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RESEARCH PAPER

Investigating the Health of a Rice Field Ecosystem Using Thermodynamic Extremal Principles

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Abstract: This study investigates the dynamic behaviour of a rice field ecosystem and aims to define its integral features using the stability concept of an ecological goal function. This function is based on the extremal principles of

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thermodynamics, which assume that certain energetic processes of ecosystems—such as the rate of exergy destruction—are directed by the self-organizing informatics of the systems towards maxima or minima.

In our study, we exploit the availability of substantially long time-series data relating to a rice field ecosystem to gain an evocative understanding of its growth trajectory in light of the thermodynamic principles. We accomplished this by constructing a model based on the STELLA 9.0 software and calculating the extremal values of growth rates (storage) and those of exergy destruction and entropy creation. The results showed that the values of both maximum dissipation and maximum exergy progressed apace with that of maximum storage till the maturation of rice and became stable thereafter, whereas maximum residence time and maximum specific dissipation values initially decreased before their asymptotic rise. A similar pattern was also observed for the maximum specific exergy. However, the maximum power dissipation curve followed a highly fluctuated course before becoming stable on the maturation of rice.

Keywords: Far-from-equilibrium system; goal-function; rice field ecosystem; thermodynamic ecology

1. INTRODUCTION

Ecosystems are complex, hierarchic, adaptive, and organized, as they are comprised of many components. These biotic and abiotic components interact to produce new emergent states that are impossible to predict accurately (Nielsen and Ulanowicz 2011). However, ecosystems exhibit certain common structural and functional characteristics that suggest they are driven by some directive principles that determine their future trajectories, such as the extremal principle of least action. Modern research in ecology aims to test the application of various goal functions in characterizing ecosystems' structure and evolution (Mauersberger and Straškraba 1987; Jørgensen *et al.* 2007). Using goal functions in ecology simplifies ecological modelling and stability concepts by introducing extremal principles from which the "integral features" of the ecosystem can be derived (Mauersberger and Straškraba 1987; Jørgensen *et al.* 2007). According to Nielsen and Jørgensen (2013), there are three goal functions: biotic, network, and thermodynamic. Biotic goal functions are related to biodiversity, biomass, species number, richness, and evenness while network goal functions involve flow matrix, respiration, and import–export analysis (Ulanowicz 1986; Baird and Ulanowicz 1989; Christensen and Pauly 1992; Fath and Patten 1999). Thermodynamic goal functions, summarized by Yen *et al.* (2014), essentially seek to maximize or minimize a thermodynamic property of the macroscopic state of the system. These include a large set: "maximum exergy storage" (Jørgensen and Svirezhev 2004), "maximum energy storage" (Odum 1988), "maximum residence time" (Fath, Patten, and Choi 2001), "maximum entropy production" (Dewar 2010; Kleidon 2010), "minimum entropy production" (Prigogine 1995; Martyushev and Seleznev 2006), "min-max principle of entropy production" (Aoki 2006), "maximum rate of gradient degradation" (Schneider and Kay 1994), "maximum power" (Lotka 1922; Brown, Marquet, and Taper 1993; DeLong 2008), "maximum empower" (Odum and Pinkerton 1955), "maximum ascendency" (Ulanowicz 1980, 2003), "minimum specific energy dissipation" (Margalef 1963), "constructal law of evolution" (Bejan and Lorente 2010), and "maximum rate of cycling" (Morowitz 1968). Several of these different quantities are, in fact, equivalent or complementary, as explained by several researchers (Jørgensen 1992, 1994; Patten 1995; Jørgensen and Nielsen 1998; Fath, Patten, and Choi 2001; Ray 2006; Yen *et al.* 2014).

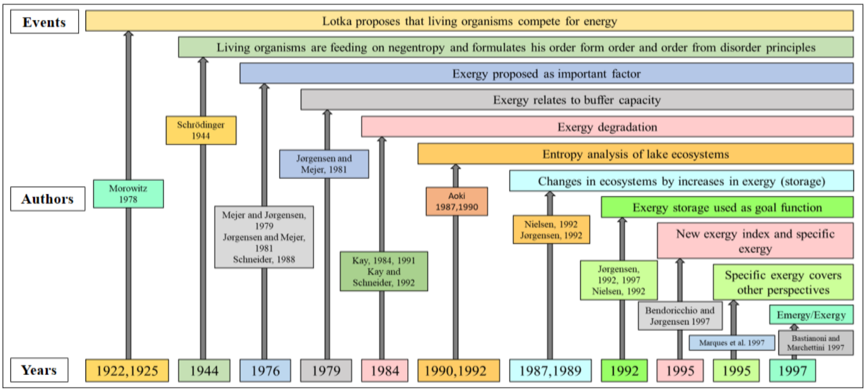
Limits and extremal principles are found to order many natural phenomena, such as animal sizes and the heights of mountain chains, and provide a rationale to order masses of data in an analytical framework. Indeed, the first such principle to explain ecological processes was formulated in 1859 by Darwin as the "survival of the fittest"—those ablest to harvest the available resources. The recognition of ecological systems as open systems powered by the sun and maintaining a dynamically stable state by exchanging energy and materials from their surroundings—like a thermodynamic engine—led Lotka to propose in the 1920s that ecosystems flourished by maximizing the rate of entropy production. Several related extremal principles have been formulated (Figure 1) towards developing the ecology theory since then. However, the examples of testing these in the field are still too few to warrant a clear direction.

In this study, we present an application of four of these formulations to data from rice fields to test their relative or collective fruitfulness in explaining the growth trajectory of rice plants. These are based on the concepts of energy, exergy, total systems throughflow, and ascendency.

