Agroecological heuristics: Xi (Ξ) biomathematical models of alpha diversity and lambda functional entropy index (λ) applied for macrofauna in diversified agroecosystems of Nicaragua

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Abstract

Agriculture causes chaos on the macrofauna associated with agroecosystems. The functions developed by macrofauna species in agroecological environments are harmful, beneficial and fundamental for food production. In order to design Xi (Ξ) biomathematical models of alpha diversity and to create a functional entropy index (λ), the taxonomic identification of macrofauna was carried out in 10 agroecosystems with conventional and agroecological production approach in five locations of Nicaragua: Boaco, Carazo, Chinandega, Estelí and Matagalpa. The capture of macrofauna was carried out in five surface sampling points of 3.1416 m² each and subsequent subtraction of five soil monoliths per subsystem. Each monolith had dimensions of 0.25 m (length) × 0.25 m (width) × 0.30 m (depth) for a total of 98 monoliths. The agroecosystems with a conventional approach presented 73 families and with an agroecological approach 124 families were observed. The dominant interaction of macrofauna families were between Scarabaeidae, Formicidae, Chrysomelidae, Elateridae and Noctuidae; especially the first two, influenced the final result of the model, generating a tendency to negativity due to its herd behaviour. The families Lumbricidae, Rhinotermitidae and Acanthodrilidae, the three gregarious, pushed the model towards positivity together with Polydesmidae and Porcellionidae. The biomathematical model Xi (Ξ) generated polynomial equations with an agroecological approach to simulate abundance, richness, dominance, uniformity, stability and functionality of the macrofauna species. The agroecosystems with an agroecological approach presented a range of λ between 41.36 to 127,095.41 much higher than the conventional approach with a range of -81.62 to 8,588.73 and a tendency to negativity.

Keywords: diversity, dominance, entropy, equity, index, interactions, macroinvertebrates

1 Introduction

Agroecology converges science, technologies, practices and movements for social change (Wezel *et al.*, 2009; Tomich *et al.* 2011) and focuses on the entire system for food production, from seed to table (Gliessman, 2017). Its objective is to optimize the interactions between plants, animals, humans and the environment (FAO, 2019).

Varghese & Hansen (2013) argue that scientific research in agroecology integrates related disciplines to help understand life in the soil (p. 8). There are various ecological indices and models that measure the degree of aggregation of species in their habitat. Some of the most widely used

are estimators calculated from regression models, including, Taylor's Potential Law (LPT) and Iwao Regression (Cabrera *et al.*, 2002).

Mathematical modeling has gained momentum in ecological studies as it determines the equilibrium conditions of the ecosystem. The historical evolution of mathematical modeling has been explored in the field of quantitative population ecology (Miranda, 2014). From the biological point of view, in the evaluation of the state of conservation / disturbance of the soil and the ecosystem, the edaphic macrofauna can be taken into an account as bioindicators of soil quality (Cabrera, 2012). Representing the interactions of organisms as a mathematical system that expresses functional behaviors increases the complexity of a model, in this field the research vision tries to explain the existing chaos and the physical ac-

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tions that originate it, to try to understand it and from that intellect propose a management of agroecosystems based on the agroecological principles.

This research was established with the objective of designing algorithms from biomathematics to simulate abundance, richness, dominance, uniformity, stability and systemic functionality of the macrofauna in a model and obtaining an index that explains the entropy resulting from these organisms within the agroecosystem managing to simulate this behaviour under dynamic equations.

Alpha diversity is the richness of taxonomic families located in a given place, within this type of diversity are richness indices, Simpson index, Shannon-Wiener index, Pielou index. Beta diversity measures the difference of families at two sites in this group found by the Sorensen coefficient of similarity and Bray-Curtis distance. Gamma diversity includes alpha and beta diversity, it is in charge of estimating the diversity of all the communities present in an area; for example: the index richness of communities. An advantage of using this type of conventional index is the ease of its application in natural ecosystems. Among the disadvantages of using these indices is that they were not created to measure agroecosystems, they do not measure the functions of taxonomic families and they do not differentiate between harmful and beneficial families. In this article, a method is proposed to create a biomathematical model of diversity Xi (Ξ) and a functional entropy index Lambda (λ) is integrated from this.

2 Materials and methods

2.1 Study location and dates

The study was developed in ten farms located in five departments of the country, between the years 2015–2018. The collection of macrofauna samples occurred in the rainy season. The altitude of the agroecosystems presented a range between 80–1253 meters. Its average annual temperature varies between 22.9-26.7 °C. Per year, the different locations accumulate between 844-1538 mm of rainfall (NASA, 2020). The soil orders that they have are the following: Alfisols, Andisols, Entisols and Mollisols (INETER & UNA, 2015). The main items highlighted in the agroecosystems were bovine livestock, basic grains and coffee; managed with a conventional and agroecological approach (Table 1).

2.2 Macrofauna sampling

The macrofauna is represented by organisms that live on the ground, organic matter in decomposition and in layers under the ground (Lavelle *et al.*, 1992). Macrofauna sampling in various studies is characterised by a similar

methodology (Anderson & Ingram, 1993; Huising *et al.*, 2012; Botina *et al.*, 2012). After reviewing the state of the art in this regard, a modification to the methodological sampling design proposed by said authors was developed and a series of materials were gathered for this study: measuring tape (five meters), alcohol (70 % %), clear plastic jars (volume = 50 ml), flat palin (high 500 mm × width 177 mm; rectangular shape), white polypropylene bags (high 95 cm × width 56 cm), two steel nails (3 plg), nylon thread (0.4 mm), hammer (552 g), brushes (2 plg), field table, data sheet, pencil and eraser.

