands depends on the yield advantage obtained. A yield advantage of the mixed crops is found when the resources are used more efficiently. Total density and mixing ratios are key factors determining the success of the mixed cropping system (Natarajan and Willey, 1980; Martin and Snaydon, 1982; Natarajan and Willey, 1986; Singh and Chauhan, 1991). When the total population is higher than optimum in a water limited environment the moisture demand of the crop is too high and the yield advantage can no longer be realised under stress conditions (Natarajan and Willey, 1986).

There are several mechanisms, involving more effective use of water resources that could lead to greater yield advantage from a mixed crop compared to the sole crops. Below-ground interactions through the root system could often lead to mixed cropping advantages (Snaydon and Harris, 1979). The root system of the cereal crops, barley and wheat, are shallow and the competition for limiting water resources is partial because of slight differences in growing period between crops. This provides an opportunity for complementary use of soil resources by component crops.

The growth period most sensitive to drought stress with respect to grain yield in some cereals (wheat) is from seedling stage up to anthesis due to the negative impact on number of ears and kernels per ear (Schpiler and Blum, 1991). In addition drought stress from anthesis to maturity affects grain yield severely by reducing kernel size (Stone and Nicholas, 1995). Zhongu and Rajaram (1994) mentioned grain yield, number of kernels per ear, biomass and plant height all to be drought sensitive depending on the time of stress.

The yield advantage in a mixed cropping system under water limited conditions has been studied by several authors using a replacement design. Not much work has been done using an additive design. Natarajan and Willey (1986) found a yield advantage in sorghum–millet intercropping under drought stress. Singh and Chauhan (1991) and Fischer (1977a,b) have shown that relatively higher densities of the component crops under drought stress reduced productivity. However, no studies have been done on the yield advantage and competition of crop ratios under drought stress in barley and wheat mixtures.

The aims of the present study were to identify crop ratios that give yield advantage under stress and to quantify the competition effect and niche differentiation of the component crops in mixtures grown under drought stress in the Central Highlands of Eritrea.

Materials and Methods

Location

The field experiments were conducted at the Halhale Research Station, Eritrea, during the off-seasons of 1998 and 1999. The experiments were conducted on a clay loam soil under irrigation from January to May when there is less expectation of rain so that stress can be controlled.

Treatments

The drought stress treatments were unstressed control (MS_1), stress at seedling stage (MS_2), and stress at heading stage (MS_3). Watering was adjusted to ensure that control plots showed little or no signs of drought stress. The control (MS_1) was irrigated regularly to maintain 60–70 % soil moisture content. In the stress treatments (MS_2 and MS_3), water was withheld at the appropriate stage of development for two weeks until 10–20% soil moisture level was reached and if the moisture control became below 20%, water was provided. This was done until the stress period was over after which irrigation was continued (for the stress treatments) similar to the control. The soil moisture content was measured and monitored using gypsum blocks. The trial was watered using flood irrigation and maximum care was taken to avoid flow of water from one plot to another.

A total of eleven crop ratios were present with two sole crops and nine mixtures. The crop ratios tested had both an additive and a replacement design. The crop ratios (in % barley/wheat) in the additive series were 25/100, 50/100, 75/100, 100/25, 100/50, 100/75 and in the replacement series 33/67, 50/50 and 67/33. The barley sole crop can be indicated as the crop ratio 100/0 and the wheat sole crop as 0/100. A ratio of 67/33 was considered the standard for mixed cropping (Woldeamlak and Struik, 2000).

Crop management

The trials were conducted during the off-season from January to April in order to be able to control the water supply, which would not have been possible during the rainy season. Crops were sown on January 3, 1998 and January 5, 1999. The site was fertilised with a rate of 100 kg ha^{-1} Di-Ammonium Phosphate (DAP, 46% P_2O_5 and 18% N) and 50 kg ha^{-1} Urea at planting and the fertiliser was adequately incorporated into the soil. Plots were kept reasonably weed-free by hand weeding twice.

Experimental design and analysis

Each experiment was laid out in a split-plot design with 2 factors (drought stress and crop ratios) in 4 replications. Drought treatments at two stages of development and an irrigated control (no stress) were arranged as main plots and proportions were laid out as sub-plots with a subplot size of 3.75 m^2. The data on biomass and grain yield were subjected to a standard Analysis of Variance using MSTAT–C. The Least Significant Difference was calculated to compare the means and the means were ranked accordingly. The statistical analysis was done separately for the additive and replacement series. The sole crops were included with the replacement series during the analysis. The linear correlations between various agronomic characters and biomass or grain yield were also assessed.

Description of the model

Inter-plant competition effects on biomass can be described by a hyperbolic model (de Wit, 1960; Spitters, 1983a; 1989; Spitters et al., 1989; Kropff and Lotz, 1993). The model has been described in detail in Chapter 7 for barley and wheat mixtures using an additive series when crop ratios were evaluated under rainfed conditions. Analysis was performed using the equation below, which can be written as:

$$Y_{12}= N_1 \times W_1 / (1+a_1 \times (N_1+\in \times N_2)) \quad (8.1)$$

in which $a_1= b_{11}/b_{10}$ and $\in = b_{12}/b_{11}$; $1/\in = c = b_{11}/b_{12}$
For species 1

$$Y_1= N_1 \times W_1 / (1+a_1 (N_1+(1/c_1) \times N_2)) \quad (8.2)$$

in which W_1 is the apparent weight of an isolated plant ($1/b_{10}$) in g plant^{-1}; a_1 is a parameter characterising inter-specific competition (b_{11}/b_{10}) and c_1 ($1/\in$) is the relative competitive ability (b_{11}/b_{12}) describing how many individuals of species 2 are equivalent to each individual of species 1. The maximum attainable yield can be estimated as the reciprocal of b_{11} ($1/b_{11}$) (Watkinson, 1981). Alike for species 2:

$$Y_2= N_2 \times W_2 / (1+a_2 (N_2+(1/c_2) \times N_1)) \quad (8.3)$$

The above parameters were also used to derive a niche differentiation index (NDI) which was estimated as

$$NDI= (b_{11} / b_{12}) \times (b_{22} / b_{21}) \quad (8.4)$$

If NDI > 1, there is niche differentiation indicating that the plants in the mixtures are sharing resources better than plants of a sole crop which means that competition for the same resources is less. NDI < 1 suggests that the species are hampering one another. If NDI= 1, the two species are competing equally for the same resources (Spitters, 1983a,b; Connoly, 1987; Spitters and Kropff, 1989; Spitters et al., 1989).

Data collected

The data collected included above-ground biomass and grain yields of the component crop species in mixtures and in sole cropping. For that purpose the plants of the component crops in the mixture were harvested at physiological maturity and weighed separately at about 87.5% dry matter (12.5% moisture content). Data recorded in this chapter are adjusted to this dry matter content. The biomass of the two component crops were added to get the total above-ground biomass of each mixture and this sum was converted into kg ha^{-1}. The grain yield of each component crop in the mixture was added to get the total grain yield of the mixture.

Stand cover was estimated by visual observation. Plant height was measured with a ruler from the soil surface to the top of the main stem excluding the awns. The number of ears m^{-2} for the component crops was counted within a quadrant of 1 m^2. These numbers were added to get the total number of ears m^{-2} of the mixtures. The number of kernels ear^{-1} was counted for five ears of each of the component crops per plot. Ear size (cm ear^{-1}) was measured using a ruler after taking five ears of each of the component crop species in the mixtures. Thousand grain weight was estimated by counting 200 seeds of each component crop per plot and multiplying their weight by 5. Harvest index (%) was estimated as the ratio of the grain yield to the above-ground biomass.

Yield advantage was quantified using the Relative Yield Total and the Land Equivalent Ratio on the basis of grain yield which is fully described in Chapter 7. RYT was calculated as

$$RYT = RY_1 + RY_2 = (Y_{12} / Y_{11}) + (Y_{21} + Y_{22}) \qquad (8.5)$$

where Y_{12} and Y_{21} are the grain yields of the mixtures of barley and wheat as component crops in the mixtures respectively; Y_{11} and Y_{22} are the grain yields of the sole crop of barley and wheat respectively. The LER was estimated for the additive design using the above formula for RYT. Hyperbolic regression analysis as in Chapter 7 (Equation 7.3) was used to estimate the reference yields for the specific densities in the additive design.

Results

Additive series

Total biomass yield

In the additive series, there was a significant effect of drought stress on biomass yield in 1998 and 1999 (Table 8.1). The total biomass was highest in MS_1 (no stress).

The difference among the crop ratios was also significant in 1998 but not in 1999. A crop ratio of 100/50 (7510 kg ha^{-1}) and 100/25 (7266 kg ha^{-1}) had the highest biomass yield in 1998. However, in 1999, a crop ratio of 25/100 (5633 kg ha^{-1}) and 100/75 (5468 kg ha^{-1}) seemed to give highest biomass yield. When averaged over the two years, 100/25 (6112 kg ha^{-1}) and 100/50 (6100 kg ha^{-1}) were among the best in total biomass yield.

There was no significant drought stress × crop ratio interaction for total biomass yield. When averaged over the two years, 100/50 in MS_1 (7526 kg ha^{-1}) and 100/25 in MS_2 (4713 kg ha^{-1}) and MS_3 (6556 kg ha^{-1}) gave highest biomass yield, and beyond that it declined (Figure 8.1).

Total grain yield

The drought stress effect was not significant for grain yield in 1998 but significant in 1999. The ranking order for grain yield was $MS_1 > MS_3 > MS_2$.

The crop ratio effect was significant in 1998 but not in 1999. A ratio of 100/25 (890 kg ha^{-1}) followed by 100/50 (682 kg ha^{-1}) resulted in the highest grain yield in 1998 whereas crop ratios of 25/100 (1918 kg ha^{-1}), 50/100 (1545 kg ha^{-1}) and 75/100 (1518 kg ha^{-1}) had the highest grain yield in 1999. When averaged over the two years, the crop ratios of 25/100 (1188 kg ha^{-1}) and 100/25 (1114 kg ha^{-1}) had the highest grain yield, but differences were not significant.

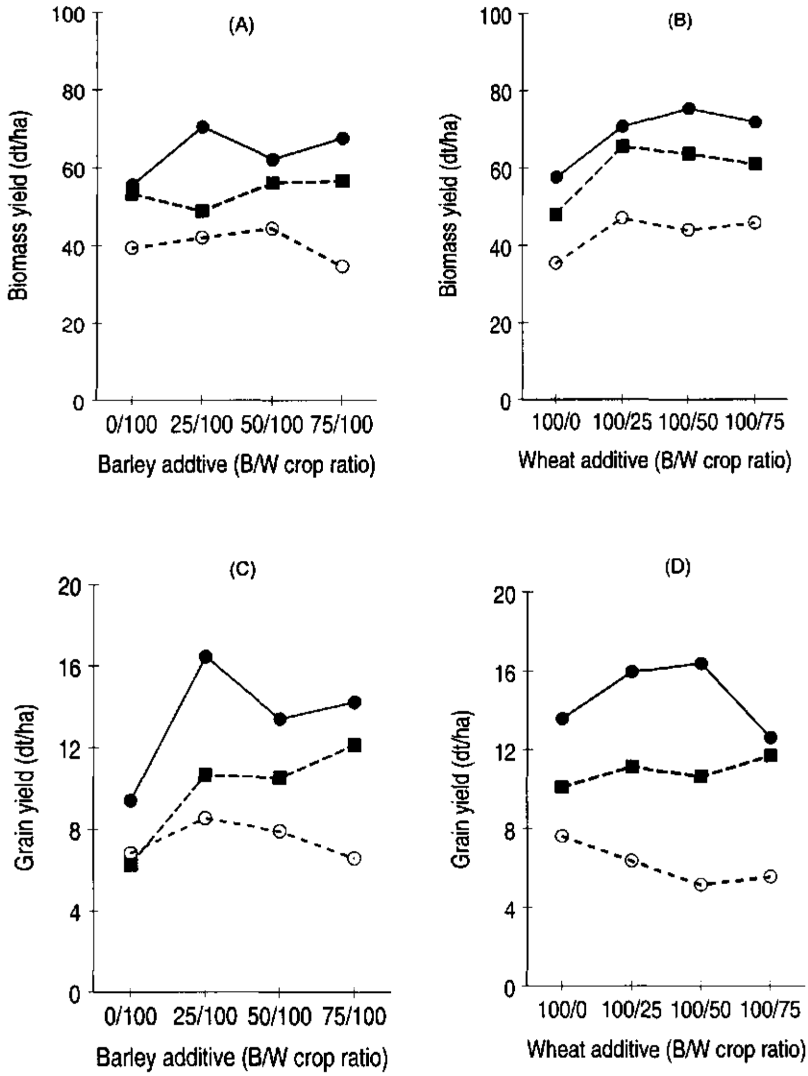
There was no significant drought stress × crop ratio interaction in grain yield in both years (Table 8.1). When averaged over the two years, in MS_1 a ratio of 100/25 (1594 kg ha^{-1}), in MS_2 25/100 (854 kg ha^{-1}) and in MS_3 75/100 (1214 kg ha^{-1}) gave highest grain yields (Figure 8.1).

Replacement series

Total biomass

There was a significant effect of drought stress on biomass yield in both years. The total biomass was highest in MS_1 (no stress). The largest reduction (36.3%) was observed when stress was applied at seedling stage (MS_2) and 24.3% reduction was found when stress was applied at MS_3. There was a significant difference in biomass yield between the different crop ratios in 1998 but not in 1999. A crop ratio of 67/33 gave the highest biomass yield in 1998 followed by a ratio of 50/50 (6603 kg ha^{-1}). In 1999, wheat sole crop had a higher biomass than the mixtures. However, when averaged over the two years, the best mixture surpassed the sole crops in biomass yield. A crop ratio of 67/33 (6118 kg ha^{-1}) and 50/50 (6002 kg ha^{-1}) had the highest total biomass yield (Table 8.2).

There was no significant interaction between drought stress and crop ratio (Table 8.2). When averaged over the two years, 67/33 gave highest biomass yield at MS_1 (7873 kg ha^{-1}) and MS_3 (5990 kg ha^{-1}) (Figure 8.1).



Figures 8.1. Mean total biomass and grain yield as affected by drought stress in the additive design of barley and wheat mixtures averaged over two years. (A) Barley additive series biomass yield; (B) Wheat additive series biomass yield; (C) Barley additive series grain yield; (D) Wheat additive series grain yield. ●- MS_1= no stress or control, ○- MS_2= stress at seedling stage and ■- MS_3= stress at heading stage. Along the y axis dt ha^{-1} in y axis is the same as quintals ha^{-1}.

Table 8.1. Total biomass (kg ha^{-1}) and grain yields (kg ha^{-1}) of additive crop ratios of barley and wheat mixed cropping as affected by drought stress in the 1998 and 1999 experiments at the Halhale Research Station, Eritrea. MS_1- no stress, MS_2- stress at seedling stage, MS_3- stress at heading stage. Means followed by the same letter are not significantly different. Means followed by the same letter are statistically not different. Values without letters are statistically not significant.