2. DATA AND APPLICATION OF THE EXTREMAL PRINCIPLE

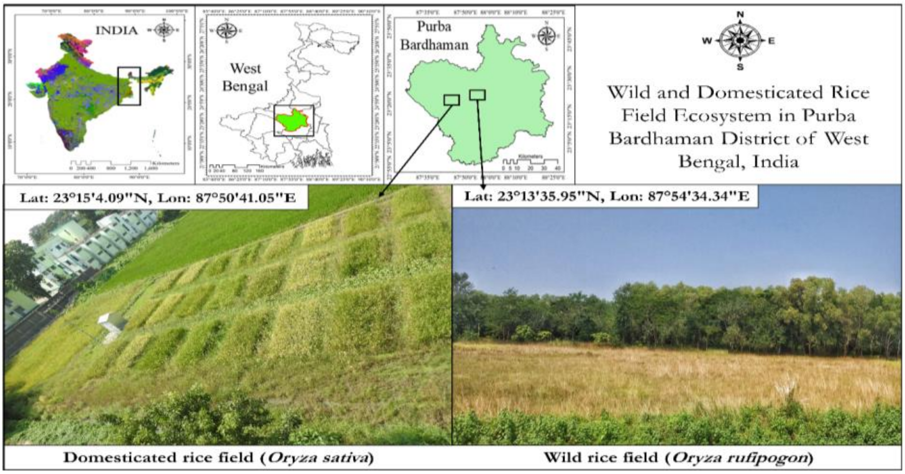
The experiment was carried out at two sites: The Crop Research and Seed Multiplication Farm (CRSMF) (Lat: 23°15'4.09"N, Lon: 87°50'41.05"E) for the ecosystem of domesticated rice fields and Bamchandaipur village (Lat: 23°13'35.95"N, Lon: 87°54'34.34"E) for the ecosystem of wild rice fields in Purba Bardhaman district, West Bengal, India (Figure 2).

Figure 1: A Chronological Snapshot of Different Propositions and Events Depicting the Evolution in the Concept of Goal Functions Through Time



Source: Authors

Figure 2: Study Sites of Domesticated (Left) and Wild Rice Field (Right) Ecosystems



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2.1. Data Collection

Field sampling was carried out for three consecutive years, from March 2016 to June 2019. The sampling was carried out at weekly intervals during the morning (7:00–10:00 IST) and evening (15:00–18:00 IST) hours throughout the study period. Accordingly, there were 170 sampling days during the entire study. There are four zones in the rice field ecosystem: benthic or littoral, limnetic, transitional, and terrestrial. Various forms of sampling were used for the multiple taxa occupying each zone to record total biodiversity. Water and soil collection and sweeping were done through a randomized complete block design method to reduce sampling bias. The eight functional compartmental guilds were assigned based on trophic levels—green plants as producers, phytophagous as herbivores, predators as carnivores, omnivores, detritivores, and parasitoids. In some cases, where direct observation of food habits was not possible, a coffee-table experiment was performed to determine the food preferences, and the guild was assigned accordingly. All the collected and calculated data are provided in Appendix 1. Water-level data for wild rice fields were recorded at weekly intervals throughout the year and averaged to identify the monthly values (Figure 5).

2.2 The Extremal Principles Tested in this Study

Four thermodynamic extremal principles were tested on the rice field data described in the previous section. These are emergy, exergy, total system throughflow, and ascendency; and are outlined here:

2.2.1. Energy

Energy and exergy, the two target functions, are based on thermodynamics. Emergy, or embodied energy (Odum 1983), is a concept that assesses how much solar radiation is required to create a particular organism (biomass). The biomass, or its free energy, is multiplied by a factor determined by the amount of solar energy required to generate one unit of energy in the organism. The number of transfer and transformation stages a system has taken away from its input source is assumed to increase the quality of energy brought into it and its energy content. Because they are farther away from solar-energy inputs than photosynthesizing primary producers, upper trophic-level animals in ecosystems are thought to have a higher energy quality.

2.2.2. Exergy

The amount of work a system can do when it is brought into equilibrium with its surroundings is thermodynamically characterized as exergy. Exergy attempts to account for both the free energy stored in biomass and the free energy stored in information. Exergy represents the quality of the ecosystem's energy. The expression for exergy calculation proposed by Mejer and Jørgensen (1979) is

$$Ex = R.T\sum_{i=0}^{n}[c_i.\ln\left(\frac{c_i}{c_i^{eq}}\right) - (c_i - c_i^{eq})] \qquad (1)$$

Where R = gas constant, T = absolute temperature, c_i = concentration in the ecosystem of the component, i. Index 0 = inorganic components of the considered chemical element and c_i^{eq} = corresponding concentration of i^{th} component at the thermodynamic equilibrium.

Boltzmann's constant (1.3803 × 10^{-23} J molecules^{-1} deg^{-1}) equals $kT\ lnI$, where I is the pieces of information we have about the state of the system and k is Boltzmann's constant (1.3803 × 10^{-23} J molecules^{-1} deg^{-1}). This means that the exergy of one bit of information is equal to $kT\ ln2$. Information transfer from one system to another is frequently a nearly entropy-free energy transfer.

As an ecosystem grows, it becomes increasingly successful in capturing and dissipating the exergy of incoming solar radiation (Schneider and Kay 1994). Schneider and Kay (1994) propose the dissipation of exergy as a target function. This exergy is employed to create and maintain organization and structure. Exergy accounts for the biomass and information stored in it; therefore, increased nutrient concentrations will likely result in more exergy. The ability to account for the system's ability to use available resources would be beneficial. The concept of specific exergy is used to describe this ability, which is defined as (Equation 2):

$$Ex_{spc} = \sum_i \beta . X_i \qquad (2)$$

Where β = quality factor, calculated based on the amount of information embedded in the genes, and X = biomass concentration of the i^{th} species relative to the total biomass concentration.

