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Environmental impact of different agricultural production systems[1]

Impacto ambiental de diferentes sistemas de produção agrícola

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ABSTRACT - The efficient use of natural resources in production systems is essential for achieving ecological balance and sustainability in these systems. Current agricultural production systems have intensified the use of fertilisers and pesticides that contribute to an increase in energy flow, accelerating the process of degradation. The aim of this study was to evaluate, using emergy analysis, the environmental performance of different irrigated production systems for different sources of water, energy and fertiliser, and of rainfed systems under different types of soil preparation. The irrigated systems were studied in the experimental area of the Sewage Treatment Station (ETE) in Tianguá, Ceará (CE), and the rainfed models at the Fazenda Normal Farm in Quixeramobim, CE. Emergy analysis basically consists of three stages: construction of the systemic energy flow diagram, elaboration of the emergy evaluation table, and calculation of the emergy indicators. A mean value of 0.04 was found under the rainfed production systems, which shows less environmental stress compared to the irrigated systems, 0.30. The influx of economic resources into agricultural systems increases the environmental load and reduces renewability. Treated domestic effluent and photovoltaic solar energy afforded an increase in emergy yield and in the environmental sustainability of the production models.

Keywords: Production models. Irrigation. Rainfed system. Environmental performance.

RESUMO - O uso eficiente dos recursos naturais nos sistemas de produção é fundamental para alcançar o equilíbrio ecológico e a sustentabilidade do sistema produtivo. Os atuais sistemas de produção agrícola têm intensificado o uso de fertilizantes e pesticidas que contribuem no aumento do fluxo de energia, acelerando o processo de degradação. Objetivou-se avaliar o desempenho ambiental de diferentes sistemas de produção irrigados em função de diversas fontes de água, energia, adubação e de sequeiro em razão de diversos preparos do solo usando a análise emergética. O estudo dos sistemas irrigados foi conduzido na área experimental da Estação de Tratamento de Esgoto (ETE) em Tianguá - CE e os modelos em sequeiro foram realizados na Fazenda Normal em Quixeramobim - CE. A análise emergética constitui-se basicamente de três etapas: construção do diagrama sistêmico de fluxo de energia, elaboração da tabela de avaliação de emergia e o cálculo dos indicadores emergéticos. Verificou-se um valor médio de 0,04 nos sistemas produção em sequeiro, o que mostra menor estresse ambiental comparado aos sistemas irrigados 0,30. A entrada de recursos da economia nos sistemas agrícolas aumenta a carga ambiental e diminui a renovabilidade. O efluente doméstico tratado e a energia solar fotovoltaica promoveu aumento no rendimento emergético e na sustentabilidade ambiental dos modelos de produção.

Palavras-chave: Modelos de produção. Irrigação. Sequeiro. Desempenho ambiental.

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INTRODUCTION

Agricultural systems in the semi-arid region are currently highly susceptible to degradation. Characterised by water scarcity and the fragility of their natural resources, agricultural areas in the semi-arid region of the Northeast show a great diversity of climate, where, over time, the exploitation of these areas has had a marked impact on sustainability.

Excessive exploitation of natural resources in areas such as the semi-arid region, accelerates the process of degradation, affecting the way the ecosystem functions, and reducing the productivity of agricultural systems (BISARO *et al*., 2014; SANTINI *et al*., 2010).

Barbosa (2006) points out that human activities have resulted in a marked degradation of natural resources. Lopes *et al*. (2009a), emphasise that production systems based only on economic aspects, using natural resources until they are exhausted, have generated the environmental unsustainability of modern agriculture.

Rabelo (2017) points out that environmental changes can be identified as starting from overexploitation of the land and the inadequate use of water resources, among other factors. Giampietro, Cerretelli and Pimentel (1992) argue that the use of technological inputs, such as the intensive use of machinery, fertilisers and agrochemicals, has driven the energy flow in the agroecosystem to unsustainable levels.

