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Indices of bio-agroeconomic efficiency in intercropping systems of cucumber and lettuce in greenhouse

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Abstract

The adoption of alternative practices and the conservation of agricultural production are becoming a component of competitiveness in the market, because consumers are increasingly concerned about the ecological and social aspects of agricultural production. The intercropping of vegetables is a system of production that can contribute to a solution. Intercropping cucumber and lettuce has not yet been studied, but knowledge of the indices of competition and the agroeconomics of these vegetables can aid the management of intercropping systems. The objective of this study was to evaluate, by means of biological and agroeconomic indices, the competition between species and the profitability of intercropping cucumber and lettuce, as a function of population densities of cucumber plants, cultivars of lettuce, and times of lettuce transplantation after cucumber transplantation. Four experiments originated from two lettuce cultivars (crisp, cv. Verônica, and Iceberg, cv. Lucy Brown) intercropped with cucumber (cv. Hokushin) planted in one and two lines in the densities of 11 100 and 22 200 pl ha^{-1}, respectively, were conducted in two greenhouses, in a randomized complete block design, to evaluate four times of lettuce transplantation (0, 10, 20 and 30 days after the cucumber transplantation). In each block were planted four plots with lettuce in sole crop in these same transplantation times, besides a plot with cucumber in monocrop, in order to determine the indices of bio-agroeconomic efficiency of the intercropping systems. A combined analysis of variance over experiments was performed for all evaluated indices to identify any significant interaction between population densities of cucumber and lettuce cultivars, or between population densities of cucumber and times of lettuce transplantation after cucumber transplantation, or between lettuce cultivars and times of lettuce transplantation after cucumber transplantation, or among population densities of cucumber, lettuce cultivars and times of lettuce transplantation after cucumber transplantation. The intercropping systems of lettuce and cucumber produced bio-agroeconomic advantages over monocultures. The intercropping system with the highest bio-agroeconomic superiority obtained was when the lettuce 'Verônica' was intercropped with cucumber at 11 100 pl ha^{-1}, with both species transplanted on the same day.

Keywords: Efficiency indicators; *Lactuca sativa; Cucumis sativus;* Protected environment.
Abbreviations: A_aggressivity index; AYL_actual yield loss; B/CR_benefit/cost ratio; C_lettuce cultivars; CR_competitive ratio; D_population densities of cucumber; DACT_days after cucumber transplantation; EXP_Experiment; GR_gross return; IA_intercropping advantage; K_relative crowding coefficient; LER_land equivalent ratio; LTACT_lettuce transplantation after cucumber transplantation; MMA_modified monetary advantage; NPM_net profit margin; NR_net return; SDCT_same day of cucumber transplantation; T_times of lettuce transplantation after cucumber transplantation.

Introduction

Olericulture has incorporated various technologies in the last two decades to increase the productivity and quality of crops and to reduce the seasonality of supply and the environmental impact (Cecílio Filho et al., 2011). The emphasis of modern agriculture is the sustainability of production, which includes aspects such as the conservation of soil and water, increasing biological diversity, and appropriate management to ensure stability of food supply and a reasonable quality of life, i.e. a healthy and safe environment (Oliveira et al., 2004). Producers are currently concerned with the use of alternative production systems for increasing profitability and improving the quality of life in rural areas whilst preserving the long-term productive capacity of the soil (Ehlers, 1999). The adoption of good agricultural practices and the conservation of agricultural production tend to become components of competitiveness in the market (Hobbs, 2003), because consumers are increasingly concerned about the ecological and social aspects of agricultural production. Among the production systems that can contribute to this objective is the intercropping of vegetables, in which two or more plantings and/or species are simultaneously grown in the same area but not necessarily harvested at the same time, i.e. they cohabit at least a significant portion of the crop cycle (Mousavi and Eskandari, 2011). The efficiency of intercropping depends directly on the cropping system and the cultures involved, which must complement one another (Bezerra Neto et al., 2003; Cecílio Filho et al., 2011). The careful choice of the component crops and their associated times of establishment are thus extremely important for maximally exploiting the advantages of intercropping systems, given that the period of coexistence between the species influences crop productivity (Cecílio Filho and May, 2002). The advantages of intercropping will be more apparent when the cultures have different requirements for the available resources, in quantity, quality, and time of demand. The efficiency of intercropping can be evaluated in different ways. The amount of food produced per unit of area is likely to be of most interest to producers. Economic analysis can also evaluate the operational profit achieved by the system (Cecílio Filho et al., 2013). The land equivalent ratio (LER) is an index for comparing intercropped and individual crops commonly used by researchers. This ratio was defined by Willey (1979) as the relative area of land under monoculture that would provide the productivity achieved by intercropping. The index expresses the production of food per unit area and reflects the interaction of the component crops under the given environmental (above- and belowground) resources (Bezerra Neto et al., 2012). It comprises the sum of the relationships between the yields obtained by each intercrop and their respective yields obtained in monocultures.

Other indices or indicators can be used to evaluate intercropping systems, such as biological-agronomic and competitive indices (relative crowding coefficient, aggressivity, competitive ratio, and actual yield loss) that were developed to describe the competitive advantages of the systems (Banik, 1996; Odulaja, 1996; Adhikary and Sarkar, 2000; Banik et al., 2000; Tahir et al., 2003; Ghosh, 2004; Banik et al., 2006; Dhima et al., 2007; Wahla et al., 2009; Nedunchezhiyan et al., 2010; Sheoran et al., 2010). These indices are important for the evaluation and characterization of intercropping systems because they reflect the influence of the competition between the cultures of the system. Their values can thus help plan the association between crops and their management (Cecílio Filho et al., 2013).

The quantitative evaluation (productivity) provided by LER and the biological (competitive) indicators for determining which vegetables to intercrop, however, must be accompanied by studies of economic feasibility, which address the quality and price of the vegetables produced. All quantitative and qualitative aspects of a vegetable grown in an intercropping system are thereby considered, increasing the reliability of recommendations of particular combinations. Furthermore, economic analyses can confirm or reject the advantages of intercropping identified by the agronomic and competitive indices (Rezende et al., 2005). An economic analysis of intercropped vegetables is also important because physical results alone cannot guarantee the success of a cultivation technique.