The sampling was carried out in the early hours of the morning or in the afternoon when the daytime temperatures have decreased. First, the agroecosystem was subdivided into as many subsystems as possible according to the design established by the farmer. In each subsystem a sampling was carried out at five different points. Within each subsystem an initial point was selected at random. The macrofauna feeds on organic matter. It is known that the surface layer, rich in organic matter, concentrates more macrofauna (CIAT, 2003). Soil organic matter, in diversified crops, shows ranges of 0.6–3.85 %, depending on the plant species present (Rodríguez, 2014); This surface organic matter in the soil is initially processed by the associated macrofauna. In the present study, a surface sampling area equivalent to 3.1416 m^2 (Fig. 1) in the form of a circle with a radius of one meter; considering increasing the probability of finding specimens greater than 2 mm in diameter, given the tropical condition of Nicaragua.
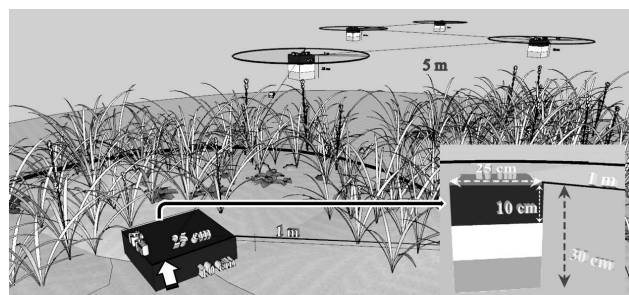

Fig. 1: *Stratified sampling of macrofauna in ten agroecosystems of Nicaragua, 2015-2018.*

To mark the 3.1416 m^2 at the center of the first sampling point, a steel nail was introduced with hammer blows, this was fastened with nylon thread extending a taut line one meter apart. To avoid losing the mark, at the end of the nylon line, another steel nail was clamped and inserted tensioning the nylon at the rear end. This established radius served as a reference to sample all the macrofauna that inhabit the soil surface within a circular area of 3.1416 m^2. Clear container of 150 ml was filled with 70 % alcohol, collected specimens

Table 1: *Location and climatic factors of ten agroecosystems in Nicaragua analysed with biomathematical models Xi (Ξ) and functional entropy index lambda λ, 2015-2018.*

Department (Location)	Agroecosystem	Latitude (N)	Length (O)	Height (m)	Soil order	Av. annual temp. (°C)	Av. annual rainf. (mm)	Main item
Boaco	San Juan[*]	12°27'24.33"	85°36'39.30"	494	Mollisols	24.5	1334	Bovine livestock
(Las Lagunas)[1]	Buena Vista[**]	12°28'15.53"	85°36'38.48"	519				
Carazo	El Manantial[*]	11°49'20.50"	86°14'22.00"	469	Entisols	23.7	1538	Basic grains
(Diriamba)[2]	El Chipote[**]	11°49'18.80"	86°14'30.80"	461				
Chinandega	Santa Rosa[*]	12°39'10.30"	87° 8'4.00"	80	Andisols	26.7	1856	
(San Felipe)[2]	Santa María[**]	12°41'18.24"	87° 5'8.70"	218				
Estelí	El Milagro de Dios[*]	13°23'42.50"	86°15'9.59"	1154	Entisols	23.7	844	Coffee
(Condega)[3]	Linda Vista[**]	13°23'58.20"	86°14'42.54"	1253				
Matagalpa	La Vecina[*]	12°58'19.16"	85°49'45.37"	818	Alfisols	22.9	1512	
(San Ramón)[3]	La Espadilla[**]	12°58'23.05"	85°49'48.08"	812				

Production approach: [*]Conventional; [**]Agroecological; 1: Rodríguez González *et al.*, (2017a); 2: Rodríguez González *et al.*, (2017b); 3: Rodríguez González *et al.*, (2017c).

were placed, and the bottle was labeled accordingly. At the center of the circle a block of soil (monolith) with dimensions of 0.25 m (length), 0.25 m (width) y 0.1 m deep. This soil was placed on a white polypropylene bag; with the help of the hand and brushes, the soil was removed to capture the macrofauna present. This procedure was carried out two more times, extracting two separate layers every 10 cm to a depth of 30 cm (Fig. 1). Having finished labeling all the clear container, a distance of five meters from the first sampling point in a random direction was measured to mark a new sampling point. This procedure was performed identically by completing five samples per subsystem. Throughout the study, within the ten farms, a total of 98 samplings were accumulated with successful extractions without replacement or unrestricted. All organisms were identified using taxonomic keys and Stereo Microscop series SZM.

2.3 Model design

A model is a simplified mathematical representation of a complex reality ... a model must balance the need to contemplate all the details with the feasibility of finding suitable solution techniques (Ramos *et al.*, 2010).

The biomathematical model xi Ξ, is designed to contrast the increase in richness in taxonomic families between agroecosystems (x-axis) against the abundance and interaction of families (y-axis). In order to develop the proposed model, the number of individuals per taxonomic family of the macrofauna in each agroecosystem must be first counted (alpha diversity). This number is multiplied by the coefficient 1 if the macrofauna family presents mostly positive functions within the agroecosystem and multiplied by the coefficient -1 if it corresponds to a family that develops negative functions for the productive species selected by the

farmer. After obtaining the sequence of positive and negative numbers, it is ordered from least to greatest by agroecosystem and in this way the resulting figure is structured where the coordinate (1,0) of the Cartesian plane corresponds to the position of the most negative family of each agroecosystem and richness level 1 for both. The family furthest to the right on the x-axis represents greater functional richness and positivity. Obtaining the equations that approximate the behavior of macrofauna families, is the biomathematical reality of a moment in time, its repeatability will depend on a similarity conditioned to environmental and management factors. Now, in order to the determine the equations, sequences executed in layers of repeated polynomial regressions with degree variations were performed; the final selection corresponds to obtain a R^2 equal to or greater than 0.65 with the lowest possible degree and that represents the reality observed in the field.

