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EFFECT OF DROUGHT STRESS ON BARLEY - WHEAT INTERCROPPING

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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) was studied for different crop ratios of barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* mixtures sown in additive and replacement series at Halhale Research Station (Eritrea) during the off-seasons of 1998 and 1999. The objective was to identify crop ratios with higher productivity and to analyse the competition and niche differentiation of component crops in mixtures grown under stress. Competition and niche differentiation were assessed by analysing the data using a hyperbolic competition model. The best yields were obtained from the crop ratios 50% barley / 50% wheat and 25% barley / 100% wheat when averaged over two years. One barley plant was as competitive as about seven wheat plants. The relative competitive ability was higher in barley than in wheat. Inter-specific competition was larger than the intra-specific competition for wheat while for barley the intra-specific competition was greater than the inter-specific. The component crops shared the same resources in a complementary way. The Niche Differentiation Index (NDI) > 1 was related to Relative Yield Total (RYT) > 1 showing that the yield advantage was due to complementary use of resources.

Key Words: Eritrea, *Hordeum vulgare*, mixed cropping, *Triticum aestivum*

RÉSUMÉ

Les effets du stress dû à la sécheresse ou à l'humidité (MS_1 – pas de stress, MS_2 – stress à la phase de germination et MS3 – stress à la phase de plantule) étaient étudiés pour différentes cultures mélangées d'orge *(Hordeum vulgare)* et de blé *(Triticum aestivum)* plantées en séries additives et de remplacement à la Station de Recherche de Halhale, (Erythrée) pendant la période hors saison de 1998 et 1999. L'objectif était d'identifier le taux de culture à productivité plus élevée et d'analyser la compétition et la différentiation de niches de cultures composantes au sein de mélangés cultivés sous stress. La compétition ainsi que la différentiation de niches étaient évaluées par l'analyse de données à l'aide d'un modèle de compétition hyperbolique. Les meilleurs rendements étaient obtenus à partir des taux de culture à 50% orge / 50% blé et 25% orge / 100% blé lorsque considérés sur une moyenne de deux années. Une plante d'orge était aussi compétitive que sept plantes de blé. La capacité relative de compétition était plus élevée chez l'orge que chez le blé. En ce qui concerne le blé, la compétition interspécifique était beaucoup plus notable que la compétition intra spécifique tandis que pour l'orge, la compétition intra spécifique était plus prononcée que l'interspécifique. Les cultures composantes partageaient les mêmes ressources d'une manière complémentaire. L'Indice de la Différentiation de Niche (NDI) > 1 était lié au Total Relatif de Rendement (RYT) > 1 révélant que l'avantage en rendement était dû à l'usage complémentaire des ressources.

Mots Clés: Erythrée, *Hordeum vulgare*, cultures mélangées, *Triticum aestivum*

INTRODUCTION

Water deficit seriously limit 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 into periods of severe drought stress.

One of the coping strategies is the cropping system called *Hanfetz* which, is practiced in the highlands of Eritrea and to a certain extent in Northern and Northern western part of Ethiopia. *Hanfetz* is a Tigrigna word for mixed cropping of barley and wheat. It is sown from the end of June to 1st week of July. *Hanfetz* is used for human consumption in the form of bread, locally known as *kitcha*. The grain is roasted for *kolo* and also used for the local beverage, *sewa*. Productivity of crop mixtures is affected by crop density and ratio. Hence, optimum total density and mixing ratios are key factors determining the success of a mixed cropping system (Natarajan and Willey, 1986 and Singh and Chauhan, 1991). Seed proportions used by farmers are 67% for barley and 33% for wheat. However, to maximise productivity with the minimum risk, optimum ratios of the component crops have to be defined.

The success of intercropping systems relative to pure stands depends on the yield advantage obtained through efficient use of available resources. Under water limited environment, when the total population is higher than optimum the moisture demand of the crop becomes too high and the yield advantage can no longer be realised (Natarajan and Willey, 1986; Fischer, 1997).

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 barley and wheat are shallow and the competition for limiting water resources is partial because of slight differences in growth stages of the crops. This provides an opportunity for complementary use of soil resources by the component crops. Natarajan and Willey (1986) found a yield advantage in sorghum-millet intercropping under drought stress.

Most earlier intercropping studies focused on yield advantage of mixtures. Spitters (1983) proposed a hyperbolic regression approach in which the yield density relation is used to determine competition between component crops and niche differentiation. This analysis requires crops to be grown in a range of densities in additive or replacement series.

The yield advantage, competition and niche differentiation of crop ratios under drought stress have not been studied in barley *(Hordeum vulgare)* and wheat *(Triticum aestivum)* mixtures. Our objectives were to determine crop ratio effect on yield under stress and to quantify the competition effect and niche differentiation in barley and wheat mixtures using the hyperbolic regression model.