Economic growth and an increase in population tend to increase the world demand for water, energy and food, intensifying the conflict between the water and energy sectors, and impacting on the environment (MARIANI *et al*., 2016). This dynamic results in substantial risks to sustainable development and to water and energy security.

Within the concept of new models of sustainable agricultural production, which highlight the need for developing less-degrading, more-efficient agriculture that ensures the conservation and inclusion of all the natural resource involved in a production system, emergy analysis, through the use of different indicators, is able to determine the influx and outflux of renewable and non-renewable resources from nature and the economy that are used in agricultural systems (ODUM, 1996).

Veisi *et al*. (2016), investigated the emergy performance and sustainability of three agricultural systems in Iran: winter wheat, grain maize and forage maize, and obtained an environmental load ratio (ELR) of 0.49, 0.86 and 0.57 respectively, and an emergy sustainability index (ESI) of 4.99, 4.12 and 2.06. The wheat production system showed the highest level of sustainability.

Feitosa *et al*. (2019), in their study of the economic and environmental sustainability of irrigated and rainfed crops, found that the production system contributed to economic growth with a low environmental load, and that the rainfed system showed long-term sustainability, and the irrigated system medium-term sustainability, with a renewability of 83.81% and 74.26% respectively.

The use of wastewater, as well as the use of photovoltaic solar energy, has aroused the interest of society in the face of accelerated population growth and increased water demand. It is believed that these alternatives ensure the better long-term environmental and economic performance of agricultural systems, allowing profitable crops to be achieved with less degradation of the natural resources.

The aim of this study was to evaluate the environmental impact of different irrigated production systems for different sources of water, energy and fertiliser, compared to varied models of rainfed production under different types of soil preparation.

MATERIAL AND METHODS

Irrigated production systems

The irrigated production models were studied in the experimental area of the Sewage Treatment Station (ETE) in Tianguá, CE, of the Companhia de Água e Esgoto do Ceará - CAGECE (3°44’ S and 40°59’ W, at an altitude of 740 m). The climate is type Aw’, Tropical with a dry season. The average annual temperature is 26 ºC with an average annual rainfall of 1,350 mm. The soil was classified as a sandy-loam Quartz Arenite Neosol.

The experiment consisted of six treatments in an experimental design of subdivided plots distributed in a completely randomised design with fifteen replications, in a 2 x 3 factorial scheme, i.e. two sources of water and energy (wastewater + photovoltaic solar energy and drinking water + mains energy), and different sources of fertiliser (mineral and organic), in addition to the controls.

The total area of the experiment (504 m^2) was cultivated with cowpea. Each experimental plot was 16.8 m^2, subdivided into 3 subplots of 5.6 m^2. The spacing between plants was 0.4 m, with 1 m between rows, as per the spacing recommendation for the Seventão 596 cultivar used in the experiment.

The six treatments were: S1A1 - Conventional production system + mineral fertiliser (drinking water

+ mains energy + mineral fertiliser); S2A1 - Renewable production system + complementary mineral fertiliser (wastewater + photovoltaic solar energy + complementary mineral fertiliser); S1A2 - Conventional production system + organic fertiliser (drinking water + mains energy + organic fertiliser); S2A2 - Renewable production system + complementary organic fertiliser (wastewater + solar photovoltaic energy + complementary organic fertiliser); S1A0 - Conventional production system with no fertiliser (drinking water + mains energy and no fertiliser); S2A0 - Renewable production system with no fertiliser (wastewater + photovoltaic solar energy and no fertiliser).

A localised drip system was used for irrigation, comprising Amanco drip tape, with a diameter of 16 mm, at a service pressure of 10 mca and nominal flow of 1.6 L h^{-1}. Irrigation management was based on the reference evapotranspiration, determined using the Penman-Monteith method (ALLEN *et al*., 1998).