The use of simulation models to predict the behavior of taxonomic families has advantages such as predicting the possible disappearance of macrofauna families that support a population pyramid; allows inferring about the selection pressure caused by the environment and climate change. The creation of models for each agroecosystem using this method generates a monitoring aimed at taxonomic families considered harmful and forces producers to realize their reality and consequently seek strategies for their management as long as the actions taken do not detract from those. macrofauna families considered beneficial. This method has been selected to distance itself from the traditional way used to measure the biodiversity of families that converge within the same agroecosystem, because currently ecology does not establish differentiation between beneficial and harmful families within productive agroecosystems.
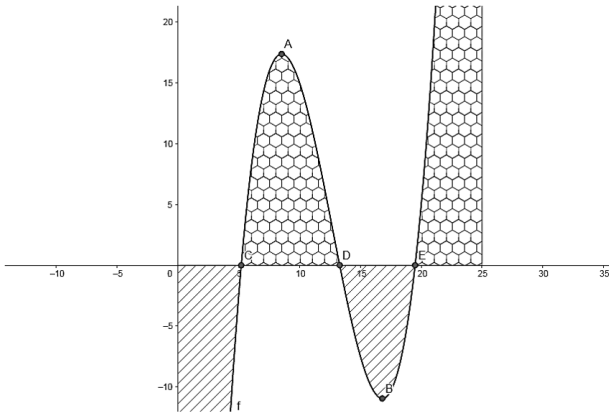
Fig. 2: *Graphic representation of the biomathematical model xi Ξ for a hypothetical agroecosystem with degree 3 polynomial equation; $f(x) = 0.1x^3 - 3.8x^2 + 43x - 135$ con $\lim_{(x \to 0)} f(x)$ y $\lim_{(xA \to 25)} f(x)$*

2.4 Model interpretation

Model theory is the most powerful of the tools available to investigate the questions of coherence, independence of concepts, definability, independence of axioms ... for the foundations of science and for exact philosophy (Bunge, 2009).

Understanding a model evokes abstraction by looking at each stroke for interpretation. When the curves are shown in quadrant I of the cartesian plane, they indicate positive interactions of the organisms within the respective agroecosystem, whereas if the curves are presented in quadrant IV, they indicate negativity in their interaction (Fig. 2). The highest position of the wave, at its crest, indicates higher dominance of organisms with positive functions (hexagonal pattern) and in the lowest position, its valley, indicates negative dominance (hatched pattern). The richness of the taxonomic families increases as the wavelengths extend along the x axis.

The dominance of the macrofauna families is observed with the amplitude of the wave being the coordinates of intersections in the x axis turning points where the dominance is minimal or zero. Equity is observed when the initial and final verticality of the undulations describe positive and negative interactions in proportional abundance. Absolute equilibrium exists if the amplitude interval, obtained by adding the amplitude of the crest and the amplitude of the valley, when cut by the x-axis presents bilateral symmetry or if the values of both amplitudes are similar. This is equivalent to a maximum functional entropy condition. The best observed behavior will be attributed to that agroecosystem capable of sustaining a larger population of functionally beneficial organisms and with proportionally similar or lower negative abundances; those agroecosystems with waves of greater amplitude towards the positive "y" axis will have the best results.

2.5 Design and interpretation of the index

On each agroecosystem there is a mathematical equation that represents the behaviour of the macrofauna populations. Its coefficients and elements show a variability that is necessary to sustain the functional balance of the agroecosystem. The functional entropy index lambda λ is obtained from the definite integral of the biomathematical model xi (Ξ), under limits established by the richness identified in each agroecosystem. One of the advantages of using this analysis is the applicability to estimate the population behaviour of living organisms within any natural ecosystem or agroecosystem. This index deviates from the discrete Shannon entropy (1948) and the entropy measurement of Rényi (1961) because it additionally integrates the biological functionality in an agroecosystem and poses a functional differential entropy. Jost (2006) analysed the Shannon and Simpson indices to determine that they do not represent "true diversity"; by obtaining effective numbers derived from these indices, he observed that they share a common set of intuitive mathematical properties.

With the present study, the solution of the differential equation is aimed at measuring alpha diversity and its entropy from its components: abundance, richness, dominance, uniformity, stability and systemic functionality. On this index, three values of functional entropy can be determined: positive, zero and negative. If organisms perform maximum positive functions, the result of the definite integral belongs to positive infinity $[\lambda \epsilon + \infty]$.

If the agroecosystem presents a maximum entropy condition due to its balance between positive and negative functions; the value of the definite integral is equivalent to zero ($\lambda = 0$). If the organisms perform mostly negative functions; the result of the definite integral belongs to negative infinity $[\lambda \epsilon + \infty]$. The absolute value of the functional entropy index $|\lambda|$ quantifies the level of chaos of the natural ecosystem or agroecosystem depending on the functions developed by the organisms present in a given time and space.

Functional entropy should be understood as the level of positive or negative chaos (disorder) of the functions (detritivores, predators, phytophages, pollinators ...) performed by individuals belonging to different families existing in an agroecosystem. The functional entropy index lambda (λ) is the result of mathematically estimating this behaviour in nature.

An organism plays a negative role when its actions within the agroecosystem have an impact on reducing systemic productivity.

An organism plays a positive role when its interactions in the agroecosystem create synergy in support of the productivity of the system.

The dominance of a taxonomic family occurs when its ecological richness exceeds that of another. If several taxonomic families perform functions considered negative, the model describes this behavior and it is said that there is a negative dominance, otherwise a positive dominance would be observed.

