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Indices of competition and bio-agroeconomic efficiency of lettuce and tomato intercrops in greenhouses

Arthur Bernardes Cecílio Filho[1] *, Francisco Bezerra Neto[2], Bráulio Luciano Alves Rezende[3], Leilson Costa Grangeiro[2], and Jailma Suerda Silva de Lima[2]

[1]**Universidade Estadual Paulista, UNESP, Jaboticabal, SP 14884-900, Brazil**
[2]**Universidade Federal Rural do Semi-Árido, UFERSA, Mossoró, RN 59625-900, Brazil**
[3]**Instituto Federal de Educação, Ciência e Tecnologia, IFECT, Vila Velha, ES 29106-010, Brazil**

***Corresponding author: rutra@fcav.unesp.br**

Abstract

Intercropping is a cropping system for the production of greenhouse vegetables. It uses space more efficiently, thus reducing the cost of production. Intercropping tomato and lettuce has not been studied, but knowledge of the competitive and agroeconomic indices of these vegetables can help in the management of the intercropping system. The objectives of this study were to assess, through biological and agroeconomic indices, the competition between species and the profitability of intercropping tomato and lettuce at different times of transplantation over two growing seasons (autumn-winter and summer-winter) in greenhouse conditions. In autumn-winter, two experiments were conducted with a randomised complete-block design and five replicates. Tomato and lettuce were the main crops in the individual experiments. Treatments were arranged in a factorial of two cropping systems (intercropping and individual crops) with four transplants of the secondary crop (0, 10, 20 and 30 days after) plus an additional treatment (individual main crop). These two experiments were repeated in summer-winter. Tomato was the dominant crop regardless of transplant order. Intercropping systems established with transplants of both species on the same day had higher values of indices of competition and bio-agroeconomic efficiency than systems with longer periods of transplants between main and secondary crops. The intercropping of lettuce and tomato in greenhouses, regardless of transplant time or order, had bio-agroeconomic advantages over individual crops. The transplantation of tomato after lettuce is recommended for greater profitability.

Keywords: efficiency indicators; intercropping; *Lactuca sativa*; *Lycopersicon esculentum*; protected environment; *Solanum licopersicum*.

Abbreviations: A-aggressivity index; AYL-actual yield loss; B/CR-benefit/cost ratio; CR-competitive ratio; DALT-days after lettuce transplanting; DATT-days after tomato transplanting; GR-gross return; IA-intercropping advantage; K-relative crowding coefficient; LER-land equivalent ratio; LTATT-lettuce after transplanting tomato; MMA-modified monetary advantage; NPM-net profit margin; NR-net return; SDLT-same day of lettuce transplanting; SDTT-same day of tomato transplanting; TTALT-tomato after lettuce transplanting.

Introduction

The cultivation of tomatoes and lettuce in protected environments became widespread in the state of São Paulo, an important production centre of vegetables in Brazil, aiming to provide vegetables of good quality throughout the year. Cultivation of vegetables in protected environments, however, increases the cost of production. Cecílio Filho et al. (2010) found that depreciation of the greenhouse is a major factor contributing greatly to the cost of producing tomatoes and lettuce (15 and 18%, respectively) as individual crops.

To help avoid a situation where producers are discouraged from using protected environments, Cecílio Filho et al. (2010) evaluated the economics of intercropping tomato and lettuce in greenhouses. They observed that this cropping system provided an increase in net income of up to 14.8% over the individual cropping of tomato and up to 850% over the individual cropping of lettuce. According to these authors, optimising greenhouse conditions, labour, and inputs contributed to the reduced cost of production and thus to the increased profitability of the intercropping system. Cecílio Filho et al. (2008), Silva et al. (2008), Barros Júnior et al. (2009), and Rezende et al. (2010) also found that intercropping systems increased production per unit area and optimised inputs and production structure, which further contributed to a higher profitability of growing vegetables in protected environments in Brazil. The higher productivities of intercropping systems compared with those of single crops can be attributed to the better use of light by the photosynthetic canopies due to the different distributions of foliage in space (Ofori and Stern, 1987) or time (Keating and Carberry, 1993). According to Beets (1982), the influence that each species has over the other depends primarily on its botanical characteristics. Trenbath (1986) reports the importance of agronomic factors, especially population density, nutrient availability, and planting season. Also, managing the time of establishment of the cultures in intercrops can minimise competition and maximise the complementarity between the temporal and/or spatial components of crops. The time of sowing or transplanting the secondary crop in relation to the main crop of an intercrop was studied by Cecílio Filho et al. (2003), Rezende et al. (2003), Costa et al. (2007), Cecílio Filho et al. (2010) and Rezende et al. (2010). These authors, who evaluated the intercrops of beet and arugula, lettuce and radish, lettuce and arugula, tomato and lettuce, and cucumber and lettuce, respectively, found that the period of coexistence of species influenced the crop productivities. Several biological and agroeconomic indices, such as land equivalent ratio, relative crowding coefficient, aggressivity, competitive ratio, actual yield loss, monetary advantage, and intercropping advantage, have been developed to describe the competitive and economic advantage of intercropping systems (Adetiloye and Adekunle, 1989; 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 characterisation of intercropping systems, because they reflect the influence of the competition among the system's component crops. Their values can thus help to plan the association between crops and their cropping management. These indices, however, have not been used for evaluating competition between tomato and lettuce in an intercropped system or for evaluating the agroeconomic advantages of each association in a protected environment. The purpose of this study was thus to evaluate, by means of biological and agroeconomic indices, the competition between species and the profitability of tomato and lettuce intercrops at different times of transplantation of both over two growing seasons.

Results

Tests of verification

In the experiment in which lettuce was transplanted after transplanting tomato, all the assumptions required in the univariate analysis of variance of residuals of the indices were verified and met. The results of testing these assumptions in terms of probability for homoscedasticity, normality, and additivity are presented in Table 1. All values of probability were above 0.05, indicating that these assumptions could not be rejected ($P>0.05$) and that the deviations between treatments for all indices are thus acceptably homogeneous (Brown-Forsythe's F test) and normally distributed (Shapiro-Wilk's W-test). Tukey´s F test for additivity indicated that the differences between two treatments were similar in different blocks, for all variables, showing no interaction between blocks and treatments. In the experiment in which tomato was transplanted after transplanting lettuce, the assumptions of homoscedasticity and additivity were not accepted in the analysis of variance of the relative crowding coefficient of lettuce, and the assumptions of additivity in the analysis of aggressivity of tomato were not accepted (Table 1). The deviations between treatments in the relative crowding coefficient of lettuce (K_l) were different, with interactions between blocks and treatments ($P<0.05$). Deviations between treatments in the aggressivity of the tomato or lettuce were different, showing no additivity between blocks and treatments ($P<0.05$). For the other indices evaluated, all assumptions required by a univariate analysis of variance were met ($P>0.05$).