Treatments	Total biomass yield			Total grain yield		
	1998	1999	Mean	1998	1999	Mean
Drought stress						
MS_1	7213 a	6449 a	6831 a	793	2100 a	1447 a
MS_2	4975 b	3625 b	4300 c	495	841 c	668 c
MS_3	6596 a	5125 ab	5861 b	593	1634 b	1114 b
Mean	6261	5066	5664	627	1525	1076
Barley additive						
25/100	4811 d	5633	5222	384 c	1918	1151
50/100	5938 cd	4891	5415	578 bc	1545	1062
75/100	5808 cd	4757	5283	678 ab	1518	1098
Wheat additive						
100/25	7266 ab	4958	6112	890 a	1337	1114
100/50	7510 a	4690	6100	682 ab	1390	1036
100/75	6235 bc	5468	5852	549 bc	1442	996
Mean	6261	5066	5664	627	1525	1076
CV%	24.1	35.6	22.6	35.3	34.4	33.7
LSD 5%						
Drought stress	1203	2010	774	NS	387	223
Crop ratio	1247	NS	NS	260	NS	NS
Drought stress × crop ratio	NS	NS	NS	NS	NS	NS

Table 8.2. Total biomass (kg ha^{-1}) and grain yields (kg ha^{-1}) for replacement crop ratios of barley and wheat mixed cropping as affected by drought stress. MS_1- no stress, MS_2- stress at seedling stage, MS_3- stress at heading stage. Means followed by the same letter are not significantly different. Values without letters are statistically not significant.

Treatments	Total biomass yield			Total grain yield		
	1998	1999	Mean	1998	1999	Mean
Drought stress						
MS_1	6649 a	6288 a	6469 a	663 a	1883 a	1273 a
MS_2	4497 b	4301 b	4399 b	473 c	1022 b	748 b
MS_3	5742 ab	5305 ab	5524 a	523 b	1330 ab	927 b
Mean	5629	5298	5464	553	1412	983
Crop ratio B/W						
0/100	4234 d	5651	4943 b	104 c	1393	748
33/67	5692 bc	5403	5547 ab	489 b	1247	868
50/50	6603 ab	5400	6002 a	731 ab	1572	1152
67/33	6896 a	5341	6118 a	656 ab	1547	1102
100/0	4722 cd	4694	4708 b	786 a	1299	1043
Mean	5629	5298	5464	553	1412	983
CV%	24.9	31.4	20.5	37.9	37.3	36.0
LSD 5%						
Drought stress	1623	1384	1009	24	692	346
Crop ratio	1171	NS	944	262	NS	NS
Drought stress × crop ratio	NS	NS	NS	NS	NS	NS

Total grain yield

The same trend was observed for grain yield with a significant effect of drought stress in both years. The grain yield of the mixtures was poorer in 1998 than in 1999.

There was a significant effect of crop ratio on total grain yield in 1998 but not in 1999. In 1998, grain yield of the barley sole crop (786 kg ha^{-1}) was higher than that of the mixtures. Among the mixtures a crop ratio of 50/50 (731 kg ha^{-1}) and 67/33 (656 kg ha^{-1}) yielded best in 1998. The lowest grain yield was recorded in the wheat sole crop. In 1999, crop ratios of 50/50 (1572 kg ha^{-1}) and 67/33 (1547 kg ha^{-1}) were relatively high in grain yield. When averaged over the two years, the above crop ratios resulted in the highest grain yield.

There was no significant interaction between crop ratio and drought stress in either year regarding grain yield (Table 8.2). In 1998, grain yield was maximum at 67/33. The sole crop outyielded the mixtures especially in MS_1 and MS_3. In 1999, grain yield reached maximum at 67/33 in both MS_1 (2398 kg ha^{-1}) and MS_3 (1662 kg ha^{-1}). When averaged over the two years, the grain yield was highest at 67/33 (1588 kg ha^{-1}) in MS_1 and MS_3 (1034 kg ha^{-1}).

The overall analysis of variance for the crop ratios (additive and replacement) in total biomass yield and grain yield is shown in Table 8.3. There was a significant difference among the drought stress treatments for both biomass and grain yield in 1998 and 1999 but not a significant drought stress × crop ratio interaction.

Agronomic characters

The effect of drought stress on selected agronomic characters is shown in Table 8.4. In 1998, plants matured earlier than in 1999. Plants in MS_2 (stress at seedling stage) were late to reach heading than those of the other stress types. Barley and wheat plants in MS_1 were taller than those either in MS_2 or MS_3. Plants stressed in the seedling stage (MS_2) were shorter than those stressed during the heading stage (MS_3). This was consistent for both mixture components. However, wheat was taller than barley in mixtures. Drought stress affected the yield components and other agronomic traits in a consistent way across years. All yield components were better under no stress, which was consistent across years and crop ratios Harvest index was poorer in 1998 than in 1999 (Table 8.4).

The relationships between some agronomic characters and biomass or grain yields are shown in Table 8.5. All agronomic characters were positively correlated with biomass yield in 1998 but not significantly so. On the other hand, in 1999, all characters were positively and significantly correlated with biomass except harvest index and number of ears m^{-2}, which were not significant. When pooled over the two years, stand cover (r=0.609*) and number of kernels m^{-2} (r=0.603*) were positively and significantly correlated with biomass whereas

Table 8.3. Mean squares of the overall analysis of variance on biomass yield and grain yield for the effects of drought stress and crop ratios (additive and replacement series) in 1998 and 1999. Mean square values without asterisk are non significant, ** shows significance at 1% and * significance at 5% level.

Source of variation	Biomass			Grain yield		
	1997	1998	Pooled	1998	1999	Pooled
Drought stress	0.549**	0.711**	0.621**	0.008*	0.138**	0.053**
Crop ratio	0..137**	0.049	0.030	0.005**	0.005	0.002
Drought stress × crop ratio	0.007	0.027	0.008	0.0001	0.004	0.001
CV%	24.7	37.7	22.0	39.7	39.9	38.1

Table 8.4. Performance of the mixtures as reflected by some selected agronomic characters for crops grown under stress and non stress conditions in 1998 and 1999. In the table, 1= MS_1–no stress or control, 2= MS_2–stress at seedling and 3= MS_3– stress at heading.

Character		1998	1999	Mean
Plant height (cm)	(1)	67.3	73.9	70.6
	(2)	55.6	60.5	58.1
	(3)	64.4	68.1	66.3
Number of ears m^{-2}	(1)	262	417	340
	(2)	187	313	250
	(3)	191	346	269
Number of kernels ear^{-1}	(1)	20	24	22
	(2)	15	20	17
	(3)	16	22	19
1000 grain weight (g/1000 seeds)	(1)	29.0	30.2	29.6
	(2)	24.1	26.0	25.1
	(3)	25.0	27.1	26.1
Ear size (cm)	(1)	7.9	7.9	7.9
	(2)	7.2	6.5	6.8
	(3)	7.7	7.1	7.4
Number of kernels m^{-2}	(1)	5240	10008	7624
	(2)	2805	6260	4533
	(3)	3056	7612	5334
Harvest index (%)	(1)	10.5	31.3	20.9
	(2)	10.2	23.5	16.9
	(3)	9.1	28.5	18.8

plant height, ear size and kernels per ear were negatively correlated with biomass but not significantly so.

Characters such as biomass (r=0.687*), harvest index (r=0.798*) and number of ears m^{-2} (r=0.679*) showed a positive and significant correlation with grain yield in 1998. In 1999, all characters had a positive and significant correlation with grain yield except number of ears m^{-2} (r=0.376) that was not significant in 1999. When averaged over the two years, biomass (r=0.860*), harvest index (0.749*), stand cover (0.459*), TGW (0.510*) and ears m^{-2} (r=0.571*) had a positive and significant correlation with grain yield (Table 8.5).

Table 8.5. Correlation coefficients for the relationships between selected agronomic characters and biomass yield or grain yield in barley and wheat mixed cropping in 1998 and 1999. In the table TGW is thousand grain weight (g/1000 seeds) (n=33 for individual years). (*) significant at 5% level.

Characters	1998		1999		Pooled	
	Biomass yield	Grain yield	Biomass yield	Grain yield	Biomass yield	Grain yield
Stand cover	0.378	0.308	0.563*	0.610*	0.609*	0.459*
Plant height	0.349	0.228	0.761*	0.690*	–0.315	–0.370
Ears/m^2	0.264	0.687*	0.275	0.376	0.401	0.859*
Kernels/ear	0.207	0.138	0.576*	0.527*	–0.315	–0.370
TGW	0.025	0.154	0.042	0.545*	0.160	0.510*
Ear size	0.174	0.099	0.599*	0.665*	–0.289	–0.356
Kernels/m^2	0.196	0.136	0.595*	0.546*	0.603*	0.571*
Biomass	------	0.687*	------	0.836*	------	0.860*
Harvest index	0.080	0.798*	0.247	0.745*	0.313	0.749*

Yield advantage

The yield advantage averaged for the stress types or crop ratios is shown in Table 8.6. In 1998, when averaged over the crop ratios, the relative yield total was >1 in the control (MS_1) as well as in stress at heading stage (MS_3) but not in stress at seedling stage (MS_2). When averaged over the stress types, a crop ratio of 50/50 with 24% gave a maximum yield advantage in the replacement series. All crop ratios showed a yield advantage except 33/67. In 1999, in all stress situations, there was a yield advantage from the mixtures compared to the sole crops. The highest yield advantage was obtained under stress at heading stage with 67% increase. The highest yield advantage in the additive design was in the crop ratios of 25/100 (1.713) or 75/100 (1.496) (Table 8.6). When averaged over the two years and crop ratios MS_1 and MS_3 showed a yield advantage but MS_2 did not. When averaged over stress types, a crop ratio of 25/100 (1.37), 75/100 (1.31) and 50/100 (1.35) gave a yield advantage in land area. When averaged over the crop ratio and stress types there was a yield advantage of 23% in terms of grain yield (Table 8.6) but the effects were statistically non significant.

Yield loss

The yield loss in MS_2 (stress at seedling stage) was higher than in the stress at heading stage (MS_3) which was consistent in both years. The yield loss in the additive series was 4.1% higher than in the replacement series. In 1998, 33/67

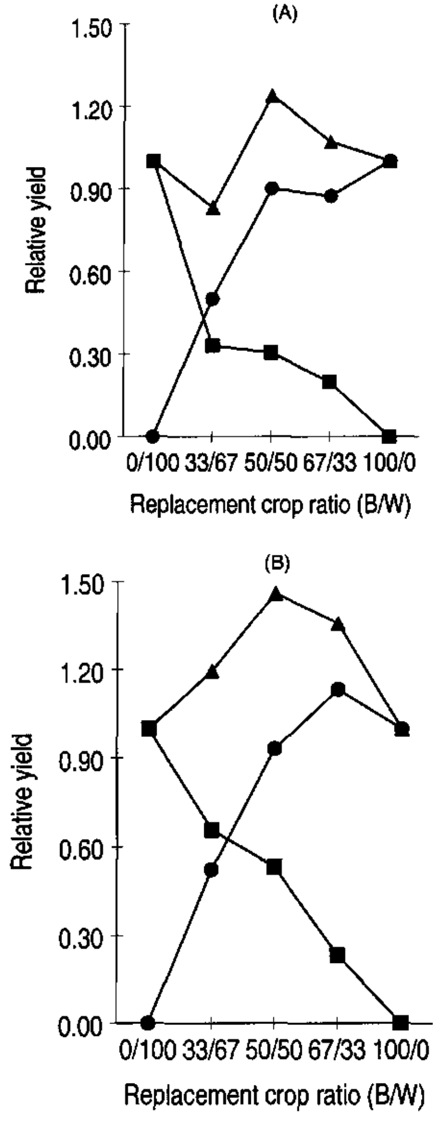


Figure 8.2. An example of relative yield of barley and wheat as component crops in mixtures and total mixtures in replacement series. (A) 1998 and (B) 1999. In the graph ●- Barley as component crop, ■- Wheat as component crop, and ▲- Mixtures.

Table 8.6. Effect of drought stress and crop ratio on the yield advantage of barley and wheat mixtures tested at Halhale 1998 and 1999. The asterisks between brackets (*) below show significance at $P \leq 0.10$.

Crop ratio	1998	1999	Mean
Stress types			
MS_1	1.552	1.227	1.390
MS_2	0.737	1.195	0.966
MS_3	1.010	1.667	1.339
Mean	1.099	1.363	1.231
Crop ratio B/W			
Relative Yield Total			
33/67	0.831	1.197	1.014
50/50	1.240	1.460	1.350
67/33	1.066	1.358	1.212
Land Equivalent Ratio			
25/100	1.027	1.713	1.370
50/100	1.186	1.397	1.292
75/100	1.123	1.496	1.310
100/25	1.230	1.058	1.144
100/50	1.026	1.332	1.179
100/75	1.123	1.254	1.210
Mean	1.099	1.363	1.231
LSD 5%			
Drought stress	NS(*)	NS	NS(*)
Crop ratio	NS(*)	NS	NS
Drought stress × crop ratio	NS	NS	NS
CV%	39.4	37.0	33.2

and 25/100 had highest yield losses when stressed at seedling stage. When averaged over the stress types, still 33/67 and 25/100 showed a higher yield loss than the rest. In 1999, 67/33, 100/25 and 100/50 showed the highest yield loss all in treatments with stress at seedling stage. When averaged over the stress types 100/50, 67/33 and 100/25 resulted in higher losses. Additive ratios of 25/100 and 100/25 also showed higher yield loss when averaged over the two years. The yield loss in barley sole crop was relatively lower than that in the wheat sole crop. The yield loss was relatively lower in 50/50 crop ratio than in all other ratios when averaged over the years and stress types (Table 8.7).

Table 8.7. Effect of drought stress and crop ratio on grain yield loss (%) in barley and wheat mixtures) in barley and wheat mixtures using different crop ratios in the 1998 and 1999 experiments. The asterisks between brackets (*) indicate significance level at P≤ 0.10.

Crop ratio	1998			1999			Mean
	MS_2	MS_3	Mean	MS_2	MS_3	Mean	1998–1999
Barley additive							
25/100	52.9	48.3	50.6	42.4	26.6	34.5	42.5
50/100	36.6	19.0	27.8	42.6	22.3	32.4	30.1
75/100	37.5	33.3	35.4	61.2	6.4	33.8	34.6
Mean	42.3	33.5	37.9	48.8	18.4	33.6	35.8
Wheat additive							
100/25	38.2	25.1	31.6	72.2	33.0	52.6	42.1
100/50	32.3	12.4	22.3	78.2	36.4	57.3	39.8
100/75	30.8	16.6	23.7	64.7	4.0	34.3	29.0
Mean	33.8	18.0	25.9	71.7	24.5	48.1	37.0
Replacement							
0/100	39.1	18.0	28.6	26.8	34.7	30.7	29.6
33/67	53.4	49.8	51.6	8.5	3.8	6.2	28.9
50/50	8.6	8.6	8.6	42.7	36.9	39.8	24.2
67/33	30.6	16.5	23.5	75.8	30.7	53.2	38.4
100/0	22.4	12.5	17.4	54.6	31.9	43.2	30.3
Mean	30.8	21.0	25.9	41.7	27.6	34.6	30.3
Grand mean	35.6	24.2	29.9	54.1	23.5	38.8	34.4

	1998	1999	Mean
LSD 5%			
Drought stress	NS	NS(*)	NS
Crop ratio	NS(*)	NS	NS
Drought stress × crop ratio	NS	NS	NS
CV%	39.5	37.6	39.7

Competition

The results on estimates of parameters of intra- and inter-specific competition and niche differentiation indices in barley and wheat mixtures of 1998 and 1999 are shown in Tables 8.8 and 8.9. The lower the value of b_{10}, the higher the apparent weight of an isolated plant. The apparent weight of an isolated plant was higher for barley than for wheat. The maximum attainable yield ($1/b_{11}$) was relatively higher for barley as a component crop which was consistent for both biomass and

Table 8.8. Estimates of parameters b_0 (1/W), b_1 (1/a) and b_2 (c/b_1) for total biomass yield and grain yield for barley and wheat as affected by the effects of drought stress and crop ratio in 1998 and 1999.