MATERIALS AND METHODS

The field experiments were conducted at the Halhale Research Station which represents the Central highlands of Eritrea during the off-seasons of 1998 and 1999. The site is 1997 m above sea level with a clay loam soil which is slightly alkaline in reaction. The experiments were conducted under irrigation from January to May when rain is not expected so that stress can be controlled.

Drought stress treatments. Three moisture (drought) stress treatments were imposed, namely (i) MS_1=*Control:* no stress throughout the growing period and the soil moisture content was maintained at 60-70% field capacity; (ii) MS_2=*Stress at seedling stage*: stress was induced early for two weeks period starting at two leaf stage and maintaining 10-20% soil moisture content; irrigation began at the end of the two weeks stress period and continued until maturity; (iii) MS_3=*Stress at heading stage:* plots were irrigated until heading stage but later stress was induced for two weeks right after heading stage with a soil moisture content maintained at 10-20%; irrigation continued at the end of the two weeks stress period until the crop reached maturity.

The top 10 cm was wetted just prior to sowing in order to ensure proper germination. The moisture content was monitored using gypsum blocks and the soil was irrigated when the moisture content was below the standard already stated.

Plots were watered using flood irrigation and water flow was prevented from one plot to another by making bands around the plots.

Crop ratio. Eleven crop ratios were evaluated including 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 and wheat sole crops had the crop ratio 100/0 and 0/100, respectively. The amounts of seed needed to obtain these ratios were assessed based on the thousand grain weight of both crops. The amount of seed planted was assumed to have 100% germination based on the germination test conducted before planting. A ratio of 67/33 was taken as a control (ratio used by majority of farmers). 'Yeha' (barley) and 'Mana' (wheat) landraces were used for the experiments as this combination is most popular for mixed cropping among farmers (Woldeamlak and Struik, 2000).

Crop management. Crops were broadcasted sown on January 3, 1998 and January 5, 1999. The site was fertilised with a blanket rate of 100 kg ha^{-1} Di-Ammonium Phosphate (DAP, 46% P_2O_5 and 18% N) and 50 kg ha^{-1} Urea (46% N) at planting and the fertiliser was incorporated into the soil. Plots were hand weeded twice. No pest control was carried out.

Experimental design and analysis. Each experiment was laid out in a split-plot design with two factors (drought stress and crop ratios) in four replications. Drought treatments at two stages of development and the irrigated control (no stress) were arranged as main plots (41.25 m^2) and the crop ratios were laid out as sub-plots of 3.75 m^2. Biomass and grain yield data were subjected to a standard Analysis of Variance using MSTAT-C. The Least Significant Difference (0.05) was calculated to compare the difference between treatment means. 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.

The data collected included above ground biomass and grain yields of the component crops in mixtures and in sole cropping. Plants of the component crops were harvested at physiological maturity and weighed separately at about 87.5% dry matter (12.5% moisture content). Grain yield was adjusted to 12.5% moisture content. The biomass and grain yield of the two component crops were added to estimate the total above ground biomass yield.

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. 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 seed weight was estimated from 200 seeds weight. Harvest index (%) was estimated as the ratio of the grain yield to the above ground biomass.

Yield advantage

Land equivalent ratio (LER). LER was used to assess the yield advantage in mixed cropping in the additive series (when the crop ratio of component crops add up, it is > than 100). The LER expresses the relative land area under sole cropping that is required to give the same yield of each species in mixtures (Spitters and Kropff, 1989; Banik, 1996).

$$LER = L_1 + L_2 = (Y_{12} / Y_{11}) + (Y_{21} / Y_{22}) \qquad (1)$$

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 respectively; Y_{12} and Y_{21} are the yields in mixtures of barley and wheat, respectively. Hyperbolic regression analysis (Equation 3) of monoculture yields against plant density was used to estimate the reference yields for the specific densities used in the additive design.

Relative yield total (RYT). The RYT was used to estimate the yield advantage in the replacement series (when the ratio of the component crops add up, it is < than 100%). The restriction in using RYT is 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:

$$RYT= RY_1 + RY_2= (Y_{12}/Y_{11}) + (Y_{21} / Y_{22}) \quad (2)$$

where 1= barley and 2= wheat; Y_{12} and Y_{21} are the yields of barley and wheat as component 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 monocrop. All RYT values greater than 1 indicate that there is at least to some extent complementarity in resource use. While RYT values less or equal to 1 indicate that the species compete fully with no resource complementarity.

Hyperbolic regression model

Intra-specific competition. Intra-specific competition is the response of individual plant biomass to plant density, but has also consequences for crop yield (Spitters, 1983):

$$Y_1= N_1/ (b_{10}+b_{11}N_1) \quad (3)$$

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}); b_{10} and b_{11} are constants.

