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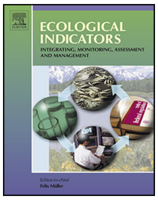

Bio-agro-economic returns from carrot and salad rocket as intercrops using hairy woodrose as green manure in a semi-arid region of Brazil

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ABSTRACT

The efficiency of an intercropping system depends mainly on the cropping system and on the crops, which should complement each other. However, the choice of crops and factors of production are extremely important for maximizing the advantages of intercropping, which, in turn, means maximizing the bio-agro-economic performance of the system. The present study sought to assess, based on appropriate indexes and indicators and using univariate and bivariate analysis, the agronomic/biological and economic returns from a system in which salad rocket was intercropped with carrot at different population densities and one of spontaneous species of the semi-arid region of Brazil, namely hairy woodrose (*Merremia aegyptia* L.), was used as green manure. The population densities of both the crops were maintained at 40%, 60%, 80%, or 100% of the recommended population for a sole crop (RPSC). The following values were recorded or calculated: green biomass of rocket, biomass of carrot roots, aggressivity indexes, competitive ratio, land equivalent ratio, productive efficiency index, canonical variable score, and four economic indicators, namely gross and net returns, rate of return, and net profit margin. The most effective combination was carrot at 40% of its RPSC intercropped with rocket at 100% of its RPSC with hairy woodrose as green manure because the combination resulted in the highest values of land equivalent ratio (1.72), productive efficiency index (0.91), canonical variable score (1.68), gross returns (R$ 41,186.91 ha^{-1}), net returns (R$ 18,621.64 ha^{-1}), rate of return (1.84), and net profit margin (52.77%), making it a highly profitable combination for the north-eastern semi-arid region of Brazil. The most effective indicators of economic value were yield and the rate of return.

1. Introduction

In evaluating intercropping systems, besides biological and physical criteria as yield and nutrient status of soil, we also need economic criteria that measure income and profitability. Planting density, or the number of plants per unit area of each species that make up the system, is particularly important because of its impact on the productivity of land and conservation of natural resources (Richetti and Ceccon, 2009).

Generally, the analysis of agronomic-biologic efficiency of intercropping systems is limited to the land equivalent ratio (LER). However, Hinkelmann and Kempthorne (2008) maintain that no simple statistical analysis can assess the performance of intercropping systems adequately because of the number of parameters that need to be taken into account, including yield, competition, and economic efficiency of different components that make up an intercropping system.

Therefore, a number of indexes need to be used in univariate analysis of variance to evaluate the agronomic-biologic efficiency and also the competitive abilities of the components of a given intercropping system including the relative crowding coefficient, which determines the dominance of one species over the other

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in intercropping; the aggressivity index, which measures the relative increase in production of one component crop of at the cost of another; and the competitive ratio, which measures the competitive ability of the crops that are grown together as intercrops.

The productive efficiency index (PEI) of intercropping systems is currently measured through data envelopment analysis (DEA), which incorporates both biological and economic benefits of intercropping (Gomes et al., 2008). Models based on DEA calculate the relative efficiency of productive units and use linear programming problems, which improves each individual observation to estimate units that present the best practices of intercropping (Bezerra Neto et al., 2007a).

In addition to univariate analysis of variance of the yields of component crops separately and together, the yields of component crops can also be subjected to multivariate analysis. The distinction between univariate and multivariate analysis is, mainly, that the latter takes into account the correlations between yields of the two crops grown together on the same plot. In general, multivariate analysis is believed to provide better interpretation of results by describing the relative superiority of treatments through 'intercropping yield' that takes into account the incomes from both the crops that make up the trial, so that researchers can bring together component crops that have similar characteristics and study the correlations between them (Cruz et al., 1991).

It is against this background that the present study sought to assess, based on appropriate indexes and indicators and using univariate and bivariate analysis, the agronomic/biological and economic returns from a system in which salad rocket was intercropped with carrot at different population densities after incorporating hairy woodrose (one of the spontaneous species of the semi-arid region of Brazil) into soil as green manure.

2. Materials and methods

2.1. Site and climate

The study was conducted in the experimental area of the Rafael Fernandes Farm of the Universidade Federal do Semi-Árido (UFERSA), Mossoró, RN, Brazil (5°11′ S, 37°20′ W; altitude, 18 m), from August 2011 to February 2012 in a semi-arid region of northeastern Brazil. The climate of the region is semi-arid and, according to the Köppen climate classification scheme, designated as 'BShw', dry and very hot, with two seasons: a dry season, which usually runs from June to January, and a rainy season, from February to May (Almeida et al., 2015).

The soil of this area was classified as an Alfissol eutrophic (EMBRAPA, 2006) and an analysis of its samples yielded the following results: pH = 6.8, $N = 1.54\,g\,kg^{-1}$, $P = 6.3\,cmol_c\,dm^{-3}$, $K = 85.2\,mg\,dm^{-3}$, $Ca = 2.01\,cmol_c\,dm^{-3}$, $Mg = 1.09\,cmol_c\,dm^{-3}$, $Na = 35.9\,mg\,dm^{-3}$, Sum of bases = $3.47\,cmol_c\,dm^{-3}$, and base saturation = 91%.

2.2. Experimental layout

The experiment was laid out using the randomized complete block design with the treatments arranged in a 4 × 4 factorial scheme with four replications. The first and the second factors were the four population densities of carrot and rocket, namely 40%, 60%, 80%, and 100% of the recommended population for a sole crop (RPSC). The values of RPSC for the region are 500,000 plants per hectare for carrot (Bezerra Neto et al., 2012) and 1,000,000 plants per hectare for rocket (Freitas et al., 2009). Each crop occupied 50% of the total area as alternating strips. Each plot consisted of two strips of four rows of each crop, flanked by two rows of one vegetable on one side and two rows of the other vegetable on the other side.