Character	Barley			Wheat		
	b_{10}	b_{11}	b_{12}	b_{20}	b_{21}	b_{22}
Biomass 1998	0.141	0.0220	0.00329	0.231	0.032	0.008
Biomass 1999	0.157	0.0180	0.00836	0.562	0.105	0.055
Grain yield 1998	0.231	0.0160	0.00230	0.398	0.126	0.035
Grain yield 1999	0.323	0.0120	0.00175	0.816	0.049	0.014

Table 8.9. Inter-specific competition and niche differentiation indices (NDI) of barley and wheat mixtures tested under stress and crop ratios (n=132). SE= standard error; * indicates statistically significant at $P \leq 0.05$.

Characters	Barley			Wheat			NDI
	b_{11}/b_{12}	SE	r^2	b_{22}/b_{21}	SE	r^2	
Biomass 1998	6.687	±0.14	0.131*	0.249	±0.01	0.716*	1.67
Biomass 1999	2.153	±0.65	0.232*	0.524	±0.19	0.580*	1.13
Grain yield 1998	6.957	±0.19	0.035	0.278	±0.07	0.359*	1.93
Grain yield 1999	6.857	±0.12	0.032	0.288	±0.09	0.356*	1.97

grain yield.

Barley was a stronger competitor than wheat in both years. This implies that the competition among barley plants was higher than among wheat plants. The competition values were greater for grain yield in 1998 and 1999. If biomass 1998 is taken as an example for barley, one barley plant was as competitive as seven (6.68) wheat plants. For wheat, four wheat plants (0.249; 1/4th) were equal to about one barley plant. This means that the influence of barley plants was greater than the influence of wheat plants. There was also niche differentiation in the experiment in both years and for biomass and grain yield. The NDI was more than unity.

Discussion

Productivity

In this study, lower yield under stress conditions could be due to low seed number and seed weight. This is in agreement with Zhonghu and Rajaram (1994) and Nelson et al. (1991) who mentioned that number of kernels per ear is reduced due by drought giving rise to low grain yield.

Plants in mixtures were shorter compared to those in sole crop because of higher competition for water among the species affecting plant height. Plants in the wheat sole crop expressed their growth potential by growing taller. This contributed to a higher biomass.

Mixed cropping resulted in a better total yield compared to sole crops due to more efficient utilisation of soil resources by the component crops. Under limited water resources higher density in additive series did not result in higher productivity because the water demand of the crops became too high.

Furthermore, the variation in grain yield between years partly could be explained due to aphid infestation that affected the ears of the plant in 1998 season. Secondly, the study was done using flood irrigation. This type of irrigation is very difficult to control precisely and this could also have contributed to the variation between years.

Competition

Plants growing in a mixture in a water limited production situation compete for water. The competition for water is different from that for light as water can be stored in the system in contrast to the resource light. It can only be stored in the soil compartment of the system in relevant quantities. The crop is affected when the demand is higher than the supply. If plants compete for water, the plant that has access to soil moisture in the deepest layers through its root system benefits. Crop species might also differ in their water use efficiency in terms of dry matter production. A more efficient species might have an advantage under drought situations. Competition for water could be analysed by simulation modelling as it is a dynamic process (Kropff, 1993). Barley and wheat have shallow root systems and water extraction is limited to the rooted zone. Mixed cropping systems have in many cases resulted in higher water use efficiency compared to sole cropping because of more efficient use of resources.

Barley was a stronger competitor than wheat regardless of the time of stress. Willey et al. (1997) believed that when one of the component crops is a strong competitor, mixed cropping is advantageous. Even without any compensation occurring, a stronger competitor such as barley would presumably achieve more or less its normal yield.

The greater weight of an isolated plant ($1/b_0$) for barley in 1998 explains the higher biomass yield in 1998 compared to 1999. The maximum attainable weight ($1/b_1$) of both component crop species in 1999 can describe the higher grain yield in 1999 compared to 1998. However, when comparing the two component crops both the weight of an isolated plant and maximum attainable yields were higher for barley than wheat. Barley can survive under adverse environmental conditions, which could be the reason for higher parameters of competition. This was also reflected in the better inter-specific competitive ability of the crop.

Niche differentiation

The NDI exceeded unity showing that the species were able to use the resources efficiently when grown together in a complementary way. The NDI value was associated with a yield advantage > 1 which shows the complementary resource use resulting in a yield advantage. The niche differentiation under adverse environmental conditions is a further proof that barley and wheat mixtures do not inhibit each other, even not when the soil resources are limited.

Conclusion

When averaged over years and stress types, these experiments showed that a crop ratio in % of 50/50 (1152 kg ha^{-1}), 25/100 (1151 kg ha^{-1}) and 100/25 (1114 kg ha^{-1}) resulted in the highest yield. The standard crop ratio of barley 67% and wheat 33% also performed very well. These ratios can serve as a means of increasing the low yields. The niche differentiation confirmed that mixed cropping barley and wheat share resources in a complementary way resulting in yield advantage even under stress conditions. However, higher crop ratios such as 100/75 or 75/100 did not result in higher grain yield because of excessive water demand during vegetative growth.

Yield stability in mixed cropping of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)*

Woldeamlak A. and P. C. Struik

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Abstract

Yield data of a large set of experiments were re-analysed in order to assess the effect of environment (locations and years) on the performance of barley and wheat mixtures, to assess whether yield stability was greater in mixed cropping than in sole cropping, and to assess which genotype combinations in the mixtures showed most stable grain yields. Grain yield data used came from studies on mixed cropping with experimental factors including genotype combinations, density, crop ratio and drought stress. Stable genotypes or cropping systems were those having reasonably high mean yield, a regression coefficient b=1.0 of the relation between grain yield of the locations and the mean yield of each genotype combination or cropping system and a standard deviation (Sd) as small as possible. Mixed cropping with a mean grain yield of 1744 kg ha^{-1}, regression coefficient (b) of 0.995 and standard deviation (Sd) ± 0.277 was more stable in grain yield than either barley or wheat sole cropping. Effects on yield caused by genotype, environment or genotype × environment interaction were significant particularly under rainfed conditions. This suggests that the relative performance of genotypes differed among environments. When the analyses under rainfed and under stress conditions were combined, there was a significant effect of genotype ($P \leq 0.01$) and environment ($P \leq 0.10$), but the interaction was not significant. Ardu 12/60 + Kenya + Mana with mean grain yield of 2309 kg ha^{-1}, regression coefficient (b) of 1.067 and standard deviation (Sd) of ±0.495 and Ardu 12/60 + Mana with mean grain yield of 1965 kg ha^{-1}, regression coefficient (b) of 0.992 and standard deviation (Sd) ±0.120 were more stable than others. The rest of the genotype combinations were less stable under varying environmental conditions. A stability test under a wider set of environmental conditions could be helpful to learn which genotype combinations are best adaptable.

Key words: genotype × environment, stability, mixed cropping, barley, wheat, Eritrea

Introduction

A major reason for the predominance of barley and wheat mixed cropping in the central highlands of Eritrea is that it can give greater stability of yield over different years. There are several mechanisms that could explain the improved yield stability. The basis for this is that if one component crop (wheat) fails or grows poorly, the other component crop (barley) makes (to some extent) use of the extra resources available and thus partly compensates for the yield loss. This compensation cannot be realised if the crops are grown separately. Such compensation was observed for example in cotton–groundnut intercropping where groundnut compensated for poor cotton growth (Patil and Koraddi, 1960), in maize–bean intercropping when maize suffered damage due to hail (Fischer, 1977a,b) and in barley–pea intercropping where a total crop failure caused by snow damage was avoided (Subedi, 1998). Another mechanism of improved stability could occur when mixed cropping reduces the severity of pests and diseases (Trenbath, 1974; Wolf, 1985; Midmore and Alcazar, 1991). Farmers in Eritrea claim that the severity of diseases and insect problems in barley and wheat mixtures is lower than that in sole crops (Woldeamlak and Struik, 2000). In this chapter, we focus on yield stability related to crop ecological factors.

Allard and Bradshaw (1964) defined stability as the adaptation to withstand unpredictable transient environmental variations. In this chapter, yield stability is defined as the lack of variation in yield under different growing conditions. The yield is considered stable if the environment or the growing conditions cause only relatively small changes.

Finlay and Wilkinson (1963) proposed a method to measure stability. It was later improved by Eberhart and Russel (1966). The method is explained in the materials and methods section of this chapter. The stability test developed permits quantitative estimates of adaptability and thus makes it feasible to identify superior performance of a genotype or cropping system over a wide range of environmental conditions.

Yield stability in mixed cropping can be realised when the yield advantage is greater under adverse weather conditions than under favourable conditions. In that case, yields also remain more stable in mixed cropping than in sole cropping, especially under stress (Rao and Willey, 1980).

The stability of crop yield over a wide range of environments has become an important focus especially in a farming system that has a problem of rainfall variability among different years (Hill, 1975). When rainfall deviates widely from the normal patterns (either too much or too little) crop failure may result. The same holds for other environmental factors. To overcome crop failure or severe yield losses specific genotype combinations must be grown. Analysing the genotype × environment interactions could be an effective tool to identify which genotypes are adaptable to certain environmental conditions (Allard and Bradshaw, 1994).

In the past, work on stability has mainly been limited to varietal mixtures within a given crop mainly examining the benefits of multilines (Rao and Willey, 1980). The stability of mixed cropping has been questioned by Fischer (1977a,b) who was doubtful whether greater stability of mixed cropping occurred when moisture was limiting as compared to wet conditions. Harwood and Price (1975) also questioned yield stability in mixed cropping as crop failure occurred after severe competition has taken place.

On the other hand yield stability in mixed cropping has been confirmed by several workers. Jodha (1979) did not doubt the possibilities of improved stability of mixed cropping in areas of lower rainfall and high risk. Ogunfowara and Norman (1974) observed less yield fluctuation than in sole cropping even under unfavourable conditions. Trenbath (1974) reviewed yield stability in mixed cropping and some evidence of yield stability was mentioned depending on the crop species. The sorghum–pigeon pea intercropping showed improved stability over a sole crop system (Rao and Willey, 1980). In maize–sorghum intercropping yield stability was observed, when rains were poor sorghum was high yielding than maize and in years of high rainfall maize was higher yielding than sorghum (Anderson and Williams, 1954). Sorghum intercropping systems were productive and stable (Rao et al., 1979). Differences in yield stability of genotype combinations in barley–pea mixed cropping was supported by Subedi (1998).

The aims of this study were to assess the effect of environments on the grain yield of mixtures of barley and wheat, to confirm the yield stability in mixed cropping of barley and wheat, and to assess which genotype combinations in the mixtures are more stable in grain yield.

Materials and Methods

Stability test

Early quantitative studies on intercropping used the coefficient of variation (CV) as a measure of stability, low CVs indicating yield stability. However, CVs have disadvantages as direct assessment of significant differences between CVs is not valid and comparison of CVs implies that a common distribution exists which is not always the case (Lightfoot et al., 1987). Actually, the use of CV is probably the most deficient method giving only a simple expression of variability in grain yield (Rao and Willey, 1980). Estimating stability using the probability of monetary return falling below a certain given disaster level of income was considered by Rao and Willey (1980), where at any given disaster level intercropping showed a much lower probability of crop failure than sole cropping. The drawback of this estimate, however, was that price structures are not static for crops and inputs. Farmers in Eritrea, do not produce barley and wheat mixed cropping for the market so monetary stability might not be relevant for the time being.

The most popular and sound method of measuring yield stability in any cropping system is the one developed by Finlay and Wilkinson (1963), later improved by Eberhart and Russel (1966). The stability parameters considered were the regression coefficient of the relation between mean grain yield of each location and the mean grain yield of each genotype or cropping systems (b), the coefficient of determination (r^2) and the standard deviation (Sd). Mean grain yield at each locations was used as the dependent variable (Y axis) and the mean grain yield of each genotype combination or cropping system as independent variable (X axis) (Pederson et al., 1978; Godawat et al., 1995). Stable genotypes are those that have relatively better mean grain yield, a regression coefficient b=1.0 and standard deviation as small as possible (Sd) (Godawat et al., 1995). Several workers have used this regression technique to examine the stability over a range of environments in either monocropping or intercropping experiments (Jowet, 1972; Singhania and Rao, 1976; Rao et al., 1979; Rao and Willey, 1980; Singh et al., 1986; Singh and Bejiga, 1990; Cantero et al., 1995; Godawat et al., 1995; Biarnes et al., 1996; Panwar et al., 1996; Boggini et al., 1997; Chopra and Viswanathan, 1999).

In this study the genotype × environment interaction and stability parameters were analysed both by Analysis of Variance and by estimating the values of the above mentioned stability parameters.

Description of the environments

The details of the locations where the experiments were carried out are given in Table 9.1. The locations vary in rainfall, elevation and soil type.

Table 9.1. Climatic, physical and chemical characteristics of the trial sites (-- = data not recorded).

Characters	Trial sites	
	Halhale	Mendefera
Elevation (m a.s.l)	1997	1900
Rainfall (mm) 1997	580	710
Rainfall (mm) 1998	656	784
Rainfall (mm) off-season 1999	0	0
Maximum temperature (°C)	30.2	28.9
Minimum temperature (°C)	9.6	5.8
Physical analysis (%)		
Sand	19.5	----
Silt	52.1	----
Clay	28.4	----
Chemical analysis		
Soil acidity (pH)	8.7	7.5
Organic matter (OM %)	2.12	1.44
Phosphorus (P_2O_5)	12.8	----
Electroconductivity (EC mmhos/cm)	0.57	0.35

Note: Data on soil analysis are from the Research and Human Resource Department of the Ministry of Agriculture, Eritrea (personal communication).

Environments were defined by the site × year combination. Grain yield data of nine environments were considered for the stability test of the genotype combinations and 11 environments for the stability test of the cropping systems, i.e. for the comparison of monocropping vs. mixed cropping. The environmental indices (Ij) were calculated as the mean of all the locations minus (−) the mean of any given location (j) computed from the grain yield of the different environments (Lal et al., 1974; Rao and Willey, 1979).