For the renewable system, the Anauger P100 photovoltaic solar motor pump set was used, consisting of a motor pump, a driver and two 95 Wp photovoltaic panels, giving a total of 190 Wp. The pump associated with the photovoltaic system is submersible, and is able to operate in photovoltaic generation systems of 100, 130 and 170 Wp. For the conventional production system irrigated with drinking water and powered by energy from the mains, a Dancor CAM W-6C series motor pump set with a power value of 0.75 hp was used.

The water used in the conventional system came from the public water supply of the district of Tianguá, CE, originating in the Jaburu reservoir. The treated domestic effluent used in the renewable system came from the Tianguá Sewage Treatment Station, which employs stabilisation pond technology.

A physical-chemical and microbiological analysis of the wastewater and drinking water was made to characterise the quality parameters for irrigation (Table 1). The attributes were determined at the Environmental Health Laboratory (LABOSAN), where the Standard Methods for the Examination of Water and Wastewater (AMERICAN PUBLIC HEALTH ASSOCIATION, 2012) were adopted.

Application of the chemical and organic fertiliser was carried out based on the chemical analysis of the soil, organic compost and wastewater, the latter for the treatments irrigated with treated domestic effluent. The chemical fertiliser was based on the Manual of Fertiliser Recommendations for the state of Ceará (AQUINO *et al*., 1993), and the organic fertiliser was based on the recommendations for organic fertiliser (FURTINI NETO *et al*., 2001).

The doses of nitrogen and potassium were applied one half at sowing and the other half 30 days after planting, whereas all the phosphorus was applied when planting. The fertilisers were applied in furrows 5 cm deep, spaced 5 cm from the plants. Table 2 shows the applied values of mineral and organic fertiliser.

Rainfed production system

The research was carried out at the Fazenda Normal Farm of Ematerce, located in Quixeramobim, CE (5º12' S and 39º17' W, at an altitude of 250 m). The climate is semi-arid, type BSw'h'. The average annual temperature is 29.5 °C with an average annual rainfall of 625 mm.

The experiment consisted of four soil tillage systems (treatments). The experimental design was completely randomised in subdivided plots with four replications, giving a total of 16 experimental units. Each

Table 1 - Physical-chemical and microbiological analysis of the wastewater and drinking water used during the experiment with irrigated cowpea in Tianguá, CE

PARAMETER	Unit	Drinking Water	Reclaimed Water	Reference for reuse*
pH	-	6.50	7.10	6 - 8.5
EC	dS m^{-1}	0.28	1.32	3.0
Total nitrogen	mg L^{-1}	0.02	13.44	30.2
Total phosphorous	mg L^{-1}	0.05	13.19	14.6
Potassium	mg L^{-1}	6.00	35.00	36.8
Calcium	mg L^{-1}	13.33	24.48	74.0
Magnesium	mg L^{-1}	3.91	0.40	32.2
Sodium	mg L^{-1}	35.33	174.0	142.5
Total coliforms	Org 100 ml	0.00	2.4*104	105

*COEMA resolution No 02 of 2017

Table 2 - Recommendations of mineral and organic fertiliser for the different treatments

Mineral fertiliser	100% mineral	Complementary
Nitrogen (urea)	20 kg ha^{-1}	6.0 kg ha^{-1}
Phosphorous (single superphosphate)	80 kg ha^{-1}	52 kg ha^{-1}
Potassium (potassium chloride)	20 kg ha^{-1}	9.0 kg ha^{-1}
Organic fertiliser	100% compost	Complementary
Organic compost	19,525 kg ha^{-1}	5,925 kg ha^{-1}

plot had a total area of 35 m^2 with a working area of 15 m^2. The total area of the experiment was 560 m^2.

The treatments included a production system with no soil preparation (T-PC), a production system with the soil prepared using a scarifier (T-ESS), a production system with the soil prepared using subsoilers and furrowers (T-PSF), and a production system with the soil prepared using subsoilers, furrowers and addition of organic fertiliser (T-SFO).