The objective of this study was to evaluate, by means of biological and agroeconomic indices, the competition between species and the profitability of intercropping lettuce (*Lactuca sativa*) and cucumber (*Cucumis sativus*) as functions of population densities of cucumber plants, lettuce cultivars, and relative times of lettuce transplantation after cucumber transplantation.

Results

All the assumptions (homoscedasticity, normality, and additivity) required in the univariate ANOVAs of residuals of the analysed indices were tested and are shown in Table 1. The assumptions of normality and additivity were not accepted in the ANOVAs of the relative crowding coefficients of lettuce (K_l), cucumber (K_c), and the system (K) and of the competitive ratios of lettuce (CR_l), cucumber (CR_c) and the system (CR), nor was the assumption of homoscedasticity for the CRs of cucumber and the intercropping system ($P < 0.05$). The assumption of normality was also violated for the intercropping advantage of lettuce (IA_l) and modified monetary advantage (MMA), and of the homoscedasticity for IA of lettuce only ($P < 0.05$). All the assumptions required by the univariate ANOVAs were satisfied for the remaining indices ($P > 0.05$). The deviations between treatments for these indices were thus acceptably homogeneous (Brown-Forsythe F test) and normally distributed (Kolmogorov-Smirnov D test). Tukey's F test for additivity indicated that the differences between two treatments were similar in different blocks for those variables, indicating no interaction between blocks and treatments.

Bio-agronomic benefits

A significant triple interaction was observed for land equivalent ratio of lettuce (LER_l) among studied factors: population densities of cucumber (D), lettuce cultivars (C), and times (T) of lettuce transplantation after cucumber transplantation - LTACT (Table 2 and Fig. 1A). In the intercrops with 11 100 and 22 200 plants per hectare of cucumber, values LER_l of 'Verônica' and 'Lucy Brown' were maximum when both cultivars were transplanted on the same day that the cucumber, and minimum when these same lettuce cultivars were transplanted at 30 days after the cucumber (Table 2 and Fig. 1A).

Within each time of lettuce transplantation and in each group of cultivars, the highest values of LER_l were obtained with the cucumber density of 11100 pl ha^{-1}, except when the lettuce was transplanted 10 days after cucumber transplantation (DACT), when the highest value of LER_l was obtained with the cucumber density of 22 200 pl ha^{-1} (Table 2). Higher values of LER_l were observed for ‘Lucy Brown’ when it was intercropped with the smaller cucumber density.
In the smaller cucumber density, no significant difference was observed between the values of LER_l of ‘Verônica’ and ‘Lucy Brown’ at different times of LTACT. In the larger cucumber density, though, the lettuce cultivars differed significantly, with ‘Verônica’ performing better when the lettuce was transplanted at 0, 10, and 20 DACT. ‘Lucy Brown’ had the higher LER_l when transplanted 30 DACT (Table 2).

For land equivalent ratio of cucumber (LER_c) and LER of the system, a significant double interaction was observed between lettuce cultivars and cucumber densities, with the cultivars differing only in the larger cucumber density, and ‘Verônica’ performed better than ‘Lucy Brown’ (Table 3). Moreover, an analysis of the effect of cucumber density on the values of LER_c and LER of the system indicated no difference between the values when ‘Verônica’ was used. With ‘Lucy Brown’, however, both LER_c and LER of the system were higher in the smaller cucumber density of 11100 pl ha^{-1} (Table 3). LER_c increased with a delay in lettuce transplantation relative to cucumber transplantation, with an estimated maximum value of 1.025 when the lettuce was transplanted 30 DACT and at least 1.000 when the lettuce was transplanted on the same day of cucumber transplantation (SDCT), (Fig. 1B). This increase was approximately 2.5%. On the other hand, LER decreased with a delay in lettuce transplantation. The estimated maximum LER was 1.700 when the lettuce was transplanted on the SDCT, and the minimum value was 1.324 when the lettuce

Table 1. Statistical significance of indices of competition and efficiency of intercropped cucumber and lettuce.

Competition/ Efficiency Indices	Brown-Forsythe *F* test	Kolmogorov-Smirnov *D* test	Tukey´s *F* test	Assumptions for RCBD
LER_l	0.1205	>0.1500	0.4765	met
LER_c	0.4955	>0.0526	0.4845	met
LER	0.2964	>0.1500	0.5785	met
K_l	0.3398	<0.0100	<0.0001 *	not met
K_c	0.5080	<0.0100	<0.0001	not met
K	0.2414	<0.0100	0.0126	not met
CR_l	0.4193	<0.0100	0.0002	not met
CR_c	0.0274	<0.0100	<0.0001	not met
CR	0.0241	<0.0100	<0.0001	not met
A_l	0.5232	0.0618	0.3650	met
A_c	0.5232	0.0618	0.3650	met
AYL_l	0.1173	>0.1500	0.4726	met
AYL_c	0.4960	>0.0507	0.4871	met
AYL	0.4712	>0.0581	0.6520	met
IA_l	<0.0001	0.0273	0.3340	not met
IA_c	0.4967	0.0516	0.4864	met
IA	0.4812	0.0596	0.3797	met
GR	0.7668	>0.1500	0.7102	met
NR	0.7668	>0.1500	0.5050	met
MMA	0.4427	0.0542	0.6139	not met
B/CR	0.3389	>0.1500	0.3842	met
NPM	0.6226	>0.1500	0.7436	met

*Values less than 0.05 were considered significant. Abbreviations: RCBD, randomized complete-block design; land equivalent ratios of lettuce (LER_l), cucumber (LER_c), and the system (LER); relative crowding coefficients of lettuce (K_l), cucumber (K_c), and the system (K); competitive ratios of lettuce (CR_l), cucumber (CR_c), and the system (CR); aggressivities of lettuce (A_l) and cucumber (A_c); actual yield losses of lettuce (AYL_l), cucumber (AYL_c), and the system (AYL); intercropping advantages of lettuce (IA_l), cucumber (IA_c), and the system (IA); gross return (GR); net return (NR); modified monetary advantage (MMA); benefit/cost ratio (B/CR); and net profit margin (NPM).