When the temperatures of the two systems vary, the entropy lost by one system does not equal the entropy acquired by the other. Still, the exergy lost by one system equals the exergy transferred and obtained by the other. In this case, exergy is more convenient than entropy. Exergy can be used to express the second rule of thermodynamics as follows (Equation 3):

$$\Delta Ex_{for\ any\ process} \leq 0 \qquad (3)$$

This implies that exergy is always lost, that is, work is lost as heat that cannot be used to perform work. The entropy and exergy formulations of the second law of thermodynamics are, of course, interchangeable.

2.2.3 Total System Throughflow (TST)

The first quantitative attempt to quantify ecosystem growth was Lotka's "maximum power idea" (Lotka 1932, which defined power as work per unit of time. The concept evolved into a theory by Odum and Pinkerton (1955), who stated that ecosystems act to maximize their power output. TST refers to the energy flow throughout the entire system (Equations 4 and 5).

$$TST = \sum_{j=1}^{n} T_j \tag{4}$$

$$T_j = \sum_{\substack{i=0 \\ i \neq J}}^{n} f_{i,j} \tag{5}$$

Where $j=1, 2, \ldots, n$

Although this concept was not explicitly related to energy quality or system organizational traits, it was indicated that systems that generated more power were better suited and favoured in evolutionary selection.

2.2.4 Ascendency

Ulanowicz (1986) created the concept of ascendency to account for the throughflow of energy in an ecosystem (T) and network (A). Ascendency refers to the part of a system's intercompartmental articulation that is dictated by the entire complexity of the collection of processes that corresponds to organized flows and is weighted by the TST (Equation 6).

$$ASC = \sum_{j=0}^{n} \sum_{i=0}^{n} f_{i,j} . \log \left(\frac{f_{i,j} . TST}{T_i T_j}\right) \tag{6}$$

Maximizing this aim function should describe the autocatalytic tendencies inherent in structuring emerging ecological networks.

Ascendency takes into account the network's size (T) and the information contained inside it. A is a massive variable; the size term T is the most important in most calculations (Equation 7).

$$\frac{A-T}{T} = I - 1 \tag{7}$$

As a result, the structural exergy should be firmly linked to A-T, whereas the exergy should be more strongly linked to the size term T but perhaps also to A because T is the most dominating term.

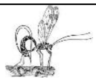
Average mutual information is dimensionless and has a limited range of values—generally between 2.0 and 6.0. In non-negative real values, TST—which scales this information quantity—can be highly variable. As a result, the ascendency metric is dominated by throughflow, resulting in highly correlated findings for power and ascendency (Jorgenson 1992).

2.3. Model Development

An eight-compartment model was constructed (Table 1 and Figure 3) to evaluate the interrelationship among extremal principles and subsequent stability analysis. The components of the model are presented in Table 1.

The model used these components as state variables to calculate the extremal principles.

Table 1: The Eight Major Components (Producer, Herbivore, Carnivore, Detritus, Detritivore, Omnivore, and Parasitoid) with Examples

Components	Examples	Components	Examples
Producer		Detritivore	
Herbivore		Omnivore	
Carnivore		Parasitoid	
Detritus		Nutrient	

Source: Authors

The description of equations (Eq) and symbols are given in Appendices 1 and 2. Equation 8 describes the carnivore dynamics, with inflows primarily based on *pred*, *detcarn*, and *pred1* and outflows primarily based on *mortfish*, *refi*, *omni3*, and *para3*. Herbivores and carnivores both had an impact on predation (Eq 8.1). Carnivores and detritivores both had an impact on the *detcarn* (Eq 8.2). Carnivores and omnivores both had an impact on *pred1* (Eq 8.3). Only carnivores had an impact on both the *mortfish* (Eq 8.4) and *refi* (Eq 8.5). Carnivores and omnivores influenced the *omni3* (Eq 8.6). Carnivores and *para* were both affected by *para3* (Eq 8.7).

Eq 9 describes the detritus dynamics, with inflows primarily based on *mortfish*, *mz*, *mort*, *mortomni*, and *mortpara* and outflows primarily based on *outdet*, *detfed*, and *omni5*. Carnivores had an impact on the *mortfish* (Eq 9.1). Carnivores and herbivores both had an impact on the *mz* (Eq 9.2). Herbivores and producers had a consequence on the *mort* (Eq 9.3). The omnivores influenced the *mortomni* (Eq 9.4). *Para* had an impact on the *mortpara* (Eq 9.5). *Detr* and *qv* influenced the *outlet* (Eq 9.6). *Detr* and water level had an impact on the *detfed* (Eq 9.7). Omnivore and *detr* were both influences on the *omni5* (Eq 9.8).

Eq 10 can be used to define the detritivore dynamics. *Detfed* is the most common inflow, whereas *detexcr*, *detcarn*, *omni4*, *para5*, and *rdetri* are the most common outflows. *Detr* and water level had an impact on the *detfed* (Eq 10.1). Detritivore and water level both influenced the *detexcr* (Eq 10.2). Carnivores and detritivores both had an impact on the *detcarn* (Eq 10.3). There were detritivore and omnivore influences on the *omni4* (Eq 10.4). Detritivore and *para5* both had an impact on *para5* (Eq 10.5). Detritivores affected the *rdetri* (Eq 10.6) Eq 11 describes the herbivore dynamics, with inflows mostly based on gr and outflows depending on *pred*, *mz*, *rz*, *omni2*, and *para5*. Herbivores and producers had an impact on the *gr* (Eq 11.1). Herbivores and carnivores both had an impact on predation (Eq 11.2). Herbivores and carnivores had an impact on the *mz* (Eq 11.3). Herbivores had an impact on the *rz* (Eq 11.4). Herbivore and omnivore interactions altered the *omni2* (Eq 11.5). Herbivore and para were both impacted by *para5* (Eq 11.6).