3 Results

The conventional approach is a way of doing agriculture using techniques such as use of synthetic fertilisers, use of herbicides, nematicides, insecticides, deep soil removal; monocultures are generally established, there is evidence of greater contamination of the soil, water and exploitation of available natural resources. It is a more hydrocarbon-dependent approach and the energy consumption of the system requires a greater subsidy from external sources.

The agroecological approach is using principles that conserve natural resources, minimize the use of synthetic inputs and maximize the use of organic fertilisers. It employs the proper management of biodiversity by integrating functional designs where polyculture and rotations are essential. It reduces dependence on hydrocarbons, productivity has a vision of sustainability and the family plays a central role in comprehensive planning in the execution of agroecological design.

Comparing the results of conventional and agroecological approaches highlights agroecosystems subjected to management techniques that can have a positive or negative impact on the population stability of macrofauna families. Studies on macrofauna in agroecosystems present difficulty in the assertive representation of population behaviour from a systemic, functional and comprehensive perspective. The macrofauna of the Buena Vista and San Juan agroecosystems, located in the department of Boaco, were the object of study. Obtaining the results allowed the construction of Xi Ξ biomathematical models of alpha diversity that describe the behaviour of the macrofauna (Fig. 3).

The "x" axis of the Xi model shows the richness (frequency) of the taxonomic families, this variable represents the number of families present and the population structure of a site in an orderly fashion. The bars on the "y" axis represent the abundance (frequency) of each taxonomic family, these are ordered from lowest to highest; from left to right and take a place depending on the value achieved, each individual observed belonging to a family, each individual is considered an interaction because their existence in that place implies actions on the agroecosystem. Richness and abundance are two concepts of ecology. If a family is considered harmful, its value will be negative, if it presents the
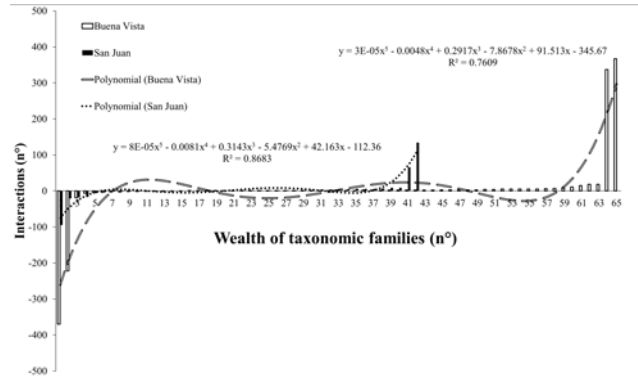

Fig. 3: *Biomathematical model Xi Ξ of alpha diversity, for the analysis of the macrofauna families behaviour in two bovine livestock agroecosystems, Las Lagunas, Boaco, Nicaragua 2015-2018.*

highest abundance among all the harmful families in a site, it will take position one of the x-axis, therefore it will fall in quadrant IV.

The Buena Vista agroecosystem presented 65 families of macrofauna, they stand out in positive systemic functionality: Lumbricidae, Rhinotermitidae, Styloniscidae, Agelenidae and Ectobiidae; negatively: Formicidae, Scarabaeidae, Elateridae, Culicidae and Acrididae. In San Juan agroecosystem, 42 families were observed, their positivity in the functions is led by: Rhinotermitidae, Lumbricidae, Theridiidae. Julidae and Japygidae. The negativity within the system is represented by: Formicidae, Noctuidae, Scarabaeidae, Tettigoniidae and Elateridae. The main functions performed were: detritivore, predator, defoliator, microbivore, dung, nectarivore, phytophagous and hematophage.

The progressive balance of the functionality of the organisms will describe a population behaviour with systemic stability if an agroecosystem is biodiverse and integrated. Those agroecosystems, where exist a huge number of organisms with negative functions influence a similar abundance of positive organisms and vice versa (Fig. 3). A reduction in the population of organisms with negative functions would be ideal, if that systemic stability is not drastically altered by human action. A richness higher than 65 was the best and belongs to the Buena Vista agroecosystem, this is reflected with a wave path extended along the x axis. The Buena Vista agroecosystem is superior in positive dominance because in its wave two upper ridges are observed and the beginning of a third, positioning itself above the trajectory described by the wave of the San Juan agroecosystem.

Both agroecosystems show equity because the initial and final verticality of the curves are proportional. The Buena Vista agroecosystem has the best behaviour because the

crests of its waves extend over positive coordinates of the axis and above the San Juan agroecosystem. Polynomial models take a semiotic algebraic form that summarizes the oscillations of the approximation curves obtained by observing the behaviour of the macrofauna populations, in this case $y = 3E\text{-}05x^5 - 0.0048x^4 + 0.2917x^3 - 7.8678x^2 + 91.513x - 345.67$ (ec$_1$) for the agroecosystem Buena Vista next to $y = 8E\text{-}05x^5 - 0.0081x^4 + 0.3143x^3 - 5.4769x^2 + 42.163x - 112.36$ (ec$_2$) for the agroecosystem San Juan.

That agroecosystem with greater availability of food for organisms with beneficial functions will project an increase in these populations; in parallel, families with harmful functions will increase in proportional terms. In natural ecosystems, before the appearance of the human being, the organisms today considered harmful, in reality, were biomass regulatory agents (phytophages), their work was to reduce the population of dominant plant species to restore functional balance. A monoculture is the best example of the existence of a dominant species, by the man hand, in a finite physical space. Herbivores (phytophages) have a direct effect on grass: fertilising and stimulating growth.

