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Research article

Sustainable production of fennel and dill by intercropping

Alessandra Carrubba[a]*, Raffaele la Torre[a], Filippo Saiano[b], Pietro Aiello[b]

[a] D.A.A.T. (Dipartimento di Agronomia Ambientale e Territoriale; Dept. for Land and Environmental Agronomy), Università di Palermo, Viale delle Scienze, 90128, Palermo, Italy

[b] D.I.T.A.F. (Dipartimento di Ingegneria e Tecnologie Agrarie e Forestali; Dept. for Agricultural and Forestal Engineering and Technology), Università di Palermo, Viale delle Scienze, 90128, Palermo, Italy

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Abstract – Intercropping is claimed to be one of the most significant cropping techniques in sustainable agriculture, and much research and many reviews attribute to its utilization a number of environmental benefits, from promoting land biodiversity to diversifying agricultural outcome. In this sense, intercropping is thought to be a useful means of minimizing the risks of agricultural production in many environments, including those typical of under-developed or marginal areas. In order to validate this hypothesis in a representative area of the semiarid Mediterranean environment, we evaluated the possibility of growing dill and fennel, both belonging to the family Apiaceae, in temporary intercropping. Our trial was performed in Sicily in 2000–01 and 2001–02; in the first year, fennel and dill were cultivated in a mixture using a substitution scheme, whereas in 2001–02 we evaluated the bio-agronomical and chemical features of fennel alone. The biological efficiency of the intercropping system was evaluated by using the Land Equivalent Ratio and the Competitive Ratio, and an estimate of the interaction effects of both crops was performed by analyzing the major vegetative and yield traits of plants, along with the chemical profile of volatiles of the fruits. Both in grain yield and in biomass yield, the most efficient cropping system was the intercropping ratio with a higher proportion of fennel, in which the competitive ratio values calculated for dill reached 1.90 for grain and 2.59 for biomass. Our results also indicate that the presence of dill exerted a clear stabilizing effect on fennel seed yield of the following year: whereas no difference in fennel seed yield was detected from one year to the following on the previously intercropped plots, in the repeated pure stand a 50% yield reduction was recorded. In the trial environment, the technique showed a good potential to improve the efficiency of resource utilization; further long-term experiments will be necessary in order to demonstrate the application of such a technique to other medicinal and aromatic plant mixtures.

intercropping / medicinal and aromatic plants / fennel / *Foeniculum vulgare* Mill. / dill / *Anethum graveolens* L.

1. INTRODUCTION

The term "intercropping" refers to the special cropping system obtained by the contemporaneous growing of two or more species, whose association may generate reciprocal interactions bearing some agronomical relevance, i.e. exerting some recognizable effect on yield expression of one or all the partners (Caporali et al., 1987). In this sense, agricultural specialists suggest intercropping as a useful means for enhancing yields for one or all the consociated species, thanks to the ability of the consociated systems to reduce weeds and pests (Baumann et al., 2000; Hatcher and Melander, 2003; Kenny and Chapman, 1988; Poggio, 2005) and to improve the exploitation of the available environmental resources with respect to monocropping systems (Arnon, 1992; Caporali et al., 1987; Park et al., 2002). Therefore, the intercropping technique is thought to minimize the risks of production and improve strategies for food production in developing and, in a broader sense, "marginal" areas.

It is well acknowledged that each intercropping system generates a typical and unique pattern of use of the existing resources, which may vary according to the chosen intercropping ratio, and it is likely to differ from that obtained if the two species were cultivated alone (Caporali et al., 1987). Competition for the use of resources may occur throughout the growth period or for a part of it, or may not occur at all if the availability of factors necessary for growth is constantly higher than the combined request from the plants (Bonciarelli, 1989).

A given intercropping system may be advantageous when there is a mutualistic relationship between the partners or when the interspecific competition is weaker than intraspecific competition. When either species, or the most productive species, is affected more by intraspecific competition than interspecific competition, the optimal plant population may be higher when intercropped than when grown separately (Willey, 1979b; Fordham, 1983).

To date, experimental reports about intercropping between medicinal and aromatic plants are rare: some of them, focused on the evaluation of their yields and quality traits when cultivated in various agroforestry systems, come to the conclusion that the introduction of such herbs into agroforestry systems could be a useful way to increase biodiversity and gain a significant income increase (Becker, 2004; Huang et al., 2002; Rao et al., 2004).

Some further interest in the potential role of medicinal and aromatic plants in intercropping systems has arisen from the widespread trend toward the cultivation of such species

* Corresponding author: acarr@unipa.it

with organic and, generally speaking, sustainable methods. An attempt to utilize some aromatic oil-bearing plants, namely *Artemisia annua* L., *Coriandrum sativum* L., *Chamomilla recutita* Rausch., *Foeniculum vulgare* Mill. and *Anethum sowa* Kurtz., as intercrops to manage aphid infestation on mustard (*Brassica juncea* L.) was performed in India by Singh and Kothari (1997), who obtained the lowest aphid population when mustard was intercropped with fennel, and the highest one when it was cultivated in mixture with coriander. Other experiments have involved the association of palmarosa (*Cymbopogon martinii* Stapf.) with redgram (*Cajanus cajan* L.) (Maheshwari et al., 1996), scented geranium (*Pelargonium* spp.) with cornmint (*Mentha arvensis* L.) (Rajeswara Rao, 2002), and Eucalyptus (*Eucalyptus* spp. (L'Her.)) with coffee (*Coffea arabica* L.), lemongrass (*Cymbopogon citratus* (DC. ex Nees) Stapf.) or palmarosa (KAU, 2002). Especially interesting are the experiments performed on species with a different production cycle, intercropped for one year or more; such an arrangement has been tested on some industrial crops (Callan and Kennedy, 1996), and when this multiple cropping involves an annual and a polyannual, the overall results of the obtained cropping system seem to be strongly dependent upon the reactivity of the polyannual, considered the "primary" crop, to the competition with the annual.

Intercropping between dill (*Anethum graveolens* L.), an annual, and clary sage (*Salvia sclarea* L.), a polyannual, may improve the overall efficiency of the cropping system, allowing some marketable production even in the year in which the main species, namely clary sage, does not have any yield (Catizone et al., 1986). With the same objective, interesting experiments on intercropping between licorice (*Glycyrrhiza glabra* L.) and cereals, such as wheat (*Triticum* spp.) or barley (*Hordeum vulgare* L.), have been conducted in southern Italy; the results of such experiments are variable, but they are generally unfavorable for the yield of fresh licorice roots, that from 22.8 t/ha in pure stands dropped to 14 t/ha for intercropping (De Mastro et al., 1993; Marzi, 1996).