Functions of competition and yield efficiency of intercropping systems

Experiment in which lettuce was transplanted after transplanting tomato

The relative crowding coefficients (Ks) and land equivalent ratio (LER) for the lettuce, tomato, and intercropping systems decreased with an increase in the times of transplanting lettuce after transplanting tomato (LTATT), with maximum values of 0.515, 63.28, and 31.956 for K_l, K_t, and K, respectively, and with maximum values of 0.664, 0.948, and 1.598 for LER_l, LER_t, and LER, respectively, when lettuce was transplanted on the same day as transplanting tomato (SDTT). Minimum values of 0.136, 38.479, and 4.387 for Ks and 0.346, 0.905, and 1.25 for LERs of the lettuce, tomato, and intercropping systems, respectively, were obtained when lettuce was transplanted 30 days after transplanting tomato (DATT). These decreases were approximately 73.6, 39.2, and 86.3% for Ks and 47.9, 4.6, and 21.8% for LER of the lettuce, tomato, and intercropping systems, respectively (Figs 1A and 1B). For the competitive ratio (CR), an increase in CR_t (tomato) and CR (intercrop) was observed, with an increase in the times of LTATT and maximum estimated coefficients of 9.927 and 10.030, respectively, at 30 DATT and minimum coefficients of 5.019 and 5.211, respectively, at SDTT (Fig 1C). These increases were approximately 49.4 and 48.1%, respectively. Moreover, a decrease of 46.4% was observed in CR_l (lettuce), with an increase in the times of LTATT, an estimated maximum coefficient of 0.192 at SDTT, and a minimum coefficient of 0.103 at 30 DATT (Fig 1C). The aggressivity of tomato (A_t) increased with an increase in the times of LTATT, with a maximum estimated value of 3.829 at 30 DATT and a minimum value of 3.556 at SDTT. The aggressivity of lettuce (A_l) decreased with an increase in the times of LTATT, with a maximum estimated value of –3.556 at SDTT and a minimum value of –3.829 at 30 DATT (Fig 1D). The increase in A_t and the decrease in A_l were approximately 7.1%. From the results of these indices, tomato was the dominant crop. The actual yield loss of lettuce (AYL_l), tomato (AYL_t), and intercrop (AYL) decreased with an increase in the times of LTATT, with maximum estimated values of 0.159, 3.396, and 3.238, respectively, when lettuce was transplanted at SDTT and with minimum values of 0.561, 3.257, and 2.697, respectively, when lettuce was transplanted at 30 DATT. These decreases were approximately 71.7, 4.1, and 16.7%, respectively (Fig 1E). For the intercropping advantage (IA), IA_l (lettuce) increased with an increase in the times of LTATT, with a maximum estimated value of 0.176 at 30 DATT and a minimum value of 3.383 at SDTT. IA_t (tomato) decreased with an increase in the times of LTATT, with a maximum value of 4.731 at SDTT and a minimum value of 4.541 at 30 DATT (Fig 1F). The increase in IA_l and the decrease in IA_t were 54.1 and 4.0%, respectively. Adjusting any regression equation for the IA (intercropping) as a function of an increase in the times of LTATT was not possible.

Experiment in which tomato was transplanted after transplanting lettuce

The K_t, K, and LER_l increased with an increase in the times of transplanting tomato after transplanting lettuce (TTALT), with maximum estimated values of 42.903 and 79.502 for K_t and K, respectively, and 0.852 for LER_t when tomato was transplanted at 30 days after transplanting lettuce (DALT) and with minimum values of 10.035, 20.835, and 0.810, respectively, for these indices, when tomato was transplanted on the same day as transplanting lettuce (SDLT) (Figs 2A and 2B). These increases were approximately 76.6, 73.8, and 4.9% for K_t, K, and LER_l, respectively. On the other hand, decreases were observed in LER_t and LER with increases in the times of TTALT, with maximum estimated values of 1.056 and 1.858, respectively, when tomato was transplanted at SDLT and with minimum values of 0.891 and 1.735, respectively, when tomato was transplanted at 30 DALT (Fig 2B). These decreases were approximately 15.6 and 6.6%,

Table 1. Indices of competition and efficiency evaluated in the experiments transplanting lettuce after tomato and tomato after lettuce.

Competition/ Efficiency Indices	Experiment in which the lettuce was transplanted at different times after transplanting tomato				Experiment in which the tomato was transplanted at different times after transplanting lettuce			
	Brown-Forsythe´s F test	Shapiro-Wilk´s W-test	Tukey´s F test	Assumptions for RCBD	Brown-Forsythe´s F test	Shapiro-Wilk´s W-test	Tukey´s F test	Assumptions for RCBD
K_l	0.1185	0.9547	0.3803	met	0.0456 *	0.1773	0.0043 *	not met
K_t	0.6299	0.1870	0.9703	met	0.0508	0.6152	0.1303	met
K	0.2975	0.1147	0.4385	met	0.2371	0.9562	0.3905	met
LER_l	0.2087	0.7493	0.6762	met	0.5838	0.2694	0.2161	met
LER_t	0.9972	0.6095	0.5453	met	0.3474	0.5039	0.0563	met
LER	0.4183	0.2525	0.6248	met	0.9920	0.5662	0.1419	met
CR_l	0.2608	0.1413	0.5966	met	0.5017	0.8841	0.3769	met
CR_t	0.5035	0.2880	0.8941	met	0.3159	0.3384	0.0855	met
CR	0.5084	0.3061	0.8809	met	0.3076	0.3219	0.0781	met
A_l	0.7184	0.1950	0.5156	met	0.2170	0.4115	0.0368 *	not met
A_t	0.8835	0.1423	0.8024	met	0.2170	0.4115	0.0368 *	not met
AYL_l	0.2058	0.7493	0.6777	met	0.5767	0.2834	0.2135	met
AYL_t	0.9277	0.5402	0.2401	met	0.3478	0.5102	0.0570	met
AYL	0.7393	0.7812	0.2829	met	0.5851	0.8770	0.0540	met
IA_l	0.1514	0.4023	0.0718	met	0.5815	0.2743	0.2134	met
IA_t	0.9286	0.5473	0.2416	met	0.3467	0.5086	0.0568	met
IA	0.4947	0.9651	0.0926	met	0.6270	0.8983	0.0560	met
MMA	0,4787	0,1492	0,3160	met	0,7206	0,8875	0,6727	met
GR	0,8418	0,5851	0,5182	met	0,9918	0,5637	0,6018	met
NR	0,8418	0,5851	0,5182	met	0,9918	0,5637	0,6018	met
B/CR	0,8289	0,5720	0,5322	met	0,9913	0,5831	0,6116	met
NPM	0,8988	0,6538	0,3086	met	0,9568	0,8655	0,8414	met

* $P < 0.05$. Brown-Forsythe´s F test, Shapiro-Wilk´s W-test, and Tukey's F-test for checking the assumptions of homoscedasticity, normality, and additivity in the residuals of the univariate analysis of variance for a randomised complete-block design (RCBD) in the indices of competition/efficiency of Relative Crowding Coefficient of lettuce (K_l), Relative Crowding Coefficient of tomato (K_t), Relative Crowding Coefficient of system (K), Land Equivalent ratio of lettuce (LER_l), Land Equivalent ratio of tomato (LER_t), Land Equivalent ratio of system (LER), Competitive Ratio of lettuce (CR_l), Competitive Ratio of tomato (CR_t), Competitive Ratio of system (CR), Aggressivity of lettuce (A_l), Aggressivity of tomato (A_t), Actual Yield Loss of lettuce (AYL_l), Actual Yield Loss of tomato (AYL_l), Actual Yield Loss of system (AYL), Intercropping Advantage of lettuce (IA_l), Intercropping Advantage of tomato (IA_t), Intercropping Advantage of system (IA), Modified Monetary Advantage (MMA), Gross Return (GR), Net Return (NR), Benefit/Cost Ratio (B/CR), and Net Profit Margin (NPM).