To obtain the functional entropy index λ and to affirm with certainty the superiority of one of the agroecosystems, the definite integral of each of the equations ec$_1$ and ec$_2$ was calculated respectively:

$$\int_0^{65} 3E - 05x^5 dx - \int_0^{65} 0.0048x^4 dx + \int_0^{65} 0.2917x^3 dx -$$
$$\int_0^{65} 7.8678x^2 dx + \int_0^{65} 91.513x dx - \int_0^{65} 345.67 dx$$
$$= 15593.4188$$

$$\int_0^{42} 8E - 05x^5 dx - \int_0^{42} 0.0081x^4 dx + \int_0^{42} 0.3143x^3 dx -$$
$$\int_0^{42} 5.4769x^2 dx + \int_0^{42} 42.163x dx - \int_0^{42} 112.36 dx$$
$$= 3179.93088$$

The upper limits for the Buena Vista and San Juan agroecosystems were 65 and 42 respectively, in correspondence with their richness. Obtaining the functional entropy index λ in this case required 54 and 74 mathematical procedures for ec1 and ec2 respectively. This index shows that the Buena Vista agroecosystem is better in its biological diversity and functional diversity compared to the San Juan agroecosystem. The result of the index shows that both agroecosystems presented positive functional entropy λ.

This same analysis was carried out in the agroecosystems: El Chipote and El Manantial, located in Diriamba (Fig. 4). In the first, the families with positive functions were: Rhi-

notermitidae, Polydesmidae, Lumbricidae, Armadillidae and Theridiidae; negative functions were performed by individuals of the families: Formicidae, Scarabaeidae, Elateridae, Argasidae and Chrysomelidae. The El Manantial was an agroecosystem characterized by the positive families like: Rhinotermitidae, Polydesmidae, Lumbricidae, Armadillidae and Clubionidae; its negativity is occupied by the families like: Formicidae, Scarabaeidae, Elateridae, Acrididae and Cercopidae. The main functions performed by these were: detritivore, predator, defoliator, micro-eater, dung, hematophage and phytophage.

These agroecosystems show functional abundance in quadrants I and IV (Fig. 4). The best richness result (29) was achieved by the El Chipote agroecosystem. The El Manantial agroecosystem shows a curve limited by a lower richness of 18 tending towards verticality at that point. Both waves have spaces occupied by populations with positive dominance, under these conditions, it is impossible to declare one agroecosystem superior to the other. In cases like this, it is better to obtain the determining value of the functional entropy index lambda λ. The definite integral for the El Chipote agroecosystems with ec$_3$ ($y = -0.0007x^4 + 0.0825x^3 - 2.6042x^4 + 29.557x - 101.11$) and El Manantial with ec$_4$ ($y = 0.0036x^4 + 0.1413x^3 - 6.0703x^2 + 57.066x - 144.07$), it was:

$$\int_0^{29} -0.0007x^4 dx + \int_0^{29} 0.0825x^3 dx - \int_0^{29} 2.6042x^2 dx +$$
$$\int_0^{29} 29.557x dx - \int_0^{29} 101.11 dx = 41.36033$$

$$\int_0^{18} 0.0036x^4 dx + \int_0^{18} 0.1413x^3 dx - \int_0^{18} 6.0703x^2 dx +$$
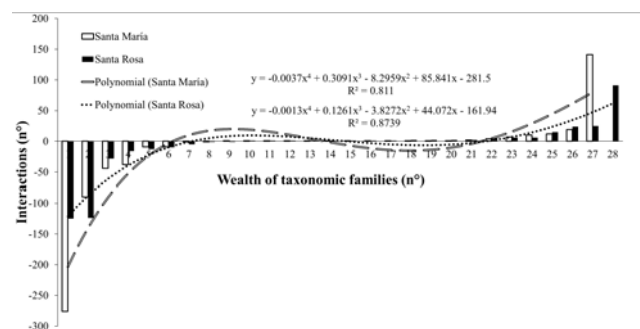$$\int_0^{18} 57.066x dx - \int_0^{18} 144.07 dx = -80.46504$$

Fig. 4: *Biomathematical model xi Ξ of alpha diversity for the analysis of the behaviour of the taxonomic families of macrofauna in two agroecosystems with basic grains, Diriamba, Carazo, Nicaragua, 2015-2018.*

The determining value of the functional entropy index λ shows the agroecosystem El Chipote superior to El Manantial, in diversity and systemic functionality. The El Manantial agroecosystem presents a negative value due to its highest curve projection, this was determined in quadrant IV. It is observed that the positive functions of the El Manantial's families agroecosystem starts until their richness is 13.

In the El Manantial agroecosystem, only 6 of the 18 families perform beneficial functions (Fig. 4). If an agroecosystem with the biomathematical model Xi Ξ shows more extended curves along the x-axis within quadrant I, it will describe the best systemic behaviour. The El Chipote agroecosystem presents greater diversity in its design for presenting land use with eight cultivated subsystems compared to El Manantial, which has six, this difference in agroecological design and management allows the sustainability of a superior richness of macrofauna (Fig. 4).
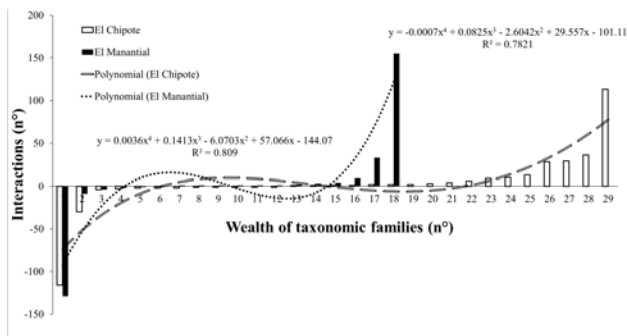

Fig. 5: *Biomathematical model xi Ξ of alpha diversity for the analysis of the behaviour of the taxonomic families of macrofauna in two agroecosystems with basic grains, La Grecia, Chinandega, Nicaragua 2015-2018.*

In Chinandega, the Santa María and Santa Rosa agroecosystems present richness of 27 and 28 respectively (Fig. 5). In a condition of close richness between agroecosystems it is important to observe the curves separation from their interactions. The positive interaction dominance is higher for the Santa María agroecosystem in richness 27, contrary to this, in parallel a scenario with a negative dominance curve is observed, leaving the Santa Rosa agroecosystem as the winner in the richness interval from zero to five. Equity is better in Santa Rosa because the initial and final verticality of its curve divided by the x-axis presents better proportionality.