Source of data

The data for stability analysis were taken from field trials summarised in Table 9.2. The details are given in the previous chapters in this thesis. In the genotype combinations tested under rainfed conditions, four barley (Yeha, IAR 485, Ardu 12/60 and Kuunto) and four wheat (Mana, Kenya + Mana, HAR 416 and K 6290) genotypes (or genotype mixtures) were grown in all possible combinations. In the trials under drought stress, three barley (Yeha, IAR 485, Ardu 12/60) and three wheat (Mana, Kenya + Mana and K 6290) genotypes (or genotype combinations) were tested in all possible combinations. The genotype combinations tested under rainfed and irrigation during the off-season were the same, except that there were genotype combinations that were not included in the drought stress trials. In all experiments a mixture of Yeha + Mana was used as a standard. In the density trials, both additive and replacement crop ratios were evaluated.

Results

Mixed cropping vs sole cropping

The stability parameters for the cropping systems over 11 environments are shown in Table 9.3. The slope of the barley monocrop was < 1 (b=0.769; Sd ±0.192) whereas that of wheat monocrop was > 1 (b=1.336; Sd= ±0.303). This showed that both monocrops were not stable under varying environmental conditions. The regression value for the mixed cropping was almost equal to 1 (b=0.995; Sd=±0.277) which proved that mixed cropping was more stable. The total mean grain yield for the mixtures (1744 kg ha^{-1}) was also higher than either the barley (1511 kg ha^{-1}) or the wheat (1283 kg ha^{-1}) monocrops. The coefficient of determination (r^2) ranged from 0.536 to 0.682. The relationship between the cropping systems and the respective location mean yields averaged over 11 environments is shown in Figure 9.1A. A higher mean grain yield of the respective locations resulted significantly in a higher grain yield of both the sole crops and the mixtures. The regression coefficient becomes higher or lower than one when the cropping system or genotype combinations give either high or low yields under varying environmental conditions.

Table 9.2. Some details on the materials and methods of the experiments with mixed cropping of barley and wheat used for stability test. The abbreviations RCBD- Randomised Complete Block Design; DAP- Di-Ammonium Phosphate.

Description	Genotype combination		Density and proportion	
	Rainfed	Off-season	Rainfed	Off-season
Location	Halhale and Mendefera	Halhale	Halhale and Mendefera	Halhale
Year	1997 and 1998	1998 and 1999	1997 and 1998	1998 and 1999
Design	RCBD	Split plot	RCBD	Split plot
Replications	4	4	4	4
Treatments	4 barley and 4 wheat genotypes	3 barley and 3 wheat genotypes	3 densities and 11 crop ratios	11 crop ratios
Stress	No stress	3 stress types	No stress	3 stress types
Plot size (m^2)	3.0	2.0	3.75	3.75
Fertiliser	100 kg ha^{-1} DAP and 50 kg ha^{-1} Urea	100 kg ha^{-1} DAP and 50 kg ha^{-1} Urea	100 kg ha^{-1} DAP and 50 kg ha^{-1} Urea	100 kg ha^{-1} DAP and 50 kg ha^{-1} Urea

Table 9.3. Comparison of stability parameters for grain yield of the sole crops (barley and wheat) and of the crop mixtures (n= 11 environments).

Parameters	Sole crops		Mixtures
	Barley	Wheat	
Mean yield (kg ha^{-1})	1511	1283	1744
Slope (b)	0.769	1.336	0.995
Standard deviation (Sd)	0.192	0.303	0.277
r^2	0.640*	0.682*	0.536*

Table 9.4. Analysis of variance of genotype × environment interaction in mixtures of barley and wheat grown under different conditions.

Source of variation	Rainfed (n=192)		Rainfed + Irrigated (n=324)	
	df	Mean square	Df	Mean square
Replication	3	0.116	3	0.536
Environment	2	0.245 **	8	0.118**
Genotype	15	0.109 **	8	0.030(*)
Genotype × Environment	30	0.074 **	64	0.019
Error	141	0.022	240	0.018

Note: (**)- significant at 1%; (*)- significant at 10%.

Genotype combinations

The analysis of variance revealed that the effects due to genotype combination, environment as well as genotype × environment interaction were significant for grain yield under rainfed conditions. However, when the analysis under rainfed and irrigated (stress trial) conditions were combined, the genotypes differed significantly ($P \leq 0.01$) in their performance and the environments were also quite variable ($P \leq 0.10$) but the interaction between the two appeared not to be significant (Table 9.4).

The stability performance of genotype combinations based on the mean grain yield, regression coefficients and standard deviation (rainfed and drought stress) is shown in Table 9.5. Among the genotype combinations tested, Ardu 12/60 + Kenya + Mana (2309 kg ha^{-1}), Ardu 12/60 + K 6290 (2221 kg ha^{-1}), and Yeha + Mana (2024 kg ha^{-1}) were yielding best, considering the average grain yield for all the test periods and environments. Among these Ardu 12/60 + Kenya + Mana, the best yielding genotype combination, had a regression value close to unity (b=1.067), suggesting stability. The standard deviation was also relatively

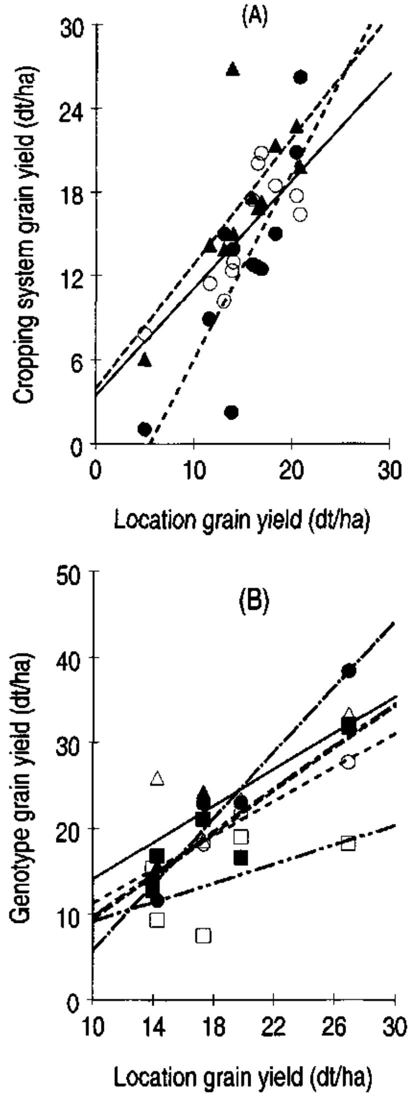

Figure 9.1. Relationship between location mean grain yield and yields of cropping systems. In Figure, A ○- Barley monocrop (r=0.800*); ●- Wheat monocrop (r=0.826*) and ▲- Mixtures (r=0.732*); (B) Relationship between location mean grain yield and genotype combination mean grain yield of selected mixtures. In Figure B, Δ- Ardu 12/60 + Kenya + Mana (r=0.780); ○- Ardu 12/60 + Mana (r=0.979*); ■- Yeha + Kenya + Mana (r=0.901*); ▲- Yeha + Mana (r=0.861); ●- Yeha + K 6290 (r=0.979*); □- IAR 485+ K 6290 (r=0.569).

Table 9.5. Stability parameters for grain yield of nine genotype combinations of barley and wheat mixtures tested under five environments. The list is in descending order for mean grain yield. * Means are statistically significant at $P \leq 0.05$. In the table Sd is the standard deviation and r^2 coefficient of determination.

Genotypes		Mean	Parameters		
		grain yield	Slope	Sd	r^2
Barley	Wheat	(kg ha^{-1})	(b)		
Ardu 12/60	Kenya + Mana	2309	1.067	± 0.495	0.608
Ardu 12/60	K 6290	2221	1.562	± 0.531	0.743
Yeha	K 6290	2202	1.931	± 0.232	0.958*
Yeha	Mana	2024	1.248	± 0.426	0.741
Yeha	Kenya + Mana	1995	1.251	± 0.347	0.812*
Ardu 12/60	Mana	1965	0.992	± 0.120	0.958*
IAR 485	K 6290	1391	0.559	± 0.467	0.324
IAR 485	Mana	1304	0.054	± 0.634	0.002
IAR 485	Kenya + Mana	1213	0.205	± 0.385	0.086

small. The rest of the genotype combinations had a regression value > 1 ranging from 1.248 to 1.931. A combination of Ardu 12/60 + Mana gave a grain yield of 1965 kg ha^{-1} with a regression value close to one. There were a few genotype combinations with a regression value < 1. These genotypes combinations with reasonable yield and regression values < 1, with relatively lower standard deviation, were also unstable. For example, Kuunto + Mana (1820 kg ha^{-1}; b=0.038; Sd=±1.164) and Kuunto + HAR 416 (1815 kg ha^{-1}; b= 0.693; Sd=±0.866) had a reasonable yield and regression value < 1. However, the standard deviation for some of the genotype combinations was relatively high.

Overall, the coefficient of determination (r^2) for the high yielding genotypes of the stable genotypes was significant for Ardu 12/60 + Mana and for Yeha + K 6290 and Ardu 12/60 + Mana both with a value of 95.8% (Table 9.5). The rest of the genotype combinations had a non significant coefficient of determination.

The mean grain yield for the respective locations and the environmental indices are shown in Table 9.6. The environmental indices using genotype combinations under rainfed conditions were negative indicating that the location mean yield was poorer than the average of the grand mean location. But the positive values showed that the location mean yield was better than average. The environmental index was positive for the density and crop ratio experiments at all locations and years except at Mendefera 1997 where it was negative. It was also negative for the effect of stress on different crop ratios at Halhale in both years.

Table 9.6. Environmental indices and location mean grain yields in barley and wheat mixed cropping studies in eleven environments. The mean grain yield (kg ha^{-1}) for the locations is that of the mixtures and does not include the monocrop.

Location / Trial	Number of treatments	Location mean grain yield	Environmental indices
(A) Genotype combination			
Rainfed			
Halhale 1997	16	1424	−329
Mendefera 1997	16	1730	−23
Halhale 1998	16	1392	−361
Stress trial (irrigated)			
Halhale 1998	27	2690	937
Halhale 1999	27	1980	227
(B) Density / crop ratio			
Rainfed			
Halhale 1997	33	1823	70
Mendefera 1997	33	1669	−84
Halhale 1998	33	2300	547
Mendefera 1998	33	2148	395
Stress trial (irrigated)			
Halhale 1998	33	626	−1127
Halhale 1999	33	1490	−263
Grand Mean		1753	---------

The positive environmental index is an indication that the environment was much more favourable for the increase in grain yield than the one with a negative index.

There was a positive relationship between the mean grain yield of the genotype combinations in each location and the mean grain yield of the respective locations. The higher the mean grain yield of the respective locations, the higher the mean grain yield of the genotypes in each location; this effect, however, was not significant. Out of the genotype combinations only three were significant (Table 9.5 and Figure 9.1B).

Discussion

This study showed that mixed cropping provides yield stability even under adverse growing conditions. This is in agreement with Rao and Willey (1980) and Subedi (1998), who confirmed the higher yield stability of mixed cropping compared to the yield stability in sole cropping.

The non significant genotype × environment interactions for grain yield (rainfed + irrigated) demonstrated that the genotypes basically had the same response to different environments. This means that the performance of these genotypes can be predicted based on their response to different environments. However, under rainfed conditions, the genotype × environment interaction was significant which suggests that the genotype ranking depended on the environment. Subedi (1998) mentioned that the genotype × environment interaction for yield and yield components was significant in barley–pea cropping systems. Variances due to genotypes, environments, and genotype × environment interactions were significant for grain yield (Jain et al., 1984; Godawat et al., 1995; Panwar et al., 1996; Biarnes et al., 1996; Vange et al., 1999).

The role of genotypic manipulations at varietal level to adjust mixed cropping systems indicated that some genotypes are more stable than others. For example, stability analysis in sorghum–pigeon pea intercropping revealed that some pigeon pea genotypes were more stable than others (Rao et al., 1979). In this study some of the high yielding genotype combinations such as Ardu 12/60 + K 6290; Yeha + K 6290 and Yeha + Mana were associated with regression values > 1, suggesting that these genotype combinations were not stable or had a stability lower than average. This indicates that they were sensitive to changes in environment. It is further proof that these genotype combinations can give optimum yield under favourable environmental conditions. Out of the genotype combinations tested only two similar ones (namely Ardu 12/60 + Kenya + Mana and Ardu 12/60 + Mana) had relatively better ecological adaptibility. The genotype combinations with low grain yield and low regression values are poorly adapted under high rainfall conditions. Genotype combinations with low regression coefficients could resist adverse environmental conditions as per the definition of Finlay and Wilkinson (1963).

One limitation, in the analysis could be that characterisation of the location based on the mean yield of all three systems (barley sole, wheat sole and mixtures). Unlike genotypes of the same species which mature more or less at the same, barley and wheat mature at different times. Barley is also much more drought tolerant than wheat. Thus a season which is favourable for barley might not be favourable for wheat or vice versa. As a result, mean yield of the three systems might not give an accurate characterisation of an environment. However, at present there is no a better system of stability analysis for mixed cropping other than the one used above.

Conclusion

Mixed cropping was significantly more stable than monocropping. Moreover, some genotype combinations were more stable than others. The instability for Yeha + K 6290 was significant. The two genotype combinations with a reasonable mean grain yield and regression value closer to 1 namely Ardu 12/60 + Kenya + Mana (2309 kg ha^{-1}) and Ardu 12/60 + Mana (1965 kg ha^{-1}) were more stable to varying environmental conditions and significant for Ardu 12/60 + Mana (r^2=0.958). The genotype combinations with regression values lower than unity and relatively lower standard deviation are more adaptable to adverse environmental conditions than others. Further study on the evaluation of stability under a wider set of environmental conditions is required so that genotype combinations with wider adaptation can be identified.

Chapter 10

General discussion

In this chapter major points emerging from the thesis are reviewed and discussed further. The major points of discussion are biodiversity in relation to mixed cropping, choice of varieties in mixtures, effect of density, yield advantage, competition and niche differentiation, stress tolerance, genotype × environment interaction (stability) and future perspectives.

Maintenance of biodiversity

Biodiversity is the biological variability within living organisms and the ecological complexes they inhabit; biodiversity exists at the genome, species and ecosystem levels (Hawtin, 1994). Eritrea is a center of diversity for many crop species. However, the biodiversity can be at a risk if there are changes in land use patterns and modern varieties will replace traditional ones. There is a growing effort to conserve the plant genetic resources in Eritrea. Genetic resources can be conserved either *ex situ* or *in situ*. Conservation *ex situ*, e.g. through gene banks, ensures that the germplasm materials are collected, stored, documented, characterised and evaluated. They can also be made available when needed. In this way the gene pool can be safe from external threats. This requires storage facilities (dry and cold) which could be expensive and there is no chance for the crop plants to evolve further under natural or human selection. *In-situ* conservation is different. This activity ranges from fully protected nature reserves to the conservation of landraces by farmers in their own land. It enables more species to be conserved under conditions that allow them to show evolution under the selection pressure of changes in environment and in human influence. The drawback is that the materials are susceptible to hazards of extreme weather, pests and diseases. It also needs technical experts to monitor and also manage the protection of the resources. However, through the application of both *in-situ* and *ex-situ* conservation the biodiversity of crop species can be maintained optimally.