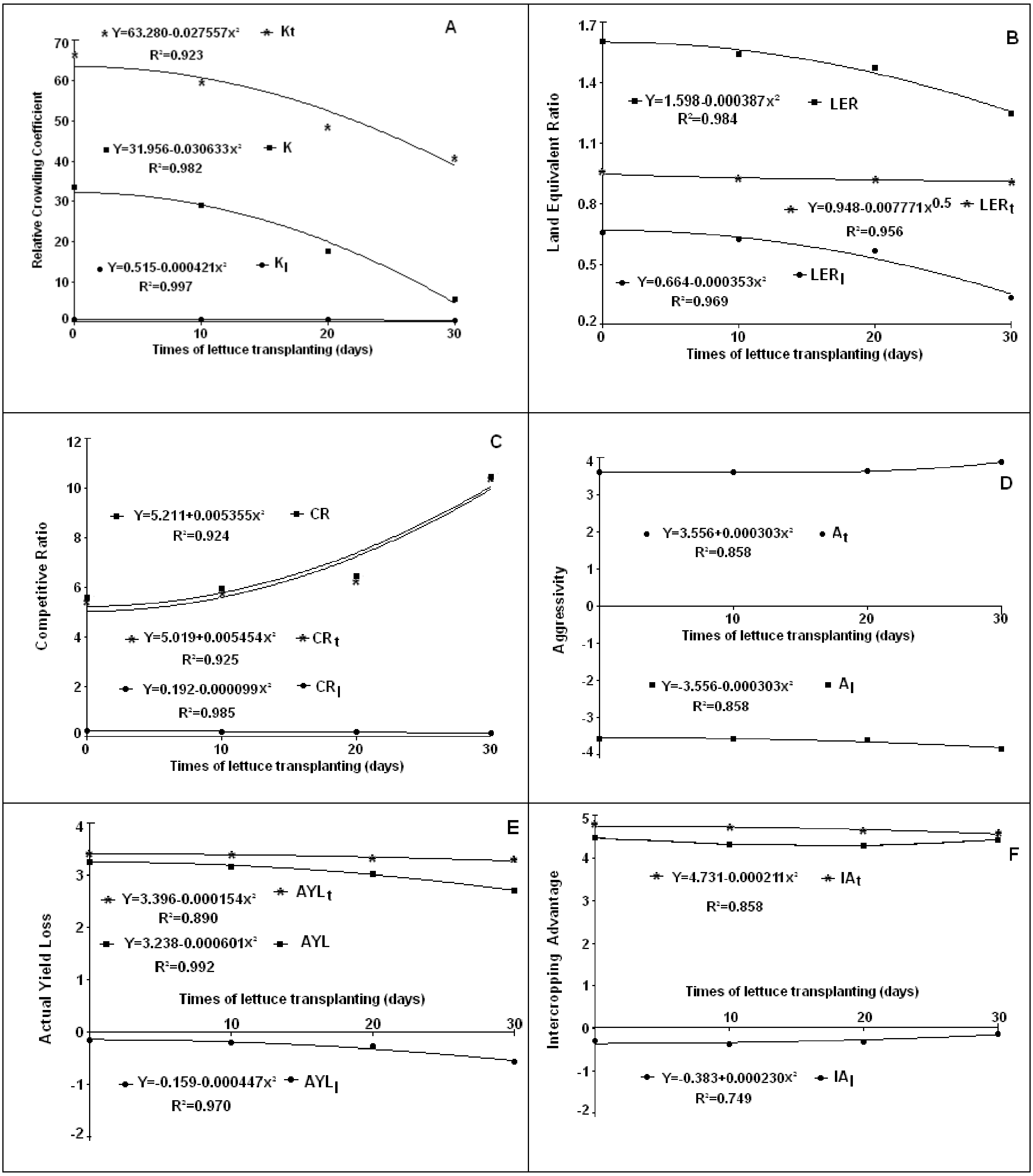

Fig 1. Response models for *(A)* Relative Crowding Coefficient of lettuce (K_l), Relative Crowding Coefficient of tomato (K_t), and Relative Crowding Coefficient of system (K); *(B)* Land Equivalent ratio of lettuce (LER_l), Land Equivalent Ratio of tomato (LER_t), and Land Equivalent Ratio of system (LER); *(C)* Competitive Ratio of lettuce (CR_l), Competitive Ratio of tomato (CR_t), and Competitive Ratio of system (CR); *(D)* Aggressivity of lettuce (A_l) and Aggressivity of tomato (A_t); *(E)* Actual Yield Loss of lettuce (AYL_l), Actual Yield Loss of tomato (AYL_t), and Actual Yield Loss of system (AYL); and *(F)* Intercropping Advantage of lettuce (IA_l), Intercropping Advantage of tomato (IA_t), and Intercropping Advantage of system (IA) as a function of lettuce transplant times after tomato transplantation.

respectively. CR_l increased with an increase in the times of TTALT, with an estimated maximum value of 0.255 at 30 DALT and a minimum value of 0.209 at SDLT (Fig 2C). This increase was 18.0%. For CR_t and CR, decreases were observed with an increase in the times of TTALT, with maximum estimated values of 4.850 and 5.061, respectively, at SDLT and minimum values of 3.906 and 4.166, respectively, at 30 DALT (Fig 2C). These decreases were 19.5 and 17.7%, respectively. Adjusting any regression equation for K_l, and for A_l and A_t as a function of an increase in the times of TTALT was not possible (Figs 2A and 2D). AYL_l and IA_l increased with the increase in the times of TTALT, with maximum estimated values of 0.077 and 0.126, respectively, when tomato was transplanted at 30 DALT and minimum values of 0.029 and 0.040, respectively, when tomato was transplanted at SDLT (Figs 2E and 2F). The increases were 62.3 and 68.3%, respectively. For AYL_t, AYL, IA_t, and IA, decreases were observed with the increase in the times of TTALT, with maximum estimated values of 3.989 and 4.021 for AYL_t and AYL, respectively, and 5.535 and 5.578 for IA_t and IA, respectively, at SDLT and with minimum values of 3.211 and 3.292 for AYL_t and AYL, respectively, and 4.448 and 4.580 for IA_t and IA, respectively, at 30 DALT (Figs 2E and 2F). These decreases were 19.5 and 18.1% for AYL_t and AYL and 19.6 and 17.9% for IA_t and IA, respectively.