In the cultivation of medicinal and aromatic plants the aspect of bare productivity, although important, is not the only one to be considered; in such special crops, as a matter of fact, particular attention must be paid to the quality features of the products. Various results have been obtained regarding the qualitative aspect of production with intercropping, and much research has demonstrated that in some cases such a technique may affect the chemical features of the consociated species, causing variations both in yield of essential oil and in composition of the extracts. For example, the alkaloid content of jimsonweed (*Datura stramonium* L.) plants seems to be affected by the cultivation of other species nearby, showing, respectively, an enhancement with lupine (*Lupinus albus* L.) or a decrease with peppermint (*Mentha piperita* L.) (Morelli, 1981). The essential oil content of peppermint is furthermore positively affected by intercropping with soybean (*Glycine max* Merr.), which also increases the menthol content of peppermint oil (Maffei and Mucciarelli, 2003).

Fennel (*Foeniculum vulgare* Mill.) and dill (*Anethum graveolens* L.) belong to the family Apiaceae, and are cultivated around the world because of their scented fruits ("seeds"). Under field conditions, dill has a typical annual behavior, since after the fructification stage the plant quickly starts to senesce and dies, whereas in fennel a new vegetation may originate after cutting from the basal parts of stems, and therefore the plant may be cultivated as an annual or a polyannual (Carrubba et al., 2003). In the latter case, yields in the first cropping year may be lower than those of the following years. A temporary intercropping of these two species could allow one, thanks to the introduction of the annual species, to gain interesting yields even in the first year.

The aim of the present trial was, therefore, to study the development pattern and yield performance of a fennel-dill intercropping; by means of the proper intercropping indices we deduced the biological efficiency and the level of competition between the two species, also evaluating how much such competition could affect seed yield and plant development. Yield levels and plant behavior of fennel in the second cropping year were taken into consideration, in order to perform a broad evaluation of the efficiency of the whole two-year cropping system.

2. MATERIALS AND METHODS

2.1. Site description

The trial was carried out in 2000–01 and 2001–02 in the experimental farm "Sparacia" (Cammarata, AG, Sicily; 37° 38' N; 13° 46' E), on soil classified as a clayey, mixed thermic, Aridic Haploxerert (NRCS, 2003), which is representative of the semiarid Mediterranean environment.

The total rainfall recorded in the trial area was higher in the first year: 503.5 mm of rain was recorded from November 2000 to the end of May 2001, compared with 337.8 mm recorded throughout the same interval in 2001–02. Some difference also concerned the diverse distribution of rainfall in both years, since in the first year 281.5 mm of rainfall were recorded from the end of December to the beginning of February, whereas in the second year rainfall was distributed throughout a longer period. In both years, the temperature reached maximum values above 30 °C in the summer months and minimum winter values that rarely fell below 0 °C.

2.2. Field experiments

In the first year of the trial, the two species were cultivated in a mixture, whereas in 2001–02 the bio-agronomical and yield behavior of the two-year-old fennel alone was evaluated. Both species were sown on 23 November 2000, with the seeds distributed in rows 30 cm apart and arranged, by the substitution of rows, in three different intercrop ratios: 33:66, 50:50, 66:33 (fennel:dill), along with pure stands of fennel and dill. The experimental plots (9 m^2, 3 m × 3 m) were laid out in accordance with a randomized complete block design with three replicates. N–P fertilization was applied only in the first year before sowing, distributing N in ureic form and P_2O_5 as triple superphosphate, in order to supply 80 and 120 kg/ha,

Table I. List of indices, formulae and selected bibliographical references used to evaluate the efficiency of an intercropping trial between fennel and dill in 2000–01.

LER (Land Equivalent Ratio); Willey, 1979a; Mead and Willey, 1980; Caporali et al., 1987		
$LER_f = Y_{fd}/Y_f$,	where:	Y_{fd} = yield (grain or biomass) of f intercropped with d
		Y_f = yield (grain or biomass) of f in pure stand
$LER_d = Y_{df}/Y_d$,	where:	Y_{df} = yield (grain or biomass) of d intercropped with f
		Y_d = yield (grain or biomass) of d in pure stand
$LER_t = LER_f + LER_d$		
CR (Competitive ratio); Willey and Rao, 1980; Paolini, 1991		
$CR_f = [(Y_{fd}/Y_f)/(Y_{df}/Y_d)] \times (Z_{df}/Z_{fd})$,		
$CR_d = [(Y_{df}/Y_d)/(Y_{fd}/Y_f)] \times (Z_{fd}/Z_{df})$,	where:	Z_{df} = frequency of species f intercropped with d
		Z_{df} = frequency of species d intercropped with f
f = fennel; d = dill		

respectively, of each element. Plant conditions were continuously monitored throughout the trial, and average plant height was periodically measured from crop emergence to harvest. At the development stage of five true leaves (3 March 2001), the crops were manually thinned to a plant density of 12 plants/m on a row. In this way, the plant population was maintained at 40 plants/m^2, and, in accordance with the intercrop ratio, this value was composed of 13 fennel and 27 dill plants in the 33:66 crop ratio, 20 plants for both species in the 50:50 crop ratio, and 27 fennel and 13 dill plants in the 66:33 crop ratio. Similarly to other Apiaceae (Lawrence, 1993; Carrubba et al., 2006), the starting dates of the most significant development stages were determined by visual assessment of the average plot conditions. For example, the start of flowering was determined to be the appearance of the first flowers on the primary umbels in at least 10% of plants, and the harvesting of seeds was performed when the plants in each plot had reached the full ripening stage, i.e., when the primary umbels were completely ripe in at least 90% of plants. This occurred on 28 June 2001 (intercropping) and 5 July 2002 (fennel in the second year). To remove any border effect, one external row, appositely sown along the experimental field, and all the plants within 0.3 m of the end of each sample row, were excluded from all the evaluations. In this way, an elementary sample area of 3 m × 2.4 m = 7.20 m^2 was obtained. In order to avoid any effect of weeds on plant performance, weeds were carefully removed by hand once a year in early spring; no further intervention was necessary, due to the fast soil coverage of the crops.

At harvest, all plants in the sample area were cut at ground level and biomass was determined. Samples were dried to constant weight at 105 °C for dry matter determination. A sample of 20 randomly selected plants was also taken to measure plant height and the number of umbels. All umbels on the remaining plants in the sample area were manually picked and on 50 randomly selected umbels the diameter was measured and the number of seeds was counted. After a short period of open-air drying, all seeds were mechanically threshed, and the seed yield data obtained were expressed in kg/ha. Four samples of 100 seeds for each species and each replicate were taken and weighed, and after oven-drying the seeds at 105 °C for 24 h, seed weights were recorded at 0% moisture content (dry mass), allowing the calculation of the moisture levels of the seeds. In the second year, the same measurements were performed on fennel. In the absence of dill, the denomination of plots was left as it was the year before; in this way, the difference between each plot was due to the diverse arrangement and number of plants per unit area, i.e., the former area that had a 33:66 fennel:dill crop ratio bore rows 90 cm apart, the former 50:50 crop ratio area bore rows that were 60 cm apart, and the former 66:33 crop ratio area had twin rows with a distance of 30 cm inside and 60 cm between twin rows.