Parameters under evaluation

To assess the environmental impact of the production systems, the three standard steps of emergy analysis were followed. First, the limits of the systems were defined for each treatment, the emergy analysis tables were then prepared for each of the models under study, and finally the indices were determined.

The emergy yield ratio (EYR) shows the ability of the system to exploit natural resources and make them available in the form of products in response to external investments (Equation 1). When the EYR = 1, it shows that the emergy from the local resources is exactly equal to the amount of emergy from the economy, therefore, the system has no potential for contributing to economic growth - small: 1 <EYR <2, moderate: 2 <EYR <5, and high: EYR> 5 (BROWN; ULGIATI, 2004; ODUM, 1996).

$$EYR = \frac{Y}{F} \tag{1}$$

where: *EYR* - Emergy yield ratio (dimensionless); *Y* - Total emergy (seJ); *F* - Renewable and non-renewable economic resources (seJ).

The environmental load ratio (ELR) shows the stress that the system exerts on the environment (Equation 2). Theoretically, ELR = 0 indicates a mature natural ecosystem, ELR <2 indicates low environmental load, 2 <ELR <3 moderately low, 3 <ELR <10 moderate impact, and ELR> 10 high environmental stress (BROWN; ULGIATI, 2004).

$$ELR = \frac{N + NS + NM}{R + RS + RM} \tag{2}$$

where: *ELR* - environmental load (dimensionless); *R* - renewable natural resources (seJ); *RM* - renewable materials from the economy (seJ); *RS* - renewable services from the economy (seJ) *NM* - non-renewable materials from the economy (seJ); *N* - non-renewable natural resources (seJ); and NS - non-renewable services from the economy (seJ).

The renewability index (R%) represents the percentage of renewable emergy that enters the system in relation to the total emergy. Highly renewable systems prevail over time due to the increased influx of renewable resources (Equation 3).

$$R = \frac{100x\left(R + RM + RS\right)}{Y} \tag{3}$$

where: *R* - Renewability (%); *R* - Renewable natural resources (seJ); *RM* - Renewable materials from the economy (seJ); *RS* - Renewable services from the economy (SEJ); Y - Emergy (seJ).

The emergy sustainability indicator (ESI) assesses the contribution of the system to the economy per unit of environmental load (Equation 4). ESI <1 indicates an unsustainable system. Systems with ESI> 1 contribute to economic growth, with no serious environmental disturbance; however, intermediate values (1 <ESI <5) refer to medium-term sustainability and ESI> 5 indicates long-term sustainability (BROWN; ULGIATI, 2004).

$$ESI = \frac{EYR}{ELR} \tag{4}$$

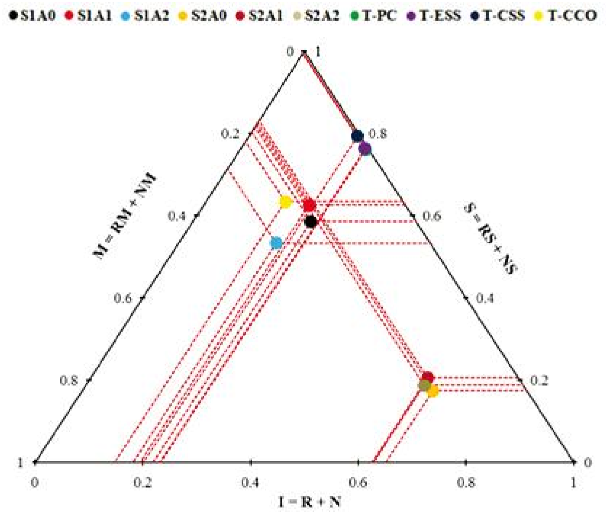
where: *ESI* - Emergy sustainability index (dimensionless); *EYR* - Emergy yield ratio (dimensionless) and *ELR* - environmental load (dimensionless).