The total area of the intercropping plot was $2.88\,m^2$ and the harvest area was $1.60\,m^2$. The spacing between rows was 0.20 m and that within a row varied according to the spacing required to attain the desired population density. The harvest area consisted of two central strips of plants, excluding the first and the last plants of each row of the strips used as borders. In each block, carrot and rocket were also grown as sole crops to obtain the data required to calculate the indexes and indicators of system efficiency. The total area under sole crop was $1.44\,m^2$ and the harvest area was $0.80\,m^2$. For rocket, the spacing was 0.20 m × 0.05 m and for carrot, it was 0.20 m × 0.10 m. The cultivars of carrot and rocket were 'Brasília' and 'Cultivated', respectively.

2.3. Management

The preparatory operations consisted of manual cleaning of the experimental area, followed by harrowing, making raised beds, and solarisation of soil (Góes et al., 2014; Oliveira, 2012). Hairy woodrose (*Merremia aegyptia* L.) was used as green manure for all the treatments. Samples of the green manure in dry basis yielded the following results: $N = 31.90\,g\,kg^{-1}$, $P = 3.20\,g\,kg^{-1}$, $K = 46.40\,g\,kg^{-1}$, $Ca = 1.8\,g\,kg^{-1}$, $Mg = 3.3\,g\,kg^{-1}$, $Fe = 428\,mg\,kg^{-1}$, $Zn = 20\,mg\,kg^{-1}$, $Cu = 11\,mg\,kg^{-1}$, and $Mn = 48\,mg\,kg^{-1}$. The choice of the green manure was based on intercropping of tuberous and leafy vegetables such as beet, lettuce, carrot, coriander, and rocket in the same region. Hairy woodrose biomass incorporated into soil at $40\,t\,ha^{-1}$ proved optimal for beet intercropped with lettuce (Silva, 2013), at $13\,t\,ha^{-1}$ for a sole crop of carrot, and at $15\,t\,ha^{-1}$ for a sole crop of rocket (Bezerra Neto et al., 2014; Linhares, 2007).

Weeds were controlled manually and the crops were irrigated twice a day using a micro-sprinkler system (Porto et al., 2011).

Carrot was sown on 10 and 11 October 2011 and harvested 105 days later; rocket was sown twice, on 10 and 11 October 2011 and on 9 and 10 January 2012, and harvested 35 days after sowing.

2.4. Evaluated indices and indicators

Yields were recorded in terms of green biomass of rocket and roots of carrot (the commercial products in each case) and the following indexes were determined: aggressivity, LER, competitive ratio, PEI, and score of the canonical variable; the economic indicators were gross returns, net returns, rate of return (RR), and net profit margin (NPM).

Aggressivity index indicates the relative increase in production of the **c** component crop (carrot in this case) over that of the **r** component crop (rocket) in an intercropping system and is given by the following expressions: $A_c = (Y_{cr}/Y_c Z_{cr}) - (Y_{rc}/Y_r Z_{rc})$ and $A_r = (Y_{rc}/Y_r Z_{rc}) - (Y_{cr}/Y_c Z_{cr})$, where A_c and A_r are the aggressivity indexes of carrot and rocket, respectively; Y_{cr} is the yield of carrot roots and Y_{rc} is the yield of green biomass of rocket (sum of the 1st and the 2nd harvest) when both are grown as intercrops; Y_c is the yield of carrot roots and Y_r is the yield of green biomass of rocket (sum of the 1st and 2nd harvest) when both are grown as sole crops; and Z_{cr} is the proportion of plant number of carrot intercropped with rocket and Z_{rc} is the proportion of plant number of rocket intercropped with carrot. If A is zero, both crops are similarly competitive; if it is not, the component crop with a positive value of A is the crop that is dominant over the crop with a negative value of A.

The LER was obtained by the following expression:

$$LER = \frac{Y_{cr}}{Y_{cc}} + \frac{Y_{rc1}}{Y_{rr1}} + \frac{Y_{rc2}}{Y_{rr2}}$$

where Y_{cr} = yield of carrot roots when carrot is intercropped with rocket; Y_{cc} = yield of carrot roots when carrot is grown as a sole crop; Y_{rc1} and Y_{rc2} = yield of green biomass of rocket in the first and the second harvest, respectively, when rocket is intercropped with carrot; and Y_{rr1}/Y_{rr2} = yield of green biomass of rocket in the first and second harvest, respectively, when rocket is grown as a sole crop. The ratio was obtained for each plot when the average of the repetitions of the plots in sole crop over blocks was used in the denominator of the partial LERs for each crop ($\mathrm{LER_c}$ and $\mathrm{LER_r}$), as recommended by Federer (2002).

The competitive ratio was obtained by the formulae suggested by Willey and Rao (1980), namely $\mathrm{CR} = \mathrm{CR_c} + \mathrm{CR_r}$, $\mathrm{CR_c} = [(\mathrm{LER_c}/\mathrm{LER_r}) \times (\mathrm{Z_{rc}}/\mathrm{Z_{cr}})]$, and $\mathrm{CR_r} = [(\mathrm{LER_r}/\mathrm{LER_c}) \times (\mathrm{Z_{cr}}/\mathrm{Z_{rc}})]$, where $\mathrm{CR_c}$ is the competitive ratio for intercropped carrot, $\mathrm{CR_r}$ is the competitive ratio for intercropped rocket, and CR is the competitive ratio for the intercropping system as a whole.

To calculate the PEI of each treatment, we used the DEA model with constant returns to the scale (Charmes et al., 1979) since there was no significant difference in the scales. The model has a mathematical formulation: X_{ik} is the *input* i value ($i = 1, \ldots, s$) for treatment k ($k = 1, \ldots, n$); Y_{jk} is the *output* j value ($j = 1, \ldots, r$) for treatment k; $_{vi}$ and $_{uj}$ are the weights attributed to inputs and outputs, respectively; and O is the treatment being analysed.

$$\mathrm{Max}\sum\nolimits_{i=1}^{r} v_i x_{io} \sum\nolimits_{j=1}^{s} u_j y_{jo} = 1$$

$$\sum\nolimits_{j=1}^{s} u_j y_{jk} = 1 \sum\nolimits_{i=1}^{r} v_i x_{ik} = 1 \leq 0, \quad k = 1, \ldots, n \quad u_j, v_i \geq o,$$
$$i = 1, \ldots, s, \quad j = 1, \ldots, r$$

The evaluation units were the treatments, a total of sixteen population combinations and the *outputs* were the green biomass yield of rocket (sum of the 1st and the 2nd harvest) and the yield of carrot roots. To evaluate the yield of each plot, it was assumed that each plot utilized a single resource with a unitary level, following an approach similar to that used by Soares de Mello and Gomes (2004), since the *outputs* incorporated the possible *inputs*.