was transplanted 30 DACT (Fig. 1B). This decrease was approximately 22.1%. ANOVAs were not performed for the Ks and CRs, because of violations in the ANOVA assumptions (Figs 1 C, D). The mean values of K_l were positive and less than unity, the mean values of K_c were negative, and the mean values of K were also negative (Table 3). The lettuce cultivars were not significantly affected by cucumber density and did not statistically differ in the aggressivity (A) of the crops (Table 3). Aggressivity of cucumber (A_c), however, increased with increasing times of LTACT, whilst aggressivity of lettuce (A_l) decreased with delayed lettuce transplantation (Fig. 1E). The increase in A_c and the decrease in A_l were approximately 7.5%. These results indicate that cucumber is the dominant crop and lettuce is the dominated crop. A significant triple interaction was observed for actual yield loss of lettuce (AYL_l) among lettuce cultivars, cucumber densities, and times of LTACT (Table 2 and Fig. 1F). The values of AYL_l for 'Verônica' in both cucumber densities and for 'Lucy Brown' in the larger cucumber density decreased with a delay in lettuce transplantation but remained stable for 'Lucy Brown' in the smaller cucumber density when the lettuce was transplanted on the SDCT. The best values of AYL_l were recorded for the cucumber densities with 'Verônica' (Fig. 1F). Within each time of lettuce transplantation, higher values of AYL_l were observed with 'Verônica' in the smaller cucumber density, except when the lettuce was transplanted 10 DACT (Table 2). The highest values of AYL_l for 'Lucy Brown' also occurred in the smaller cucumber density (Table 2). No significant differences were observed in AYL_l between the lettuce cultivars in the smaller density, except when the lettuce was transplanted 30 DACT, with 'Lucy Brown' performing better than 'Verônica'. In the larger cucumber density with lettuce transplanted 0, 10, and 20 DACT, however, AYL_l differed significantly between lettuce cultivars, with 'Verônica' performing better than 'Lucy Brown'. 'Lucy Brown' had performance similar to 'Verônica' 30 DACT (Table 2). Only dual interactions in the actual yield loss of cucumber (AYL_c) and AYL of the intercropping system were observed between the lettuce cultivars and the cucumber densities, with the lettuce cultivars differing only in the larger cucumber density and with 'Verônica' performing better than 'Lucy Brown'. The only difference in the AYLs between the cucumber densities was found in 'Lucy Brown', with higher values of AYLs observed in the smaller density (Table 3). AYL_c increased with a delay in lettuce transplantation, reaching a maximum when the lettuce was transplanted 30 DACT and a minimum when the lettuce was transplanted on the SDCT (Fig. 1G), representing an increase of approximately 3.5%. The regression equation for AYL as a function of the times of LTACT could not be adjusted (Fig. 1G).ANOVAs were not performed for intercropping advantage of lettuce (IA_l) because the assumptions were violated. Consequently, the effects of lettuce cultivar, cucumber density and times of lettuce transplantation could not be determined (Fig. 1H). The mean values of IA_l were negative for 'Verônica', 'Lucy Brown', and both cucumber densities. Only dual interactions in the intercropping advantage of cucumber (IA_c) and IA of the intercropping system were observed between the cultivars of lettuce and the cucumber densities. The cultivars differed only in the larger cucumber density, with 'Verônica' performing best (Table 3). Higher (positive) values of IA_c or IA were observed for 'Lucy Brown' with the smaller density. IA_c or IA as a function of the cucumber densities in the intercropping system did not differ significantly for 'Verônica'. No adjustments were obtained for the regression equations for IA_c and IA as a function of times of LTACT (Fig. 1H).

Economic benefits

No significant interactions among the treatment factors were identified for the economic variables (Table 4). Significant differences in the gross return (GR), however, were found