Data analysis and preparation of the ternary diagrams was carried out using the XLSTAT® tool together with Microsoft Excel®. All energy flows for each component in physical units (joules, grams, USD) were quantified for an area of one hectare. As such, they were represented in the same metric unit (seJ), avoiding the use of standardisation methods and allowing direct graphical representation of the results.

RESULT AND DISCUSSION

By analysing the relationship between incoming natural resources and those from the economy (services and materials), both renewable and non-renewable (Figure 1), it could be seen that the renewable irrigated systems (S2A0, S2A1 and S2A2) showed better emergy performance, a result of the smaller amount of emergy originating in resources from the economy, since the emergy influx from services and materials was smaller compared to those from nature.

Figure 1 - Ternary diagram of the ratio between the emergy from renewable and non-renewable natural resources (I = R + N), inputs (M = RM + NM) and services (S = RS + NS) in the different irrigated and rainfed cropping systems



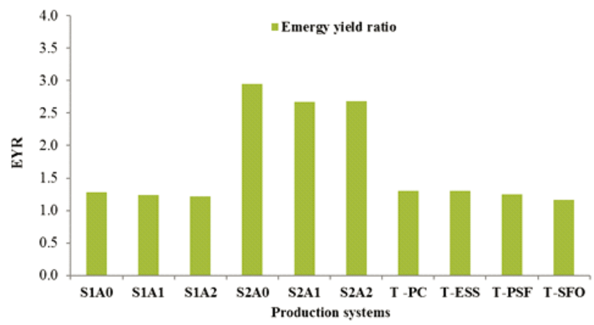
The conventional irrigated production systems (S1A0, S1A1 and S1A2) showed lower rates of renewability, emergy yield and sustainability, and greater environmental load, due to the smaller participation of natural resources in the production process. The S1A2 model had the lowest performance due to a greater influx of inputs (organic compost) and services.

The rainfed production systems proved to be highly dependent on the emergy flow from services; however, this situation did not negatively affect the indicators, since the component with the highest influx corresponded to family labour (renewable service), approximately 60%. These systems were also characterised by the small influx of inputs from the economy, a situation that caused less stress to the environment and consequently an increase in the indices of renewability and sustainability. An exception occurred in the T-SFO system, due to this production model including the input of organic compost (20%).

Meireles, Araújo Neto and Oliveira (2011), in a study of sustainability in the agricultural model of the River Faé basin, found that production activities using pesticides developed in the basin represent a serious risk, not only to the sustainability of the agricultural model, but particularly to the lives of the farmers.

In relation to the emergy yield ratio, the rainfed and conventional irrigated systems showed less potential for socioeconomic contribution than did the renewable irrigated systems, since in the conventional irrigated models the average EYR was 1.24, and in the rainfed models 1.25, showing that the emergy from non-renewable resources in the economy is nearly equal to the amount of emergy from the final product; these systems therefore, showed little potential for contributing to economic growth (Figure 2).

Figure 2 - Emergy yield ratio between conventional and renewable irrigated production systems and rainfed production models in the Northeast of Brazil