A bivariate analysis of variance was performed on crop yields, where each source of variation was tested by the criterion of Wilks (Λ). Once the significant treatments were identified, we proceeded to the analysis of the canonical variable score or the canonical discriminant function Z, which consisted of finding a linear combination of p original variables (X_i) as follows: $Z = E_1X_1 + E_2X_2 + . + E_pY_p$. The characteristic roots of the matrix HE^{-1} (H = matrix of sums of squares and cross-products for treatment and E^{-1} inverse of the matrix of sums of squares and cross-products of the experimental error) were then extracted, using the iterative method for calculating the eigenvalues and autovectors, being the matrix coefficients of the autovectors of the solution for the coefficients E_i, where $I = 1, 2, \ldots, p$ of the linear combination in Z. After this, the scores of the function Z were obtained from the vectors registered in each experimental unit, reducing it to a single value.

The gross return (GR) was obtained through the value of the production per hectare based the price paid to producers in the region in February 2012. For carrot, the amount paid was R$ 0.80 $\mathrm{kg^{-1}}$ and for rocket, it was R$ 1.40 $\mathrm{kg^{-1}}$. The current exchange rate of the US dollar is $1 = R$ 4.00, as on February 2016. The GR is represented by the following expression: $\mathrm{GR} = Y_{cr} \cdot P_c + Y_{rc} \cdot P_r$, where Y_{cr} and Y_{rc} are the yields (tonnes per hectare) of carrot and rocket, respectively, as intercrops, and P_c and P_r are the prices of 1 kg of carrot and rocket, respectively, charged by the region's producers.

Net return (NR) was calculated as NR = GR − PC, where PC (production costs) is the summation of all expenses (input and labour) in each intercropping system.

The RR was obtained as RR = GR/PC (Beltrão et al., 1984) and the NPM as the ratio of NR to GR expressed as a percentage.

2.5. *Data analysis*

A univariate analysis of variance was performed using SISVAR 3:01 (Ferreira, 2000) to assess the yields of the component crops, aggressivity, competitive ratio, LERs, PEI, the first canonical discriminant function (Z), gross income, net income, RR, and NPM. Three assumptions of the univariate analysis were tested. To test for the additivity of the model, Tukey's test for non-additivity was applied to yield residuals data of each of the component crops.

The assumption of bivariate normality was performed by plotting the squared Mahalanobis distances against the chi-square percentiles (Lavorenti, 1998). The assumption for equality of covariance matrices was verified by Box's M test statistics (Norusis, 2006), and the hypothesis that the crop yields are independent was tested by Bartlett's test of sphericity based on residual correlations (Pallant, 2001).

Regression analyses were performed on the evaluated variables by fitting the response surface between the variable and the population densities through Table Curve, a software package (Jandel Scientific, 1991).

3. Results and discussion

3.1. *Assumptions of univariate and multivariate analysis*

The validity of each of the three assumptions was tested by a different method: the assumption of homoscedasticity was assessed by Bartlett's χ^2 test: the value of χ^2 varied from 0.190 to 0.337; that of normality, by the W-statistic of Shapiro–Wilk: the value varied from 0.520 to 0.717; and that of additivity, by the F-test of Tukey: the value varied from 0.053 to 0.668. In the residuals of the univariate analysis of variance of the variables A_c, A_r, $\mathrm{CR_c}$, $\mathrm{CR_r}$, $\mathrm{LER_c}$, $\mathrm{LER_r}$, LER, PEI, Y_c, and Y_r and in the first canonical discriminant function (Z), the probability values were higher than 0.052. These results mean that none of the three assumptions can be rejected ($p > 0.05$) through univariate analysis of variance of the residuals of all variables. The results of the Bartlett's χ^2 test suggest that the treatment variances of each variable are homogeneous to an acceptable degree.

The results of Shapiro–Wilk's W-statistic yielded non-significant values for all the variables analysed, suggesting that the residuals of these variables are normally distributed, obviating any need to transform them. Tukey's F-test for additivity showed that differences between any two treatments were similar for all the blocks and for all the variables, thus eliminating the possibility of any interaction between the blocks and the treatments.

The tests for checking the validity of the assumptions for multivariate analysis of variance in the yields of crops were performed using Box's M statistic, the correlation coefficient (r) for the plot, and Bartlett's test for sphericity. The test of equality of group covariance matrices, based on 45 degrees of freedom, yielded a value of 73.959, which is non-significant ($p = 0.168$) and therefore does not invalidate the assumptions of the analysis. This indicates that the covariance matrices of the yield residuals were similar among the treatments.

The coefficient of correlation of the Q–Q plot between the yields of the two crops was of 0.994 and therefore significant at 1% probability level in relation to the critical value of 0.974, based on 45 degrees of freedom. It is therefore accepted that the yields of carrot and the green biomass of rocket conform to a bivariate normal distribution. Bartlett's test of sphericity showed that $\chi^2 = 18{,}969$ ($p = 0.000$, with two degrees of freedom), leading to the rejection of the hypothesis that the yields of the two crops are independent of each other – a rejection that, in turn, leads to the inference that the assumptions for the bivariate analysis were valid.