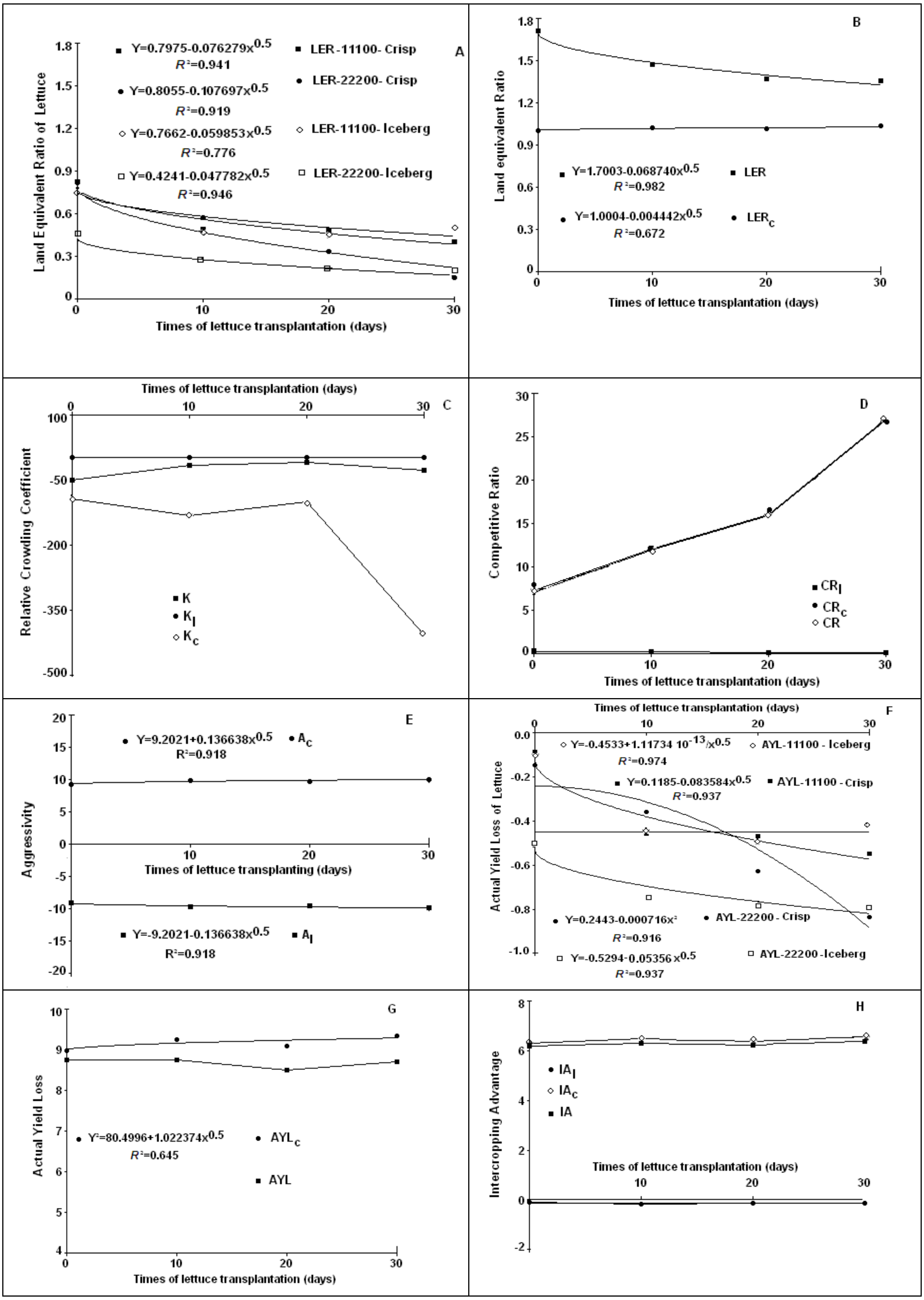


Fig 1. Response models for (A) land equivalent ratio of lettuce (LER_l); (B) land equivalent ratios of cucumber (LER_c) and the system (LER); (C) relative crowding coefficients of lettuce (K_l), cucumber (K_c), and the system (K); (D) competitive ratios of lettuce (CR_l), cucumber (CR_c), and the system (CR); (E) aggressivities of lettuce (A_l) and cucumber (A_c); (F) actual yield loss of lettuce (AYL_l); (G) actual yield losses of cucumber (AYL_c) and the system (AYL); and (H) intercropping advantages of lettuce (IA_l), cucumber (IA_t), and the system (IA) as a function of lettuce transplantation times after cucumber transplantation.

Table 2. Mean land equivalent ratios of lettuce (LER_l) and actual yield losses of lettuce (AYL_l) under different cultivars of lettuce, cucumber densities, and times of lettuce transplantation after cucumber transplantation.

Times of lettuce transplantation (days)	LER_l				AYL_l			
	Crisp lettuce cv. Verônica		Iceberg lettuce cv. Lucy Brown		Crisp lettuce cv. Verônica		Iceberg lettuce cv. Lucy Brown	
	Cucumber densities (plants/ha)							
	11 100	22 200	11 100	22 200	11 100	22 200	11 100	22 200
0	0.823 aA *	0.762 bC	0.810 aA	0.440 bD	- 0.09 aA	- 0.15 bC	- 0.10 aA	- 0.51 bD
10	0.488 bA	0.574 aC	0.518 aA	0.238 bD	- 0.46 bA	- 0.36 aC	- 0.45 aA	- 0.74 bD
20	0.475 aA	0.329 bC	0.492 aA	0.198 bD	- 0.47 aA	- 0.63 bC	- 0.49 aA	- 0.78 bD
30	0.404 aA	0.148 bD	0.455 aA	0.190 bC	- 0.55 aB	- 0.84 bD	- 0.42 aA	- 0.79 bD

* Different lowercase letters within row inside each lettuce cultivar indicate significant difference between population densities of cucumber in each time of transplantation and different uppercase letters within row at the same cucumber density indicate significant difference between groups of lettuce cultivars in each times of transplantation of the crops by Tukey's tests at 5% probability.

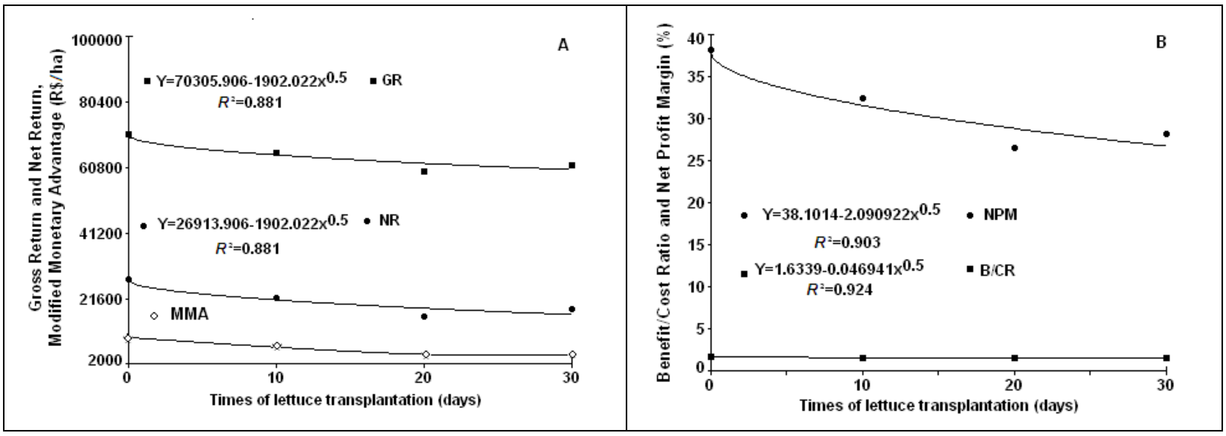


Fig 2. Response models for (A) gross return (GR), net return (NR), and modified monetary advantage (MMA) and (B) benefit/cost ratio (B/CR) and net profit margin (NPM) as a function of lettuce transplantation times after cucumber transplantation.

between lettuce cultivars and cucumber densities. 'Verônica' had higher values of GR in the smaller cucumber density. Significant differences in the net return (NR) occurred only between cucumber densities, with a higher mean value in the smaller density (Table 4). These two variables decreased with a delay in lettuce transplantation. GR and NR were highest when the lettuce was transplanted on the SDCT and lowest when the lettuce was transplanted 30 DACT (Fig. 2A). These decreases were approximately 14.8 and 38.7%, respectively. ANOVAs were not performed for modified monetary advantage (MMA) because the assumption of the normality was violated (Table 1), consequently, the effects of lettuce cultivars, cucumber densities and times of lettuce transplantation could not be determined (Table 4 and Fig. 2A). The mean values of the modified monetary advantage (MMA) were positive for 'Verônica', 'Lucy Brown', and both cucumber densities. The regression equation for MMA as a function of the times of LTACT could not be adjusted (Fig. 2A). The benefit/cost ratio (B/CR) and net profit margin (NPM) did not differ significantly between lettuce cultivars and cucumber densities, i.e. the cultivars of lettuce and the cucumber densities behaved similarly for these variables (Table 4). These variables, though, decreased with increasing times of LTACT (Fig. 2B).