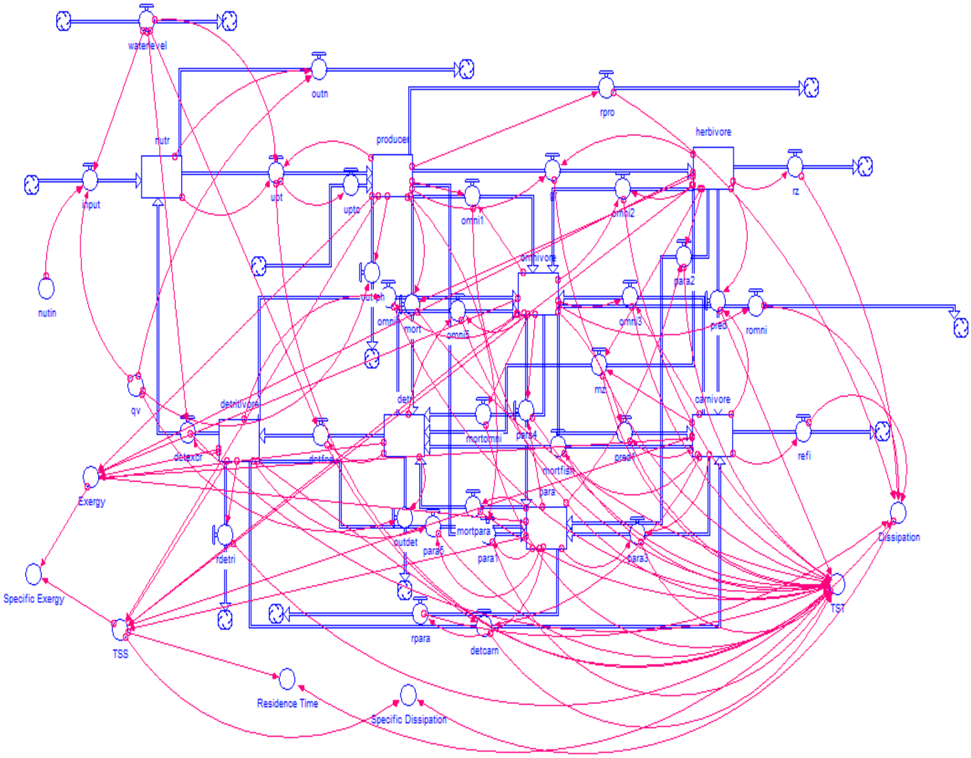
Eq 12 can be used to define nutrient dynamics. Outflows are primarily based on *up* and *outn* while inflows are primarily based on input and *detexcr*. *Nutin*, *qv*, and the water level all had an impact on the input (Eq 12.1). Detritivores and the water level both influenced the *detexcr* (Eq 12.2). *Nutr*, producers, and the water level all had an impact on the *upt* (Eq 12.3). *Nutr* and *qv* had an impact on the *outn* (Eq 12.4).

Eq 13 can be used to define the omnivore dynamics; outflows are primarily based on *mortomni*, *pred1*, *para4*, and *romni*. In contrast, inflows are primarily based on *omni1*, *omni2*, *omni3*, *omni4*, and *omni5*. Producers and omnivores had an impact on the *omni1* (Eq 13.1). Herbivore and omnivore interactions altered the *omni2* (Eq 13.2). Carnivores and omnivores influenced the *omni3* (Eq 13.3). There were detritivore and omnivore influences on the *omni4* (Eq 13.4). *Detr* and omnivore had an impact on the *omni5* (Eq 13.5). The omnivore had an impact on the *mortomni* (Eq 13.6). Carnivores and omnivores both had an impact on *pred1* (Eq 13.7). *Para* and omnivores had an influence on *para4* (Eq 13.8). The omnivorous had an impact on the *romni* (Eq 13.9).

Eq 14 can be used to define parasite dynamics. Outflows depend primarily on *mortpara* and *rpara* while inflows are primarily based on *para1*, *para2*, *para3*, *para4*, and *para5*. *Para* and producer had an impact on *para1* (Eq 14.1).

Para and herbivore had an effect on *para2* (Eq 14.2). *Para* and carnivore had an impact on *para3* (Eq 14.3). *Para* and omnivore had an impact on *para4* (Eq 14.4). *Para* and detritivore affected *para5* (Eq 14.5). *Para* impacted the *mortpara* and *rpara* (Eq 14.6, 14.7).

Figure 3: The Calculation Framework of Extremal Principles Values in STELLA 9.0



Source: Authors

Eq 15 can be used to define the producer dynamics. *Upt* and *uptc* are the most common inflows whereas *gr*, *mort*, *out ph*, *omni1*, *para1*, and *rpro* are the most common outflows. *Nutr*, producers, and the water level all had an impact on the *upt* (Eq 15.1). *Up* had an impact on the *uptc* (Eq 15.2). Producers and herbivores both had an impact on the *gr* (Eq 15.3). Producers and herbivores both had an impact on the *mort* (Eq 15.4). *qv* and producers influenced the *out ph* (Eq 15.5). Omnivores and producers had an impact on the *omni1* (Eq 15.6). *Para* and producers had an impact on *para1* (Eq 15.7). Producers had an impact on the *rpro* (Eq 15.8).