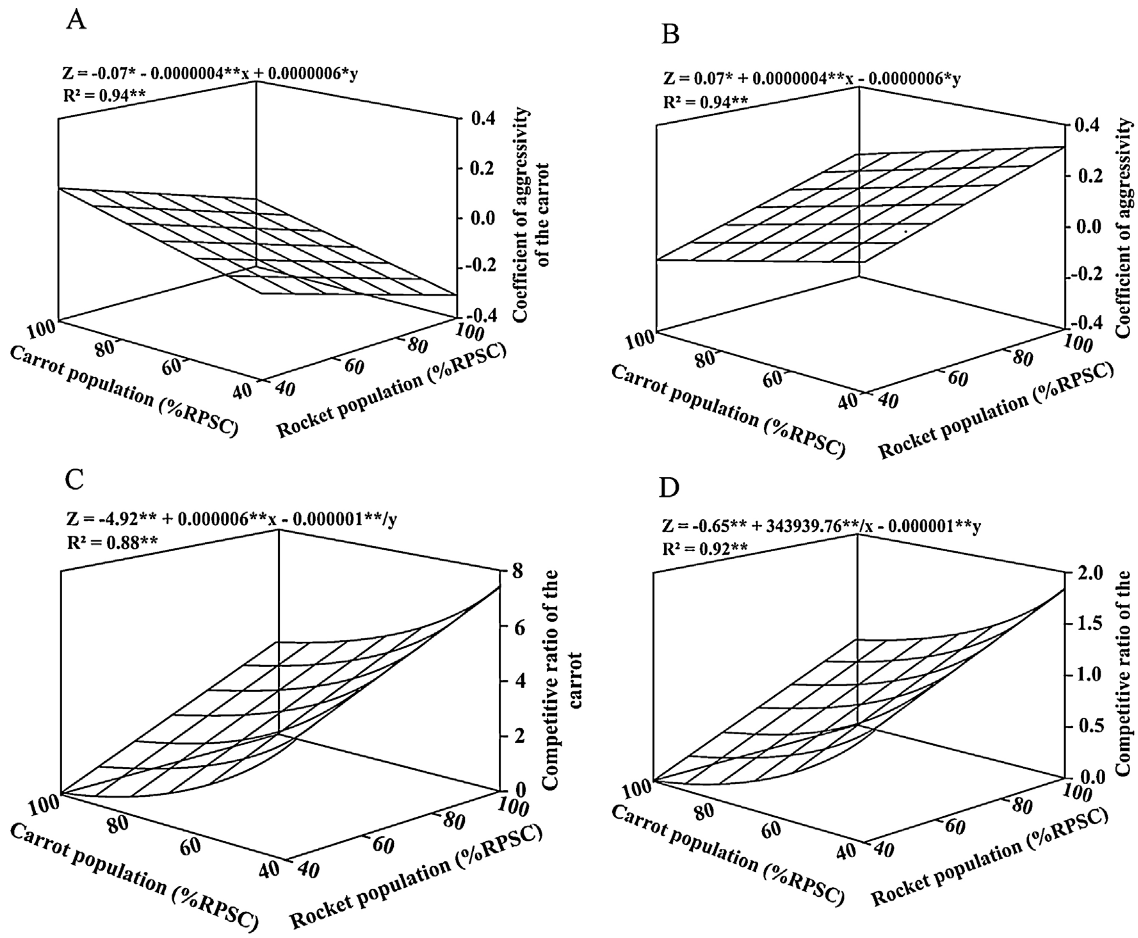


Fig. 1. Coefficient of aggressivity of the carrot (A) and rocket (B) and competitive ratio of the carrot (C) and rocket (D) in bicropping of rocket intercropped with carrot under different population combinations.

Bivariate analysis of variance of the yields led to the following latent or canonical roots extracted from the matrix HE^{-1}: $\lambda_1 = 6.293$, accounting for 97.96% of the variation and $\lambda_2 = 0.131$, accounting for 2.04% of total variation under intercropping. These results are consistent with those reported by Bezerra Neto et al. (2007b) in that, among all canonical roots, the first was the more important and explains most of the total variation found in the original data. Thus, the coefficients of the first canonical vector obtained of these roots were: $Z = 0.038Y_c + 0.034Y_r$.

3.2. Hairy woodrose as green manure

Using several spontaneous species of the Caatinga biome as green manure for intercrops involving tuberous and leafy vegetables has proved successful. One such species is hairy woodrose (*Merremia aegyptia* L.), native to north-eastern Brazil; juicy and with a pleasant smell, it is relished by animals. The species is widely distributed, found in forests, fences, clearings in the woods, and fields and grows in soils of different textures (Góes, 2007). Hairy woodrose is an annual climber, herbaceous, with a cylindrical, grooved, and glabrous stem, with shaggy pubescence. The leaves are yellowish, membranous, and alternate; the inflorescence consists of bunches of 6–9 lily-like flowers; and the fruit is a subglobose capsule.

Hairy woodrose can produce 36 t ha^{-1} of green biomass, which contains in term of dry basis 2.62% N, 0.17% P, 1.20% C, 1.2% K, 0.90% Ca, and 1.08% Mg, making the plant a good source of green manure for use on family-managed farms (Linhares, 2009).

Hairy woodrose has proved its agronomic and economic efficiency not only in intercrops – beet and lettuce (Silva, 2013), carrot and rocket (Carvalho, 2011; Paula, 2011), carrot and coriander (Fernandes, 2012), rocket and coriander (Moreira, 2011), and rocket, carrot, and lettuce (Oliveira, 2012) – but also in sole crops, the optimal amount of green manure to be worked into soil being 13 t ha^{-1} for carrot (Bezerra Neto et al., 2014), 45 t ha^{-1} for beet (Silva, 2013), 15 t ha^{-1} for rocket (Linhares, 2007), and 7 t ha^{-1} for lettuce (Góes et al., 2011).

The results of these studies are being disseminated widely and growers are being encouraged to adopt the practice as an important strategy for more efficient use of resources and more efficient production of intercrops or polycultures in north-eastern Brazil.

3.3. Indices of competition and agronomic/biological performance

There was no significant interaction between population densities of carrot and rocket with respect to aggressivity coefficients (A_c and A_r), competitive ratios of carrot and rocket (CR_c and CR_r), LER, the ratio for carrot (LER_c) and that for rocket (LER_r), PEI, and the score of the canonical variable (Z). As the next step, the response surface was adjusted for each index or indicator of efficiency of the intercropping system as a function of the population densities of the components crops.