Economic feasibility

Experiment in which lettuce was transplanted after transplanting tomato

The gross return (GR), net return (NR), and modified monetary advantage (MMA) of intercropping systems decreased with the increase in the times of LTATT, with maximum estimated values of R$ 264194.60, R$ 216917.60, and R$ 79076.64per hectare, respectively, when lettuce was transplanted at SDTT and minimum values of R$ 238792.40, R$ 191 515.40, and R$ 36 958.20 per hectare, respectively, when lettuce was transplanted at 30 DATT. These decreases were 9.6, 11.7, and 49.5%, respectively (Fig 3A). A similar behaviour was also seen in the benefit/cost ratio (B/CR) and net profit margin (NPM), registering maximum estimated values of 5.6 and 82.1%, respectively, when lettuce was transplanted at SDTT and minimum values of 5.1 and 80.2%, respectively, when lettuce was transplanted at 30 DATT. The decreases in B/CR and NPM were 9.7 and 2.3%, respectively (Fig 3B).

Experiment in which tomato was transplanted after transplanting lettuce

Behaviour opposite to the previous experiment was observed for GR, NR, and MMA of intercropping systems. These indices increased with an increase in the times of TTALT. The maximum estimated values for GR (R$ 274474.64 ha^{-1}), NR (R$ 227 197.50 ha^{-1}), and MMA (R$ 97 731.93 ha^{-1}) occurred when tomato was transplanted at 30 DALT. The minimum values for GR (R$ 248 743.00 ha^{-1}), NR (R$ 201 466.50 ha^{-1}), and MMA (R$ 92 075.29 ha^{-1}) occurred when tomato was transplanted at SDLT. The decreases in GR, NR, and MMA were 9.4, 11.3, and 5.8%, respectively (Fig 4A). A similar behaviour was also observed with B/CR and NPM, registering maximum estimated values of 5.8 and 82.7%, respectively, when tomato was transplanted at 30 DALT and minimum values of 5.3 and 80.9%, respectively, when tomato was transplanted at SDLT (Fig 4B), causing losses of 9.5 and 2.2% in B/CR and NPM, respectively.

Discussion

No violation of the assumptions of the analyses of variance for homoscedasticity, normality, and additivity was observed in the analyses of the indices of competition or efficiency of intercropping systems in the experiment as a function of the times of transplanting lettuce after transplanting tomato. These assumptions, however, were violated in the analyses of aggressivity indices and the relative crowding coefficient of lettuce in the experiment as a function of the times of transplanting tomato after transplanting lettuce. Indices of each plot were achieved through a homogeneous standardisation for individual crops, considering the average value of individual crops over blocks in the denominator of the indices, as recommended by Bezerra Neto and Robichaux (1996) and Federer (2002). This standardisation was used to avoid the possibility of having a complex distribution of the sum of the ratios that define the LERs and other indices, making the analysis of variance of such indices non-representative, which could lead to errors in the validity of the assumption of normality, homogeneity, and additivity. Moreover, the standardisation was also used to validate the estimated models, statistically depicting the performance of these indices as a function of establishment times of lettuce-tomato intercropping.

Indices of competition and bio-agronomic efficiency

Transplanting lettuce after transplanting tomato

The indices of K and LER decreased with increasing times of LTATT (Figs 1A and 1B) due to increased interspecific competition for environmental resources, especially light. The longest period between species transplantation was as follows: the larger the tomato plants at the time of lettuce transplantation, the lower the amounts of solar radiation available for lettuce plants, which grew under the canopy of tomato. The change in the light spectrum due to shading affects the morphogenic (Beets, 1982 and Varlet-Grancher and Gautier, 1995) and physiological processes (Keating and Carberry, 1993) of the shaded species. This relationship explains the lower accumulations of dry matter observed in transplanted lettuce later and therefore, were smaller values for K_l, K, LER_l, and LER, since the yield of lettuce in intercropping acts directly proportionally to obtain these indices. The performance of lettuce intercropped with tomato agrees with the results obtained by Rezende et al. (2010), who evaluated cucumber (supported) intercropped with lettuce in greenhouses. They also found a strong influence of the time of lettuce transplantation on the cucumber (main crop in intercropping). Lettuce yield was reduced by 70%, depending on the population of cucumbers and the growing season, when lettuce was transplanted 30 days after cucumber transplantation compared to the transplantation of the two species on the same day. In our study, higher values of K_t and LER_t, compared to those of K_l and LER_l, were observed. Tomato plants grow vertically and their leaves are above those of lettuce, so tomato plants do not suffer from competition for solar radiation. The higher values for K_t and LER_t indicated that tomato was more competitive than lettuce, thereby identifying it as dominant over the associated crop. All values of K and LER of the systems were greater than 1, indicating the higher biological and agronomic efficiencies of intercropping systems over those of individual crops (Nedunchezhiyan et al., 2010) and demonstrating a productive advantage of intercropping by a better use of the area and the available resources (Banik et al., 2006). According to Jagannath and Sunderaraj (1987), in any comparison of benefits between intercropping systems with different areas of land occupation, the advantage of intercropping via LER stems from two different sources that are generally confounded: a) from the land factor (area occupied by each component crop) and b) from the biological/agronomic factor (from tested factors/treatments). This advantage in LER in the intercropping systems studied ranged from 1.25 to 1.60 and came from the biological/agronomic factor arising from the times of transplantation tested, since the area occupied by each crop in the different systems was the same. The indices CR_t, CR, and A_t increased with an increase in the times of LTATT, while CR_l and A_l decreased (Figs 1C and 1D). These results confirm those using K and LER, ratifying tomato as the dominant crop (index with positive sign) and lettuce (index with negative sign) as the dominated crop (Table 1). Based on the values of the four indices, lettuce interfered slightly with tomato growth. The dominance of tomato, though, based on the indices CR and A, increased when lettuce was transplanted later compared to tomato (Figs 1C and 1D), characterising the tomato as a species better able than lettuce to use the available resources. The average values of CR_t at the different times of lettuce transplantation were higher than the average values of CR_l, 28.3-103.2 times higher between the first and last time of lettuce transplantation, representing how the tomato was more competitive than lettuce. According to Willey and Rao (1980) and Aasim et al. (2008), the CR index captures the competitive ability of crops better than the indices K and A. Behaviour similar to those of K and LER was also observed in AYL (Fig 1E). The values of AYL_t and AYL were positive and higher than the values of AYL_l, which were negative. This superiority can be attributed to the aggressiveness of tomato and to other factors such as morphology and physiology, particularly in the position of its photosynthetic canopy above the lettuce leaves, allowing it to better use the photosynthetically useful radiation. AYL_l was offset by AYL_t, providing positive values for AYL ranging from 3.24 (324%) at SDTT to 2.70 (270%) at 30 DATT, about twice the values of LER, at both SDTT and 30 DATT, indicating the advantage of intercropping systems. Like LER, AYL was calculated based on crop productivity in an intercropping system compared to the productivity of individual crops. However, the AYLs of crops differ in the fact of this index consider the proportion of crops in the area, which implies an advantage in using AYL over LER to assess the benefit of intercropping systems (Banik et al., 2000; Dhima et al., 2007). Negative values of IA_l and positive values of IA_t and IA were also recorded, indicating a clear advantage of intercropping lettuce and tomato for the transplant times studied. This index, which is an indicator of economic feasibility of intercropping systems (Dhima et al., 2007), indicated that all intercropped treatments were advantageous.