Discussion

The ANOVA assumptions for homoscedasticity, normality, and additivity were not violated in the analyses of most bio-agroeconomic indices of the component crops or intercropping systems as a function of the times of LTACT, lettuce cultivars, and cucumber densities. Some assumptions, though, were violated in the analyses of the Ks, IA_l and CRs, of lettuce, cucumber, and the system. The indices of each plot were acquired by homogeneous standardization for individual crops, considering the average value of the individual crops over blocks in the denominator of the indices, as recommended by Bezerra Neto and Robichaux (1997) and Federer (2002). This standardization avoided the possibility of complex distributions of the sum of the ratios that define the LERs and other indices, rendering the ANOVAs of such indices non-representative, which could lead to errors in the validity of the assumptions of normality, homoscedasticity, and additivity. Moreover, the standardization also validated the estimated models, statistically depicting the performance of these indices as a function of the times of LTACT, lettuce cultivars, and cucumber densities.

Productive viability of intercrops

LER_l decreased with increasing times of LTACT (Fig. 1A), due to increased interspecific competition for environmental resources, especially light. The longer the period between transplantations, the larger were the cucumber plants when the lettuce was transplanted. Consequently, less solar radiation was available to the lettuce that grew under the cucumber canopy. Changes in the light spectrum from shading affect the morphogenic (Beets 1982; Varlet-Grancher and Gautier, 1995) and physiological processes (Keating and Carberry, 1993) of the shaded species, accounting for the lower accumulation of dry matter in the late-transplanted lettuce and hence the lower values of LER_l. The highest

Table 3. Mean relative crowding coefficients of lettuce (K_l), cucumber (K_c), and the system (K); aggressivities of lettuce (A_l) and cucumber (A_c); land equivalent ratios of lettuce (LER_l), cucumber (LER_c), and the system (LER); actual yield losses of lettuce (AYL_l), cucumber (AYL_c), and the system (AYL); intercropping advantages of lettuce (IA_l), cucumber (IA_c), and the system (IA); and competitive ratios of lettuce (CR_l), cucumber (CR_c), and the system (CR) under different lettuce cultivars, cucumber densities and times of lettuce transplantation.

	K	K_l	K_c	A_l	A_c	LER	LER_c	AYL_c	AYL	IA_l	IA_c	IA	CR_l	CR_c	CR
						11 100 22 200	11 100 22 200	11 100 22 200	11 100 22 200		11 100 22 200	11 100 22 200			
Lettuce cultivars															
Verônica	- 36.72	0.20	- 333.10	- 9.77 a	9.77 a	1.56 aA 1.51 aA*	1.01 aA 1.05 aA	9.12 aA 9.53 aA	8.72 aA 9.04 aA	- 0.21	6.39 aA 6.68 aA	6.11 aA 6.54 aA	0.09	20.76	20.85
Lucy Brown	- 14.94	0.26	- 34.10	- 9.53 a	9.53 a	1.64 aA 1.19 bB	1.07 aA 0.92 bB	9.74 aA 8.25 bB	9.38 aA 7.55 bB	- 0.14	6.83 aA 5.78 bB	6.70 aA 5.63 bB	0.20	10.09	10.29
Cucumber density															
11 100 plants/ha	- 38.55	0.35	- 300.70	- 9.81 a	9.81 a	–	–	–	–	- 0.20	–	–	0.19	6.53	6.72
22 200 plants/ha	- 13.11	0.11	- 66.50	- 9.49 a	9.49 a	–	–	–	–	- 0.14	–	–	0.08	24.33	24.41
Transplantation times (days)															
0	- 50.03	0.68	- 93.40	- 9.18	9.18	1.71 †	1.00	8.96	8.75	- 0.13	6.28	6.15	0.24	6.97	7.21
10	- 16.33	0.10	- 132.10	- 9.74	9.74	1.47	1.02	9.24	8.74	- 0.20	6.47	6.27	0.12	11.90	12.02
20	- 9.63	0.07	- 100.00	- 9.69	9.69	1.37	1.01	9.09	8.50	- 0.17	6.37	6.20	0.10	15.90	16.00
30	- 27.34	0.06	- 408.90	- 9.99	9.99	1.35	1.03	9.34	8.69	- 0.18	6.55	6.37	0.10	26.93	27.03

*Different lowercase letters within row indicate significant difference between population densities of cucumber in each lettuce cultivar and different uppercase letters within column indicate significant difference between lettuce cultivars in each cucumber density by Tukey's tests at 5% probability.† The mean values of bio-agronomic indices in the times of lettuce transplantation cannot be compared because the transplantation times is a 'quantitative factor', and therefore is recommended the adjustment of a response function to this data by regression.

Table 4. Mean gross return (GR), net return (NR), modified monetary advantage (MMA), benefit/cost ratio (B/CR), and net profit margin (NPM) under different lettuce cultivars, cucumber densities, and times of lettuce transplantation.