The response surface was adjusted to the aggressivity coefficient of carrot with the maximum value of 0.10 obtained by decreasing the rocket population and increasing the carrot population such that the combination was 100% of the RPSC for carrot and 40% of

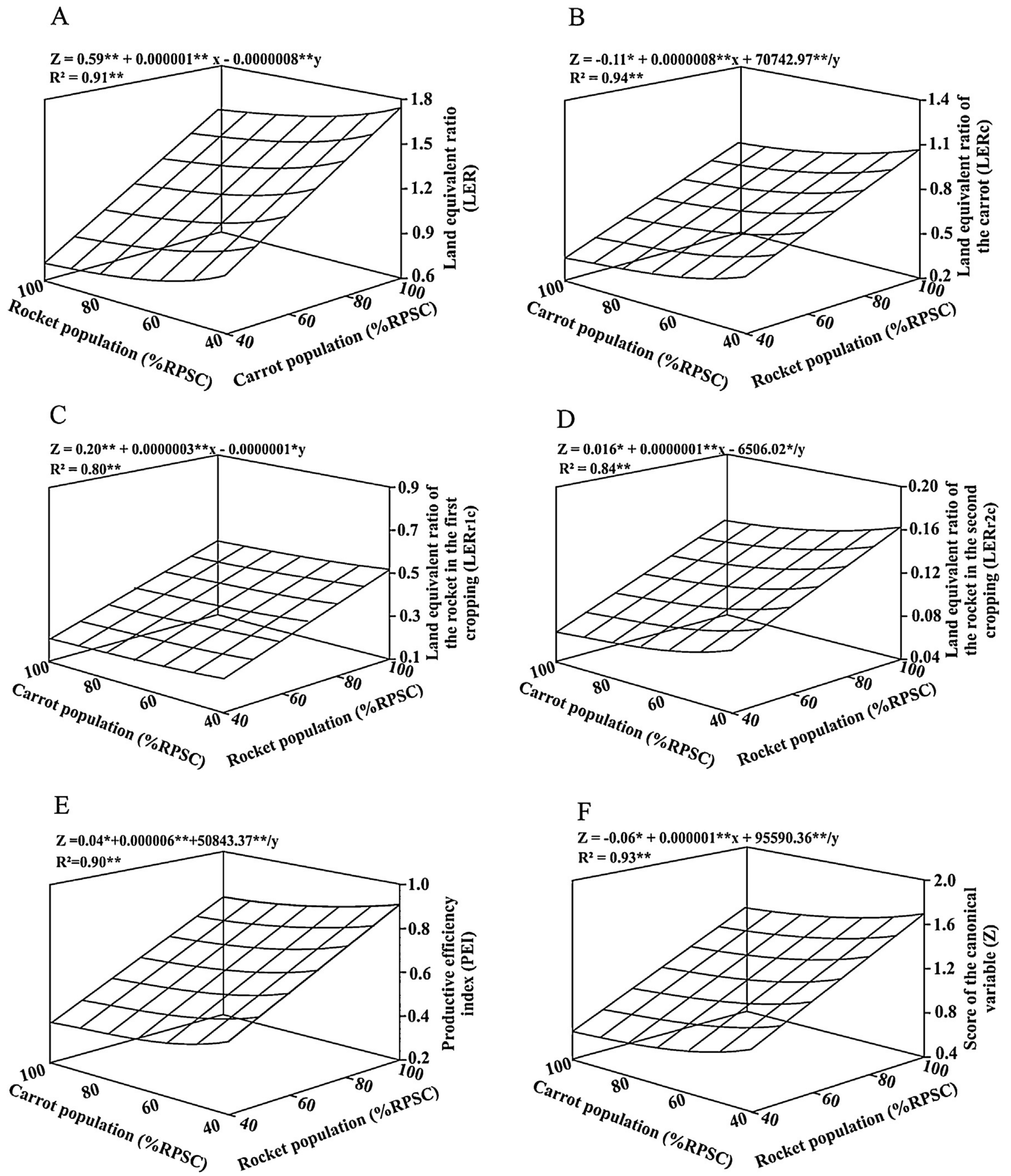
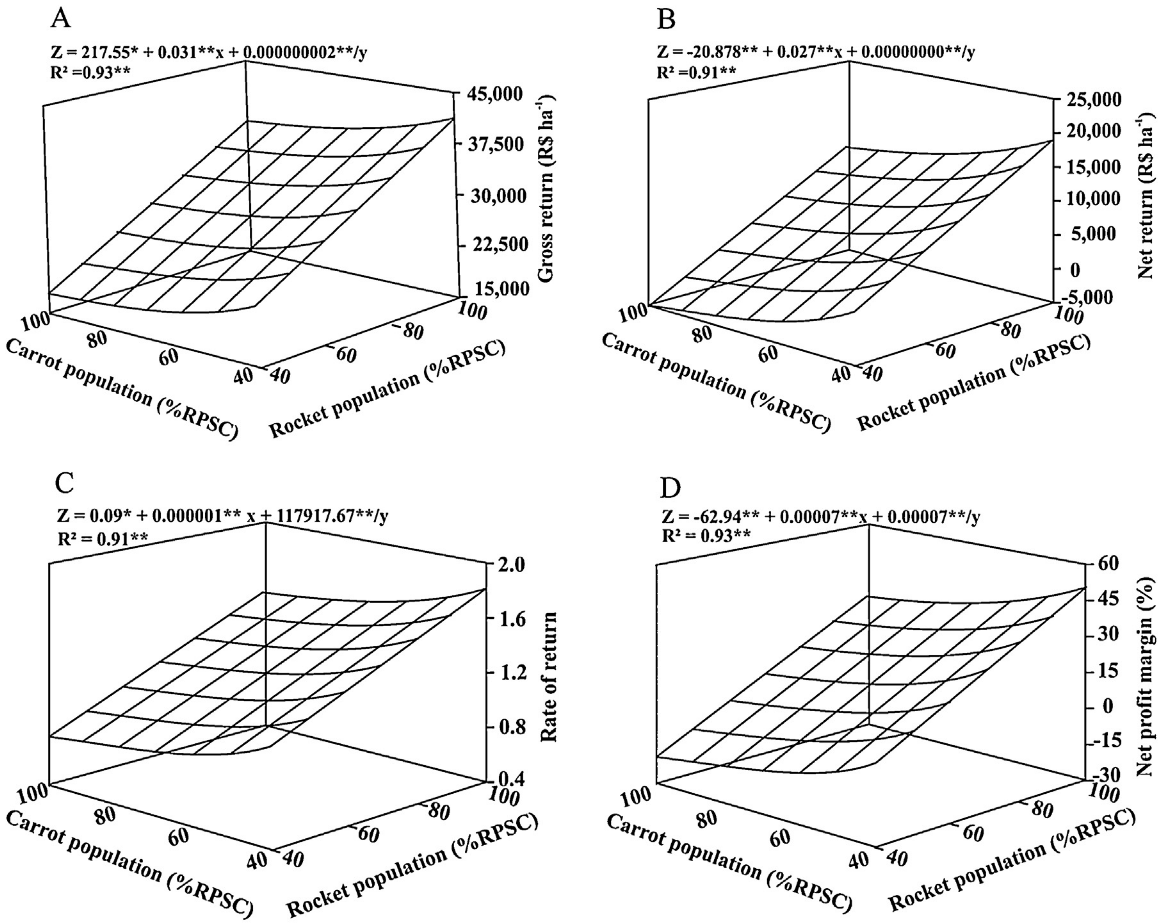