The volatile components of fruits (dill and fennel in the first year, and fennel only in the second) were evaluated in the D.I.T.A.F. laboratories at the University of Palermo, by combining headspace–solid-phase microextraction (HS-SPME) with gas chromatography - mass spectrometry (GC - MS), following procedures used with other Apiaceae in similar trials (Di Prima et al., 2000; Carrubba et al., 2006).

2.3. Statistical data management and intercropping indices

All data were submitted to statistical analysis according to the chosen experimental design by means of the statistical package STATISTICA v.5.1 (Statsoft Inc., USA, 1984–1997), and a standard analysis of variance was performed separately on data for each year and species. When the statistical analysis highlighted the occurrence of a significant difference, the separation of means was performed by Tukey's Honestly Significant Difference test (Gomez and Gomez, 1984).

The chosen intercropping indices, calculated based on data for seed and biomass yield (Tab. I), were:

(1) The Land Equivalent Ratio (LER). Although subjected to many revisions and criticisms (Connolly et al., 2001), the Land Equivalent Ratio still remains one of the most utilized indicators for the efficiency of intercropped systems. When calculated for the grain yield, it indicates the area required by the pure stand to produce the same yields obtained by intercropping. When the population density is the same under

intercropping and in pure stands (as in our case), the value of the Land Equivalent Ratio identifies numerically with the Relative Yield Total, allowing further consideration of the efficiency of the intercropped system in comparison with the pure stands (Caporali et al., 1987).

Values higher than 1 indicate that there is some ecological complementarity between the intercropped partners (Aarssen, 1983), i.e., a differentiated demand exists on the contended resources. In this case, intercropping allows a higher biological efficiency compared with the pure stand for one or both components; therefore, intercropping would provide a substantial productive advantage. Values lower than 1 indicate the opposite conclusion that the intercropped system is inefficient compared with the pure stand because of one or both components.

(2) The Competitive Ratio (CR). This represents the ratio between the variation in dry matter of each species when intercropped, compared with its pure stand and corrected by their relative proportion in the mixture. Like the Land Equivalent Ratio, the Competitive Ratio provides information about the degree of competition between the two species, but in addition it enables the level of competition between the two species to be determined. A Competitive Ratio equal to 1 describes a balance of competition, whereas values higher than 1 indicate that the given component is more competitive than the other, i.e., it behaves as "dominant" (Willey and Rao, 1980; Paolini, 1991). A *t* test was performed on both indices to detect any statistical differentiation between them and the reference value of 1.

3. RESULTS AND DISCUSSION

3.1. Crop development and vegetative behavior

The aim of the experiment was to examine the yield response and the plant performance of fennel and dill, grown at different intercropping ratios according to a substitution scheme. In both species, plant emergence was recorded in the first days of January 2001, i.e., 41–43 days after sowing. In order to observe the growth variations over time of both consociated species, in both years plant height was repeatedly measured from plant emergence to harvest (Fig. 1). As shown in the graphs, in all cases the development trend fits very well to a quadratic curve, with an increase in slope as the mean air temperatures started to rise and with maximum height values occurring around flowering time. In 2000–01, the start of flowering was recorded 125–127 days after emergence for dill and 141–147 days after emergence for fennel, i.e., 70–73% and 80–84%, respectively, of total cycle duration from emergence to harvest. The reproductive phase, from the start of flowering to harvest time, lasted 47–51 days for dill and 29–35 days for fennel, i.e., respectively, 27–29% and 16–20% of total cycle duration for each species.

In the first trial year, in which both species were grown, fennel reached lower height values than dill; probably as a consequence of the shading suffered throughout the reproductive stages, in consociated fennel plants the primary umbels began to appear about one week after the pure stand. The ripening of seeds was uniform and they were harvested on 28 June 2001. After a summer stasis, the fennel from the previous year regrew, and from the first days of January 2002, although of small size, the canopy was quite uniform. As in the first trial year, crop development in the second year was measured until harvest time. In all plots, the start of flowering was detected in the last days of May, and the seeds were harvested on the first days of July 2002.

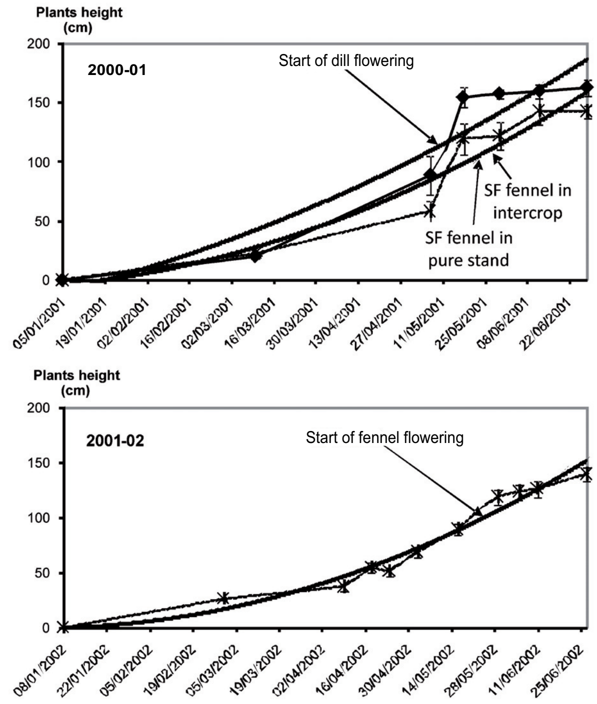

Figure 1. Average height of fennel and dill plants in 2000–01 (top) and of fennel alone in 2001–02 (bottom) in a field trial performed in Sparacia (Cammarata, AG, Sicily). For each species, each point is the average of plant height measurements from three intercropping ratios and one pure stand; vertical bars indicate the mean standard deviation. For each dataset, the thick lines represent the calculated quadratic regression curve. Regression equations and R^2 are respectively: $y = 0.004\ x^2 - 296.8\ x + 6{\cdot}10^5$ with $R^2 = 0.92$ (Fennel in 2000–01); $y = 0.002\ x^2 - 215.0\ x + 4{\cdot}10^6$ with $R^2 = 0.90$ (Dill in 2000–01); $y = 0.004\ x^2 - 360.2\ x + 6{\cdot}10^7$ with $R^2 = 0.97$ (Fennel in 2001–02). The arrows mark the start of flowering (SF) for each species. Fennel in intercrop started flowering about one week after fennel in pure stand.