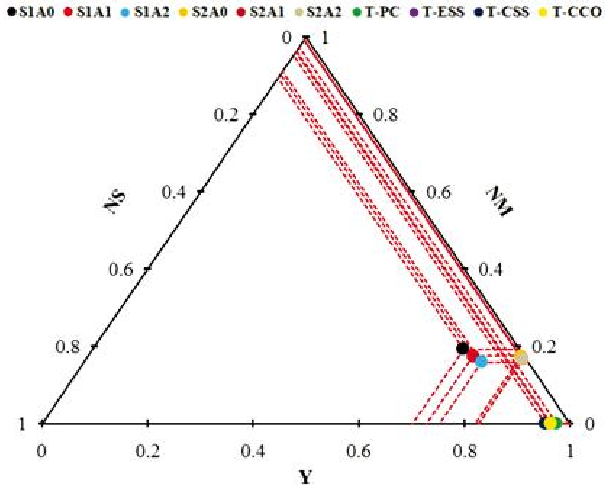


systems and rainfed production models in the Northeast of Brazil

The mean EYR of 2.77 in the renewable irrigated systems indicates a greater socioeconomic contribution due to the lower influx of resources from the economy in these production models, a result of using treated domestic effluent associated with photovoltaic solar energy. It was found that the production systems using wastewater and renewable energy (S2A0, S2A1 and S2A2) showed better rates of emergy yield compared to the conventional irrigated systems (S1A0, S1A1, and S1A2), and in comparison to the rainfed crops (T-PC, T-ESS, T-PSF and T-SFO), due to the smaller emergy flow of resources from the economy.

The ternary diagram of the emergy yield ratio showed that the renewable irrigated systems had a higher return compared to the non-renewable external investments (NM and NS). Whereas the conventional irrigated systems showed less ability for exploiting local resources and making them available in the form of products in response to external investments, due to the smaller share of internal resources in the total emergy (Figure 3).

Figure 3 - Ternary diagram of total emergy (Y) in relation to the non-renewable resources of the economy (NM and NS) that expresses the emergy yield ratio (EYR) of the production models



Albuquerque, Dantas Neto and Silva Neto (2012), in an emergy evaluation of the castor bean intercropped with irrigated sugar cane in the semi-arid region, found a ratio of 1.77, showing that the system has a low to moderate return. This emergy yield ratio is higher than that of the rainfed (1.25) and conventional irrigated (1.24) models, and lower than the renewable irrigated systems (2.77).

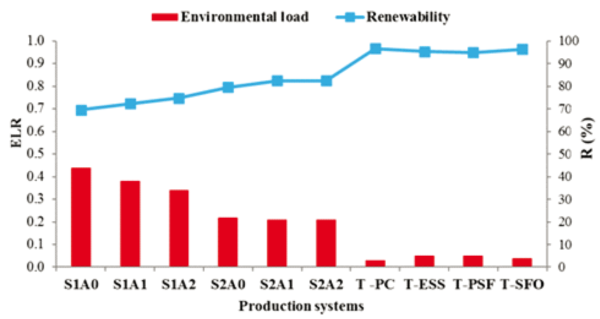
According to Pereira and Ortega (2010), an improvement in this index depends on the reduced use of economic resources. La Rosa, Siracusa and Cavallaro (2008) point out that the adoption of more-ecological agricultural methods that use less external inputs and recycle products, both internal and by-products, such as intercrops, affords better emergy yield ratios, since it reduces the influx of external resources from the economy to the production system.

The rainfed crops showed low emergy yield due to their high dependence on resources from the economy, especially services. Despite the high renewability of these systems, the low influx of renewable natural resources in the final emergy flow had a significant influence on the potential for contributing to economic growth. For Odum (1996), the higher EYR value is a clear indicator of the net contribution of the system to the economy.

With regard to the environmental load ratio, rainfed production systems had less environmental impact due to the smaller amount of input emergy from non-renewable inputs from the economy. The basis of these production systems were external resources, but they consisted basically of renewable services, which did not affect the environmental sustainability of these systems (Figure 4).

The mean value of 0.04 in the rainfed production systems shows less environmental stress compared to the irrigated systems, 0.30, since the higher the ELR, the greater the environmental impact caused by the production system due to the use of non-renewable resources from the economy. Gonçalves *et al*. (2018), quantified emergy sustainability in conventional strawberry production by means of environmental indicators, and found an environmental load index of 3.76.