Fig. 2. Land equivalent ratio of the system (A), land equivalent ratio of the carrot (B) and rocket in the first (C) and second cropping (D), productive efficiency index (E) and score of the canonical variable (F) of the rocket in bicropping intercropped with carrot under different population combinations.

the RPSC for rocket (Fig. 1A). The corresponding maximum value of the aggressivity coefficient of rocket was 0.34, obtained in the combination consisting of 40% of the RPSC for carrot and 100% of the RPSC for rocket (Fig. 1B). In carrot, most of the determined values were negative, which makes carrot as the crop over which the other intercrop, namely rocket, is dominant. In rocket, these values were positive, confirming its status as the dominant of the two crops for the population combinations tested. The dominance of rocket in most combinations is related to the yield of its two harvests and to the pattern of development of carrot, which offers rocket the opportunity to be dominant.

The largest competitive ratios for carrot and rocket – 7.39 and 1.67, respectively – were obtained by decreasing the carrot population and increasing the rocket population such that the combination consisted of 40% of the RPSC for carrot and 100% of the RPSC for rocket (Fig. 1C and D). The *form* of the economic product of each intercrop and its *proportion*, namely underground tuberous roots in the case of carrot, at 40% of its RPSC, and above-ground green biomass in the case of rocket, at 100% of its RPSC – ensured that each component used the environmental resources such as water, sunlight, and nutrients with maximum efficiency. This index expresses the exact degree of competition between the species by indicating the number of times the dominant species is more competitive than the dominated species (Eskandari and Ghanbari, 2010).

For LER of the intercropping system and of its individual components (LER_c, LER_{r1}, and LER_{r2}), response surfaces were also adjusted



*** The current exchange rate of the US dollar is $1 = R$ 4.00, as on February 2016.**

Fig. 3. Gross return (A), net return (E), rate of return (C) and net profit margin (D) of rocket in bicropping intercropped with carrot under different population combinations.

to populations of both the crops. For the LER, it was found that the population combination of higher biological efficiency consisted of carrot at 40% of its RPSC and rocket at 100% of its RPSC, with a value of 1.72 (Fig. 2A). This result demonstrates a better productive performance of the intercropped system in terms of utilization of environmental resources and shows that the two grows as sole crops would need 72% more area to reach the yields from the intercropping system.

For the LER for carrot (LER_c), the maximum value of 1.07 was obtained in the population combination consisting of 40% of the RPSC for carrot and 100% of the RPSC for rocket (Fig. 2B), whereas the corresponding figure for rocket was 0.50 for the first harvest ($\text{LER}_{\text{r}1}$) and 0.16 for the second harvest ($\text{LER}_{\text{r}2}$), obtained in the combination consisting of 40% of the RPSC for carrot and 100% of the RPSC for rocket (Fig. 2C and D).

The consistently low values of LER in the case of rocket, irrespective of the strength of its population, showed that rocket was more productive as a sole crop. In comparing the proportions – in terms of area occupied – of different components that make up an intercropping system, the advantage of intercropping as reflected in the LER is derived from two different sources, generally confounded: (a) the land factor (area occupied) and (b) biological or agronomic factor (the treatments tested) (Montezano and Peil, 2006).

Recently, PEI has been used for evaluating intercropping systems by means of DEA, which incorporates the biological and economic advantages of these systems (Gomes et al., 2008). In the present experiment, the PEI increased with increase in rocket population and decrease in carrot population and peaked at 0.91 in the combination consisting of 40% of the RPSC for carrot and 100% of the RPSC for rocket (Fig. 2E). This pattern matched that of LERs, showing that the most efficient combination consisted of a smaller population of carrot and a higher population of rocket.

It must be kept in mind that PEI, besides crop yields, also takes into account the rate of return as an indicator of the economic value of a treatment. Similar results were observed by Bezerra Neto et al. (2007b) in carrot and lettuce as intercrops: when evaluated using univariate and multivariate methods, the PEI worked equally well for different cultivars of carrot and lettuce.

Combining indexes to reduce what is essentially a multivariate problem to one that is univariate always involves some loss of information contained in the original data. What is important is that the chosen method of analysis examines the relationship between two or more component variables of the system (Gomes et al., 2008). Therefore, Bezerra Neto et al. (2007a,b) maintain that the LER and the PEI are indexes that provide some indication of the magnitude of advantage gained from combined production, and can be applied to any intercropping situation. Furthermore, the analysis performed by PEI (through the DEA models) coincides with the classical analysis of variance for univariate responses and simplifies statistical analysis in multidimensional cases. The use of PEI appears to be relevant to the analysis of intercropping experiments set up to identify the best combination of two or more crops.