Tomato transplantation after lettuce transplantation

The values of K, K_t, K_l, LER_l, CR_l, A_l, AYL_l, and IA_l (Figs 2 A-F) increased with increased times of TTALT, thus indicating a decrease in the interference from tomato in the productive performance of lettuce. Moreover, the values of LER_t, LER, CR_t, CR, A_t, AYL_t, AYL, IA_t, and IA decreased with increased times of TTALT, suggesting a small interference from lettuce to the productive performance of tomato when its transplantation was delayed compared to lettuce. Late transplants of tomato thus suffered an increased competition with lettuce because the plants of lettuce were taller by the time of the tomato transplantation. Many authors, cited by Sinoquet and Caldwell (1995), agree that the division of radiation between the component crops of an intercropping is primarily established or influenced by the vertical dominance. Competition for light is thus increased when a species attains a greater height than the associated species. The taller species in an intercropping system benefits by having its leaves above those of its competitor. Even with little interference from tomato on lettuce in this experiment, the indices of competition and efficiency of tomato were higher than those of lettuce at different times of the tomato transplantation, indicating that tomato was better able to compete for environmental resources than lettuce and was the dominant crop in the intercropping systems. The dominance of tomato can be explained by its higher aggressiveness, which is an important tool to determine the competitive ability of a crop when grown in association with another (Khan et al., 2001; Tahir et al., 2003). The values of K and LER were above unity in all intercropping systems, indicating the advantage of intercropping compared to individual crops in the use of environmental resources of plant growth (Yilmaz et al., 2008). Due to the higher efficiency of lettuce in the use of environmental resources, especially light, when tomato was transplanted after lettuce, the values of LER obtained were higher than those obtained when lettuce was transplanted after tomato (Figs 1B and 2B). The highest productivities of intercropping systems established with transplanting tomato after lettuce can be attributed to the better use of light by the photosynthetic canopy of crops in intercropping; these two crops have different foliar distributions in both space (Ofori and Stern, 1987) and time (Keating and Carberry, 1993). The values of CR_t at all times of tomato transplantation were above unity, corresponding to 94% of the values of CR of the intercropping, indicating that tomato was a better competitor than lettuce, as advocated by Cecilio Filho et al. (2010). When CR is greater than unity, one crop is negatively affecting another (Vasilakoglou and Dhima, 2008). The decrease in this index with an increase in the times of tomato transplantation was thus due to a minor negative effect of lettuce in the association. In short, CR is an important tool for determining the degree to which one crop competes with another (Wahla et al., 2009). Despite the decrease in values of AYL_t (398.9 to 321.1%), AYL (402.1 to 329.2%), IA_t (5.535 to 4.448), and IA (5.578 to 4.580) with an increase in the times of TTALT, a gain in productivity of lettuce can be observed in all treatments (AYL_l of 2.9 to 7.7% and IA of 0.040 to 0.126), where the interference on tomato was very low, giving positive values for AYL_l and IT_l (Figs 2 E and F). This result reinforces those obtained with the other indices in all treatments, where tomato was the dominant crop and lettuce was the dominated crop. Moreover, in agreement with Banik and Bagchi (1996), the index AYL provides more precise information about the nature of competition and the behaviour of each species in the intercropping system, since it takes into account both the signal (positive or negative) and the values of the indices. In addition to being an indicator of agronomic advantage, IA can also be an indicator of economic feasibility of intercropping systems (Aasim et al., 2008). Since the values of IA, IA_t, and IA_l were all positive, these indices definitely indicate an advantage to intercrops of lettuce and tomato, with transplanting lettuce after transplanting tomato or vice versa. The values of IA_t and IA_l followed the same trend as the values of AYL, AYL_t, and AYL_l.