Figure 4 - Environmental load ratio and renewability index in conventional and renewable irrigated production systems and rainfed production models in the Northeast of Brazil

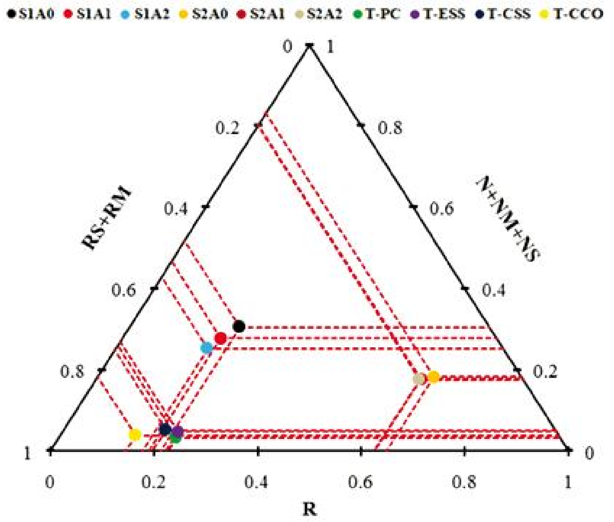


The renewability index refers to the use of renewable resources from nature and the economy in relation to the total emergy flow of the system. As such, it was found that the rainfed systems had a higher percentage of renewability, greater than 90%, which makes them more sustainable in the long run, due to the lower use of non-renewable resources from the economy.

In relation to the irrigated systems, the greatest renewability was seen in systems that used wastewater and photovoltaic solar energy (S2A0, S2A1 and S2A2), with mean values of around 80%; whereas in the conventional irrigated systems (S1A0, S1A1 and S1A2), the average index was 70%. This difference was attributed to the greater influx of renewable resources from nature in those models in which there was an interaction between the treated domestic effluent and photovoltaic solar energy. Ortega *et al*. (2010), in a study of the emergy in vegetable production systems under organic management, found that the systems under study showed high renewability, greater than 60%.

From the ternary diagram of the environmental load ratio, it was found that the rainfed production systems had less environmental impact, despite the greatest influx of emergy being external (economy). However, 70% of the external resources were renewable services, which does not put much pressure on the environment. The intensified use of mechanisation has increased environmental stress in these systems (Figure 5).

Figure 5 - Ternary diagram of the ratio of non-renewable resources to renewable resources that shows the environmental impact (ELR) of the production models



The renewable irrigated systems (S2A0, S2A1 and S2A2) had a lower environmental load compared to the conventional irrigated systems (S1A0, S1A1 and S1A2) due to the greater influx of renewable natural resources (wastewater) and also the lower influx of non-renewable resources from the economy (chemical fertilisers and electrical services).

Vitória and Rodrigues (2016), in a study of the emergy efficiency of sugarcane, found that dependence on chemical fertilisers reduces the fraction of renewable energy and increases environmental degradation, resulting in a less sustainable production system, and highlighted that the use of alternative sources of fertiliser may improve sustainability and reduce the environmental load.

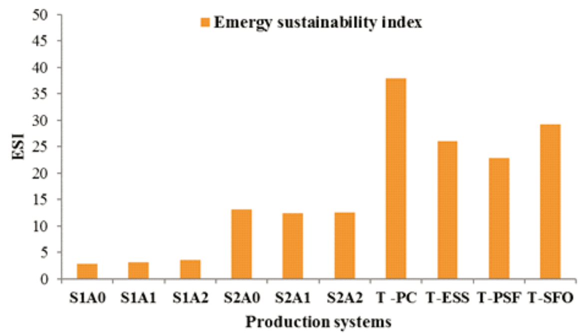
It is therefore evident that an increase in the amount of purchased non-renewable resources (economy) increases the ELR due to its adverse effect on the environment in terms of emergy, use in extraction, processing and transportation to the point of consumption (GHALEY; PORTER, 2013).

Totino (2016), in an emergy analysis of agricultural production systems in Argentina, saw greater environmental impact, with an ELR of 2.04. For Bastianoni and Marchettini (2000), the use of natural ecological processes to maintain the natural complexity can reduce the need for external inputs in production, which improves the environmental load index.