	GR (US$/ha)	NR (US$/ha)	MMA * (US$/ha)	B/CR	NPM (%)
Lettuce cultivars	**				
Verônica	39,410.00 a	13,057.08 a	4,711.35	1.50 a	31.76 a
Lucy Brown	36,193.84 b	11,344.51 a	2,829,72	1.47 a	30.73 a
Cucumber densities					
11 100 plants/ha	44,055.16 a	13,774.51a	3,270.70	1.51 a	31.96 a
22 200 plants/ha	31,548.68 b	10,627.08 b	4,270.38	1.45 a	30.54 a
Times of lettuce transplantation (days)		†			
0	41,554.00	15,952.87	5,638.71	1.64	38.17
10	38,358.80	12,757.67	4,096.17	1.49	32.33
20	35,075.87	9,474.74	2,633.45	1.38	26.44
30	36,219.00	10,617.88	2,713.85	1.41	28.05

*ANOVAs were not performed for MMA due to violations of the assumptions.** Means with different lowercase letters within a column indicate significance by Tukey's tests at 5% probability. The mean values of economic indices in the times of lettuce transplantation cannot be compared because the transplantation times is a 'quantitative factor', and therefore is recommended the adjustment of a response function to this data by regression.

values of LER_l were obtained when lettuce was intercropped with cucumber at the lower density (11 100 pl ha^{-1}) in both groups of lettuce cultivars. This result is due to the lower interspecific competition between species compared to their association in the larger cucumber density. Moreover, the small increase in LER_c with increasing time of LTACT (Fig. 1B) was due to the vertical growth of the cucumber plants and to their leaves being above the lettuce without suffering competition for solar radiation. These higher values of LER_c indicated that cucumber was more competitive than lettuce and thus dominant. All values of LER of the systems were larger than unity, despite the decrease in LER with increasing time of LTACT (Fig. 1B), indicating the advantages of intercropping over monocultures in the use of environmental resources (Tosti et al., 2010). As stated by Jensen (1996), the potential advantages of intercropping are determined by the degree of complementarity of resource use between the component species. The average values of K were higher for lettuce than for cucumber, indicating cucumber's dominance in the mixture. This result was not unexpected because cucumber is usually more competitive than lettuce. K_cK_l was less than unity in all intercropped systems, indicating a yield disadvantage and showing that the species produced less than the expected yields (Willey and Rao, 1980; Ghosh, 2004). This result, however, disagrees with the LERs of the intercrops, which were greater than unity. The mean values of CR_c in the different treatment factors were higher than the mean values of CR_l. In the groups with 'Verônica' and 'Lucy Brown', CR_c was about 231 and 51 times higher, respectively, than CR_l. In the smaller and larger cucumber densities, CR_c was about 34 and 304 times higher, respectively, than CR_l. Between the first and final lettuce transplantations, CR_c was 29 and 269 times higher, respectively, than CR_l. These results show that cucumber was more competitive than lettuce (Table 3) and were confirmed by the values of LER_l and A_l (with a negative sign as the dominated culture), which decreased with increasing time of LTACT. LER_c and A_c (with a positive sign as the dominant culture) increased with increasing time of LTACT (Fig. 1). According to Aasim et al. (2008), the CR index expresses the competitive ability of crops better than do K and A. LER, CR, and A identified a very small interference of lettuce on cucumber. The dominance of cucumber expressed by these ratios increased the later lettuce was transplanted (Fig. 1A, B, D, E) and showed how cucumber used the available resources better than did lettuce. AYL_l varied similarly to LER_L (Fig. 1F). These indexes were negative in all treatment factors studied. AYL_c and AYL were positive and higher than AYL_l. This superiority can be attributed to the aggressiveness of cucumber and other factors such as morphology and physiology and especially the position of its photosynthetic canopy above the lettuce leaves, which allowed it to better use the photosynthetically active radiation. AYL_l, then, was offset by AYL_c, providing positive values of AYL and indicating the advantage of the intercropping system. AYL, as LER, was calculated based on crop yields in the intercropping system compared to the respective individual crops. AYL, though, considers the ratio of the crops in an area and so is superior to LER for expressing the advantage of the intercropping system (Banik et al., 2000; Dhima et al., 2007). The negative values of IA_l and the positive values of IA_c and IA followed the same trend as AYL_l, AYL_c, and AYL, clearly indicating the advantage of intercropping lettuce and cucumber with these lettuce cultivars, cucumber densities, and times of LTACT. IA, in addition to indicating agronomic advantage, can also be considered as an indicator of the economic viability of intercropped systems (Aasim et al., 2008). The results for IA in this study indicated that all intercropping systems tested were advantageous.

Economic advantage

Regardless of the treatment factors tested, all intercropping systems recorded economic viability, corroborating the results of Cecílio Filho et al. (2013) with lettuce intercropped with tomato. The differences in GR between the lettuce cultivars and between cucumber densities and the differences in NR between cucumber densities were due to the yield and quality of the products produced by the intercropped systems. MMA (based on LER) was positive in all intercropped systems, indicating not only an economic advantage but also a definite advantage in productivity. The benefit/cost ratio (B/CR) and the net profit margin (NPM) confirmed these results. LER, CR, AYL, and IA illustrated the agronomic-biological superiority of the intercropping system with Verônica in the smaller cucumber density at the first time of LTACT. This superiority translated to a higher economic advantage.

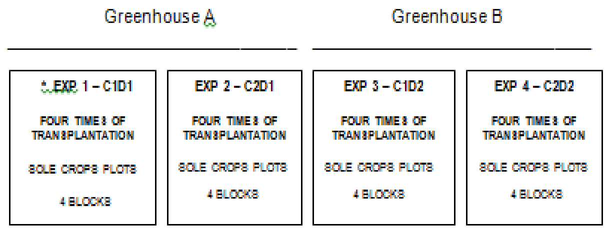
Materials and Methods

Site and climate

Four experiments were carried out simultaneously on 27 Aug 2005 in two greenhouses, one beside the other, with two experiments in each greenhouse of 614.4 m^2, both with 3-m arched ceilings, at the São Paulo State University, Jaboticabal, São Paulo, Brazil, at an altitude of 575 m, latitude of 21°15'22" S, and longitude of 48º15'58" W. The experiments had the same duration and ended on Nov 22, 2015. The climate of Jaboticabal is classified as subtropical with rainy summers and relatively dry winters. The maximum, mean, and minimum air temperatures during the trial period were 30.8, 23.2, and 17.5 °C, respectively, and a mean relative humidity of 40% was maintained by a hygrometer in a meteorological shelter in the centre of the greenhouses at a height of 1.5 m. The soil used was an Oxisol.