The assumptions of homogeneity, normality, and additivity of the errors of the univariate analysis of variance of the yields of carrot (Y_c) and rocket (Y_r) and of the score of the canonical variable (Z) were shown to be valid, and so were the assumptions of homogeneity of covariance matrices, of bivariate normality, and Bartlett's sphericity. The correlation coefficient (Q–Q plot) between the two yields was 0.9937 and therefore significant ($p = 0.000$). Thus, it can be safely assumed that the yields of carrot and rocket conform to a bivariate normal distribution. The test for equality of covariance matrices, based on 45 degrees of freedom, was 73.95 and therefore not significant ($p = 0.168$) and did not violate the assumptions of the analysis. This result indicates that the covariance matrices of the yields of carrot and rocket are similar between treatments. The test of Bartlett's sphericity was $\chi^2 = 18.969$, $p = 0.000$, leading to rejection of the hypothesis that the crops yields are independent. Therefore, the assumptions for the bivariate analysis were reasonably satisfied, which, according Lavorenti (1998), is necessary for validating confidence intervals.

The scores obtained in each experimental unit after a univariate analysis of variance yielded the following results. A response surface was observed for the scores of the canonical variable: as their values increased, the carrot population decreased and the rocket population increased; the maximum value (1.68) was reached in the combination consisting of 40% of the RPSC for carrot and 100% of the RPSC for rocket (Fig. 2F). In other words, the intercropping efficiency was maximum when the population density of carrot was the lowest and the population density of rocket was the highest, confirming the obtained values of PEI and LER of 0.91 and 1.72, respectively.

According to Bezerra Neto et al. (2007a), the bivariate method is superior because of its greater discriminating capacity and its ability to show the behaviour of factors – treatments through the canonical variable technique.

3.4. Economic indicators

There was no significant interaction between population densities of carrot and rocket that was reflected in gross returns, net returns, RR, and NPM. Therefore, response surfaces were also obtained for each of the economic indicators: again, the value of each indicator increased with an increase in the population of rocket and a decrease in the population of carrot. The highest values all the four indicators were attained in the combination consisting of 40% of the RPSC for carrot and 100% of the RPSC for rocket: gross return (R$ 41,186.91 ha^{-1}), net return (R$ 18,621.64 ha^{-1}), RR (1.84), and NPM (52.77%) (Fig. 3A–D). The superiority of this combination must be attributed to the crop yields, made possible by more efficient use of environmental resources and inputs and seen in the indexes of agronomic/biological efficiency and competitiveness.

Bezerra Neto et al. (2005) analysed the agro-economic viability of an intercropping system comprising carrot and lettuce: because both the components were members of the family Oleraceae, the four economic indicators peaked when the populations of both the components were maximum: gross return, R$ 73,560.40 ha^{-1}; net return, R$ 55,613.20 ha^{-1}; RR, 4.10; and NPM, 75.32%. The economic indicators reflected the advantages observed in the agronomic/biological indexes of efficiency, deriving maximum economic advantage from the agronomic superiority of the combination of lower densities of carrot and higher densities of rocket.

4. Conclusions

The combination that led to maximum agronomic/biological efficiency and economic advantage consisted of carrot at 40% of the RPSC and rocket at 100% of the RPSC. It was this combination, grown after incorporating hairy woodrose as green manure in the soil, that resulted in maximum values of all the critical indexes and economic indicators: land equivalent ratio (1.72), productive efficiency index (0.91), score of the canonical variable (1.68), gross returns (R$ 41,186.91 ha^{-1}), net returns (R$ 18,621.64 ha^{-1}), RR (1.84), and NPM (52.77%). Therefore, this particular combination can be recommended highly to those who grow vegetables on family farms in north-eastern Brazil. Bivariate analysis of variance of the yields of carrot and rocket and data envelopment analysis using these yields and the rate of return as an indicator of the economic value of the factors-treatments were effective in identifying the best intercropping system. These results will be used as an important strategy for using environmental resources more efficiently and for deriving maximum benefits from intercropping systems involving carrots and rocket on family-owned farms in north-eastern Brazil.

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References

Almeida, A.E.S., Bezerra Neto, F., Costa, L.R., Silva, M.L., Lima, J.S.S., Barros Júnior, A.P., 2015. Eficiência agronômica do consórcio alface-rúcula fertilizado com flor-de-seda. Rev. Caatinga 28, 79–85.

Beltrão, N.E., Nobrega, M.L.B., Azevedo, D.M.P., Vieira, D.J., 1984. Comparação entre indicadores agroeconômicos de avaliação de agroecossistemas consorciados e solteiros envolvendo algodão upland e feijão "Caupi". Boletim de Pesquisa 15, CNPA, Campina Grande, PB, pp. 21.

Bezerra Neto, F., Oliveira, L.J., Santos, A.P., Lima, J.S.S., Silva, I.N., 2014. Otimização agroeconômica da cenoura fertilizada com diferentes doses de jitirana. Rev. Cienc. Agron. 45, 305–311.

Bezerra Neto, F., Barros Júnior, A.P., Negreiros, M.Z., Oliveira, E.Q., Silveira, L.M., Câmara, M.J.T., 2005. Associação de densidades populacionais de cenoura e alface no desempenho agronômico da cenoura em cultivo consorciado em faixa. Hortic. Bras. 23, 233–237.

Bezerra Neto, F., Gomes, E.G., Oliveira, A.M., 2007a. Produtividade biológica em sistemas consorciados de cenoura e alface avaliada através de indicadores agroeconômicos e métodos multicritério. Hortic. Bras. 25, 193–198.

Bezerra Neto, F., Gomes, E.G., Nunes, G.H.S., Oliveira, E.Q., 2007b. Desempenho de sistemas consorciados de cenoura e alface avaliados através de métodos uni e multivariados. Hortic. Bras. 25, 514–520.

Bezerra Neto, F., Porto, V.C.N., Gomes, E.G., Cecílio Filho, A.B., Moreira, J.N., 2012. Assessment of agroeconomic indices in polycultures of lettuce, rocket and carrot through uni- and multivariate approaches in semi-arid Brazil. Ecol. Indic. 14, 11–17.

Carvalho, F.W.A., (Tese (Doutorado em Agronomia: Fitotecnia)) 2011. Tamanho de parcela e viabilidade agroeconômica do consórcio cenoura e rúcula. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, RN, pp. 79.