3.2. Biomass yield, seed yield and yield components under intercropping

The values obtained for biomass and seed yields in both crops from the different treatments are reported in the replacement diagrams (after De Wit, 1960) in Figures 2 and 3. At harvest, both species expressed the highest biomass yields as pure stands. In fennel, the statistical analysis stressed a significant differentiation ($P \leq 0.05$) between the biomass value of 7.2 t/ha measured on pure stand and all the others; the

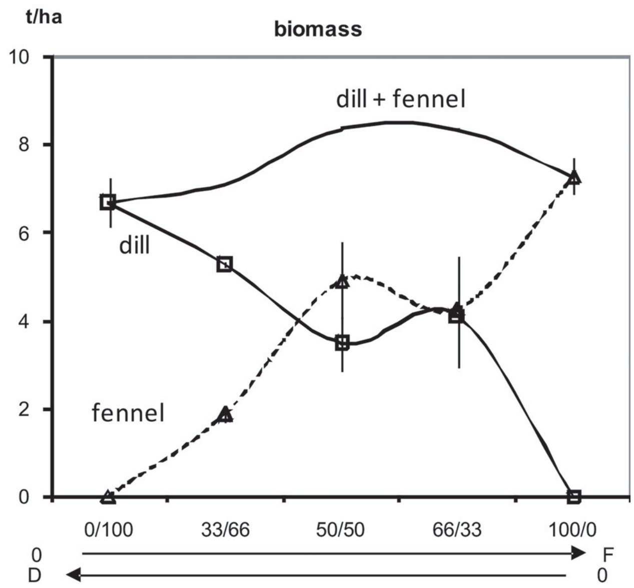

Figure 2. Replacement graph for the biomass yield measured on fennel and dill in intercropping at Sparacia (Cammarata, AG, Sicily) in 2000–01. Each point is the average of three replicates. The vertical bars represent the standard error of each mean. On the X axis the intercropping ratios are represented, the first digit referring to fennel, from 0/100 (dill in pure stand) to 100/0 (fennel in pure stand). The directions of the arrows at the bottom indicate respectively the growing presence of each component in the intercropping.

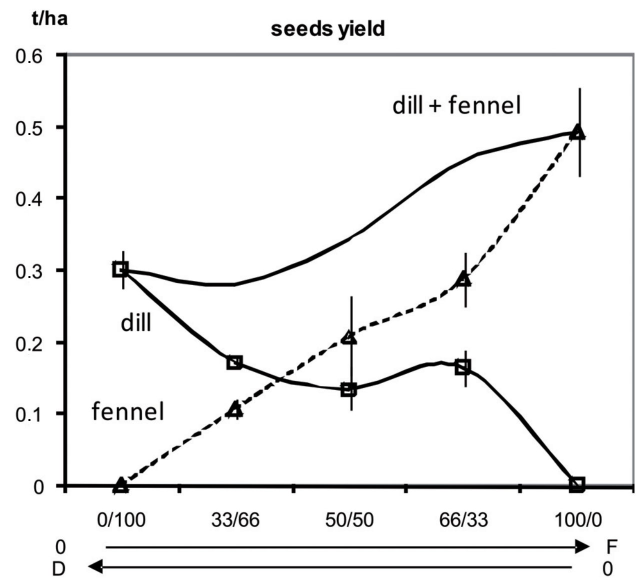

Figure 3. Replacement graph for the grain yield measured on fennel and dill in intercropping at Sparacia (Cammarata, AG, Sicily) in 2000–01. Each point is the average of three replicates. The vertical bars represent the standard error of each mean. On the X axis the intercropping ratios are represented, the first digit referring to fennel, from 0/100 (dill in pure stand) to 100/0 (fennel in pure stand). The directions of the arrows at the bottom indicate respectively the growing presence of each component in the intercropping.

minimum value of 1.8 t/ha was reached by the 33:66 treatment, i.e. the one in which fennel was grown together with a larger amount of dill.

In dill the same trend was approximately maintained, and the maximum biomass value was also reached by the sole crop, with a sharp decrease with an increasing density of the intercropped species.

As found for the biomass values, total seed yields measured under each intercropping ratio also showed a decreasing trend in relation to the densities of the respective consociated species; once again, both crops expressed the highest values as pure stands, gaining 0.5 t/ha for fennel and 0.3 t/ha for dill, whereas yields in the intercropped treatments were lower and decreased with the lowering of plant density.

Such a result may sound obvious, since a reduced yield could be just a barely multiplicative consequence of the different plant populations for each species according to the intercropping ratios. As shown in Figures 4 and 5, however, both the seed mass and the weight of one individual plant, that remained on rather constant levels across the first intercropping ratios, expressed a differentiation at the maximum competition level, i.e. when each crop was accompanied by the highest density of the other one. In the case of dill such a behavior was especially evident, and when accompanied by the highest amount of fennel, individual dill plant weight and seed yield rose up to 30.9 g/plant and 1.2 g/plant, respectively, with an increase of about 85% and 64% with respect to pure stand.

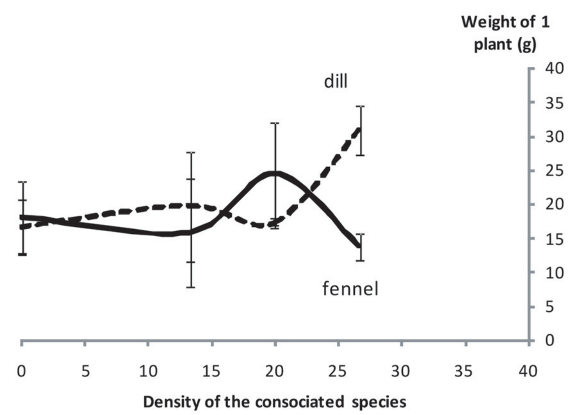

Figure 4. Unitary mass per plant (g) measured for fennel and dill in intercropping in 2000–01 at Sparacia (Cammarata, AG, Sicily), as a function of the presence of the competitor species in the mixture. Each point is the average of three replicates. The vertical bars represent the standard deviation for each mean.

The statistical analysis evidenced this superiority stating that, in dill, seed yield per plant in the 66:33 treatment was significantly ($P \leq 0.01$) higher than under all the other cropping conditions, including pure stands.