Landraces are populations of genetically heterogeneous plants found in traditional agricultural systems resulting from long years of farmers' selection and natural selection under local conditions (Chang, 1994). Landraces are still used extensively in subsistence crop production in the tropics. In Eritrea, farmers give a considerable importance to landraces. These landraces have been selected and maintained by Eritrean farmers over a long period of time. Thus they are adjusted to the specific requirements of the area and environmental conditions. However, it may not mean that there are no landraces with undesirable characteristics. These landraces can still be used for future crop improvement programmes. In mixed cropping of barley and wheat, two or more landraces of the same or different crop species are used. This is one of the strategies for sustainable productivity and maintenance of biodiversity. Thus in Eritrea, mixtures should receive a considerable attention not only because of possible advantages such as higher total yield, better diet quality or more animal feed but also because maintaining landraces has value in itself. Mixtures might become difficult to manage in large-scale cultivation especially during harvesting when mechanisation is introduced. However, mixtures can be managed successfully like sole crops using mechanisation if they are planted in strips.

Farmers can maintain biodiversity in many ways. For example selecting plants with good ears or seed colour but of different types in the field before harvesting, keeping seed of landraces from previous harvests, restoring variation before planting, borrowing or exchanging seeds of landraces from neighbours or relatives and planting more than two landraces in the same field. The maintenance of biodiversity on farm could be strengthened if incentives or awards are given to farmers in any form (agricultural tools, inputs, etc.) who keep or use landraces for planting.

Choice of crops / varieties in mixed cropping

Crop yield is based on the genetic constitution of a given cultivar but is also determined by the availability of environmental resources (solar radiation, nutrients and water). High crop yield is obtained in mixed cropping when particular cultivars are grown in such a way that they capture and utilise environmental resources in a complementary way. So choice of correct combinations of crops and crop varieties ensures the most efficient use of the limiting resources, which is one of the key elements for high crop yield.

Selection and screening of germplasm

The evaluation of varieties for their suitability for mixed cropping has not been extensively studied. Varieties of food crops with specific adaptation to mixed cropping have been established in several crop species. For example bean–cowpea at CIAT (Wien and Smithson, 1979) and sorghum in ICRISAT (Willey and Rao, 1979). Before varieties can be evaluated, it is necessary to define the mixed cropping system based on the knowledge of climate of the area in which the crops are to be grown, survey of the prevalent mixed cropping practices and agronomic practices necessary to raise the productivity of the mixed cropping system. The climate in which barley and wheat mixed cropping is common has been described; surveys on mixed cropping was conducted before the evaluation of genotypes took place. Agroclimatic analysis for Asmara, Eritrea done by Simane and Struik (1993) showed that in 1960s, early 1970s and 1980s there was a severe drought period in Asmara. Close relationship between annual rainfall and the length of the growing season was also observed. The growing period was relatively short when intermittent drought periods were more frequent. Based on the agroclimatic analysis, selection of crop species and cultivars for drought prone areas and yield stability assessment was suggested. Furthermore the use of mixtures of varieties with different maturity groups was mentioned as a strategy to minimise the risk of crop failure due to unfavourable weather conditions.

Some of the landraces evaluated in this study were collected from farmers' fields and were used for generations either as a sole crop or in mixed cropping (e.g. the barley landrace Yeha and the wheat landrace Mana). Other genotypes included were those tested in sole cropping in research stations but never evaluated for mixed cropping; for example Ardu 12/60 (barley), IAR 485 (barley), HAR 416 (wheat) and K 6290 (wheat).

It has been argued that evaluation of genotypes screened for sole crops can well be used in predicting their performance under mixed cropping without testing the materials under that situation. To conclude that a genotype is suitable for mixed cropping simply on the basis of their known sole crop performance could, however, be misleading especially under erratic climatic conditions. So the assumption that the best varieties for sole cropping could be equally well used for mixed cropping is not always valid (Baker, 1978; Willey and Rao, 1979). Rejecting low yielding types during the test for sole cropping could be useful during initial selection. Later testing should then include mixed cropping to identify genotypes that are compatible and suitable to mixed cropping (Davis and Wooley, 1993). Screening a number of germplasm collections for mixed cropping could also be considered as a suitable selection strategy before a breeding programme is enhanced.

The negative relationship between grain yields and biomass in sole crops and mixed cropping in barley and wheat already gave a clue that the genotypes that performed well in sole cropping did not perform similarly well under mixed cropping in biomass and grain yield at Halhale in 1997 eventhough this relation was not significant (Chapter 3). This finding suggests the fact that promising genotypes identified in sole cropping situation are not necessarily the most appropriate for overall productivity in mixed cropping. Fukai and Midmore (1993) also believed that sole crop yield might not be a guide for predicting the performance of genotypes in mixed cropping because of the competition effect of the component crops in mixtures that should be known.

Traits for mixtures

Crop phenology

Difference in growth patterns can be achieved if one of the component crops is earlier in maturity. However, the positive effect of delaying the maturity period of one of the component crops might depend on the overall cropping system and the length of the available growing period. Too much delay of one of the component crops will lead to a yield loss. If a crop with a short cycle is mixed with a relatively late maturing one, they should show a difference in pattern of demand of environmental resources over time. In Eritrea, the length of the growing season is unpredictable due to erratic rainfall distribution. Thus the barley and wheat genotypes in mixtures could only have small differences in crop phenology making their demands of soil resources at slightly different times. Mixed cropping would then have best relative results when the actual duration of the cycle as determined by environmental factors would match the duration of the cycle of the latest maturing one, whereas the environment would impose so much stress during the later phase of the growing cycle that sole cropping of the late maturing type would not be successful.

Plant architecture
Differences in plant architecture play a major role in the competitive relationships between species under mixed cropping and their ability to exploit the aerial environmental resources in a better way than under sole cropping. Cultivars, which are compatible in this way, will give the best overall result in mixtures by optimally exploiting aerial space. Barley is more vigorous, earlier and establishes a large leaf area and biomass faster than wheat (Lopetz et al., 1995). The early vigour of barley results in earlier shading of the soil thus ensuring less soil evaporation for better growth; the more vigorous growth also suppresses weeds; barley produces leaves at a faster rate than wheat, which contributes to its greater vigour compared to other cereals.

Plant height
Plant height is also a major factor determining competition in mixed cropping. If both component crops are of the same height throughout the growing season, both crops could suffer from competition and yield losses. Barley and wheat make a good combination for several reasons. Barley grows rapidly during early stages and thus intercepts most of the light early in the season, whereas it is overgrown later in the season by the wheat so that the later maturing wheat can take over the function of intercepting light by the canopy. Moreover, wheat is less sensitive to lodging and its sturdy stems can support the barley crop, thus preventing lodging.

Harvest index
Selecting genotypes with a relatively high harvest index is desirable so that the competition of component crops can be minimised. Types with a high harvest index will typically be high yielding, but relatively short. Harvest index was one of the important traits considered in the evaluation of barley and wheat genotypes in mixed cropping in this thesis but values were generally low due to high biomass combined with low grain yield. There is much scope for improvement.

Root system

It is expected that the differences in the root system between barley and wheat are small. The root systems are also rather shallow compared to other cereals such as sorghum or millet. Crop species could be relatively suitable for mixed cropping because of their complementary rooting patterns that share resources (either moisture or nutrients). In theory, it is possible to select for complementarity of the rooting pattern in mixtures but in practice it is difficult to examine all root systems especially if one is screening hundreds of genotypes to be used for mixed cropping.

Changes in the ratio of mixtures

Genotypes in mixtures could change their frequency or the ratio in response to the environmental conditions. The proportion of species and genotypes within species at harvest could differ from the proportions at sowing. The relative proportion obtained at harvest can also vary depending on whether the seasons are normal in rainfall, disease pressure, or occurrence of drought, etc. Farmers usually restore the desired proportions of the species and landraces before sowing, but they can not manage the frequency of the different genotypes within the landraces. The landraces have to be harvested over a number of seasons in order to see the long-term shifts in genotype composition of the landraces. In the research described in this thesis it was not possible to record the changes in frequencies or genotypes within the landraces, but it was possible to assess the changes in frequencies of the crop species.

The data show that the shifts in proportion were quite different for the two years and for the different genotype combinations. In 1997, the proportion of barley was 88.5% and that of wheat was 11.5%, after an initial ratio of 67% and

Table 10.1. Proportion (%) of barley and wheat mixtures in terms of grain yield at Halhale, Eritrea in 1997 and 1998. The genotype combinations are listed in descending order according to their rank in grain yield in Chapter 3. Yeha + Mana was included as a control. The original ratio was barley 67%/wheat 33%.

Genotype	1997		1998		Mean	
Combinations	Barley	Wheat	Barley	Wheat	Barley	Wheat
Ardu 12/60 + Kenya+Mana	88.2	11.8	29.4	70.6	58.8	41.2
Ardu 12/60 + K 6290	89.7	10.3	33.0	67.0	61.4	38.6
Kuunto + Mana	87.4	12.6	69.8	30.2	78.6	21.4
Kuunto + HAR 416	96.2	3.8	89.2	10.8	92.7	7.3
Yeha+Mana	81.1	18.9	38.5	61.5	59.8	40.2
Mean	88.5	11.5	52.0	48.0	70.3	29.7

33%, respectively. However, in 1998 the average final proportion of barley was only 52% and that of wheat 48%. This year effect was due to less rainfall in 1997, which was in favour of barley. In 1998, the rainfall condition was favourable for wheat hence the proportion of wheat became much higher than its proportion in the sowing material. The proportion of barley to wheat in 1998 was almost 50/50 which is still acceptable because farmers expect either to get more yield of barley and some yield of wheat or at least similar harvests from both (total yield) (Table 10.1).

Comparing the genotypes, in 1997 Kuunto had a higher proportion (amounting to 96.2%) when grown with HAR 416 than when grown with Mana. Also in 1998, it maintained a higher proportion (89.2%) when grown with HAR 416 than when grown with Mana. The proportion of Kuunto was higher than the proportion of the other barley genotypes because it was able to dominate the wheat genotype grown with it in a better way. Among the wheat genotypes, Mana (in 1997) or Kenya + Mana (in 1998) showed the highest proportions compared to the rest of the wheat genotypes (Table 10.1).

Yield advantage

Requirements of the grower

Analysing the yield advantage from mixing two species must be partly based on the requirements of the grower. If the requirement is simply for total maximum yield regardless how much yield comes from either species then for a mixture to give a yield advantage, it must exceed the maximum yield of the higher yielding species in sole crop. This applies only when the two cereals being grown are equally acceptable. In Eritrea, barley and wheat in mixtures are not equally important and the farmer aims at different amounts of yield or some yield of each crop species. A yield advantage of a mixture occurs if more yield is obtained from a given area compared to a sole crop. On the other hand, a yield advantage can also take place without the component mixture exceeding the yield of the higher yielding species in sole crops.

Yield advantage analysis

Commonly relative yield total in replacement series or land equivalent ratio (LER) in additive series are used to assess the yield advantage of a mixed crop relative to that in respective sole crops. Both indexes (RYT and LER) compare the productivity of the cropping systems in a particular season. Although RYT or LER are used for sole crop–mixed crop comparison, it can be used to evaluate different agronomic practices of particular crop combinations in mixed cropping. A higher RYT or LER indicates a more productive cultural practice.

Willey (1979a,b) stated that other criteria might be important in situations where a full yield of sole crop needs to be obtained or in cases where all crops are sold. In such conditions product energy (caloric yield) or monetary return could be used. In barley and wheat mixed cropping, farmers expect the *hanfetz* system to provide them with more yield of barley than of wheat or equal yield of both and the products are rarely sold in markets because the crop is produced for own consumption. The caloric yield might be similar, as both are mainly a source of carbohydrate. So the financial or caloric advantages are not relevant in this cropping system.

Yield advantage can be estimated based on the maximum yields of a sole crop obtained in optimum plant densities (Willey, 1979). If there is only one sole crop treatment then it is assumed that the treatment will produce the maximum sole crop yield. This is not always the case because the density used by farmers is not the same as in research stations where resource input (such as fertiliser or chemicals etc.) is higher. So it is likely that the advantage of mixed cropping could be overestimated (Fukai, 1993). The overestimation is also likely to occur in an additive experiment where the density in mixed cropping of two components is higher (Ofori and Stern 1986).

The yield advantage might be calculated using the yield of the respective cultivar in sole cropping. However, when sole crop yields differ among cultivars, rather high yield advantage may be obtained relative to the cultivars of low sole crop yields. In yield advantage analyses, the highest yield of a cultivar in sole cropping can be used if both component crops are equally important in mixtures or if the objective of producing mixtures is for sale to the market (Fukai, 1993). In barley and wheat mixtures, both crops are not equally important in mixed cropping and the objective is not for sale. In this study while estimating the yield advantage (RYT) of cultivars, the ratio of the yield of component mixtures and their respective sole crops was used rather than the maximum yield of any sole crop in the experiment.

The concept of yield advantage analysis does not include the time factor, as it is the summation of ratios of yield in the mixed cropping to that in sole cropping. This tends to overestimate the advantage of mixed cropping particularly when component crops differ greatly in maturity time. One way of overcoming this limitation of yield advantage analysis when the component crops have large differences in maturity is the use of the Area × Time Equivalency Ratio (ATER). This can be described as LER × Time Ratio (Hiebsch and McCollum, 1987). ATER = $(Y_{12} / Y_{11}) + (t_2/t_1)\ (Y_{21}/Y_{22}) \times$ in which t_1- a period of late maturing species and t_2- of early maturing species. Y_{12} and Y_{21} are yields in mixtures of species 1 (the late one) and 2 (the early one) respectively while Y_{11} and Y_{22} are yields of species 1 and 2 in sole crop respectively. In this way the yield of a short duration crop is adjusted according to the duration of the crop relative to the late maturing one (Fukai, 1993). When ATER was used for numerous crops to estimate the yield advantage it was found that ATER underestimates the advantage of intercropping when component crops differ in their growth duration. One reason for this is that it is not common to be able to plant a crop immediately after the harvesting of a preceding crop. This concept of ATER does not, however, apply to barley and wheat mixed cropping because of the short difference in maturity periods between the component crops.

Results on yield advantage becomes less applicable if the cultural practices or the inputs used in research stations are by far different from those applied in the farming system. In this study, attempts have been made to consider factors or practices, which makes mixtures advantageous under conditions in peasant farming. For example, the genotypes used in the study were mostly landraces that are known to farmers; failure or near failure of mixtures that can be anticipated due to drought were included through stress trials done during the off-season; sowing was done by broadcasting and the sowing was done before the beginning of the rain (dry planting) in the growing season. So some of the farmers' practices were applied in this study so that the result of yield advantage becomes applicable in the farming system.

Effect of density

Mixtures gave higher total yield at higher population pressure as compared to the sole crops. This emphasises the need for optimum populations in mixtures, which could even provide higher benefits of mixtures in advanced agriculture. There is evidence that higher overall densities in additive designs maintain higher yields in mixed cropping than in sole cropping (Fischer, 1977a,b; Willey, 1980). The overall mixed crop population is greater than the average sole crop densities, in additive design (Ahmed and Rao, 1982). By this method, if sole crop densities are not optimally high, a yield advantage might be apparent merely because of more nearly optimum population pressure achieved in the mixtures especially in the additive designs (Fischer, 1979). In barley and wheat mixtures, the yield advantage with an increase in plant population is perhaps not so surprising because an advantage of mixing two species is particularly likely to occur when the individual species utilise slightly different parts of the environmental resources. In this way the mixture utilises a greater total amount of the environmental resources.