The sums of *rdetri*, *refi*, *romni*, *rpara*, *rpro*, and *rz* was utilized to determine dissipation in Eq 16. The exergy dynamics can be defined using Eq 17, which is the sum of all the producers, herbivores, omnivores, carnivores, deter and detritivores, and para. Where the values of $nutin = 40$ and $qv = 0.05$. When the TST was divided by TSS, Eq 18 was used to calculate the residence time. When the dissipation was divided by throughflow-derived storage (TSS), Eq 19 was utilized to define the specific dissipation. When the exergy was divided by TSS, Eq 20 was utilized to define the specific exergy. Eq 21 can be used to calculate the TSS, which is the sum of all of the carnivore, detritivore, herbivore, omnivore, para, and producer populations. The TST is defined by Eq 22 as the sum of *detcarn*, *detexcr*, *detfed*, *gr*, *mort*, *mortfish*, *mortomni*, *mortpara*, *mz*, *omni1*, *omni2*, *omni3*, *omni4*, *omni5*, *para1*, *para2*, *para3*, *para4*, *para5*, *pred*, *pred1*, and *upt* (Refer Appendix 1).

3. RESULT AND DISCUSSION

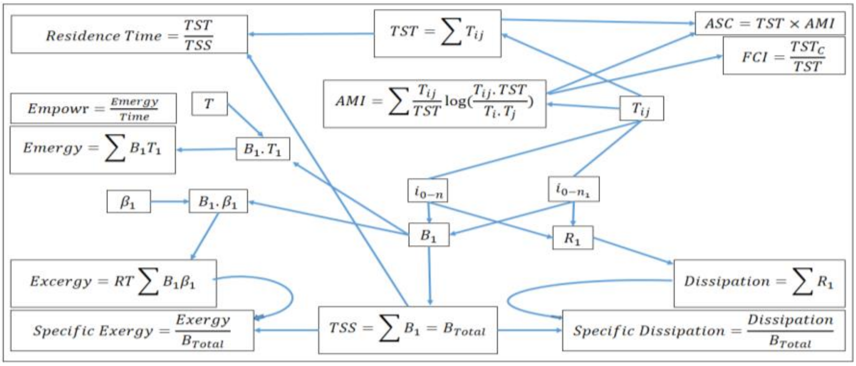
3.1. Integration of Goal Function

Theoretical approaches have dominated the investigation of the thermodynamic extremization principle. Consistencies between energy storage and dissipation showed that existing thermodynamic extremization principles might be unified. Hence, interaction between the two categories (energy storage and dissipation) is possible.

Based on the aforementioned theories, the extremal principles could be integrated as shown in Figure 5. Maximal energy storage implies maximum energy dissipation (metabolic rate). Because living species always dissipate energy, an ecological system can improve energy dissipation by increasing energy storage (biomass) until the energy storage reaches a maximum (that is, the system becomes resource-limited). By combining maximum energy dissipation and maximum energy storage, all thermodynamic extremization concepts are compatible.

Numerous thermodynamic extremization principles have been proposed and applied to ecological issues. Many of the energy quantities have been linked (Figure 4) to ecological quantities including biomass, food-web complexity (e.g., link density), growth rates, life-cycle duration, and community stability, all of which have been shown to follow predictable trajectories during ecosystem evolution (Odum 1969; Loreau 1998). The relevant literature is scattered and distinguishing between possible extremization principles has received much attention. Despite their apparent differences, multiple thermodynamic extremization principles may be boiled down to two main themes: energy storage and dissipation (Fath, Patten, and Choi 2001). Various energy storage and energy dissipation principles are discussed in their paper.

Figure 4: Mathematical Integration of Extremal Principles



Source: Authors
Note: All acronyms have been elaborated in paragraph 2.2

According to energy-dissipation principles, natural systems utilize energy at extreme rates. Maximum energy dissipation indicates high throughput whereas minimum energy dissipation indicates efficient energy utilization (that is, organisms using energy as fast as possible). Maximum energy dissipation does not always imply poor use of other resources—such as water or nutrients—as efficient use of these resources is sometimes required for high energy dissipation. In this study, two scenarios are considered: maximum entropy creation and maximum power. According to the principle of maximal entropy production (MEP), all non-equilibrium thermodynamic systems produce entropy as quickly as feasible, returning the system to a state of maximum entropy as soon as possible (Martyushev and Seleznev 2006). Several attempts have been made to derive generic proof for far-from-equilibrium systems (Dewar 2003, 2005), but none have been successful (Grinstein and Linsker 2007). The rate of "useful" energy usage (e.g., conversion to biomass or reproduction) (Jorgensen and Svirezhev 2004), the rate of "emergy" use (Odum 1996, Hall 2004, Tilley 2004), and "fitness" or rate of reproduction have all been linked to power (Brown, Marquet, and Taper 1993). Loreau (1998) proposes that adequate definitions of power should be based on ecological processes because each of these definitions of power only covers one component of energy consumption (e.g., demography, resource use).

The exergy principle has been provided as a tentative thermodynamic law that might be used as a hypothesis in the present research. Ecosystems have a lot of different paths and much exergy flowing through them. Increases in system features such as distance from thermodynamic ground, structure, heterogeneity, organization, gradients, and energy quality result from incremental exergy increases that accompany rising path lengths. As throughflows increase with the increase of path length, this feature becomes more aligned with exergy and emergy. ASC (ascendency) in ecosystem networks leads to the maximum of these values because TST corresponds to power output, which is often a substantial component of ascendency. As a result, the four extreme principles of exergy maximization, emergy, power, and ascendency are linked by a single process: exergy propagation in ecological networks. According to our findings, exergy, emergy, power, and ascendency are all found in the structure and microscopic dynamics of energy, matter flows, and storages in ecosystems.