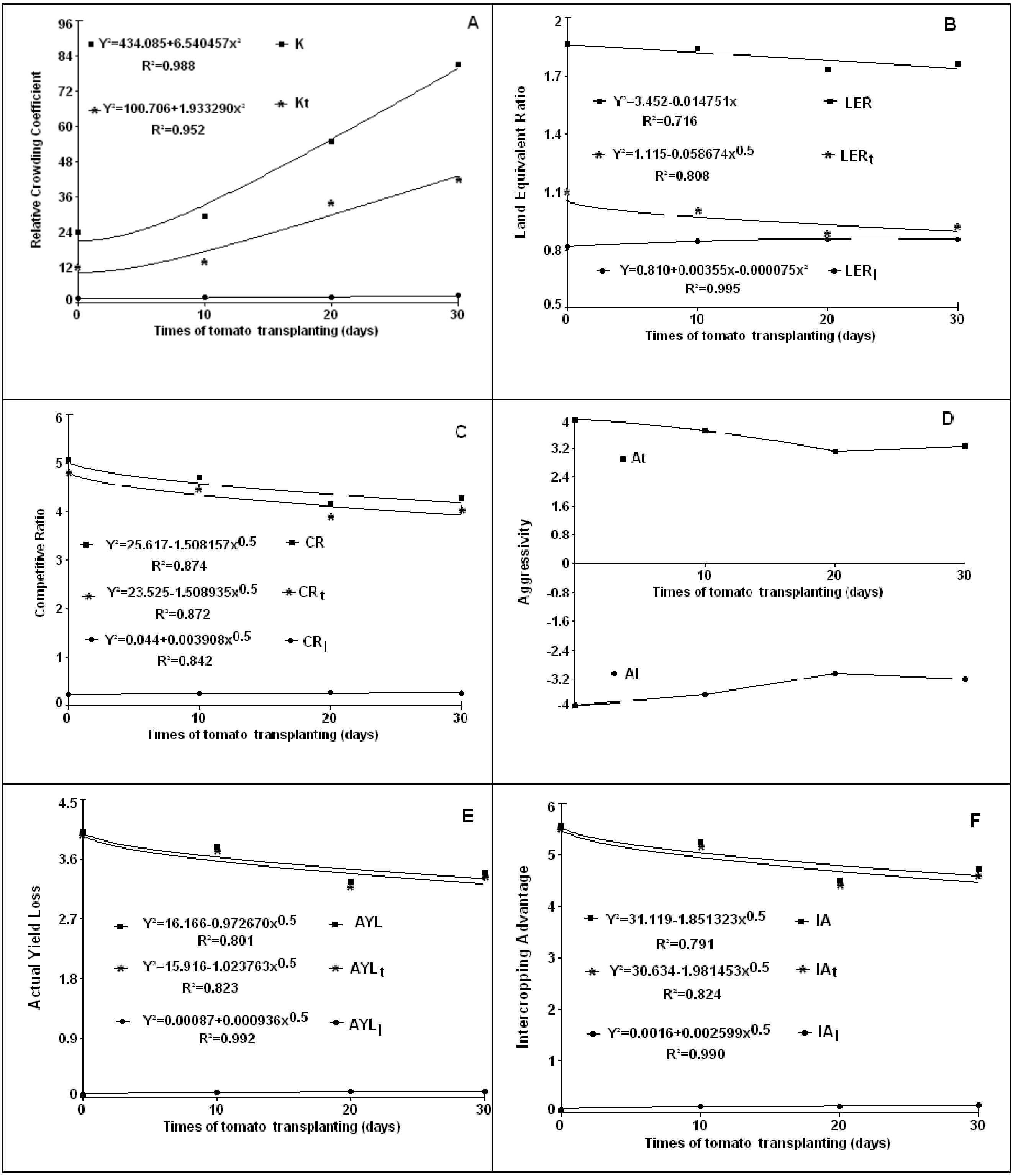

Fig 2. Response models for (A) Relative Crowding Coefficient of lettuce (K_l), Relative Crowding Coefficient of tomato (K_t), and Relative Crowding Coefficient of system (K); (B) Land Equivalent Ratio of lettuce (LER_l), Land Equivalent Ratio of tomato (LER_t), and Land Equivalent Ratio of system (LER); (C) Competitive Ratio of lettuce (CR_l), Competitive Ratio of tomato (CR_t), and Competitive Ratio of system (CR); (D) Aggressivity of lettuce (A_l) and Aggressivity of tomato (A_t); (E) Actual Yield Loss of lettuce (AYL_l), Actual Yield Loss of tomato (AYL_t), and Actual Yield Loss of system (AYL); and (F) Intercropping Advantage of lettuce (IA_l), Intercropping Advantage of tomato (IA_t), and Intercropping Advantage of system (IA) as a function of tomato transplant times after lettuce transplantation.

Economic indicators

Regardless of the time of transplantation, all intercropping systems in both experiments registered economic viability, confirming the results obtained by Cecilio Filho et al. (2010). The values of MMA (based on LER) were positive in all intercropping systems, indicating not only an economic advantage but also a definite advantage in productivity (Figs 3 and 4). MMA together with GR, NR, B/CR, and NPM had their highest values when the cultures were transplanted on the same day (time 0) and their lowest values when transplanting occurred 30 days after the transplantation of another crop. The higher values are due to the greater total productivity of the intercropping system at the first time of transplantation, while lower values were due to a lower total productivity of the associated system at the final transplantation. These results confirm the values obtained by the indices CR, AYL, and IA, indicating that the agronomic-biological superiority obtained in the systems at the first time of transplantation resulted in a larger economic advantage.

Responses of the models adjusted for GR, NR, MMA, B/CR, and NPM in Experiment 1, when the intercrops were established with transplants of lettuce after tomato (Fig 3), differed from those in Experiment 2, when the intercrops were established with transplants of tomato after lettuce (Fig 4). In the first experiment, reductions were registered in the evaluated indices, while increases were observed in the second experiment. This difference in the adjustment of the responses was due to the poor quality of the lettuce produced in the intercrops established with transplants of lettuce 10 days after transplanting tomato. The lettuce plants were by then etiolated due to the deep shade produced by tomato, and lettuce consequently returned a very low price per kilogramme of product.

Materials and methods

Experimental site

Four experiments were conducted in two greenhouses with arched roofs covered with a low-density, transparent polyethylene film 150 μm thick and coated with compounds against ultraviolet rays. The greenhouses are located at UNESP, Jaboticabal, São Paulo, Brazil, at an altitude of 575 m, longitude of 21º15'22" S, and latitude of 48º15'58" W. The climate of Jaboticabal is classified as subtropical with rain in summer and relatively dry winters. The mean annual rainfall is 1424.6 mm, and the maximum, mean, and minimum temperatures are 22.2ºC, 28.9ºC, and 16.8ºC, respectively. The soil of the area is Oxisol.

Experimental design and treatments

The four experiments were conducted in pairs, in two seasons. Experiment 1, conducted from April 17 to September 9, 2003 (autumn-winter), had tomato as the main crop and lettuce as the secondary crop. Lettuce was transplanted 0, 10, 20, and 30 days after the transplantation of tomato (DATT). For each time of establishment of the intercropping, an individual crop of lettuce was also installed, aiming to isolate possible differences of the environment on plant behaviour. Experiment 2 had the same treatments as Experiment 1 but was conducted from January 30 to May 27, 2004 (summer-winter). In Experiment 3, conducted from April 17 to September 23, 2003, the transplantation of tomato was assessed after that of lettuce and at the same time as in Experiment 1. From January 30 to June 24, 2004, Experiment 4 was conducted with the same treatments as Experiment 3. Each experiment was conducted under a randomised complete-block design in a 2 × 4 + 1 factorial with five replications. The treatments were arranged in two cropping systems (intercropping and individual crops), four transplantations of the secondary crop with the main crop after 0, 10, 20, and 30 days, plus an additional treatment of an individual planting of the main crop. The experimental units consisted of 10 tomato plants and 40 lettuce plants, with a total bed area of 3 m^2 (1.20 m x 2.5 m). The central 6 and 20 tomato and lettuce plants, respectively, were harvested to evaluate the characteristics of the plants.

Cropping systems and management

Chemical analyses were performed on the soil (0-20 cm depth) of the greenhouses prior to the experiments. Liming and fertilisation of the tomato intercrops and individual crops in the four experiments were performed as recommended by Trani et al. (1997a): calcined limestone with a relative power of total neutralisation of 122% and fertilizers such as ammonium nitrate, superphosphate, and potassium chloride were used. Fertilisations of coverage have been made for lettuce and tomato, as recommended by Trani et al. (1997a, b) for each crop.

The cultivars of tomato and lettuce used were Debora Max F1 and Vera, respectively. Seedlings of tomato and lettuce were grown in respective trays with 128 and 288 cells. Lettuce seedlings with four leaves were transplanted 0.25 m apart with 0.30 m between rows. Tomato seedlings with four leaves were transplanted 0.50 m between plants in the rows apart with 0.60 m between single rows and1.20 m between double rows. The stacking of the tomato plants was made with plastic ribbons, perpendicular to the ground, involving each of the two stems of the plant. The ribbon was tied to two wires arranged parallel to the ground, one situated close to the soil surface and the other at a height of 2 m. The upper wire was supported by wooden stacks and bamboo sticks.