Figure 6 illustrates the trend of plant height at harvest time in both species with varying competition levels. In fennel, the trait did not show any difference from one treatment to the

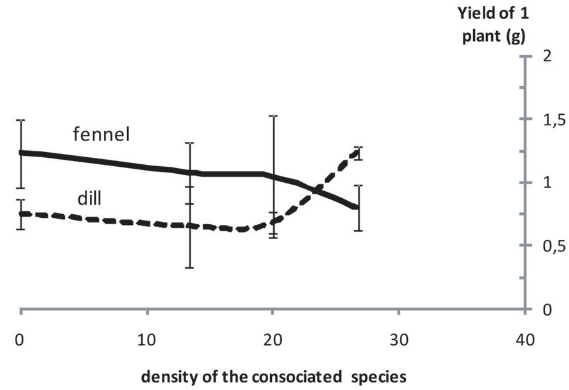

Figure 5. Trend of seeds yield per plant (g) measured for fennel and dill in intercropping in 2000–01 at Sparacia (Cammarata, AG, Sicily), as a function of the presence of the respective competitor species in the mixture. Each point is the average of three replicates. The vertical bars represent the standard deviation for each mean.

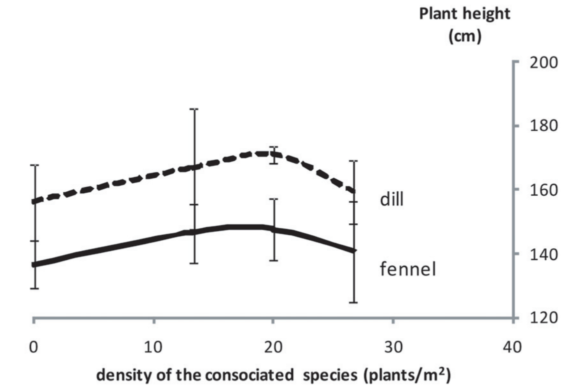

Figure 6. Plants height at harvest time (cm) measured for fennel and dill in intercropping in 2000–01 at Sparacia (Cammarata, AG, Sicily), as a function of the presence of the respective competitor species in the mixture. Each point is the average of three replicates. The vertical bars represent the standard deviation for each mean.

other, and the measured values ranged from 136.5 cm in the pure stand to 147.6 cm in the 50:50 crop ratio. In dill, the same parameter showed instead statistically significant differences ($P \leq 0.05$), leading to a clear distinction between the pure stand and the 66:33 crop ratio, which averaged values lower than 160 cm, and the other two intercropped treatments, bearing values around 167–171 cm. In both species, the lowest height values were recorded on the sole crops, in which only intraspecific competition played some role. In such plots, the two species expressed a strong differentiation: in fennel the dominance of intraspecific competition led to shorter but heavier plants, whereas in dill it led to shorter and lighter ones. In the intercropped plots, where the interspecific competition started to exert its effects, both species showed a growth in height, accompanied by a modification in plant mass and seed mass that reached its highest differentiation at the maximum competition level, i.e. when each crop was grown together with the maximum frequency of its respective competitor.

Since dill is always taller than fennel, a possible explanation of this feature could probably be linked to the different reaction of both crops to the competition for light. The proportion of light received by plants in the intercropped systems is claimed to be one of the essential elements in competition between plants (Baldy and Stigter, 1997), and the differences in coping with shading are often claimed as a crucial factor in plant dry matter accumulation (Pronk et al., 2007).

Fennel plants were generally shorter and heavier than dill ones, with smaller umbels and a lower number of rays in each umbel. In our trial this feature was already evident in the pure stands, in which fennel expressed a lower plant height and a higher biomass value compared with dill. As an effect of interspecific competition, when consociated with dill plants, fennel plants tended to become higher; such variation did not bear a parallel increase in seed yield and weight per plant, which in fennel always kept around values lower than those reached in the pure stand. Conversely, the presence of fennel in mixture seemed to force up dill plant performance, and the yields of dill plants seemed to be more affected by intraspecific competition than by interspecific competition.

Variations in allocation strategy are claimed to play an important role in assessing yields and overall plant performance in many plant communities (Pronk et al., 2007; Rees and Bergelson, 1997; Rao et al., 1998). The great difference between the two species that shows up as concerns their respective growth mechanisms might therefore be explained as if dill plants "invest" more than fennel plants in accumulation of dry matter in biomass and seeds, in a strategy for survival aiming to react to interspecific competition, stretching at the maximum level the yield potential of each individual plant.

3.3. Intercropping indices

Both fennel and dill are herbaceous crops selected for monoculture systems; since they belong to the same botanical family, and have a similar growth and yield pattern, it is to be expected that their biomass and seed yield are affected by intercropping with each other. Reasonably, the effect that one crop may exert on the other should vary with the intercropping ratio, i.e. as the effects of the intraspecific competition are substituted by those exerted by the interspecific competition. It is generally assumed that a crop is more competitive when it forms a larger proportion of the total population (Saka et al., 1993), but the outcome of such competition may be different according to the physiological and morphological characteristics of the competitors (Pronk et al., 2007).

The values calculated for both intercropping indices, based on biomass and grain yield, are shown in Table II. The values for total $LER_{biomass}$, calculated based on the aerial biomass dry yield, increase from the 33:66 to the 66:33 cropping ratio, i.e., with an increasing proportion of fennel in the mixture, even though they do not diverge (at $P \leq 0.05$) from 1 in all cases, showing that the efficiency of these intercropping ratios is practically equal to that of the pure stands. The total

Table II. Values of the Land Equivalent Ratio (LER) and Competitive Ratio (CR) calculated for grain and biomass yield obtained from a fennel:dill intercropping in Sparacia (Cammarata – AG – Sicily) in 2000–01. The notations n.s.; * and ** refer to the significance of the t−test calculated between each calculated value and the reference value of 1; degrees of freedom for calculation of t−test = 2.

Biomass yield					
–kg/ha–					
	$LER_{b(biomass)}$			$CR_{b(biomass)}$	
	LER_{bf}	LER_{bd}	LER_{btot}	CR_{bf}	CR_{bd}
33:66	0.25	0.79	$1.04^{n.s.}$	$0.66^{n.s.}$	$1.56^{n.s.}$
50:50	0.67	0.52	$1.19^{n.s.}$	$1.31^{n.s.}$	$0.89^{n.s.}$
66:33	0.58	0.62	$1.20^{n.s.}$	0.43^{*}	2.59^{*}
Grain yield					
–kg/ha–					
	$LER_{g(grain)}$			$CR_{g(grain)}$	
	LER_{gf}	LER_{gd}	LER_{gtot}	CR_{gf}	CR_{gd}
33:66	0.22	0.58	0.80^{*}	$0.77^{n.s.}$	$1.38^{n.s.}$
50:50	0.42	0.45	$0.87^{n.s.}$	$0.92^{n.s.}$	$1.09^{n.s.}$
66:33	0.58	0.54	$1.12^{n.s.}$	0.53^{**}	1.90^{*}

LER_{grain} values, calculated on total grain yield, show a similar trend to the values recorded for $LER_{biomass}$, reaching their maximum value in the 66:33 treatment, composed of 2/3 fennel and 1/3 dill. The values of LER obtained from this intercropping ratio might allow the quantification of its higher level of efficiency of about 20% in the case of biomass and 12% as concerns seed yield. The severity of the t−test, however, being affected by the variability between repetitions, in most cases does not confirm the statistical difference from unit, and the only allowed conclusion relies on terms of tendency. Both in the case of biomass and in seed yield, the intercropping ratio with a higher proportion of fennel was shown to be the most efficient among the tested cropping systems, and the partitioning of total LER values into their two partial values, respectively belonging to fennel and dill, shows that in the 66:33 ratio both species took advantage of intercropping.