In the Santa María agroecosystem the main taxonomic families identified with positive functions were: Rhinotermitidae, Syrphidae, Lumbricidae, Staphylinidae and Tenebrionidae; its negativity was represented by Scarabaeidae, Formicidae, Chrysomelidae, Elateridae and Cydnidae. In the Santa Rosa agroecosystem, the families

with positive functional behaviour were: Rhinotermitidae, Tenebrionidae, Carabidae, Lumbricidae and Theridiidae; those families considered negative are: Noctuidae, Chrysomelidae, Ixodidae, Formicidae and Scarabaeidae. In summary, the identified functions correspond to detritivore, nectarivore, predator, phytophagous, dung, defoliator, microvivore and hematophage.

The integral defined in the Santa María agroecosystem with ec_5 (y= -0.0037x^4+0.3091x^3-8.2959x^2+85.841x-281.5) and in Santa Rosa with ec_6 (y= 0.0013x^4+0.1261x^3-3.8272x^2+44.072x-161.94), it was:

$$\int_0^{27} -0.0037x^4 dx + \int_0^{27} 0.3091x^3 dx - \int_0^{27} 8.2959x^2 dx +$$
$$\int_0^{27} 85.841x dx - \int_0^{27} 281.5 dx = -291.9433$$

$$\int_0^{28} 0.0013x^4 dx + \int_0^{28} 0.1261x^3 dx - \int_0^{28} 3.8272x^2 dx +$$
$$\int_0^{28} 44.072x dx - \int_0^{28} 161.94 dx = 8588.73195$$

The determining value of the functional entropy index λ shows that the Santa María agroecosystem was inferior to the Santa Rosa agroecosystem. Still, under conditions of richness and a close mathematical limit, the systemic functionality of the Santa Rosa agroecosystem is better because it presents a curve with less negativity. In quadrant IV, the Santa María agroecosystem begins with a curve much lower compared to the Santa Rosa agroecosystem, until both are in richness 6, the values of their populations are balanced, leaving the Santa Rosa agroecosystem with the best quantified results at starting from the wave described when x tends to the value of its richness with different results from the classical analysis of population densities. In Condega, municipality of Estelí; the agroecosystem El Milagro de Dios
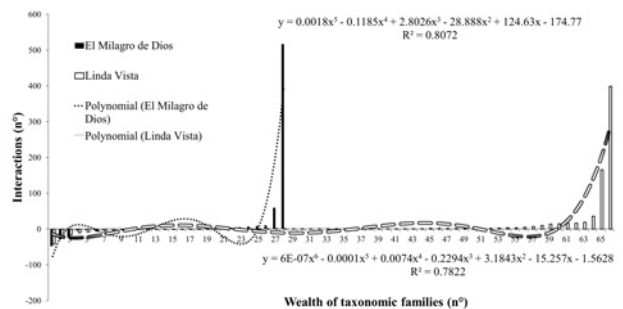

Fig. 6: *Biomathematical model xi Ξ of alpha diversity for the analysis of the behaviour of the taxonomic families of macrofauna in two agroecosystems with coffee, Condega, Estelí, Nicaragua, 2015-2018.*

nicipality of Estelí; the agroecosystem El Milagro de Dios

obtained a richness of 28 and Linda Vista presented superior behaviour with 66 taxonomic families. The curve described by the agroecosystem El Milagro de Dios has a narrow behaviour and in its final section of interaction (richness = 28) it generates a verticality caused by a larger population of Rhinotermitidae, dominance associated with a gregarious behaviour, reveals a population imbalance between the present organisms. A more extended and subtle curve, such as the Linda Vista agroecosystem in its oscillation, shows better equity between species, better balance and proportionality (Fig. 6).

The definite integral for the El Milagro de Dios agroecosystem was calculated with ec_7 (y= $0.0018x^5$-$0.1185x^4$+ $2.8026x^3$-$28.888x^2$+$124.63x$-174.77) and in Linda Vista with ec_8 (y= $6E$-$07x^6$-$0.0001x^5$+$0.0074x^4$-$0.2294x^3$+$3.1843x^2$-$15.257x$-1.5628), it was:

$$\int_0^{28} 0.0018x^5 dx - \int_0^{28} 0.1185x^4 dx + \int_0^{28} 2.8026x^3 dx -$$
$$\int_0^{28} 28.888x^2 dx + \int_0^{28} 124.63x dx - \int_0^{28} 174.77 dx$$
$$= -81.6293$$

$$\int_0^{66} 6E-07x^6 dx - \int_0^{66} 0.0001x^5 dx + \int_0^{66} 0.0074x^4 dx -$$
$$\int_0^{66} 0.2294x^3 dx + \int_0^{66} 3.1843x^2 dx - \int_0^{66} 15.257x dx -$$
$$\int_0^{66} 1.5628 = 127095.41902$$

In the El Milagro de Dios agroecosystem, the taxonomic families with positive and most representative functions were: Lumbricidae, Rhinotermitidae, Agelenidae, Tetragnathidae and Lithobiidae; the negativity of its curve is modeled by the families: Scarabaeidae, Formicidae, Gryllidae, Cercopidae and Cicadidae. The Linda Vista agroecosystem presented positive functional families such as: Lumbricidae, Acanthodrilidae, Porcellionidae, Styloniscidae and Ectobiidae; the negative families were Scarabaeidae, Formicidae, Gryllidae, Cicadidae and Acrididae. The identified functions correspond to detritivore, predator, phytophagous, dung, defoliator and microvivore.