Indices of competition and bio-agroeconomic efficiency

The traits evaluated were the yield for lettuce (fresh weight of shoots) and the yield of commercial fruit for tomato. The indices of competitive and bio-agroeconomic efficiency of the component crops and intercropping systems were determined as follows:

a) Relative crowding coefficient (K) – K is a measure of the relative dominance of one species over another in an association. It was suggested by de Wit (1960) and later developed by Hall (1974). It is calculated by the following expressions: $K = K_t K_l$, $K_t = Y_{tl} Z_{lt} / (Y_t - Y_{tl}) Z_{tl}$, and $K_l = Y_{lt} Z_{tl} / (Y_l - Y_{lt}) Z_{lt}$, where K_t and K_l are the relative crowding coefficients of tomato and lettuce, respectively; Y_{tl} and Y_{lt} are the yields of tomatoes and lettuce, respectively, as intercrops; and Y_t and Y_l are the yields of tomatoes and lettuce, respectively, as individual crops. Z_{tl} is the sown proportion of tomato intercropped with lettuce, and Z_{lt} is the sown proportion of lettuce intercropped with tomato. When the product of the two coefficients $K_t K_l$ is greater than unity, the intercropping is advantageous; when it equals unity, intercropping provides no benefit; when it is less than unity, intercropping is disadvantageous.

b) Land equivalent ratio (LER) – LER was presented by Willey and Osiru (1972) for the evaluation of advantage in

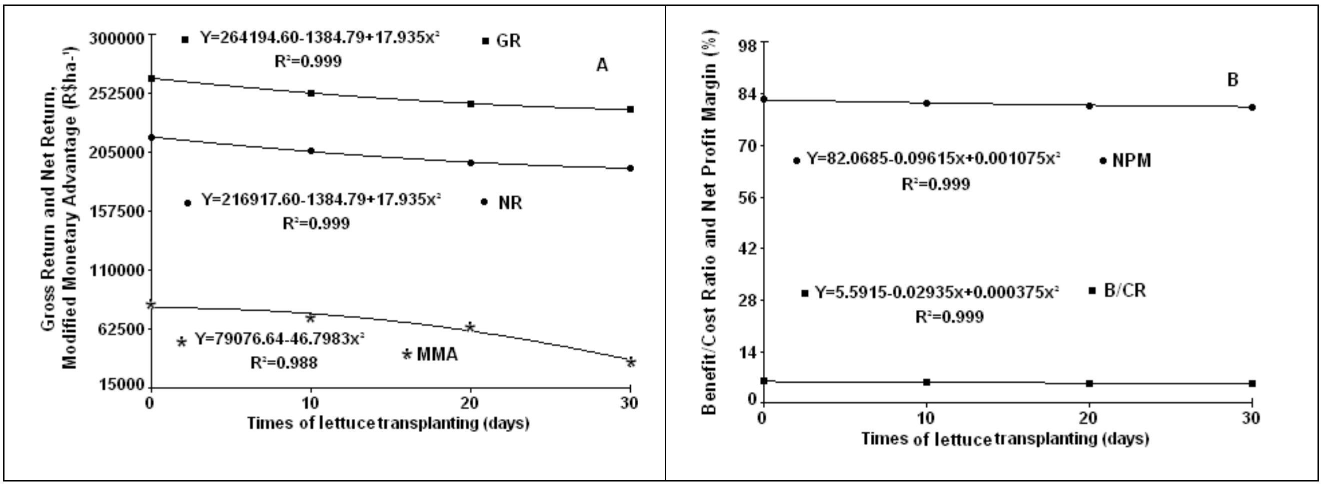

Fig 3. Response models for *(A)* Gross Return (GR), Net Return (NR), and Modified Monetary Advantage (MMA); and *(B)* Benefit/Cost Ratio and Net Profit Margin (NPM) as a function of lettuce transplant times after tomato transplantation.

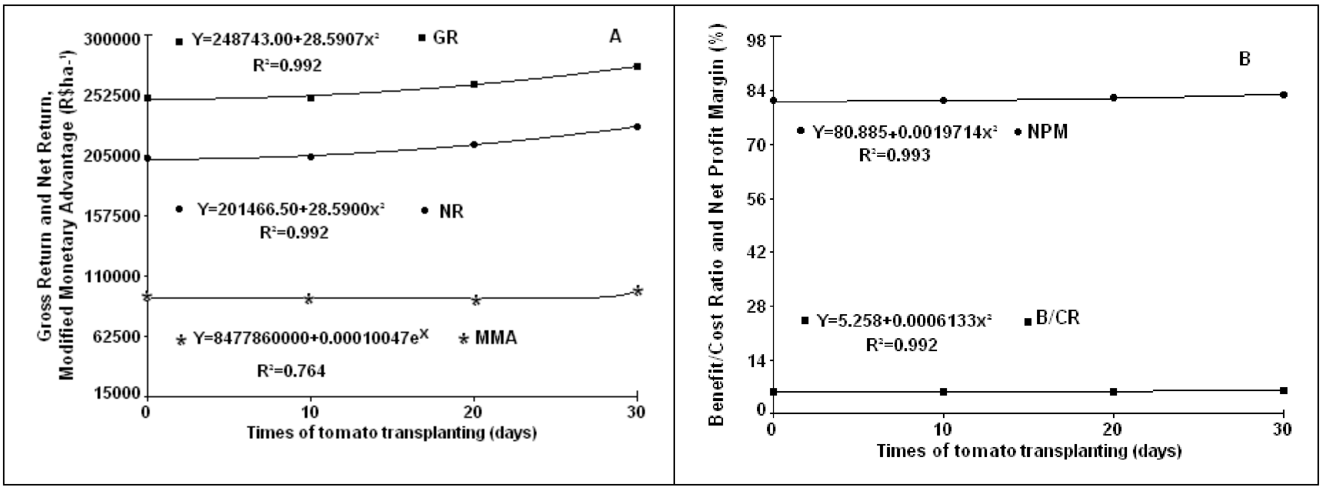

Fig 4. Response models for *(A)* Gross Return (GR), Net Return (NR), and Modified Monetary Advantage (MMA); and *(B)* Benefit/Cost Ratio and Net Profit Margin (NPM) as a function of tomato transplant times after lettuce transplantation.