Competition and niche differentiation

A special feature of mixed cropping is that for some time during growth, the component crops compete with each other for available resources. The common observation is that barley grows faster than wheat at the early stages of the mixture. This early growth often leads progressively to barley being dominant in terms of competition. Despite this competition in favour of barley, the two component crops have not inhibited each other and have shared resources (Table 10.2). Especially when barley approached maturity wheat was able to capture aerial resources and utilise residual soil moisture so it was partial competition.

Differences in the duration of the cycle of the component crops and the resource capture at different times in barley and wheat mixed cropping make competition for resources less intense than when the components have a similar growth rhythm. Considering over the entire growing season, it is expected that the resource is captured and used more efficiently than in sole cropping. Rao and Willey (1980), Rao (1986), Cenpukdee and Fukai (1992) and Fukai and Trenbath (1993) believe that when mixed cropping components have similar growth duration their peak requirements for resources commonly occur at about the same time and competition for limiting resources is more intense. When component crops differ in growth duration, the competition could be either substantial, low or negative.

Achieving an optimum balance of competitive ability among the component crops is not easy. However, it is necessary to reduce the competition by selecting for less competitive and more efficient plant types or change cultural practices. This will allow optimum plant population to be established and result in higher yield potential. For the dominated crop (such as wheat as a component crop) the objectives should be to exploit the niches left by the dominant crop after its maturity and take advantage of aerial environment through its higher plant height.

Table 10.2. Comparison of competitive ability and niche differentiation (NDI) in barley and wheat mixtures under rainfed conditions and under irrigation with stress (Chapters 7 and 8 of this thesis).

Characters/Locations	Rainfed			Irrigation with stress		
	Barley	Wheat	NDI	Barley	Wheat	NDI
	b_{11}/b_{12}	b_{22}/b_{21}		b_{11}/b_{12}	b_{22}/b_{21}	
Total biomass yield						
Halhale 1997	3.05	0.330	1.01	6.68	0.249	1.66
Halhale 1998	1.97	0.998	1.97	2.15	0.524	1.13
Total grain yield						
Halhale 1997	2.38	0.543	1.29	6.96	0.278	1.93
Halhale 1998	2.01	0.986	1.99	6.86	0.288	1.98

Stress tolerance

Identifying genotypes tolerant to stress conditions and using optimum agronomic packages (density or crop ratio) depending on the soil resources availability can optimise the productivity due to a more efficient use of limited resources.

Mechanism of stress tolerance

Stress resistance is a complex phenomenon that could be based on morphological, physiological and biochemical characters of a crop. Crop plants could prevent drought stress by their ability to complete the life cycle before the appearance of the stress. This is drought escape, which is a very practical and important attribute in drought resistance as in the case of barley in a mixed cropping system. Drought escape becomes effective when the stress appears during or after heading stage. Drought avoidance is another mechanism of drought resistance in which genotypes maintain relatively high leaf water potential in periods of drought. Root growth and development are the key features. However, observations and measurements on root systems as a screening technique in barley and wheat mixed cropping is difficult under field conditions.

Different timing of drought had an impact in affecting the biomass or grain yield. Stress at seedling stage was more destructive than stress at heading stage. Genotypes were more sensitive to water deficits at seedling stage. So the recovery of the genotypes from stress at heading stage was fast compared to the recovery from stress at seedling stage. Indeed, grain yield and biomass were affected by stress at heading stage but not as much as stress during seedling stage. Simane and Struik (1993) have described the consequence of stress at heading stage in wheat; they indicated that stress during heading resulted in premature death of leaves and reduced assimilatory capacity and grain yield as compared to non stress situation.

Indicators for traits in stress tolerance

Various indicators of drought resistance have been used in barley and wheat mixed cropping to identify genotypes or crop ratios showing improved drought resistance. These included drought susceptibility index, biomass, grain yield, yield components, plant height and crop phenology. The approach of drought resistance requires the development of a strong collaborative programme involving plant breeders and agronomists/ physiologists in examining promising cultivars for different physiological traits related to plant–water relations. The use of line source sprinkler irrigation during the dry seasons under field conditions is helpful. Physiological traits such as canopy temperature, stomatal resistance, leaf water potential, leaf area, leaf firing etc. can assist in identifying the mechanism of drought resistance. Other traits such as good seedling emergence and lack of leaf desiccation are also essential.

Screening of landraces under stress

Utilisation of the existing germplasm collections in mixed cropping before deciding for a long term breeding programme to improve yield is a positive step. There is no doubt on the need of developing materials that are drought tolerant with a capacity to adapt to varying environmental conditions. For the time being barley and wheat landraces / genotypes collected from local germplasm were evaluated under stress for their productivity in mixed cropping.

There was a variation among the genotype combinations in drought resistance and in maintaining yields under water deficit conditions. The response of the genotype combinations under rainfed and irrigated conditions was similar considering biomass yield. The genotypes that resulted in better biomass yield under rainfed conditions responded also similarly under irrigated or stress conditions but this was not the case for grain yield (Figure 10.1). There was a positive relationship between harvest index and grain yield in both cases (irrigated and stress conditions) with a harvest index of not more than 25%. The low grain yield and high biomass caused this poor harvest index.

Genotype-Environment interaction

Yield stability is needed in situations where the environmental conditions are harsh and where crop production is strongly affected by biotic and abiotic stress. There are several cases where mixed cropping was reported as stable while in other cases it was considered as not stable. The applicability of genotype × environment interaction in this study is explained below. Furthermore, a genotype usually reacts to favourable and unfavourable environmental conditions and hence might vary in its performance. The same level of performance can not be expected in all environments. A genotype may change its performance from environment to environment but in a predictable way.

Environment

The environments considered here for the stability test (Chapter 9) both represented rainfed and irrigation (including drought stress) conditions. Harsh conditions were provided partially in the test conducted during the off-season. The testing locations had a varying amount of rainfall. Stability is also enhanced when crops hinder the spread of pests and disease or when one crop compensates for the damage of the other. These mechanisms were not considered, however, these have partially operated in this study. For example, aphid infestation

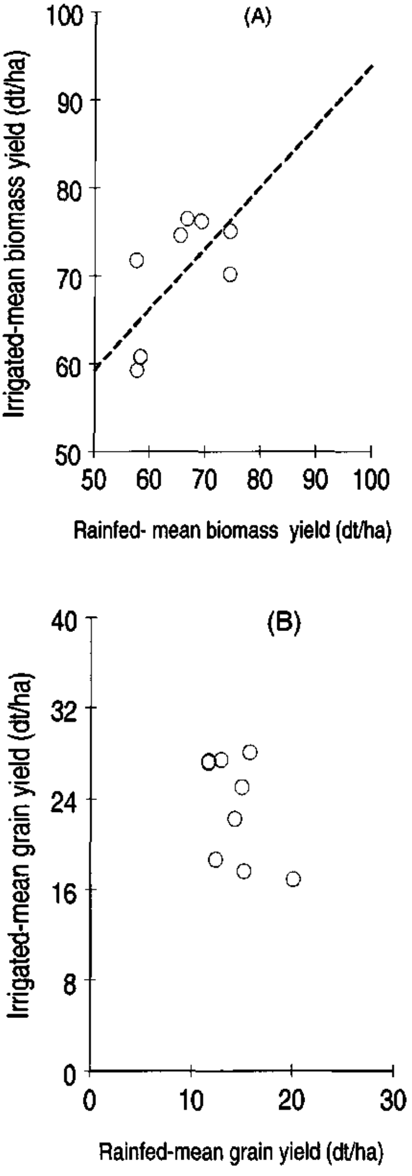

Figure 10.1. Relationship between (A) Biomass yield under rainfed vs biomass yield under irrigated (stress trials) (r=0.681*) conditions; (B) Grain yield under rainfed vs grain yield under irrigated conditions (stress trials) (r=–0.529ns).

occurred in 1998 during the off-season but not in 1999. Specific studies on the effect of pests on yield stability might be required.

Yield stability

From the study on stability analysis, indeed mixed cropping (of barley and wheat) showed a higher stability as compared to sole cropping. This is in agreement with the experiences of local farmers in Eritrea who claim that barley and wheat mixed cropping provides yield stability under varying environmental conditions. Indeed, greater improvements in yield stability could be expected from a mixed cropping system where the effects of adverse environment on the two crops are sufficiently different to allow meaningful compensation by the better growing one. In this mixed cropping system (barley and wheat), barley is a hardy crop and tolerates adverse environmental conditions more than wheat and can be cultivated by farmers under sub-optimal conditions. The other advantage of the crop is that it matures earlier than wheat.

Others look at stability as a means of similar performance in various environments. This means that a stable system should not respond even to a good environment. A system that shows this lack of fluctuation over seasons could be important for small farmers but in practice this does not happen especially with crops that have a low yield potential. In Eritrea, where the rainfall situation is erratic the aim of a cropping system is to use available environmental resources in a proper way so that better yields could be obtained under favourable environment but at the same time provide yield even in an unfavourable situation.

If two genotypes have similar yield stability (in terms of the parameter values), the one with greater yield level would be preferable. Fortunately, the barley and wheat mixed cropping did not show the same yield stability compared to the sole crop and the mean yield level was higher for mixed cropping. However, among the genotype combinations, Ardu 12/60 + Mana was stable but lower than the best yielding combination by a grain yield of 337 kg ha^{-1}. This implies that Ardu 12/60 + Kenya + Mana which was equally stable but with higher mean yield level is preferable.

Future perspectives

The thesis was able to answer several proposed objectives listed in the general introduction. However, it proved not possible to accommodate or address all research questions through this thesis. The promising research results presented in the thesis have to be verified on farm and demonstrated in specific farming systems before the technology is released to be used by farmers. Based on this thesis, new research lines that should be addressed can be suggested.

Verification on farm
The results have to be verified in fields of individual farmers. This helps in evaluating the genotype combinations on farmers' fields in a specific farming system. Few best mixtures including the control (Yeha + Mana) can be verified. After farmers are convinced that the mixtures are promising they will slowly adopt the best genotype combination if the materials were not known to them previously.

Demonstration trials
After verification the most promising genotype combinations including the control (Yeha + Mana) can be demonstrated to farmers on demonstration sites. Special field days may be organised in which farmers can get an opportunity to see and get acquainted with materials that are promising. This can assist as an adoption of the research technology and as a feed-back system from research to farmers and vice versa. These on-farm activities can be done in cooperation with and participation of institutions like the Ministry of Agriculture (Extension, Research department etc.), the University of Asmara and other partners with research technicians or experts, developmental agents, extension workers, farmers and students (University) involved in the transfer and adoption of the technology.

Ecophysiological models
Inter-plant competition processes can be explained in terms of the distribution of the growth limiting resources over the species in mixtures and the processes the resources (soil and aerial) are acquired and utilised. To understand the competitive interactions for these resources, the dynamic ecophysiological approach is indispensable (Spitters and Kropff, 1989).

Genetic composition of landraces
A varietal mixture of the same crop or of different species can change its genetic composition according to the variation in rainfall or pest incidence. Certain proportions can be used during initial planting. Thereafter the seeds for planting the next season could be done at random from the harvest without making new compositions or ratios of the mixtures (Almekinders and Louwaars, 1999). In this way it is possible to identify which genotype compositions are able to survive or multiply under certain growing conditions (both favourable or non favourable). Landrace composition responsible for better yield stability can also be known.

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Summary

General introduction

The fieldwork of this thesis was done in Eritrea, which is located in the Horn of Africa. The climate ranges from hot arid adjacent to the Red Sea to temperate sub-humid with a mean temperature of 19 °C in the highlands. There are two rainy seasons namely the short rainy season from March to April and the main one from the end of June to beginning of September. The total annual rainfall ranges from 200 mm in the lowlands to more than 700 mm in the highlands. Areas in the Green Belt Zone in the eastern escarpment of the central highlands even get rainfall above 1000 mm per year. In some years, the problem of inadequate rainfall is compounded by variability in amount and distribution.

Agriculture is the major source of income for about 80% of the population, main activities being arable farming, livestock rearing and fishing. Generally, yields are low for most crops. In good years, the degree of food self sufficiency in Eritrea ranges from 50 to 75%. In the year 1998, it was estimated that up to about 85–90% of the food needs was produced from local agriculture.

This study focused on one of the agro-ecological zones in Eritrea which is the Central Highland Zone (CHZ) with a rainfed cereal / pulse based land use system. This zone has an altitude > 1500 m above sea level; it is cool, semi arid with 600-700 mm of rain per year. The main crops in the highlands are barley, taff (Tigrigna word for *Eragrostis teff*), wheat, oil seeds and legumes. Other crops that are grown and deserve attention are sesame and cotton, which are high value cash crops. Factors that limit crop productivity are erratic rainfall (drought) in some seasons, crop pests, inappropriate crop management practices, lack of adequate technology and shortage of inputs. The use of drought tolerant crop species or varieties, cropping systems, crop management practices, adequate farming inputs (seeds, fertilisers, insecticides), farm technology etc. can be regarded as some of the solutions.

Biodiverse mixed cropping system of barley and wheat

A normal cropping system in the Central highlands of Eritrea is a mixed cropping of barley and wheat; it is called *hanfetz* (Tigrigna word). The mixture is sown from mid June to mid July. The seed is usually broadcasted by hand. Farmers use proportions of 67% barley and 33% wheat. Mixtures are harvested using a sickle by cutting the stems close to the groundlevel. The harvesting period is from the end of October to mid November. Mixtures may give higher yields, better yield stability, better food quality, more animal feed and resistance to pests. Farmers will continue to grow barley and wheat mixtures as long as the Eritrean agriculture is a low input one with a high risk of drought.

Effect of genotype combinations on the productivity of barley and wheat mixtures

One of the factors that affect the productivity of mixtures is the type of genotype combinations. Some genotypes are better combiners than others and the component crops need to exploit different ecological niches. The genotypes have to complement each other in morphology, architecture, phenology and growth, thus making better overall use of resources when grown together rather than separately. Field trials on varietal or landrace (genotype) combinations were conducted in 1997 and 1998 at Halhale and in 1997 at Mendefera. Eight sole crops (4 barley + 4 wheat) and sixteen mixtures (4 barley × 4 wheat) were tested. Most of the genotypes tested were landraces even though other varieties were included for comparison. The common mixture of Yeha + Mana served as a control. The aim was to identify the best genotype combinations in mixtures that produce highest in terms of biomass yield or grain yield. Differences in biomass yield among the genotype combinations were statistically significant but not consistent. The grain yield in mixed cropping was usually higher than in sole cropping of barley at Halhale. When averaged over the two years, a mixture of Ardu 12/60 (barley) + Mana + Kenya (wheat) was the best. There was generally a poor correlation between grain yield under sole cropping and grain yield in mixed cropping in 1997. The plant characteristics providing the best prediction for yielding ability were harvest index, biomass, stand cover and thousand grain weight. Some of the best mixtures including the control (Yeha + Mana) need to be tested in on farm verification trials at a diversity of locations before they can be released.