Diversification in the Linda Vista agroecosystem is greater compared to El Milagro de Dios. The limits established to integrate were 28 (El Milagro de Dios) and 66 (Linda Vista) in correspondence with both agroecosystems. The determining value of the functional entropy index λ after obtaining its definite integrals makes clear the superiority of the Linda Vista agroecosystem over El Milagro de Dios. If we isolate the behaviour of the curve of the agroecosystem El Milagro de Dios in quadrant IV, three sectors that fall to-

wards negativity are observed, this occurs in richness 1, 9 and 23. This behaviour was conclusive for obtaining a negative result in the index. The level of chaos (absolute value of the functional entropy index) is higher in the Linda Vista agroecosystem with 127095.41902 λ, tending towards functional positivity, being a satisfactory initial state for a dynamic agroecosystem that shows greater systemic stability.

In San Ramón, municipality of Matagalpa, Nicaragua, the macrofauna of the La Vecina and La Espadilla agroecosystems were analysed; they obtained richness of 17 and 28, respectively (Fig. 7). The curves that represent them, reached a mostly positive interaction, highlighting their lines in quadrant I. The greatest positivity of both agroecosystems was led by the Lumbricidae family. A more pronounced verticality is observed in the La Vecina agroecosystem (richness = 17), this is not the ideal behaviour. The curves that extend with wide limits with respect to others, obtain the best result (Polynomial La Espadilla) (Fig. 7).
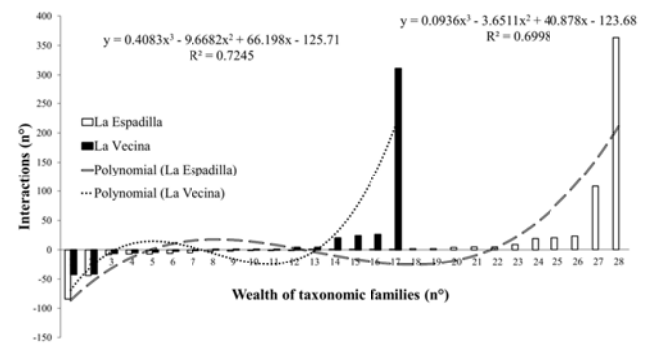

Fig. 7: *Biomathematical model xi Ξ of alpha diversity for the analysis of the behaviour of the taxonomic families of macrofauna in two agroecosystems with coffee, San Ramón, Matagalpa, Nicaragua, 2015-2018.*

For the La Espadilla agroecosystem, its definite integral was calculated with ec_9 (y= $0.0936x^3$-$3.6511x^2$+$40.878x$-123.68) and in La Vecina with ec_{10} (y= $0.4083x^3$-$9.6682x^2$+$66.198x$-125.71):

$$\int_0^{28} 0.0936x^3 dx - \int_0^{28} 3.6511x^2 dx + \int_0^{28} 40.878x dx -$$
$$\int_0^{28} 123.68 dx = 227.77067$$

$$\int_0^{17} 0.4083x^3 dx - \int_0^{17} 9.6682x^2 dx + \int_0^{17} 66.198x dx -$$
$$\int_0^{17} 125.71 dx = 120.6582$$

In the La Espadilla agroecosystem, the main families with functions that tend towards positivity are Lumbricidae, Rhinotermitidae, Spirostreptidae, Styloniscidae and Staphylin-

idae, and negativity is represented by Formicidae, Scarabaeidae, Chrysomelidae, Gryllidae and Lygaeidae. The La Vecina agroecosystem has mainly positive families such as Lumbricidae, Styloniscidae, Spirostreptidae, Rhinotermitidae and Scolopendridae and families with a tendency to negativity such as Scarabaeidae, Formicidae, Pentatomidae, Chrysomelidae and Gryllidae. The main functions determined were detritivores, predator, defoliator, microvivore, phytophagous and dung. The diversified agroecosystems in San Ramón, Matagalpa have coffee as their main crop. Coffee cultivation in the La Espadilla agroecosystem was established in an agroforestry system surrounded by multiple subsystems of medicinal, ornamental, energy, forage and forest plants; creating in this way an ideal condition for the sustainability of the macrofauna.

The determining value of the functional entropy index (λ) is categorical when determining with its definite integral that the La Espadilla agroecosystem is superior to the La Vecina agroecosystem by 107.11247 λ above; where lambda "λ" represents the unit of measurement for the functional entropy of agroecosystems.

When looking at figure 7 when the richness of taxonomic families is between 6-13, the curve representing the La Espadilla agroecosystem stands out oscillating in quadrant I. Those models that describe a superior behaviour occupying a greater proportion in quadrant I will be inherent curves of agroecosystems integrated with families of organisms that perform mostly positive functions.

In this study it was found that agroecosystems under the conventional approach, presented a lower richness between 17 and 42 taxonomic families, registering a total richness of 73 families of macrofauna, while the agroecosystems with an agroecological approach presented higher richness between 27 and 65 families for a total richness of 124 the taxonomic families.

4   Discussion

The population of insects is affected by biotic and abiotic factors, knowledge of the response of these individuals to these factors offers a profound response to the community functioning of organisms made up of several species (Begon *et al.*, 1996). Vera & Pinilla (2020) consider the Lumbricidae family as a positive agent within the trophic collector guild as part of a study of preliminary approximation to a multimetric macroinvertebrate index. These fluctuations are difficult to represent because their atypical bihaviour conditions non-parametric distributions, considering these fluctuations without verifying their functions creates an incomplete image of the reality found in the agroecosystem. López

et al., (2014) considered that Fomicidae is a harmful family when they behave as important defoliators in perennial crops within agroecosystems with cocoa. In a study conducted by De los Santos *et al.*, (2019) identified 4 large functional groups (predators, detritivores, phytophagous and soil engineers), as well as their abundance and diversity distributed in the main soil strata. Barrera (2006) consider the concept of economic threshold incorrect from the IPM approach because it does not recognize that natural mortality is the most important and cheapest element to avoid pest outbreaks from the dynamics of populations and their natural enemies. The pest suppressor functionality of certain organisms should be qualified as a dynamic data with assertive adjustments in each agroecosystem.