experiments of maize and bean intercropping. It was defined by Willey (1979) as the relative area of land under individual crop conditions required to provide the yield reached in intercropping. LER particularly indicates the biological efficiency of the intercropping in using the resources of the environment compared to individual crops (Mead and Willey, 1980). It is currently the most widely used index by researchers in evaluating the efficiency of intercropping systems. LER is calculated as $\mathrm{LER} = \mathrm{LER}_t + \mathrm{LER}_l$, where LER_t and LER_l represent the LER of the individual crops (tomato and lettuce, respectively, in the present work). Comparison of these individual indices can indicate the relative competitive ability between the component crops. Thus, $\mathrm{LER}_t = \mathrm{Y}_{tl}/\mathrm{Y}_t$ and $\mathrm{LER}_l = \mathrm{Y}_{lt}/\mathrm{Y}_l$. The value of unity is the critical value. When LER is greater than unity, the intercropping favours growth and yield of the component crops. In contrast, when LER is less than unity, the intercropping negatively affects the growth and yield of the crops grown in association (Caballero et al., 1995). A homogeneous standardisation was used for obtaining the LERs of each plot, considering the mean value of individual crops over blocks in the denominator of LER_t and LER_l, according to Bezerra Neto and Robichaux (1996) and Federer (2002).

c) Aggressivity (A) – A is an index that indicates how much the relative increase in yield of the *t* component crop (tomato, in this case) is greater than that of the *l* component (lettuce) in an intercropping system. It was proposed by McGilchrist and Trenbath (1971) to measure the dominance of one crop over another. This index is calculated as $\mathrm{A}_t = \left(\mathrm{Y}_{tl}/\mathrm{Y}_t\mathrm{Z}_{tl}\right) - \left(\mathrm{Y}_{lt}/\mathrm{Y}_l\mathrm{Z}_{lt}\right)$ and $\mathrm{A}_l = \left(\mathrm{Y}_{lt}/\mathrm{Y}_l\mathrm{Z}_{lt}\right) - \left(\mathrm{Y}_{tl}/\mathrm{Y}_t\mathrm{Z}_{tl}\right)$. If A is zero, both crops are equally competitive. If A is positive, then the component crop with a positive signal is dominant and the crop with a negative signal is dominated.

d) Competitive ratio (CR) – CR was obtained through the formulae suggested by Willey and Rao (1980): $CR = CR_t + CR_l$, $CR_t = [(LER_t / LER_l) \times Z_{lt} / Z_{tl}]$, and $CR_l = [(LER_l / LER_t) \times Z_{tl} / Z_{lt}]$, where CR_t is the competitive ratio for intercropped tomato, CR_l is the competitive ratio for intercropped lettuce, and CR is the competitive ratio for the intercropping system. CR_t and CR_l were obtained from aggressivity. CR simply represents the ratio of the individual LERs of the two component crops and takes into account the proportion of the crops in which they are initially sown. CR is another method of evaluating competition between different crops. This index gives a better measure of competitive ability of the component crops.

Also, it has some comparative advantages over the K and A indices. In an intercropping system, the crop presenting the higher CR is better able to use the environment resources when compared to the other component crop.

e) Actual Yield Loss (AYL) – AYL is the proportionate yield loss or gain of intercrops compared to the individual crops (Banik et al., 2000). This index takes into account the actual sown proportion of the component crops with their respective single crops and provides more precise information about competition than do the other indices between and within the component crops. It also provides more precise information about the behaviour of each crop in intercropping systems, as it is based on yield per plant. Partial Actual Yield Loss also represents the proportionate yield loss or gain of each crop grown as intercrops compared to their pure stands. AYL can be calculated with the following formulae (Banik 1996):

$AYL = AYL_{tomato} + AYL_{lettuce}$

$AYL_{tomato} = \{[(Y_{tl}/Z_{tl})/(Y_t/Z_t)] - 1\}$

$AYL_{lettuce} = \{[(Y_{lt}/Z_{lt})/(Y_l/Z_l)] - 1\}$

Positive or negative values of AYL indicate the advantage or disadvantage of the intercropping, i.e. to give a quantitative assessment of the advantage/disadvantage accumulated in any situation of intercropping when the primary purpose is to compare yield on a per plant basis. The magnitudes of the partial AYLs of crop components in an intercrop situation reflect the nature of competition between and within crop components.

f) Intercropping Advantage (IA) – IA is another index that has been used by Banik et al. (2000) and Dhima et al. (2007), with the following formulae that have been adapted to the study:

$IA = (P_t \text{ x } AYL_t) + (P_l \text{ x } AYL_l)$

$IA_{tomato} = P_t \text{ x } AYL_t$ and $IA_{lettuce} = P_l \text{ x } AYL_l$

According to Banik et al. (2000), this index, in addition to expressing the advantage or disadvantage of intercrops, can be an indicator of the economic feasibility of intercropping systems.

g) Gross return (GR) – GR represents the value of combined yields in each intercropping system, irrespective of production costs (PC). It was obtained from $GR = Y_{tl} P_t + Y_{lt} P_l$, where Y_{tl} and Y_{lt} are the yields in tonne per ha of tomatoes and lettuce, respectively, as intercrops, and P_t and P_l are the prices of 1 kg of tomatoes and lettuce, respectively, charged by Companhia de Entrepostos e Armazéns Gerais de São Paulo (CEAGESP) in the months in which the vegetables were collected and updated to November 2010.

h) Net return (NR) – Calculated as NR = GR – PC, where PC is the summation of all expenses (inputs and labour) in each intercropping system.

i) Modified Monetary Advantage (MMA) – Calculated using the formula proposed by Beltrão et al. (1984): MMA = NR (LER – 1)/LER. According to these authors the higher the MMA and NR, the more profitable is the intercropping system.

j) Benefit/Cost Ratio (B/CR) – Obtained as B/CR = GR/PC (Beltrão et al., 1984).

k) Net Profit Margin (NPM) – Derived as the ratio of NR to GR and expressed as a percentage.

Data analysis

A univariate analysis of variance for a randomised complete-block design was performed using the SAS programme (Dewiche and Slaughter, 2003). A combined analysis of variance over crop growing seasons was performed for all evaluated indices to look for any significant interaction between cropping seasons and times of transplanting the component crops. Since these factors did not interact, the index values are reported as a mean of two growing seasons. The procedure for fitting the response curve to the transplanting times of each crop was performed using the software Table Curve (Jandel Scientific, 1991). The response functions were evaluated based on the following criteria: biological rationale, significance of the mean square error of regression (MSEr), high coefficient of determination (R^2), and significance of regression parameters, using the *t* test at 5% probability.

Conclusions

The intercropping of lettuce and tomato or tomato and lettuce in protected cultivation, regardless of the transplant time of the secondary crop into the main crop, had bio-agroeconomic advantages over individual crops. Intercropping is profitable and is recommended with tomato transplantation after lettuce transplantation. Tomato was the dominant crop and lettuce was the dominated crop in intercrops established with lettuce transplantation after tomato transplantation and in intercrops established with tomato transplanted after lettuce transplantation. Higher indices of competition and bio-agroeconomic efficiency were observed in intercropping systems established with transplants of both species on the same day. The relative crowding coefficient, land equivalent ratio, aggressivity, actual yield loss, intercropping advantage, and modified monetary advantage obtained through the homogenous standard method, using the average value of individual crops over blocks in the denominator, are the indices in which the assumptions of the analyses of variance were met.

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