From Equation 3 the average weight per plant (W_1; g $plant^{-1}$) can be derived as:

$$W_1= Y_1/N_1= 1/(b_{10} + b_{11}N_1) \quad (4)$$

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

$$1/W_1= b_{10} +b_{11}N_1 \quad (5)$$

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} (plant g^{-1}) is the reciprocal of the biomass or yield of an isolated plant (W_1=1/ b_{10}). The slope ($b_{11,}$ m^2 g^{-1}) 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 ratio b_{11}/b_{10} is the measure of intra-specific competition. At low plant density there is no inter-plant competition so that 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 inter-specific competition. If adding plants of one species affects $1/W_1$ 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 in a mixture with species 2 can be calculated as:

$$1/W_1= b_{10} + b_{11}N_1 + b_{12}N_2 \quad (6)$$

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 et al., 1989).

Niche differentiation Index (NDI). The index represents the ratio between intra-specific competition (b_{11}/b_{12}) and inter-specific competition (b_{12}, b_{21}).

$$NDI= (b_{11} / b_{12}) \times (b_{22} / b_{21}) \quad (7)$$

If this ratio exceeds unity, there is niche differentiation and intra-specific competition exceeds inter-specific competition. Plants in the mixtures together capture more resources and use resources better than sole crop which means that the species are not fully competitive for the same resources. If NDI = 1, then the two species are competing equally for the same resources. If NDI < 1, suggests that the two species are competing for the same resources. This means that there is some kind of inhibition caused by competition for the same resources and that the species are restricted in their growth by the requirement of the same resources (Spitters, 1983; Connoly, 1987 and Spitters *et al.*, 1989).

Hyperbolic regression model. Analysis for competition and niche differentiation was performed using the hyperbolic regression model. The non linear regression procedure of SPSS was used to fit the model (Equation 12a and 12b) in order to determine the parameter values b_0, b_1, b_2, w, c and a.

For species 1:

$$Y_{12} = N_1/(b_{10} + b_{11}N_1 + b_{12}N_2) \quad (8)$$

$$Y_{12} = (N_1/b_{10})/(b_{12}/b_{10}) + (b_{11}/b_{10} \times N_1) \quad (9)$$

$$\times (b_{12}/b_{10} \times N_2)$$

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

$$(b_{12}/b_{11} + b_{11}/b_{10}) \times N_2]$$

which can be re-written as

$$Y_{12} = N_1 (10)\, W_1 / (1+a_1 (10) (N_1 + \in \times N_2)) \quad (11)$$

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

$c = b_{11}/b_{12}$

For species 1

$$Y_1 = N_1 \times W_1 / (1+a_1 (N_1 + (1/c_1) \times N_2)) \quad (12a)$$

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 intra-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). For species 2:

$$Y_2 = N_2 \times W_2 / (1+ a_2 (N_2 + (1/c_2) \times N_1)) \quad (12b)$$

RESULTS

Biomass and grain yield. In additive series, the total biomass yield was not affected by the drought stress x crop ratio interaction. Biomass yield in the additive series was greatest with MS_1 (no stress) and the least with MS_2. Biomass yield was greater in additive mixtures with 100% stands of barley than with 100% stands of wheat. Grain yield in the additive series was greater for MS_1 and least for MS_2. The crop ratio effect was significant in 1998 but not in 1999. There was also no significant drought stress x crop ratio interaction in grain yield in both years (Table 1).

In replacement series, there was no significant interaction between drought stress and crop ratio. Total biomass in the replacement series was highest in MS_1 (no stress) at least when stress was applied at seedling stage (MS_2) (Table 2). The best mixture surpassed the sole crops in biomass yield. A crop ratio of 67/33 and 50/50 had the highest total biomass yield when averaged over the two years.

There was a significant effect of grain yield in drought stress in both years. Stress at seedling stage showed highest yield reduction with 36% in the replacement series. The yield reduction was lower than that in the additive series.

When pooled over the two years, number of kernels m^{-2} was positively correlated with biomass but other characteristics were not correlated with biomass (Table 3). Grain yield was correlated with biomass, ears m^{-2}, harvest index, stand cover, TGW and kernels m^{-2} when pooled over the two years.

Yield advantage. The land equivalent ratio of all the mixtures in the additive series was greater than 1.0 but difference between mixtures were not significant. The relative yield total was also greater than 1.0 showing a yield advantage with no significant difference among mixtures (Table 4).

Competition and niche differentiation. There was significant difference between the parameters for grain yield and biomass in wheat in all the years but for barley, there was significant difference only for biomass in both years (Table 5). The lower the value of b_{10}, the higher would be 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 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 than in 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; $1/4^{th}$) were equal to about one barley plant. This means that the influence of barley plants was greater than the influence of wheat plants.

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 (Table 6).