The value of total LER_{grain} significantly decreases as the intercropping ratio varies, reaching the lowest value (0.80, different from 1 at $P \leq 0.05$) in the treatment in which dill is represented at the highest level, i.e. 33:66. In this case, the partitioning in the two partial LER_{grain} demonstrates that, at this ratio and at the chosen population density, fennel has a much lower competitive ability with respect to dill.

The Competitive Ratio, calculated both for biomass and for seed yield, showed values significantly diverse from unit in the 66:33 treatment, i.e., significantly lower than 1 for fennel and, conversely, significantly higher than 1 for dill. Under the given experimental conditions, in other words, dill was about two times more competitive than fennel, as concerned both biomass and seed yield. That is, when cultivated in a lower proportion, dill succeeds in optimizing the use of available resources, achieving the highest level of efficiency, both in seed and in biomass yield, in the intercropping system and therefore behaving as a "dominant" species.

Table III. Results of the pooled ANOVA performed on fennel seeds and biomass yields in 2000–01 and 2001–02 in Sparacia (Sicily). Data for the first year refer to an intercropping with dill, whereas in 2001–02 fennel was grown alone: the first value in the ratio refers to the frequency of fennel in the intercropping of 2000–01. Means sharing the same letter (including partials) are not significantly different at $P \leq 0.05$.
* = difference significant at $P \leq 0.05$; ** = difference significant at $P \leq 0.01$; n.s. = no significant difference.

			Seed yield (t/ha)	**Biomass yield (t/ha)**
Source of variation		DF		
Total		23		
Year		1		
	2000/01		0.27	4.55
	2001/02		0.28	3.99
Calc. *F*			$< 1^{n.s.}$	$1.49^{n.s.}$
Intercropping Ratio				
		3		
	33:66		0.24	2.13
	50:50		0.21	3.72
	66:33		0.30	4.72
	100:0		0.36	6.52
Calc. *F*			4.80*	$< 1^{n.s.}$
Year x Intercropping Ratio				
		3		
2000/01	**33:66**		0.11 c	1.83
	50:50		0.21 bc	4.89
	66:33		0.29 bc	4.22
	100:0		0.49 a	7.26
2001/02	**33:66**		0.38 ab	2.42
	50:50		0.20 bc	2.55
	66:33		0.31 bc	5.22
	100:0		0.23 bc	5.77
Calc. *F*			11.94**	$2.06^{n.s.}$
Residual	(error)	16		

3.4. Biomass and seed yield in the second trial year

As shown in Table III, the yield data collected on fennel in the second trial year was not significantly different from that obtained in 2000–01, and a pooled ANOVA performed on the two-year data produced both for seed and biomass yield a not significant F value, attesting to the lack of any statistical difference between the mean values, that in both years averaged about 280 kg/ha of seeds and 4 t/ha of biomass.

In order to evaluate the efficiency of the whole two-year cropping system for each intercropping ratio, it is possible to

Table IV. Volatile compounds identified in fennel and dill seeds from an intercropping trial performed in Sparacia (Cammarata, AG) in 2000–01 and 2001-02, and results of ANOVA performed over both years (fennel) and for 2000–01 only (dill). Values refer to four intercropping treatments, including pure stands.

	Fennel											Dill				
	2000–01				2001–02				ANOVA			2000–2001				ANOVA
	PS*	33:66	50:50	66:33	PS	33:66	50:50	66:33	Year (*DF: 1*)	Treatment (*DF: 3*)	Y × T (*DF: 3*)	PS	33:66	50:50	66:33	Treatment (*DF: 3*)
	----------------%---------------				----------------%--------------							----------------%--------------				
α–thujene	0.11	0.12	0.10	0.24	0.10	TR†	0.15	0.14	1.05 NS	1.74 NS	< 1 NS	ND§	ND	ND	0.03	1.00 NS
α–pinene	23.99	23.88	23.64	22.6	24.15	27.51	27.87	25.59	10.08**	1.22 NS	1.08 NS	0.34	0.36	0.29	0.41	< 1 NS
camphene	3.42	2.85	2.99	3.54	2.73	3.26	2.74	3.07	5.89*	3.01 NS	5.29 **	ND	ND	ND	ND	–
sabinene	0.74	0.75	0.61	0.74	0.79	0.93	0.88	0.87	17.00***	1.27 NS	1.49 NS	ND	ND	ND	ND	–
β–pinene	1.27	1.25	1.17	1.00	1.13	1.19	1.44	1.16	< 1 NS	1.79 NS	1.82 NS	0.12	0.11	0.1	0.11	< 1 NS
β–myrcene	5.86	5.44	5.99	5.85	5.41	6.18	5.60	5.85	< 1 NS	< 1 NS	5.58 **	0.48	0.60	0.54	0.63	1.45 NS
α–phellandrene	2.91	3.04	2.74	2.73	3.41	3.92	5.25	3.28	19.67***	3.06 NS	3.63 *	6.19	7.26	5.45	6.72	< 1 NS
α–terpinene	0.09	0.10	0.08	0.08	ND	ND	ND	ND	–	–	–	ND	ND	ND	ND	–
p–cymene	0.19	0.29	0.18	0.24	1.00	0.84	2.07	0.63	21.81***	2.46 NS	3.00 NS	0.55	0.70	0.50	0.76	< 1 NS
limonene	13.07	12.69	13.19	13.20	11.24	12.66	11.69	12.16	22.97***	1.20 NS	2.79 NS	79.80	77.56	78.72	76.78	< 1 NS
ocimene	0.14	0.18	0.13	0.15	TR	TR	0.05	0.06	1.03 NS	< 1 NS	1.89 NS	0.17	0.25	0.18	0.24	1.73 NS
α–terpinene	2.15	2.87	1.65	2.04	2.81	3.09	2.76	2.32	4.26*	1.86 NS	< 1 NS	ND	ND	ND	ND	–
sabinene hydrate (*cis*)	0.19	0.22	0.20	0.21	0.05	TR	0.06	TR	54.87***	< 1 NS	< 1 NS	ND	ND	ND	ND	–
fenchone	35.06	31.20	35.06	36.43	27.21	27.01	23.97	27.57	48.28***	1.40 NS	1.56 NS	ND	ND	ND	ND	–
terpinolene	0.65	1.17	1.02	1.07	0.67	0.71	0.62	0.68	13.98**	2.07 NS	1.76 NS	0.09	0.32	0.09	0.10	1.33 NS
limonene oxide (*cis*)	ND	ND	ND	ND	ND	ND	ND	ND	–	–	–	0.11	0.13	0.12	0.14	< 1 NS
camphor	0.68	0.40	0.65	0.67	0.53	0.43	0.41	0.53	6.90*	3.27 *	1.39 NS	ND	ND	ND	ND	–
estragole	0.85	0.90	0.76	0.65	1.74	1.20	1.13	1.46	19.30***	1.20 NS	1.24 NS	ND	ND	ND	ND	–
anethole	8.50	12.49	9.77	8.46	17.02	11.07	13.30	14.64	9.06**	< 1 NS	2.34 NS	ND	ND	ND	ND	–
dill ether	ND	ND	ND	ND	ND	ND	ND	ND	–	–	–	0.08	0.12	0.07	0.21	< 1 NS
δ–dihydro carvone (*cis*)	ND	ND	ND	ND	ND	ND	ND	ND	–	–	–	0.14	0.10	0.15	0.09	< 1 NS
δ–dihydro carvone (*trans*)	ND	ND	ND	ND	ND	ND	ND	ND	–	–	–	6.60	3.93	6.85	4.48	< 1 NS
δ–carvone	ND	ND	ND	ND	ND	ND	ND	ND	–	–	–	5.51	8.53	6.97	9.57	< 1 NS