Growth and light use efficiency in barley and wheat grown as sole crops and in mixtures

The varietal or landraces mixtures were studied in more detail in terms of crop growth and light use efficiency. A rapid increase of plant height for barley as a component crop in mixtures was observed up to 70 DAS, when it reached maximum plant height. Wheat plants in mixtures were first suppressed but later on grew taller than barley. When barley matured it left the resources for wheat. This could contribute to better over all utilisation of soil resources. Leaf area index of mixtures was higher than for wheat sole crop. The wheat sole crop showed higher light use efficiency than either barley sole crop or the mixtures. Plant height and biomass yield were positively correlated. The study suggested that indeed mixtures of barley and wheat may show better light use (efficiency) than barley sole crop. The temporal difference in growth patterns of the component crops may enable the mixture to utilise resources in a complementary way. Crops / varieties of barley and wheat selected for different growth patterns on time can increase productivity.

Yield advantage in genotype combinations of barley and wheat mixtures

The yield advantage of mixed cropping that can be obtained relative to its sole crop depends on the type of genotype combination. Relative yield total was used to estimate the yield advantage in the genotype combination with a replacement ratio. There was significant difference in yield advantage in both biomass and grain yields. When averaged over the two years a combination of Yeha + Kenya + Mana and Yeha + HAR 416 showed highest relative yield total. The control, Yeha + Mana, also showed a yield advantage in biomass and grain yields relative to the sole crops. RYT values > 1 suggested that depending on the genotype combination mixed cropping showed a yield advantage relative to the sole crop both in biomass and grain yields. Barley showed a higher competition ratio than wheat. There was a relationship between competition ratio and grain yield. The higher the competition ratio the better the grain yield.

Response of genotype combinations of barley and wheat to drought stress

Shortage of water is limiting production in arid and semi-arid regions of the tropics. In Eritrea, rainfall distribution is erratic and in some years drought is severe and hence yields are low. Mixed cropping is an insurance against abiotic stress but the use of drought tolerant genotypes could optimise productivity. Two trials were conducted at Halhale in 1998 and 1999 during the off-season using irrigation in order to analyse the response of varietal or landrace mixtures to drought stress and to identify a mixture with reasonable grain yield and resistance to drought. Three drought stress treatments and nine varietal or landrace combinations were tested. There was a statistical significant difference among the genotype combinations and drought stress in grain yield but the interaction was not significant. When averaged over the two years and stress types, Ardu 12/60 + K 6290, Yeha + K 6290 and IAR 485 + Mana were the best yielding. Some of the genotypes produced higher yield while the Drought Susceptibility Index (DSI) was > 1, indicating poor drought resistance. However, the higher yield was due to better yielding ability under favourable conditions rather than to drought resistance. Yeha + Mana, IAR 485 + Mana and Ardu 12/60 + Mana were combinations resistant to stress. It can be noted that IAR 485 + Mana was one of the best yielding and yet the combination was also resistant to drought. There was variation among the genotypes in drought resistance as component crops. Yeha (barley) and Mana (wheat) showed the best resistance to stress. The biomass and grain yields were better under stress at heading rather than under stress at seedling stage.

There was a negative relationship between DSI and grain yield. The lower the DSI, the higher the grain yield. There was a positive correlation between yield loss and DSI where lower DSI resulted in lower yield loss. There were genotype combinations with better resistance to drought and relatively lower yield loss ranging between 9.8 to 18.0%. Mixed cropping showed a yield advantage over the sole crops when averaged over the years, genotypes and stress types.

Evaluation of barley and wheat mixed cropping in additive and replacement series

Important factors affecting productivity of barley and wheat mixed cropping are crop densities and crop ratios. Excessively dense plant stands can result in misuse of limiting resources and lower productivity. Optimum plant density and proportion in mixed cropping may generally help to facilitate and ensure maximum resource utilisation. Therefore, barley and wheat mixed cropping was evaluated in additive and replacement series at two locations, namely Halhale and Mendefera in 1997 and 1998. The objective was to identify optimum sowing densities and crop ratios, to assess the yield advantage of mixed cropping and to analyse competition between these crops quantitatively using a mathematical model. Three sowing densities and eleven crop ratios both in additive series and replacement series were tested. A crop ratio of barley 67% / wheat 33% used by farmers in Eritrea was included as a control. When averaged over the two years, a crop ratio of 100/50 and 25/100 gave highest yields at Mendefera. At Halhale, a ratio of 100/50 and 100/25 gave highest grain yields. Better total yields were obtained in additive series than in the replacement series, especially at a basic sowing density of 200 plants m^{-2} even though the effects were not significant. A crop ratio of 50/50 in the replacement series showed highest grain yield at Halhale and 33/67 and 67/33 at Mendefera.

The yield advantage was higher in additive series than in replacement series because it needs higher plant population pressure and the optimum density was beyond the density of the replacement series. Land Equivalent Ratio values above 1 showed a yield advantage in mixtures in land area required. In this study, the yield advantage was either due to density effect or complementary use of resources. The drawback of additive design is that the yield advantage may be due to higher plant population. However, the hyperbolic regression approach has indicated that there was a complementary use of resources and hence a yield advantage caused by mixing. The relative competitive ability for barley was greater than for wheat in mixtures. For example for grain yield at Mendefera in 1998 for barley, one barley plant was equally competitive as about eight wheat plants. For wheat, one wheat plant was equal to about four barley plants. For wheat, inter-specific competition was stronger than intra-specific, whereas for barley intra-specific competition was larger than inter-specific competition. The traditional crop ratio of barley 67% / wheat 33% proved indeed optimal in the replacement series. The promising densities and crop ratios need to be verified on farm along with the best genotype combinations before they can be released for use.

Effect of drought stress on the yield advantage and competition in barley and wheat mixtures differing in crop ratios

In mixed cropping, use of resources can be affected by the amount of soil resources available. Productivity can be maximised if proper ratios of the component crops are used. If the total population is higher than optimum then the moisture demand for the crops become too high. There are limited studies done on the effects of moisture availability on the yield level, yield advantage and competition of mixed cropping. Thus three drought stress types and eleven crop ratios were tested at Halhale during the off-season of 1998 and 1999. The aim was to identify a crop ratio that gives a yield advantage under stress and to quantify the competition effects and niche differentiation of the component crops in mixtures. A crop ratio of 25/100 gave the highest grain yield followed by 50/50. There was not much variation in grain yield between the replacement and additive series. Higher density under limited water resources increased the demand to such a level that it affected productivity. When averaged over the years and stress types there was a yield advantage of 23% relative to the sole crops.

Wheat plants suffered less competition from other wheat plants than from barley plants. For example in 1998, in biomass yield for barley, one barley plant was as competitive as seven (6.68) wheat plants. For wheat, four wheat plants (0.249; $1/4^{th}$) were equal to about one barley plant. This means that the influence of barley plants was greater relative to the influence of wheat plants. The Niche Differentiation Index (NDI) was evident in all years. NDI values above unity proved that the species inhibit each other less despite the competition as both used resources in a complementary way. NDI values above unity were related to RYT above 1 which was an indication that the yield advantage was due to sharing of resources even under stress conditions.

Yield stability in mixed cropping of barley and wheat

One of the advantages of mixed cropping is yield stability. There are several mechanisms that could explain improved yield stability including better yield advantage during adverse weather conditions, making adequate use of space and resources and creating a buffer against pests and diseases. Most of the work done on yield stability of mixed cropping has been limited to mixtures of genotypes within a given crop species. Further there are no previous studies done on stability in barley and wheat mixed cropping. Therefore the aim of this study was to assess the effect of environment on the performance of barley and wheat mixtures, to confirm the yield stability in barley and wheat mixtures and to evaluate which genotype mixtures are more stable than others. Stable genotypes or cropping systems were those having reasonably higher mean yield; a regression coefficient b=1.0 and standard deviation (Sd) as small as possible. Effects on yield caused by genotype and environment were significant but the genotype × environment interaction was not significant. Mixed cropping with a mean grain yield of 1744 kg ha^{-1}; a slope of 0.995 and standard deviation (Sd) ±0.277 was significantly more stable than either barley or wheat sole cropping under varying environmental conditions. Some genotype combinations (namely Ardu 12/60 + Kenya + Mana and Ardu 12/60 + Mana) were more stable under varying environmental conditions than other genotype combinations. Further evaluation on the stability under wider environmental conditions is required so that genotype combinations with wider adaptation can be known.

Future perspectives

The objectives of the thesis have been met, however, there are future research directions that can be addressed. The results have to be verified on farm under a wider set of ecological conditions. This will help to evaluate the genotype combinations on farmers' fields in a specific farming system in the area. The most promising genotype combinations including the control (Yeha + Mana) can be demonstrated to farmers after verification of their yielding ability. Special field days may be organised in which farmers can get an opportunity to see and select materials, which are promising. Other future research directions will be the future development of ecophysiological models in order to understand the competition for resources; a study on the shifts in genetic composition or frequency of landraces and the genotypes therein under mixed cropping, and further stability tests under a wider set of environmental conditions.

Samenvatting

Algemene inleiding

De veldproeven die in dit proefschrift worden beschreven, werden uitgevoerd in Eritrea, in de Hoorn van Afrika. Het klimaat in dit land varieert van heet en droog in de nabijheid van de Rode Zee tot gematigd en vrij vochtig met een gemiddelde temperatuur van 19 °C in de hooglanden. Het land kent twee regenseizoenen, namelijk een kort regenseizoen van maart tot april en het belangrijkste regenseizoen van eind juni tot begin september. De totale hoeveelheid neerslag per jaar varieert van 200 mm in de laaglanden tot meer dan 700 mm in de hooglanden. Er zijn zelfs gebieden in de zogenaamde Green Belt Zone, die ligt in de oostelijke glooiing van de Centrale Hooglanden, die meer dan 1000 mm per jaar krijgen. Er is niet alleen sprake van te weinig neerslag in sommige jaren, maar ook zijn de hoeveelheid en de verdeling grillig.

Landbouw is de belangrijkste bron van inkomsten voor ongeveer 80% van de bevolking. De belangrijkste sectoren zijn akkerbouw, veeteelt en visserij. In het algemeen zijn de opbrengsten voor de meeste gewassen laag. In goede jaren ligt de zelfvoorzieningsgraad voor voedsel in Eritrea tussen de 50 en 70%. In het goede jaar 1998 liepen de schattingen voor de voedselzelfvoorziening uiteen van 85 tot 90%.

Deze studie richt zich op één van de agro-ecologische zones in Eritrea, namelijk de Centrale Hoogland Zone (CHZ). In deze zone is het landgebruik gebaseerd op de regenafhankelijke teelt van granen en peulvruchten. De zone ligt op 1500 m boven zeespiegel en hoger. Het is er koel en semi-aride met 600 – 700 mm neerslag per jaar. De belangrijkste gewassen zijn gerst, teff (*Eragrostis teff*), tarwe, oliegewassen en peulvruchten. Andere gewassen die geteeld worden en aandacht verdienen, zijn sesamzaad en katoen. Dit zijn waardevolle marktproducten. De productiviteit wordt belemmerd door factoren als grillige neerslag of droogte, ziekten en plagen, verkeerde teelttechnieken, gebrek aan technische middelen en gebrek aan *inputs*. Oplossingen voor deze problemen moeten worden gezocht in de richting van het telen van droogtetolerante gewassen of rassen, het optimaliseren van teeltsystemen, het verbeteren van teelttechnieken, het adequaat gebruik van *inputs* (zaad, kunstmest, insecticiden), de juiste bedrijfstechnologie, enzovoorts.

Het biodiverse mengteeltsysteem van gerst en tarwe

Een gebruikelijk teeltsysteem in de Centrale Hooglanden van Eritrea is de mengteelt van gerst en tarwe; dit systeem wordt in het Tigrigna *hanfetz* genoemd. Het zaaizaadmengsel wordt – gewoonlijk breedwerpig – gezaaid tussen medio juni en medio juli. Het mengsel heeft meestal een verhouding van 67% gerst en

33% tarwe. Het menggewas wordt met de sikkel geoogst door de stengels dicht bij de grond af te snijden. De oogstperiode is van eind oktober tot medio november. Mengsels geven hogere opbrengsten, een betere opbrengststabiliteit, een betere voedselkwaliteit, meer stro (benut als veevoer) en een betere resistentie tegen ziekten en plagen. De boeren in Eritrea zullen waarschijnlijk doorgaan met het verbouwen van mengsels van gerst en tarwe zolang de landbouw in Eritrea gekenmerkt blijft door een lage inzet van hulpmiddelen, aangezien het klimaat een hoge kans op droogte met zich meebrengt.

Effecten van genotypencombinaties op de productiviteit van mengsels van gerst en tarwe

Eén van de factoren die de productiviteit van mengsels beïnvloeden is de combinatie van genotypen. Sommige genotypen zijn meer geschikt voor mengteelt dan andere. De bestanddelen van een mengsel dienen verschillende ecologische niches te benutten. De genotypen van het soortenmengsel dienen dan ook complementair te zijn ten aanzien van morfologie, architectuur, fenologie en groeipatroon, teneinde de hulpbronnen beter te kunnen benutten dan mogelijk is in een monocultuur van één van de gewassen van het mengsel. In veldproeven werden combinaties van (land)rassen uitgeprobeerd. Dat gebeurde in 1997 en 1998 in Halhale en in 1997 op een locatie bij Mendefera. Acht monoculturen (vier van gerst en vier van tarwe) en 16 mengsels (alle mogelijke combinaties van vier gerstrassen en vier tarwerassen) werden getest. De meeste rassen waren landrassen, hoewel er ook homogene rassen werden getoetst. De in dit gebied gebruikelijke combinatie Yeha (gerst) + Mana (tarwe) diende als standaard. Het doel was de beste genotypencombinaties voor de mengteelt te vinden, die de hoogste opbrengsten aan biomassa of aan graan konden leveren. De verschillen in biomassa waren statistisch betrouwbaar, maar niet consistent. De korrelopbrengsten van de mengsels waren in Halhale meestal hoger dan die van de monoculturen. Gemiddeld over de twee proefjaren was het mengsel van Ardu 12/60 (gerst) en Mana + Kenya (tarwe) het best. In 1997 was het verband tussen graanopbrengst in de monocultuur en de korrelopbrengst in de mengteelt meestal slecht. De planteigenschappen die het best met het opbrengend vermogen waren gecorreleerd, waren oogstindex, biomassa, stand van het gewas en duizendkorrelgewicht. Sommige van de beste mengsels (met in begrip van de standaard Yeha + Mana) moeten verder worden getest onder praktische omstandigheden op uiteenlopende locaties.

Groei en lichtbenuttingsefficiëntie in mengsels van gerst en tarwe

De genotypencombinaties werden nader onderzocht op groei en lichtbenuttingsefficiëntie. Gerst bleek een snelle toename in planthoogte te vertonen tot 70 dagen na zaaien, toen het zijn maximale hoogte bereikte. De tarweplanten in de mengsels werden eerst onderdrukt, maar werden later hoger dan de gerstplanten. Bij het afrijpen van de gerst waren de resterende hulpstoffen beschikbaar voor tarwe. Daardoor kan de benutting van de hulpbronnen in de bodem beter zijn. De bladoppervlakte(index) was hoger voor het mengsel dan voor de tarwe-monocultuur. De tarwemonocultuur had een hogere lichtbenuttingsefficiëntie dan de gerstmonocultuur of de mengteelt. Planthoogte en biomassa-opbrengst waren positief gecorreleerd. Het onderzoek suggereerde dat mengsels van gerst en tarwe inderdaad een betere lichtbenutting(sefficiëntie) kunnen vertonen dan de gerst-monocultuur. Het verschil in de tijd in groeipatroon van de beide gewassen van het mengsel kan het voor het mengsel mogelijk maken de hulpbronnen beter te benutten. Indien gewassen of hun rassen zodanig worden geselecteerd dat de complementariteit optimaal is kan de productiviteit hoger zijn dan bij de mono-culturen.