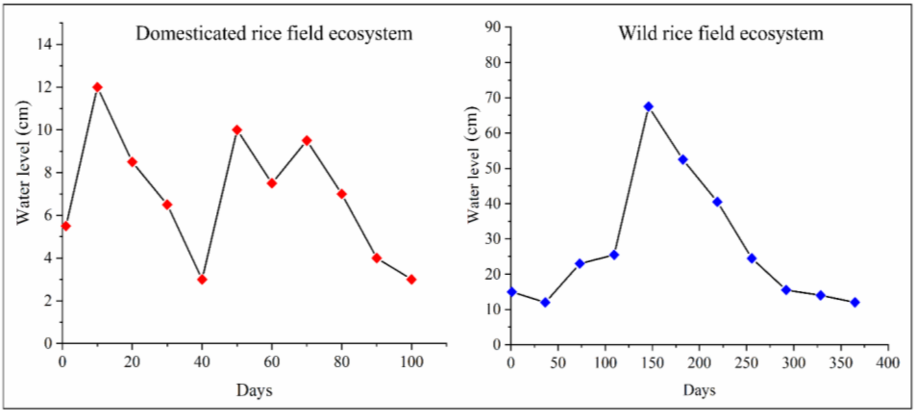
3.2. Health of Rice Field Ecosystem in Relation to the Extremal Principles

The present study showed that nutrition and water level are the most important and main regulatory parameters for wild and domesticated rice field ecosystems.

The nutrient content and water level in domesticated and wild rice fields were different. The nutrient content of a domesticated rice field was 40 $mgCg^{-1}$ but only 18 $mgCg^{-1}$ in a wild rice field environment. Water concentration in domesticated rice field systems varies between 2.8–12 cm, but in wild rice field systems, it varies between 10–70 cm due to higher rainfall during monsoon seasons. Figure 5 depicts the water level in the domesticated and wild rice field ecosystems. Figures 6 and 7 describe the conditions of extremal principles in the domesticated and wild rice field ecosystems, respectively.

Zehe *et al.* (2010) studied the maximum energy dissipation and the connection between water flow and soil structure. They concluded that biological soil structures are crucial for infiltration and soil water flow. Hence, the burrows created by the worms allow for a more efficient redistribution of water within the soil, which implies a more efficient dissipation of free energy. In the present comparison, the maximum dissipation values for the domesticated rice field ecosystem touch 175 KJ near around 100 days of rice cultivation and then decrease with time, whereas, in the wild rice ecosystem, the value is nearly 16 KJ around 120 days of cultivation and remain stable throughout the study period. Hence, it could be said that the water flow of the domesticated rice fields was controlled and infiltration of the water-forming network within the soil structure is temporary with high dissipative energy—implying higher entropy production. However, no such mechanism occurred in the wild rice ecosystem. The field was a natural wetland system and was always inundated by water flow depending upon rainfall. Although the values of maximum dissipation were lower than domesticated fields, the value (17.5 KJ) reached an asymptote beyond the shattering of rice seeds, implying lower entropy in the system. Sheng *et al.* (2020) add that the shattering of rice seeds is an evolutionarily beneficial phenomenon for wild rice varieties. This trait is beneficial for dispersal, preventing the seeds from drying and losing seed dormancy.

Figure 5: Temporal Variation of Water Levels in Domesticated (Annual Plant) and Wild Rice (Perennial Plant) Field Ecosystems



Source: Authors

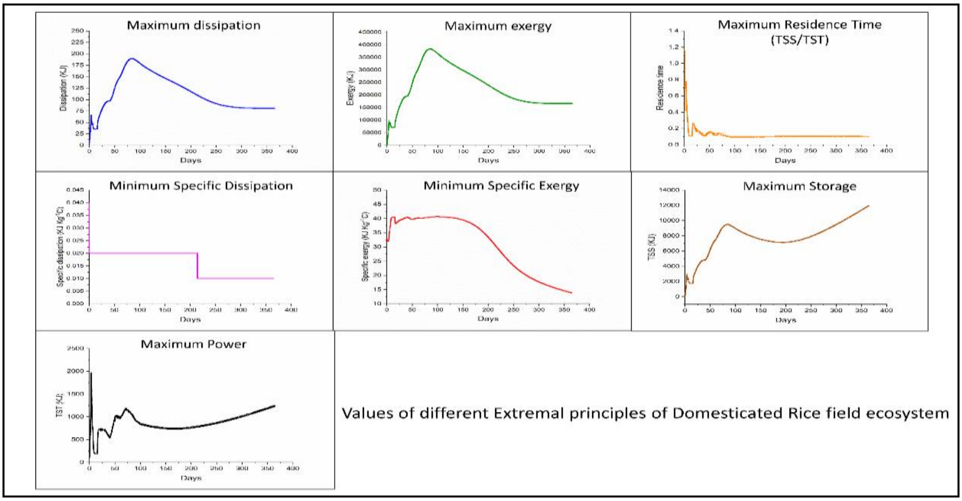
In the present study, the minimum specific dissipation of the domesticated rice field ecosystem was constant (0.020) during rice cultivation. However, the values are a bit higher for wild rice fields (0.020–0.040), meaning the values were greater till the panicle initiation stage of rice and behaved the same as domesticated fields after the development of reproductive structures. Ludovisi, Pandolfi, and Taticchi (2005) propound that specific dissipation is a good indicator of ecosystem health. Moreover, the higher the specific dissipation of a system, the lower the capacity of a system to convert the incoming entropy energy into internal organization. The nutrient input of the wild rice fields was non-controlled, resulting in differential resource utilization by the rice plants until the crop reached its sexual maturity. After the panicle initiation period to shattering, the system behaved quite self-organized. However, in the domesticated fields, the nutrient input was controlled throughout the study. Hence, all the rice plants showed high productivity and greater self-organization compared with wild rice throughout the period, from germination to harvest. Despite having higher entropy in the system, the rice plants managed the nutrients efficiently in the domesticated rice fields.