There was also niche differentiation in the experiments in both years and for biomass and grain yield. The NDI was more than unity. The degree of niche differentiation was higher for grain yield than for biomass in both years (Table 6). Niche differentiation greater than 1 suggested that despite the competition in favor of barley the component crops did not inhibit each other from sharing resources in a complementary way. The component crops in mixtures together better

TABLE 1. Total biomass 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

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 x crop ratio	NS	NS	NS	NS	NS	NS

Note: Means followed by the same letter within columns are not significantly different (P=0.05)

TABLE 2. Total biomass 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

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 x crop ratio	NS	NS	NS	NS	NS	NS

Note: Means followed by the same letter within columns are not significantly different (P=0.05)

TABLE 3. Correlation coefficients of agronomic characters with biomass yield and grain yield in barley and wheat mixed cropping in 1998 and 1999; TGW is thousand grain weight (g/1000 seeds) (n=33 for individual years)

Characters	1998		1999		Pooled	
	Biomass yield	Grain yield	Biomass yield	Grain yield	Biomass yield	Grain yield
Plant height	0.35	0.23	0.76*	0.69*	-0.32	-0.37
Ears m^{-2}	0.26	0.69*	0.28	0.38	0.40	0.86*
Kernels/ear	0.21	0.14	0.58*	0.53*	-0.32	-0.37
TGW	0.03	0.15	0.04	0.55*	0.16	0.51*
Ear size	0.17	0.10	0.60 *	0.67*	-0.29	-0.36
Kernels m^{-2}	0.20	0.14	0.60 *	0.55*	0.60*	0.57*
Biomass	-	0.69*	-	0.84*	-	0.86*
Harvest index	0.08	0.80*	0.25	0.75*	0.31	0.75*

Note: *-significant at 5% level

TABLE 4. Effect of drought stress and crop ratio on the Land Equivalent Ratio and Relative Yield Total of barley and wheat mixtures tested at Halhale 1998 and 1999

Crop ratio	1998	1999	Mean LER/RYT
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			
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
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
Mean	1.099	1.363	1.231
LSD 5% LER / RYT			
Drought stress	NS(*)	NS	NS(*)
Crop ratio	NS(*)	NS	NS
Drought stress _ crop ratio	NS	NS	NS
CV%	39.4	37.0	33.2

Note: The asterisks between brackets (*) show significance at P≤ 0.10

TABLE 5. Inter-specific competition and niche differentiation indices (NDI) of barley and wheat mixtures tested under stress and crop ratios (n=132)

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

Note: * indicates statistically significant at P _ 0.05; SE= standard error

TABLE 6. 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 drought stress and crop ratios

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

utilized resources than in sole crop, which means that the species were sharing resources at different times during the growing period.

DISCUSSION

Grain yield. In this study, grain yield under stress conditions was related to low kernel number and seed weight agreeing with Nelson *et al.* (1991). Mixed cropping resulted in more yield compared to sole crops with more efficient water use. With soil water deficits higher density in additive series did not result in more yields. The variation in grain yield between years could be due to aphid infestation in 1998 and inadequate control of the flood irrigation.

Yield advantage analysis. Land Equivalent Ratio (LER) and Relative Yield Total (RYT) showed that it was advantageous to grow barley and wheat in mixtures. The yield advantage could be because the two crop species are complementary in resource use or the density effect. This indicates that higher sole crop yield could be obtained with higher density. However, mixtures with greatest density did not have greater yield than lower density.

The replacement approach is more suitable in order to address the issue of yield advantage of mixed cropping. In this 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 facing 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.

Competition. Barley and wheat have shallow root systems and water extraction is limited to the rooted zone. Inter cropping systems have in many cases resulted in higher water use efficiency compared to sole cropping. Barley was a stronger competitor than wheat regardless of the time of stress. When comparing the two component crops both the weight of an isolated plant and maximum attainable yields were higher for barley than for 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 under soil resources limitations.

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. Differences in plant height could help the crops to utilise resources at different times in a better way. A rapid increase of plant height is observed for barley during early stages of plant growth. Wheat plants in mixtures were first suppressed but later on grew taller than barley. Furthermore 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 (Woldeamlak *et al.*, 2001).

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 on competitive ability 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 particular 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 *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.

CONCLUSION

When averaged over years and stress types, these experiments showed that a crop ratio of 50/50, 25/100 and 100/25 resulted in better 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. However, higher crop ratios did not result in higher grain yield in mixtures because of excessive water demand during vegetative growth. The relative competitive ability was higher in barley than for wheat. Despite the competition in favour of barley the component crops did not inhibit each other from sharing resources over time due to differences in phenology (differences in maturity), growth and plant height. The niche differentiation confirmed that intercropping barley and wheat allowed the component crops to share resources in a complementary way resulting in yield advantage under stress conditions.

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