Concurrentierelaties en opbrengstvoordeel in mengsels van gerst en tarwe onder invloed van genotypencombinatie

Het opbrengstvoordeel van mengteelt ten opzichte van de monoculturen hangt af van de genotypencombinatie. Om het opbrengstvoordeel van mengteelt te schatten bij een gelijke dichtheid van mengteelt en monoculturen werd het relatieve opbrengsttotaal (RYT) bepaald. Zowel voor de totale biomassa als voor het graan werden significante verschillen tussen genotypencombinaties in opbrengstvoordeel gevonden. Gemiddeld over de twee jaren bleken de combinaties Yeha + Kenya + Mana en Yeha + HAR 416 de hoogste waarde voor het relatieve opbrengsttotaal te vertonen. De standaard, Yeha + Mana, gaf ook een opbrengstvoordeel ten opzichte van de beide monoculturen te zien voor zowel de biomassa- als de graanopbrengst. Relatieve opbrengsttotalen groter dan 1 gaven aan dat er een opbrengstvoordeel was in afhankelijkheid van genotypen-combinatie. Gerst bleek meer concurrentiekrachtig dan tarwe. Er bestond een verband tussen competitie-ratio en korrelopbrengst. Bij een hogere competitie-ratio was ook de korrelopbrengst hoger.

Reactie van genotypencombinaties van gerst en tarwe op droogtestress

Een tekort aan water leidt tot lagere opbrengsten in aride en semi-aride gebieden in de tropen. In Eritrea is de verdeling van de regenval grillig en in sommige jaren is er sprake van ernstige droogte. Onder zulke omstandigheden zijn de opbrengsten laag. Mengteelt kan gezien worden als een verzekering tegen deze abiotische stress. Echter het selecteren van de juiste genotypencombinatie kan de productiviteit nog verder optimaliseren. Er werden twee proeven uitgevoerd in Halhale, in 1998 en 1999, buiten het groeiseizoen. In deze proeven werd met behulp van irrigatie de reactie van (land)rassenmengsels op droogtestress getoetst, teneinde een mengsel te vinden dat een redelijke opbrengst combineerde met een hoge resistentie tegen droogte. Drie droogtestressbehandelingen en negen combinaties van (land)rassen werden onderzocht. Er werden statistisch betrouwbare verschillen gevonden voor de rassencombinaties en de stressbehandelingen ten aanzien van de korrelopbrengst, maar de interacties tussen deze factoren waren niet significant. Gemiddeld over twee jaar en over de stressbehandelingen bleken Ardu 12/60 + K 6290, Yeha + K 6290 en IAR 485 + Mana de beste combinaties. Sommige rassen produceerden goed, maar vertoonden een hoge waarde voor de droogtegevoeligheidsindex (DGI), hetgeen betekent dat ze een geringe droogteresistentie vertoonden. De hogere opbrengst leek meer een kwestie van een beter opbrengend vermogen onder gunstige omstandigheden dan een betere resistentie tegen droogte. Yeha + Mana, IAR 485 + Mana en Ardu 12/60 + Mana waren combinaties met een zekere mate van resistentie tegen droogte. IAR 485 + Mana was zowel één van de best opbrengende combinaties als ook één van de combinaties met de beste droogteresistentie. Er was wel degelijk sprake van variatie in droogteresistentie tussen de verschillende genotypen in de mengteeltsituatie. Yeha (gerst) en Mana (tarwe) vertoonden de hoogste resistentie tegen stress. De opbrengsten aan biomassa en graan waren beter bij stress tijdens het in de aar schieten dan bij stress in de zaailingfase.

Er bestond een negatief verband tussen de DGI en korrelopbrengst. Hoe lager de DGI hoe hoger de korrelopbrengst. Er werd een positief verband gevonden tussen opbrengstverlies en DGI: een lagere DGI gaf een lager opbrengstverlies. Er waren genotypencombinaties met een betere resistentie tegen droogte en een relatief laag opbrengstverlies tussen 9.8% en 18.0%. Mengteelt gaf een opbrengstvoordeel ten opzichte van de monoculturen wanneer de resultaten werden gemiddeld over de jaren, genotypen en types stress.

Evaluatie van mengteelt van gerst en tarwe door middel van additieve reeksen en verdringingsreeksen

De productiviteit van mengsels van gerst en tarwe wordt in belangrijke mate bepaald door zaaidichtheid en de zaaizaadaandelen van de gewassen. Buitensporig dichte gewasbestanden kunnen aanleiding geven tot slecht gebruik van beperkende hulpbronnen en van daaruit tot een lagere productiviteit. Een optimale plantdichtheid en een optimale verhouding tussen de componenten kunnen bijdragen aan een maximale benutting van hulpbronnen. Derhalve werd mengteelt van gerst en tarwe getoetst in zowel een additieve reeks als in een verdringingsreeks, in de jaren 1997 en 1998, zowel op de locatie Halhale als op de locatie bij Mendefera. Het uiteindelijke doel was om de optimale zaaidichtheid en de optimale zaaizaadaandelen van beide gewassen te bepalen. Daarnaast was het de bedoeling om het opbrengstvoordeel van mengteelt vast te stellen en om de concurrentie tussen gerst en tarwe kwantitatief te analyseren op basis van een mathematisch model. De proeven omvatten drie basisdichtheden en elf gewasverhoudingen in een additieve reeks en in een verdringingsreeks. De standaard was een gerst / tarwe verhouding van 67%:33%, zoals die ook gebruikelijk is onder boeren in Eritrea. Gemiddeld over de twee jaren gaven de verhoudingen 100/50 en 25/100 de hoogste opbrengsten in Mendefera. In Halhale gaven 100/50 en 100/25 de hoogste opbrengsten. De opbrengsten lagen hoger in de additieve reeks dan in de verdringingsreeks, vooral bij een basale zaaidichtheid van 200 planten per m^2, hoewel dit effect niet significant was. In de verdringingsreeks werden de hoogste opbrengsten gevonden voor 50/50 in Halhale en voor 33/67 of 67/33 in Mendefera.

Het opbrengstvoordeel was hoger in de additieve reeksen dan in de verdringingsreeksen. Dit werd veroorzaakt door de relatief hoge optimale zaaidichtheid. De waarden voor de "*Land Equivalent Ratio*" waren vaak hoger dan 1, hetgeen aanduidt dat er voor dezelfde opbrengst meer land nodig is bij een monocultuur als in de mengteeltsituatie. Het opbrengstvoordeel kan worden veroorzaakt door de hogere standdichtheid of door het feit dat beschikbare hulpbronnen efficiënter worden gebruikt. Het nadeel van proeven met additieve reeksen is dat het opbrengstvoordeel een gevolg kan zijn van de hogere dichtheid. De benadering met de hyperbolische regressie toonde evenwel aan dat er wel degelijk sprake was van complementair gebruik van beschikbare hulpbronnen en dat derhalve ook een deel van het opbrengstvoordeel te wijten was aan het mengen van de twee gewassen zelf. In de mengsels had gerst een groter relatief competitief vermogen dan tarwe. Dit kan geïllustreerd worden aan het volgende voorbeeld: in Mendefera in 1998 was 1 gerstplant net zo competitief als ongeveer 8 tarweplanten. Voor tarwe gold dat 1 tarweplant ongeveer net zo competitief was als 4 gerstplanten. Bij tarwe was de interspecifieke concurrentie sterker dan de intraspecifieke concurrentie, terwijl bij gerst de intraspecifieke concurrentie sterker was dan de interspecifieke concurrentie. De traditionele verhouding van 67% gerst en 33% tarwe bleek inderdaad optimaal in de verdringingsreeks. De veelbelovende dichtheden en gewasaandelen dienen nog eens geverifieerd te worden onder praktische omstandigheden, samen met de beste genotypencombinaties voordat de technologie kan worden vrijgegeven voor praktische toepassing.

Effecten van droogtestress op het opbrengstvoordeel en op de concurrentie in mengsels van gerst en tarwe bij verschillende gewasverhoudingen

In mengteeltsituaties kan de benutting van hulpbronnen worden beïnvloed door de hoeveelheid beschikbare bodemhulpbronnen. De productiviteit kan worden gemaximaliseerd als de gewascomponenten van het mengsel in de juiste hoeveelheden aanwezig zijn. Indien de totale populatie boven de optimale dichtheid ligt, kan de behoefte aan water te hoog worden. Er is slechts weinig onderzoek uitgevoerd naar de effecten van beschikbaarheid van water op de opbrengst, het opbrengstvoordeel en de concurrentie in mengteelten. Derhalve werden drie types droogtestress en 11 gewascombinaties getest. De proeven vonden in 1998 en 1999 plaats in Halhale buiten het normale groeiseizoen. Het doel was om de gewasverhoudingen te vinden die bij stress het hoogste opbrengstvoordeel gaven. Bovendien werd gepoogd de concurrentie-effecten en de nichedifferentiatie van de gewassen in mengteeltsituatie onder droogtestress te kwantificeren. Een gewasverhouding van 25/100 gaf de hoogste korrelopbrengst, gevolgd door een verhouding 50% gerst / 50% tarwe. Er was niet veel verschil in korrelopbrengst tussen de vervangingsreeks en de additieve reeks. Een hogere dichtheid onder beperkende vochtcondities deed echter de waterbehoefte zo sterk toenemen dat de productiviteit werd verlaagd. Gemiddeld over de jaren en de droogtebehandelingen was het opbrengstvoordeel van de mengsels 23% ten opzichte van de monoculturen.

Tarweplanten leden minder onder de concurrentie van andere tarweplanten dan onder de concurrentie van de gerstplanten. Zo bleek voor de biomassaopbrengsten in 1998 1 gerstplant voor gerst net zo concurrentiekrachtig als ongeveer 7 tarweplanten. Voor tarwe waren vier tarweplanten waren gelijk aan 1 gerstplant. Dat betekent dat de invloed van gerstplanten aanmerkelijk groter was dan de invloed van tarweplanten. De Niche Differentiatie Index (NDI) bleek duidelijk te verschillen van 1. Een NDI groter dan 1 betekent dat de soorten elkaar minder beconcurreerden dan verwacht, omdat de soorten de hulpbronnen op complementaire wijze benutten. NDI waarden boven 1 bleken samen te gaan met RYT waarden boven 1. Dit was een aanwijzing dat de standdichtheden van de monoculturen optimaal waren en dat de mengsels dezelfde hulpbronnen zodanig deelden dat een opbrengstvoordeel mogelijk was.

Opbrengststabiliteit in mengteelt van gerst en tarwe

Eén van de voordelen van mengteelt is opbrengststabiliteit. Verschillende mechanismen kunnen het optreden van een hogere opbrengststabiliteit verklaren. Daartoe behoren een groter opbrengstvoordeel onder ongunstige weersomstandigheden, een betere benutting van de beschikbare ruimte en hulpbronnen en buffering tegen ziekten en plagen. Onderzoek naar dergelijke verschijnselen is meestal beperkt tot gewassen bestaande uit verschillende rassen van dezelfde soort. Er is in elk geval geen onderzoek bekend naar de stabiliteit van mengteelt van gerst en tarwe. Derhalve werd gepoogd de effecten van omgeving op de productiviteit van de mengteelt van gerst en tarwe te omschrijven, teneinde de grotere stabiliteit van mengsels aan te tonen en na te gaan welke rascombinaties in de mengsels de stabiliteit het meest verhoogden. De effecten van genotype en milieu op de opbrengst waren significant, maar de genotype × milieu interactie was dat niet. Inderdaad bleek mengteelt over de verschillende milieus stabieler te zijn dan monocultuur. Sommige genotypencombinaties (Ardu 12/60 + Kenya + Mana en Ardu 12/60 + Mana) waren stabieler over de milieus dan andere genotypencombinaties. Verdere evaluatie van stabiliteit over een breder scala van milieus is nodig om de genotypencombinaties met het beste aanpassingsvermogen te identificeren.

Toekomstperspectieven

De doelstellingen van het programma beschreven in dit proefschrift werden gerealiseerd. Op basis van de resultaten kunnen nog wel nieuwe onderzoekslijnen nader worden aangeduid. De resultaten dienen nog in de praktijk op een grotere schaal en onder een breder traject van omstandigheden bevestigd te worden. Op deze wijze kan beter worden aangeduid welke genotypencombinaties het beste zullen voldoen onder praktijkomstandigheden. De meest belovende combinaties (met inbegrip van de standaard Yeha + Mana) kunnen dan – na verificatieproeven – in demonstratievelden aan de boeren worden getoond. Via het organiseren van demonstratiedagen kunnen boeren vervolgens kennis maken met deze nieuwe combinaties en kunnen ze zelf keuzes maken voor hun eigen situatie. Verder is het gewenst om de ecofysiologische modellen verder te ontwikkelen om een beter begrip te krijgen van de concurrentie om hulpbronnen in dergelijke teeltsystemen, maar ook om de verschuivingen in genotypenfrequenties (zowel van landrassen in mengsels als van typen binnen de landrassen) in mengteelten met verschillende rassen per soort te beschrijven en te verklaren. Ook zijn nadere proeven ten aanzien van opbrengststabiliteit van dergelijke mengsels nodig. et of environmental conditions.

About the author

Woldeamlak Araia was born and grew up in Eritrea. After finishing High School (in Eritrea) he joined the Alemaya College of Agriculture, Ethiopia and graduated with a Bachelor of Science (BSc) degree in Plant Sciences in 1973. After working for some years, he joined the Graduate Studies in Alemaya University of Agriculture, Ethiopia and graduated with a Masters of Science (MSc) degree in Agronomy in 1983. He also attended specialised training courses in various institutions to upgrade his knowledge of plant breeding, seed technology and agronomy ranging from 1 to 4 months, namely those at the International Agricultural Centre (IAC), Wageningen, the Netherlands in 1986, the International Centre for Agricultural Research in Dry Areas (ICARDA), Syria in 1989 and 1992, the International Centre for Research in the Semi Arid Tropics (ICRISAT), India in 1991, and the Giza University, Egypt in 1991. Woldeamlak has worked with Rural Development Projects and in the Institute of Agricultural Research, Ethiopia (Mekele, Adet / Bahrdar) as a senior research expert and also in various positions in research centers as Head of the Field Crops Department, Project Coordinator (*Lathyrus sativus*), Representative of the Food Legume Program and Head of Research Center in different years. He has published various articles in journals, chapters in books or proceedings, bulletins and newsletters that are listed at the end of the thesis. In June 1992 he joined the University of Asmara, College of Agriculture and Aquatic Sciences, in Eritrea and is currently working as Lecturer II. He teaches courses in Field Crops Production, Seed Technology, Dryland Agronomy, etc. Besides he is engaged in research activities. Woldeamlak is married and is currently the father of three children (two boys and one girl).

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