Hovelius (1997) compared the exergy and energy values for salix, winter wheat, and winter rape cultivation in Sweden. She reports that the exergy values were always greater than the energy values depicting the quality of energy utilized by the crops. In the domesticated rice fields, the values ranged between 350,000–400,000 KJ, which was 10 times higher than the wild rice fields throughout the study, confirming the better energy quality in the system. It also showed better resource utilization and nutrient accumulation in the biomass of rice seeds in the domesticated rice fields. The values in the wild rice fields increased like a growth curve and reached an asymptote after shattering, implying the gradual accumulation of nutrients throughout the growth period. However, the values increased till crop maturity in the domesticated rice field and then decreased after harvest, that is, the post-harvest situation of rice straws in the field. The present findings are in agreement with Hoang and Alauddin (2011). Jekayinfa *et al.* (2022) observed that the use of machinery in the processing and production of soybean crops fetches higher exergy values. In the domesticated rice fields, the labour cost, tractors for irrigation, use of fertilizers and pesticides, and weeding resulted in higher cumulative exergy values than in the wild rice fields. Similar results were obtained by Yıldızhan (2017) during his study on wheat production in Turkey.

The minimum specific exergy was almost identical for wild and domesticated rice field ecosystems (40 KJ kg^{-1} ^{o}C), showing no change in the specific exergy at each phenological stage from germination to shattering in the wild rice fields. However, variation was observed for domesticated rice fields. Hence, minimal useful work was observed for domesticated rice fields. The wild rice field ecosystem possesses more faunal biodiversity than the domesticated rice fields, resulting in a complex food web and more ecological interactions among the organisms. Hence, the specific exergy change between the two trophic levels is minimum and uniform. However, the man-made or domesticated system is destroyed after a certain time or harvest. Also, irrigation destroys the soil structure, altering the existing biodiversity and specific exergy.

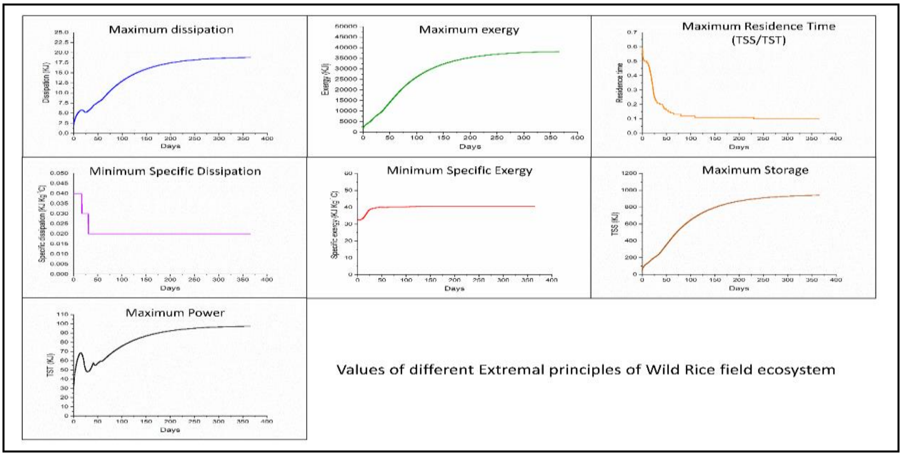
The average maximum residence time in the domesticated rice fields was (0.6), while in the wild rice fields, it was (0.35)—showing higher throughput-derived storage in the previous field than the latter with the same TST values. Schramski *et al.* (2015) advocate that the average residence time of an ecological system is dependent upon the body size, temperature, and structural organization of the system. With the increase of species number in the wild rice fields, the TST, maximum power, or cycling of the nutrients and energy transfer was low compared to domesticated rice fields. The maximum storage (TSS) was almost 10 times higher in the domesticated fields. Hence, the ratio between TSS and TST appeared to be small for the wild rice system.

Figure 6: Temporal Variation of Seven Different Extremal Principles (Dissipation, Exergy, Residence Time, Specific Dissipation, Specific Exergy, TSS-storage, TST-power) in the Domesticated Rice Field Ecosystem



Source: Authors

Figure 7: Temporal Variation of Seven Different Extremal Principles (Dissipation, Exergy, Residence Time, Specific Dissipation, Specific Exergy, TSS-storage, TST-power) in the Wild Rice Field Ecosystem



Source: Authors

4. CONCLUSIONS

The present research shows that current extremization theories could be merged to exhibit a pattern of significant correlation. This integration of extremization ideas ought to make using them easier and enable a change in emphasis toward empirical investigations.

It could be concluded that maximum dissipation and maximum exergy progressed apace with that of maximum storage till the maturation of rice and became stable thereafter. In contrast, maximum residence time and maximum specific dissipation values initially decreased before their asymptotic rise. A similar pattern was also observed for maximum specific exergy. However, the maximum power dissipation curve followed a highly fluctuated course before becoming stable on the maturation of rice.