PS = pure stand; † TR = traces; § ND = not detected
* = difference significant at P ≤ 0.05; ** = difference significant at $P \leq 0.01$; NS = no significant difference.

compare the values for seed and biomass yields that are, respectively, obtained. Such a comparison allows one to make some observations about the sharing of resources between biomass and seeds in the different cropping systems. The plots of pure stands of fennel showed a sharp decrease in yield from one year to the next, and this reduction, that was about 20% for total biomass, overpassed 50% for seed yield.

In the other plots, in the absence of a competitor, a linear increase in yield and main yield components, in accordance with the number of plants per unit area, would have been expected to occur from the former 33:66 treatment to the pure stand. On the contrary, fennel yielded rather uniformly; obtaining similar yields from greatly different plant densities suggests that something different from plant population concurred in forming yield results. It is interesting to notice how the highest seed yields (375.7 kg/ha) were recorded in the former 33:66 intercropping ratio, which bore the lowest number of plants per square meter, i.e., from one year to the following, the former 33:66 treatment gained more than 70% seed yield.

A hypothesis could be that in such treatment, occupied in the preceding year by the largest amount of dill, the previous competition resulted in the sharing of a higher quote of carbohydrates in roots, that allowed the plants to cope with the less favorable climatic conditions of the second trial year. As a matter of fact, root accumulation is claimed to be an important aspect of plant strategy under competition (Rees and Bergelson, 1997).

In order to explore this aspect, various aspects of plant architecture were examined, and their relation to yield was considered, but in our trial no statistical difference in the measured yield components between treatments was stated and none of the examined yield factors showed an evident direct correlation to yield. Nevertheless, we observed a general trend of more productive plants in plots with a lower population density. This could be because this lower plant density allowed a higher number of seeds per umbel and a higher number of umbels per plant, resulting in a higher overall productivity per plant.

According to our trial, it seems possible to conclude that the repeated cultivation of fennel following itself does not bring satisfactory yield results; the presence of dill in the mixture in the first year, on the other hand, brings some stabilization of fennel yields, leading to an enhancement of seed production.

3.5. Chemical traits

The chemical composition of seeds (Tab. **??**) agreed with that reported in the literature: the most represented volatile component of fennel seeds was fenchone (24–36% of total volatiles), a generally unwelcome component, followed by α-pinene (22–28%), whereas other components were represented at much lower levels. In dill, the most represented compound was typically limonene (77–80%), followed by δ-carvone (6–10%), α-phellandrene (5–7%) and δ-dihydrocarvone (*trans*) (4–7%), whereas all other volatiles had values lower than 1%. Statistical analysis showed that seed composition was very slightly affected by intercropping. Only the camphor content in fennel showed a significant response to this factor; a decrease in camphor content occurred with an increasing proportion of dill in the mixture (from 0.68% in the pure stand to 0.40% in the 33:66 ratio). The content of many chemical components, such as sabinene, α–phellandrene, p–cymene and others, were otherwise strongly influenced by variability over years, although no definite cause-effect relationship was detected.

4. CONCLUSION

Both fennel and dill are herbaceous crops selected for monoculture systems, and their biomass and seed yield are affected by intercropping with each other. Although the mechanisms involved in yield assessment are not completely clear, it is evident that in terms of seed and biomass yield, the most efficient and advantageous cropping ratio, at least among those under study, was 66:33 (2/3 fennel and 1/3 dill). At such a ratio, dill behaved as the "dominant" species, i.e., interspecific competition brought lower effects than intraspecific competition, dealing with a competitivity about double that of fennel.

An evaluation of the overall efficiency of the two-year system evidences the unfeasibility, under the given experimental conditions, of the repeated cultivation of fennel; the occurrence in the second year of higher yield levels on the treatments that in the previous one had been more affected by competition, allows one to think that some mechanism of root storage should have taken place. Such a mechanism leads to a substantial seed yield advantage of the intercropping 2-year system with respect to repeated fennel cultivation: in almost all the formerly consociated treatments, the harvest of the second year outyielded the one obtained from the same plots in the first one. On the whole, the introduction of the annual into the cropping system allowed us to gain interesting yield levels, enhancing its overall efficiency.

The seed aromatic pattern of the fruits was more affected by the year-to-year variation than by the different cropping techniques. Our work allows the identification of intercropping as a useful tool for improving the efficiency of resource utilization, stabilizing yields and minimizing production risks in cultivation of medicinal and aromatic plants. Further long-term experiments will be necessary in order to extend over time the validity of such conclusions, and to demonstrate the application of this technique to other medicinal and aromatic plant mixtures.

REFERENCES

Aarssen L.W. (1983) Ecological combining ability and competitive combining ability in plants: toward a general evolutionary theory of coexistence in systems of competition, Amb. Nat. 122, 707–731.

Arnon I. (1992) Agriculture in drylands, Principles and practice, Elsevier, The Netherlands, 979 p.

Baldy C., Stigter C.J. (1997) Agrometeorology of multiple cropping in warm climates, Quae Editors, India, 237 p.

Baumann D.T., Kropff M.J., Bastiaans L. (2000) Intercropping leeks to suppress weeds, Weed Res. 40, 359–374.

Becker B.N. (2004) Integration of medicinal and culinary herbs in an agroforestry combination on St. Croix, United States Virgin Islands, Degree thesis, University of Florida, 75 p.