Charmes, A., Cooper, W.W., Rhodes, E., 1979. Measuring the efficiency of decision-making units. Eur. J. Oper. Res. 3, 339.

Cruz, C.D., Magalhães, P.C., Pereira Filho, I.A., 1991. Análise bivariada do rendimento de milho e feijão em sistema consorciado. Rev. Ceres. 38, 332–339.

EMBRAPA, 2006. Empresa Brasileira de Pesquisa Agropecuária. Sistema Brasileiro de Classificação de Solos, Centro Nacional de Pesquisas de Solos, Rio de Janeiro, Embrapa, pp. 306.

Eskandari, H., Ghanbari, A., 2010. Environmental resource consumption in wheat (*Triticum aestivum*) and bean (*Vicia faba*) intercropping: comparison of nutrient uptake and light interception. Not. Sci. Biol. 2, 100–103.

Federer, W.T., 2002. Statistics issues in intercropping. In: El-Shaarawi, A.H., Pergorsh, W.W., Piergorsch, W. (Eds.), Encyclopedia of Environmetrics. Wiley, New York, pp. 1064–1069.

Fernandes, Y.T.D., (Dissertação (Mestrado em Agronomia: Fitotecnia)) 2012. Viabilidade agroeconômica do cultivo consorciado de cenoura e coentro em função de diferentes quantidades de jitirana e arranjos espaciais. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, RN, pp. 79.

Ferreira, D.F., 2000. Sistema SISVAR para análises estatísticas: Manual de orientação. Universidade Federal de Lavras/Departamento de Ciências Exatas, Lavras, pp. 37.

Freitas, K.K.C., Bezerra Neto, F., Grangeiro, L.C., Lima, J.S.S., Moura, K.H.S., 2009. Desempenho agronômico de rúcula sob diferentes espaçamentos e épocas de plantio. Rev. Cienc. Agron. 40, 449–454.

Góes, S.B., (Dissertação (Mestrado em Fitotecnia)) 2007. Desempenho agroeconômico de alface lisa em função de quantidades de jitirana incorporadas ao solo e de seus tempos de decomposição. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, pp. 84.

Góes, S.B., Sá, J.B., Bezerra Neto, F., Linhares, P.C.F., Góes, G.B., Moreira, J.N., 2011. Productive performance of lettuce at different amounts and times of decomposition of dry scarlet star glory. Rev. Cienc. Agron. 42, 1036–1042.

Góes, S.B., Sá, J.B., Duda, G.P., Bezerra Neto, F., Silva, M.L., Linhares, P.C.F., 2014. Changes in the pH and macronutrients in soil fertilized with hairy woodrose in different amounts and times of incorporation. Rev. Caatinga 27, 1–10.

Gomes, E.G., Souza, G.S., Vivaldi, L.J., 2008. Two-stage inference in experimental design using DEA: an application to intercropping and evidence from randomization theory. Pesq. Oper. 28, 339–354.

Hinkelmann, K., Kempthorne, O., 2008. Design and Analysis of Experiments, vol. 1., second ed. Wiley-Interscience, New York, pp. 631.

Jandel Scientific, 1991. Table Curve: Curve Fitting Software. Jandel Scientific, Corte Madera, California, pp. 280.

Lavorenti, N.A., (Thesis (Doctorate in Applied Statistics)) 1998. Fitting Models in a Bivariate Analysis of Intercropping. University of Reading, England, pp. 310.

Linhares, P.C.F., (Dissertação (Mestrado em Agronomia: Fitotecnia)) 2007. Produção de rúcula em função de diferentes quantidades e tempo de decomposição de jitirana. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, RN, pp. 58.

Linhares, P.C.F., (Tese (Doutorado em Fitotecnia)) 2009. Vegetação espontânea como adubo verde no desempenho agroeconômico de hortaliças folhosas. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, pp. 109.

Montezano, E.M., Peil, R.M.N., 2006. Sistemas de consórcios na produção de hortaliças. Rev. Bras. Agrocienc. 12, 129–132.

Moreira, J.N., (Tese (Doutorado em Agronomia: Fitotecnia)) 2011. Consorciação de rúcula e coentro adubada com espécie espontânea sucedida pelo cultivo de rabanete. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, RN, pp. 115.

Norusis, M.J., 2006. SPSS 14.0 Guide to Data Analysis, CD-ROM ed. Prentice Hall, Englewood Cliffs, NJ.

Oliveira, L.J., (Tese (Doutorado em Agronomia: Fitotecnia)) 2012. Viabilidade agroeconômica do bicultivo de rúcula e coentro consorciado com cenoura em função de quantidades de jitirana e densidades populacionais. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, RN, pp. 102.

Pallant, J., 2001. SPSS Survival Manual. Open University Press, Buckingham/Philadelphia, pp. 286.

Paula, V.F.S., (Dissertação (Mestrado em Agronomia: Fitotecnia)) 2011. Viabilidade agroeconômica de consórcios de cenoura e rúcula em diferentes quantidades de jitirana e arranjos espaciais. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, RN, pp. 63.

Porto, V.C.N., Bezerra Neto, F., Barros Júnior, A.P., Moreira, J.N., 2011. Combination of lettuce and rocket cultivars in two cultures inter cropped with carrots. Hortic. Bras. 29, 404–411.

Richetti, A., Ceccon, G., 2009. Análise econômica de sistemas de produção de milho safrinha em cultivo consorciado. In: Seminário Nacional De Milho Safrinha, Rio Verde. ABMS: FESURV, Anais, Rio Verde, pp. 207–213.

Silva, I.N., (Dissertação (Mestrado em Agronomia: Fitotecnia)) 2013. Bicultivo de alface consorciada com beterraba sob diferentes quantidades de jitirana incorporadas ao solo e arranjos espaciais. Universidade Federal Rural do Semi-Árido (UFERSA), Mossoró, RN, pp. 73.

Soares de Mello, J.C.C.B., Gomes, E.G., 2004. Eficiências aeroportuárias: uma abordagem comparativa com análise de envoltória de dados. Rev. Econ. Adm. 3, 15–23.

Willey, R.W., Rao, M.R., 1980. Ratio for quantitative competition between intercrops. Exp. Agric. 16, 117–125.