Natural grasslands without soil removal compared to minimal removal in annual crops showed a higher proportion of individuals of the Lumbricidae family in natural grasslands. Anthropogenic actions would be compromising the fulfillment of ecosystem functions (Domínguez *et al.*, 2009). Over time this interaction has given rise to a series of adaptive strategies, both by plants and herbivores, which in general terms allow coexistence (García, 2008). The presence of the Lumbricidae family was determined in all the agroecosystems under study, the proportions of this family were higher in agroecological agroecosystems.

Puerta (2008) considers that the landscape can be constituted as a heterogeneous and dynamic scenario in which certain areas present a positive global balance, that is, where there is effective regeneration, while others have a negative balance, thus finding themselves in support or even population regression. The macrofauna represents an indicator of the positive ecological balance, measuring it using xi Ξ models makes it easier to verify the existence of a positive or negative final balance. Marchioro & Krechemer (2018) found that Diabrotica sp. (Coleoptera: Chrysomelidae) has species that overlap in cultivated areas. The analysis of niches showed that they occupy a small proportion of the suitable habitats available to them, if they invade new areas, there is a risk of spreading into adjacent regions. Peña *et al.*, (2018) states that the sustainability indices improved as more richness or diversity of cultivated plant species was found in the evaluated agroecosystems. For a system to be classified as sustainable in its agri-environmental dimension, it must obtain a positive result with the functional entropy index lambda (λ), where the systemic disturbance is proportionally beneficial for humans and for nature.

Carabids (Coleoptera: Carabidae), provide important services in agroecosystems. The dominance structure of the carabidological assemblages and the habitat preferences of the most stenotopic species can be indicative of the suc-

cessional state and the degree of disturbance of that agroe-cosystem (Paleologos *et al.*, 2007). Entropy is central in the Second Law of Thermodynamics, in an isolated system any activity increases entropy; in quantum mechanics, Von Neumann extended entropy to quantum systems by means of the density matrix (Pacheco, 2020).

The analytical expressions of the generalized versions of some of the better-known continuous probability densities tend to the classical densities generated by the Boltzmann-Gibbs-Shannon statistic when q → 1 (Sotolongo *et al.*, 2009). Each of the organisms present in the agroecosystem contributes to the total integration of functions, making it impossible to describe reality if we only verify the abundance of organisms from classical statistics. In a study conducted by Beltrán & Pinzón (2018) determined that in plantations of advanced ages of pine, termites are interacting with the natural dynamics of the plantations by contributing to the decomposition of cellulosic material and the improvement of soil fertility. Pohlan *et al.* (2019) state that in areas around 800 meters above sea level for cocoa and coffee crops the diversification of products and services implies an environmental and ecological assessment that includes flora, fauna, water and biomass.

Lombardi (1998) states that a widely used resource in physics consists of representing the behaviour of dynamic system expressing their initial state in geometric language. The study of stability was one of the fundamental theoretical elements of the Chaos Theory. Multidisciplinary studies where mathematical and physical principles are used, not only statistical, in a creative way; show the current relative reality and a dynamic modeling that shows the future of agroecosystems. Campo & Duval (2014). When applying traditional indices of diversity on the vegetation, they found that in the Lihué Calel National Park, Argentina, there is a large number of species in the area, that the community does not have dominant species and therefore the diversity is greater; that it is an equitable formation and that all species are abundant. Pohlan (2006) states that the improvement of the quality of coffee can be extrapolated to other crops diversified farms will have a much greater probability of surviving the crisis, whose main objective must always be based on sustainability and in harmony with agroecological principles.

Tapia *et al.*, (1999) determined that all the agroforestry systems they studied showed higher density of macrofauna and biomass than the natural regeneration section. The results suggest the improvement of the operation of recycling processes in the soil and sustainability of production. The design of precision agroecosystems should prioritize organisms that perform functions to simulate the bi-

haviour of natural ecosystems; the measurement of the existing chaos product of this process can be obtained with the biomathematical model xi Ξ and the functional entropy index lambda λ.

5   Conclusions

Agroecosystems under the conventional approach presented between 17 and 42 taxonomic families, registering a total of 73 families of macrofauna. Agroecosystems with an agroecological approach presented between 27 and 65 families for a total of 124. The dominant presence of macrofauna families such as Scarabaeidae, Formicidae, Chrysomelidae, Elateridae and Noctuidae; especially the first two, influence the final result of the model generating a tendency to negativity due to its herd behaviour. The families Lumbricidae, Rhinotermitidae and Acanthodrilidae, the three gregarious, push the model towards positivity together with Polydesmidae and Porcellionidae; with a population density lower than the previous ones. The biomathematical model xi Ξ can be used in any agroecosystem in Nicaragua and the world; it generates polynomial equations with an agroecological approach to simulate abundance, richness, dominance, uniformity, stability and functionality of the species. Most of the agroecosystems analysed with an agroecological approach presented greater population stability of the macrofauna families present, mostly tending towards positivity with a range of λ between 41.36 to 127,095.41 much higher than the conventional approach with a range of -81.62 to 8588.73 with a tendency to negativity. The functional entropy index λ from the Xi (Ξ) model quantifies the level of chaos in correspondence with the attributes of diversity and functional integration of existing organisms in a defined space and time.

Conflict of interest

he authors declare that there are no conflicts of interest in the preparation and publication of this research.

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