Bonciarelli F. (1989) Avvicendamento e consociazione, in: Fondamenti di agronomia generale (in Italian), Edagricole, Bologna, Italy.

Callan E.J., Kennedy C.W. (1996) Intercropping stokes aster: seedling growth under a soybean canopy, in: Janick J. (Ed.), Progress in new crops, ASHS press, Arlington, VA, pp. 363–367.

Caporali F., Paolini R., Campiglia E. (1987) La consociazione fra piante erbacee, Nota I, Basi biologiche e vantaggi produttivi (In Italian, with English abstract), Riv. Agronomia 21, 3–17.

Carrubba A., la Torre R., Di Prima A., Saiano F. (2003) Bio-agronomical behaviour and seed composition of some Apiaceae grown in a Mediterranean semi-arid environment, Agroindustria 2, 81–86.

Carrubba A., la Torre R., Saiano F., Alonzo G. (2006) Effect of sowing time on coriander performance in a semiarid Mediterranean environment, Crop Sci. 46, 437–447.

Catizone P., Marotti M., Toderi G., Tetenyi P. (1986) Coltivazione delle piante medicinali e aromatiche (In Italian) Patron, Bologna, Italy.

Connolly J., Goma H.C., Rahim K. (2001) The information content of indicators in intercropping research, Agr. Ecosyst. Environ. 87, 191–207.

De Mastro G., Marzi V., Ventrelli A. (1993) Influence of temporary intercropping on the productivity of Liquorice (*Glycyrrhiza glabra* L.), Acta Hortic. 344, 523–528.

De Wit C.T. (1960) On Competition, Verslagen van Landbouwkundige Onderzoekingen 66, 1–82.

Di Prima A., Carrubba A., Saiano F., Alonzo G., Calabrese I. (2000) Sicilian *Coriandrum sativum* seeds. Analysis of the volatile components by SPME/GC-MS, Proc. Int. Workshop "Gli aromi come marcatori della biodiversità", Ragusa Ibla, Italy, May, Co.R.Fi.La.C. – Ragusa (RG- Italy), pp. 23–24, in press.

Fordham R. (1983) Intercropping – What are the advantages? Outlook Agr. 12, 142–146.

Gomez K.A., Gomez A.A. (1984) Statistical procedures for agricultural research, John Wiley & sons Inc., New York, USA.

Hatcher P.E., Melander B. (2003) Combining physical, cultural and biological methods: prospects for integrated non-chemical weed management strategies, Weed Res. 43, 303–322.

Huang W., Luukkanen O., Johanson S., Kaarakka V., Raisanen S., Vihemaki H. (2002) Agroforestry for biodiversity conservation of nature reserves: functional group identification and analysis, Agroforest. Syst. 55, 65–72.

KAU (Kerala Agricultural University) (2002) Package of Practices Recommendations: Crops, 12th Edition, in: Jose A.I. et al. (Eds.), Kerala Agricultural University, Trichur, India.

Kenny G.J., Chapman R.B. (1988) Effects of an intercrop on the insect pests, yield and quality of cabbage, New Zeal. J. Exp. Agr. 16, 67–72.

Lawrence B.M. (1993) A planning scheme to evaluate new aromatic plants for the flavor and fragrance industries, in: Janick J., Simon J.E. (Eds.), New Crops, Wiley, New York, pp. 620–627.

Maffei M., Mucciarelli M. (2003) Essential oil yield in peppermint/soybean strip intercropping, Field Crops Res. 84, 229–240.

Maheshwari S.K., Sharma R.K., Gangrade S.K. (1996) Spatial arrangement in palmarosa - redgram intercropping system, Crop Res. 11, 141–144.

Marzi V. (1996) Risultati di un quinquennio di prove sulla coltivazione della Liquirizia (*Glycyrrhiza glabra* L.) in differenti condizioni pedoclimatiche (In Italian), Proc. Int. Conv. "Coltivazione e Miglioramento di Piante Officinali", Trento (Italy), pp. 73–95.

Mead R., Willey R.W. (1980) The concept of a "Land Equivalent Ratio" and advantages in yields from intercropping, Exp. Agr. 16, 217–228.

Morelli I. (1981) I principi attivi delle piante medicinali (In Italian), Edagricole, Bologna, Italy.

NRCS (2003) Keys to Soil taxonomy, Ninth Edition, USDA NRCS, Soil Survey Staff, Washington DC.

Paolini R. (1991) Determinazione dell'effetto competitivo tra piante erbacee. 1. Aspetti metodologici. (In Italian, with English abstract), Riv. Agronomia 25, 473–480.

Park S.E., Benjamin L.R., Watkinson A.R. (2002) Comparing biological productivity in cropping systems: a competition approach, J. Appl. Ecol. 39, 416–426.

Poggio S.L. (2005) Structure of weed communities occurring in monoculture and intercropping of field pea and barley, Agr. Ecosyst. Environ. 109, 48–58.

Pronk T.E., During H.J., Schieving F. (2007) Coexistence by temporal partitioning of the available light in plants with different height and leaf investments, Ecol. Model. 204, 349–358.

Rajeswara Rao B.R. (2002) Biomass yield, essential oil yield and essential oil composition of rose-scented geranium (*Pelargonium* species) as influenced by row spacings and intercropping with cornmint (*Mentha arvensis* L.f. *piperascens* Malinv. Ex Holmes), Ind. Crops Prod. 16, 133–144.

Rao M.R., Nair P.K.R., Ong C.K. (1998) Biophysical interactions in tropical agroforestry systems, Agroforest. Syst. 38, 3–50.

Rao M.R., Palada M.C., Becker B.N. (2004) Medicinal and aromatic plants in agroforestry systems, Agroforest. Syst. 61, 107–122.

Rees M., Bergelson J. (1997) Asymmetric light competition and founder control in plant communities, J. Theor. Biol. 184, 242–247.

Saka A.R., Haque I., Said A.N., Lupwayi N.X., El-Wakeel A. (1993) Forage legumes in Crop - Livestock systems in Sub-Saharan Africa, Environmental Sciences Working Document No. 24, International Livestock Center for Africa (INCA), Addis Ababa, Ethiopia.

Singh D., Kothari S.K. (1997) Intercropping effects on mustard aphid (*Lipaphis erysimi* Kaltenback) populations, Crop Sci. 37, 1263–1264.

Willey R.W. (1979a) Intercropping – its importance and research needs. Part I. Competition and yield advantages, Field Crops Abstr. 32, 1–10.

Willey R.W. (1979b) Intercropping – its importance and research needs. Part II. Agronomic relationship, Field Crops Abstr. 32, 73–85.

Willey R.W., Rao M.R (1980) A competitive ratio for quantifying competition between intercrops, Exp. Agr. 16, 117–125.