For the sustainability indicator, which assesses the contribution of a system to the economy in relation to its environmental impact, it was found that the rainfed systems (T-PC, T-ESS, T-PSF and T-SFO) have long-term sustainability due to the lower use of non-renewable resources (Figure 6).

The renewable irrigated systems (S2A0, S2A1 and S2A2) are also sustainable in the long term due to a greater use of renewable resources and wastewater, and fewer inputs (fertilisers, organic compost and electrical services). The mean ESI of 3.25 for the conventional irrigated systems shows medium-term sustainability. Gonçalves *et al*. (2018), quantified emergy sustainability in conventional strawberry production by means of environmental indicators, and found a sustainability index of 0.35, less than the values found in the present study.

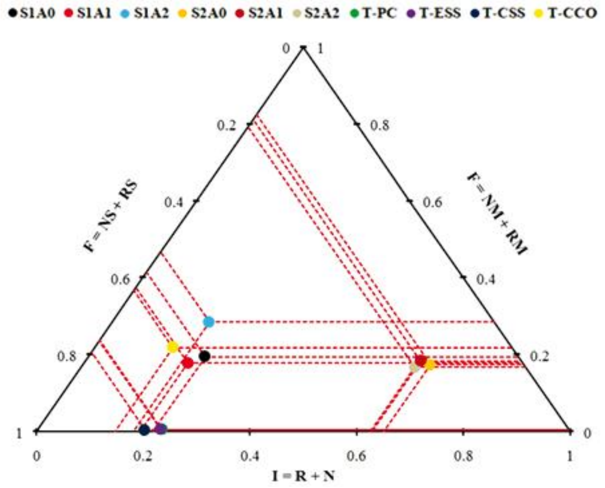
Figure 6 - Sustainability indicator in conventional and renewable irrigated production systems and rainfed production models in the Northeast of Brazil



Feitosa *et al*. (2019), in a study of the economic and environmental sustainability of irrigated and rainfed crops, found that the systems contributed to economic growth with low environmental load and a renewability of 83% and 74% respectively.

The ternary diagram of the emergy sustainability index (ESI) shows that rainfed agricultural systems are sustainable in the long term due to the lower environmental load of these systems, a result of the small number of non-renewable inputs (Figure 7). Among the rainfed crops, the T-SFO system included

Figure 7 - Ternary diagram of the sustainability index (ESI) in irrigated and rainfed production models in the Northeast of Brazil



a greater share of inputs (organic compost), which increased emergy flow and reduced emergy yield and consequently, sustainability.

In the conventional irrigated systems, the increase in emergy from resources from the economy afforded less emergy yield and a greater environmental load, resulting in medium-term sustainability; whereas in the renewable systems, the large amount of natural emergy favoured emergy yield and a reduction in environmental load and consequently, long-term sustainability.

Gonçalves *et al*. (2018), in an emergy analysis of a conventional system of strawberry production, found that the system proved to be far more dependent on resources from the economy (F), i.e. paid resources, compared to other non-conventional systems, showing that organic crops make better use of resources from the environment and are therefore more sustainable.

Lopes *et al*. (2009b), in a study of one sustainability index in irrigated perimeters in the state of Ceará, clearly demonstrated the difference between production units regarding the sustainability of the model adopted by the producers, where a mean index value of 0.54 pointed to compromised sustainability.

CONCLUSIONS

1. The rainfed production models had less environmental impact in relation to the irrigated crops due to the lower influx of non-renewable inputs from the economy;
2. The influx of natural resources (wastewater and photovoltaic solar energy) afforded less environmental impact in the irrigated production models;
3. Treated domestic effluent and solar photovoltaic energy promote an increase in emergy yield and environmental sustainability in the production models;
4. The influx of resources from the economy into agricultural systems increases the environmental load and reduces renewability.

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