Experimental procedure

These four experiments were conducted in two greenhouses because there was no space to put all the treatments resulting from the combinations of the levels of three factors in a single greenhouse, because it was small. Thus, each experiment was outlined in a randomized complete block design with four replications in order to better control the sources of variation (shading, luminosity, temperature, etc.) of spaces occupied by treatments inside the greenhouse, since they were open at your sides. The studied factors were: two population densities of cucumber (D = 11 100 and 22 200 pl ha^{-1}), two lettuce cultivars (C = Verônica, Crisp group and Lucy Brown, Iceberg group) and four times (T) of lettuce transplantation (0, 10 20 and 30 days after cucumber transplantation). In each block were planted four plots with lettuce in sole crop in these same times of transplantation, besides a plot with cucumber in monocrop, in order to determine the indices of bio-agroeconomic efficiency of the intercropping systems. The distribution of these experiments (EXP) in the greenhouses and the factors studied in each of them are shown below:



***EXP 1 – C1D1** – Lettuce cultivar 'Verônica' (C1) intercropped with cucumber in the population density of 11 100 pl ha^{-1} (D1).

EXP 2 – C2D1 – Lettuce cultivar 'Lucy Brown' (C2) intercropped with cucumber in the population density of 11 100 pl ha^{-1} (D1).

EXP 3 – C1D2 – Lettuce cultivar 'Verônica' (C1) intercropped with cucumber in the population density of 22 200 pl ha^{-1} (D2).

EXP 4 – C2D2 – Lettuce cultivar 'Lucy Brown' (C2) intercropped with cucumber in the population density of 22 200 pl ha^{-1} (D2).

The experimental units consisted of 21 and 40 lettuce plants in the treatments with the 'Lucy Brown' and 'Verônica' lettuces, respectively, with five and 10 plants of cucumber in the treatments with one and two rows of plants, respectively, in the beds. The total area of each experimental unit in all treatments was 2.75 m^2 (1.10 x 2.50 m). All plants except the first and last plants of each row were harvested for evaluating the characteristics of the lettuces and cucumbers. In all experiments the lettuce has been harvested 42 DACT and the cucumber when it reached 25 cm in length.

Management and cropping systems

The soil of the experimental area for all experiments was prepared by ploughing and subsequent lifting of the seedbeds. The soil was sampled from the 0-0.20 m layer for evaluating fertility. The soil was not limed, because the base saturation of the soil (75 and 85% in the two greenhouses) was suitable for the cultivation of cucumber and lettuce, as recommended by Trani et al. (1997a, b). All treatments were fertilized with N, P, and K at rates recommended by Trani et al. (1997a) for cucumbers, because cucumbers have a higher demand than lettuce for nutrients. The fertilizations were made separately for each crop, based on the recommendations of Trani et al. (1997a, b). In the planting of cucumber in sole crop, were applied 40, 200 and 100 kg ha^{-1} of N, P_2O_5 and K_2O, respectively (Trani et al., 1997a), while for sole crop of lettuce were applied the same amounts of N and P and 50 kg ha^{-1} of K_2O, as recommended by Trani et al. (1997b). In the intercropping systems, the doses of N, P and K corresponded to those applied to the cucumber. In top-dressing, both sole crop and intercropping, the fertilizations were made separately for each crop, based on the recommendations of Trani et al. (1997a, b). The experiments were irrigated by drip-tubes. The management of pests and diseases in the crops was done using products registered for both crops, such as the insecticide tiametoxam and the fungicides: azoxystrobin and difenoconazole. After the lettuce harvest, the products used were the insecticides avermectin, thiamethoxam and lufenuron, and the fungicides chlorothalonil, azoxystrobin, and difenoconazole.

Cucumber seedlings were grown in 128-cell polystyrene trays and were transplanted on the same day when shoots were expanded. The spacing for the cucumber crop with one row was 1.80 m between rows and 0.50 m between plants in the row. For the cucumber crop with two rows of plants in the bed, the spacing between double rows was 1.20 m, 0.60 between rows, and 0.50 m between plants in the row. Each plant was secured to a rod with plastic tape vertically, and auxiliary branches were thinned to a height of 0.40 m. The buds were thereafter allowed to develop fixed to wires arranged parallel to the ground and spaced at 0.40 m. The apical meristems were removed when the plants had two fruits and three shoots. The main stems were removed when the plants were approximately 2 m tall and had 19 nodes. The lettuce seedlings were grown in 288-cell trays and were transplanted at the four-leaf stage with spacings of 0.40 x 0.35 m and 0.25 x 0.25 m for 'Lucy Brown' and 'Verônica', respectively. The cucumbers were harvested three times a week when they were with 0.20-0.25 m in length, and the lettuces were harvested on a single day when the treatments attained the commercial standards (head formation for 'Lucy Brown' and size for 'Verônica').

Assessed indices

The productivity of lettuce (fresh weight of shoots) and the yield of cucumbers (0.20-0.25 m in length with no physical damage and few bends or with bends of less than 30° to the longitudinal axis) were evaluated. The competitive and bio-agroeconomic efficiencies of the component crops and intercropping systems were determined by the following indices.

a) Land equivalent ratio (LER) - accurately evaluates the greater biological efficiency of intercropping and was calculated in this study as (Willey, 1979):

$$LER = LER_c + LER_l$$

Where LER_c and LER_l represent the LER of individual cucumber and lettuce crops, respectively. A comparison of these individual indices can indicate the relative competitive ability of the component crops. Thus, $LER_c = Y_{cl}/Y_c$, where Y_{cl} is the yield of intercropped cucumbers and lettuce, and Y_c is the mean yield of monocropped cucumbers from all blocks; and $LER_l = Y_{lc}/Y_l$, where Y_{lc} is the yield of intercropped lettuce and cucumbers, and Y_l is the mean yield of monocropped lettuce from all blocks (Bezerra Neto and Robichaux, 1997; Federer, 2002). Unity is the critical value. When LER is >1, intercropping favours the growth and yield of the component crops. When LER is <1, intercropping negatively affects the growth and yield of the crops (Xu et al., 2008).

b) The relative crowding coefficient (K) was suggested by De Wit (1960) and is calculated as:

$$K = K_c K_l$$

$$K_c = Y_{cl} Z_{lc} / (Y_c - Y_{cl}) Z_{cl}$$

$$K_l = Y_{lc} Z_{cl} / (Y_l - Y_{lc}) Z_{lc}$$

Where K_c and K_l are the coefficients for cucumber and lettuce, Z_{cl} is the proportion of cucumber plants intercropped with lettuce plants, and Z_{lc} is the proportion of lettuce plants intercropped with cucumber plants. When K_cK_l is equal to, less than, or greater than unity, the intercropping system has no advantage, a disadvantage, or an advantage, respectively (Bhatti et al., 2006; Chaichi et al., 2007).

c) The competitive ratio (CR) was obtained with the formula suggested by Willey and Rao (1980):

$CR = CR_c + CR_l$

$CR_c = [(LER_c/LER_l) \times Z_{lc}/Z_{cl})]$

$CR_l = [(LER_l/LER_c) \times Z_{cl}/Z_{lc})]$

Where CR is the ratio for the intercropped system, CR_c is the ratio for intercropped cucumbers, and CR_l is the ratio for intercropped lettuce. CR_c and CR_l were obtained from the aggressivity index (see below). CR simply represents the ratio of the individual LERs of the two component crops and takes into account the proportions of the crops in which they are initially sown. It is an alternative means of evaluating the competition between different crops and provides a better measure of competitive ability of the component crops. That is, CR provides the exact degree of competition by indicating the number of times in which the dominant species is more competitive than the dominated species (Eskandari and Ghanbari, 2010; Egbe et al., 2010). CR also has some advantages over the K and A indices; in an intercropping system, the crop with the higher CR makes better use of the environmental resources.

d) Aggressivity (A) is an index that indicates how much the relative increase in the yield of one component crop is greater than that of the other crop of an intercropping system. The index was proposed by McGilchrist and Trenbath (1971) to measure the dominance of one crop over another and is calculated as:

$$A_c = \left(Y_{cl}/Y_c Z_{cl}\right) - \left(Y_{lc}/Y_l Z_{lc}\right)$$

$$A_l = \left(Y_{lc}/Y_l Z_{lc}\right) - \left(Y_{cl}/Y_c Z_{cl}\right)$$

Both crops are equally competitive when A is zero. When A is positive, the crop with a positive signal is dominant, and the crop with a negative signal is dominated.

e) Actual yield loss (AYL) is an index proposed by Banik (1996) and is calculated as:

$AYL = AYL_c + AYL_l$

$AYL_c = \{[(Y_{cl}/Z_{cl})/(Y_c/Z_c)] - 1\}$

$AYL_l = \{[(Y_{lc}/Z_{lc})/(Y_l/Z_l)] - 1\}$

Positive or negative values of AYL indicate the advantage or disadvantage of intercropping, i.e. it provides a quantitative assessment of the advantage/disadvantage accumulated in any system of intercropping when the primary purpose is to compare yield on a per-plant basis (Dhima et al., 2007; Yilmaz et al., 2008). The magnitudes of the individual AYLs of the component crops in an intercropped system reflect the nature of the competition between and within the crops.

f) Intercropping advantage (IA) is another index used by Banik et al. (2000), Dhima et al. (2007), and Yilmaz et al. (2008), adapted for this study as:

$IA = (P_c \times AYL_c) + (P_l \times AYL_l)$

$IA_c = P_c \times AYL_c$

$IA_l = P_l \times AYL_l$.

This index expresses the advantage or disadvantage of the intercrops and can be an indicator of the economic feasibility of intercropping systems (Banik et al., 2000).

g) Gross return (GR) represents the value of combined yields in each intercrop system, irrespective of production costs (PC), and is calculated as:

$GR = Y_{cl} P_c + Y_{lc} P_l$

Where Y_{cl} and Y_{lc} are the yields in tonnes per ha of cucumbers and lettuce, respectively, as intercrops, and P_c and P_l are the prices of 1 kg of cucumbers and lettuce, respectively, charged by Companhia de Entrepostos e Armazéns Gerais de São Paulo in the months in which the vegetables were collected and updated to Aug 2007.

h) Net return (NR) is calculated as:

NR = GR – PC

Where PC is the total of all expenses (inputs and labour) of each intercropping system.

i) Modified monetary advantage (MMA) is calculated using the formula proposed by Beltrão et al. (1984):

MMA = NR (LER – 1)/LER

These authors suggest that higher MMAs and NRs indicate more profitable intercropping systems.

j) The benefit/cost ratio (B/CR) (Beltrão et al., 1984) is obtained as:

B/CR = GR/PC

k) The net profit margin (NPM) is the ratio of NR to GR, expressed as a percentage.

Data analysis

A univariate analysis of variance (ANOVA) for treatments designed in randomized complete-blocks was performed for each index in each experiment using the SAS programme (Dewiche and Slaughter, 2003). A combined analysis of variance over experiments was performed for all evaluated indices to identify any significant interaction between population densities of cucumber and lettuce cultivars (D x C), or between population densities of cucumber and times of lettuce transplantation after cucumber transplantation (D x T) or between lettuce cultivars and times of lettuce transplantation after cucumber transplantation (C x T), or among population densities of cucumber, lettuce cultivars and times of lettuce transplantation after cucumber transplantation (D x C x T). For the qualitative factor, the separation procedure for means was performed by Tukey's test at 5% probability. For the quantitative factor, the procedure for fitting the response curve to the transplantation times was performed using the software Table Curve (Jandel Scientific, 1991). The response curves were evaluated based on the following criteria: biological rationale, significance of the mean square error of regression, high coefficient of determination (R^2), and significance of the regression parameters, using t tests at 5% probability.

Conclusions

The intercropping systems of lettuce and cucumber in greenhouse, regardless of the lettuce cultivar, population density of cucumber, and times of crop transplantation, produced bio-agroeconomic advantages over monocultures. The intercropping system with the highest bio-agroeconomic superiority obtained was when the lettuce 'Verônica' was intercropped with cucumber at 11 100 pl ha^{-1}, with both species transplanted on the same day. The indices of land-use efficiency, competition, aggressivity, actual yield loss, intercropping advantage, gross return, net return, benefit/cost ratio and net profit margin (NPM), obtained by homogeneous standardization using the mean values of the replicates of the individual crops over the blocks, met the assumptions of the analyses of variance.

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