Although they are uncommon, empirical investigations of thermodynamic extremization principles are crucial to our comprehension and use of these strategies. We used a dynamic ecosystem modelling technique in wild and domesticated rice fields to see how they reacted to various environmental conditions. This result indicates that wild rice fields are healthier and more stable than domesticated ones. Our approach might be modified to forecast a wider variety of ecological patterns that could help determine how applicable thermodynamic concepts are to ecology. Exciting areas of study include the development of quantitative theories and the empirical verification of these hypotheses, which should make it easier to apply thermodynamic concepts to common ecological issues.

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APPENDIX 1: Symbols and Initial Inputs Used in the Construction of the Model

Symbol	Explanation	Values and Equations
pred	Predation rate of carnivore upon herbivore	IF (herbivore>3) THEN (0.1*carnivore*(herbivore-0.1)/(1+herbivore)) ELSE (0)
detcarn	Predation rate of carnivore upon detritivore	0.33*carnivore*0.17*detritivore/(detritivore+1)
pred1	Predation rate of carnivore upon omnivore	0.1*carnivore*(omnivore-0.1)/(0.5+omnivore)
mortfish	Mortality rate of carnivore	0.02*carnivore
refi	Respiratory rate of carnivore	0.06*carnivore
omni3	Predation rate of omnivore upon carnivore	0.04*(carnivore-0.1)*(0.2*omnivore)/(carnivore+2)
para3	Parasitization rate of parasite/parasitoid upon carnivore	carnivore*para*0.00001
mz	Mortality rate of herbivore	0.2*herbivore+0.04*carnivore*(herbivore-0.1)/(1+herbivore)
mort	Mortality rate of producer	0.25*producer+0.17*(producer-0.1)*herbivore/(producer+2)
mortomni	Mortality rate of omnivore	0.034245*omnivore
mortpara	Mortality rate of parasite/parasitoid	para*0.03
outdet	Outflow rate of detritus	detr*(qv+0.9)
detfed	Feeding rate of detritivore upon detritus	(0.1*detr)++((IF (waterlevel<10) THEN (waterlevel*detr/3) ELSE (detr/3)))
omni5	Feeding rate of omnivore upon detritus	omnivore*detr*0.0176
detexcr	Excretion rate of detritivore	(0.1*detritivore)++((IF (waterlevel<10) THEN (waterlevel*detritivore/3) ELSE (detritivore/3)))
omni4	Feeding rate of omnivore upon detritivore	0.04*(detritivore-0.1)*(0.1*omnivore)/(detritivore+1)
para5	Parasitization rate of parasite/Parasitoid upon detritivore	detritivore*para*0.00001
rdetri	Respiratory rate of detritivore	0.09*detritivore
gr	Grazing rate of herbivore upon producer	IF (producer>30) THEN (0.4*herbivore*(producer-1)/(2+producer)) ELSE (1)
rz	Respiratory rate of herbivore	0.125*herbivore

omni2	Predation rate of omnivore upon herbivore	0.04*(herbivore-0.1)*(0.2*omnivore)/(herbivore+1)
para2	Parasitization rate of parasite/parasitoid upon herbivore	herbivore*para*0.00001
input	Nutrient input into system from out-source	(nutin*qv)++((IF (waterlevel<10) THEN (waterlevel*nutin/3) ELSE (nutin/3)))
upt	Nutrient uptake rate by producer	(IF (nutr>0.2) THEN (1.0*producer*(nutr-1)/(5+nutr)) ELSE (0))+((IF (waterlevel<10) THEN (waterlevel*nutr/3) ELSE (nutr/3)))
outn	Nutrient outflow rate from system	qv*nutr
omni1	Grazing rate of omnivore upon producer	0.04*(producer-0.1)*(0.2*omnivore)/(producer+2)
para4	Parasitization rate of parasite/parasitoid upon omnivore	para*omnivore*0.00001
romni	Respiratory rate of omnivore	0.02*omnivore
para1	Parasitization rate of parasite/parasitoid upon producer	para*producer*0.00001
rpara	Respiratory rate of parasite/parasitoid	0.001*para
out_ph	Outflow of producer from system	producer+qv+0.1*producer
rpro	Respiratory rate of producer	0.02*producer
qv	Outflow constant	0.05
nutin	Nutrient input into the system from out-source	40
producer	Autotrops in the system	35
para	Parasite/parasitoid in the system	1
omnivore	Omnivore in the system	1.5
nutr	Nutrient in the system	1.6
herbivore	Herbivore in the system	10
detritivore	Detritivore in the system	0.6
detr	Detritus in the system	16
carnivore	Carnivore in the system	1

2 APPENDIX 2: Equations Used in the Construction of the Model

Equations	**No**
$carnivore(t) = carnivore(t - dt) + (pred + detcarn + pred1 - mortfish - refi - omni3 - para3) \times dtINIT\ carnivore = 1$	8
Inflows	
$pred = IF\ (herbivore > 3)\ THEN\ (0.1 \times carnivore \times (herbivore - 0.1)/(1 + herbivore))\ ELSE\ (0)$	8.1
$detcarn = 0.33 \times carnivore \times 0.17 \times detritivore/(detritivore + 1)$	8.2
$pred1 = 0.1 \times carnivore \times (omnivore - 0.1)/(0.5 + omnivore)$	8.3
Outflows	
$mortfish = 0.02 \times carnivore$	8.4
$refi = 0.06 \times carnivore$	8.5
$omni3 = 0.04 \times (carnivore - 0.1) \times (0.2 \times omnivore)/(carnivore + 2)$	8.6
$para3 = carnivore \times para \times 0.00001$	8.7
$detr(t) = detr(t - dt) + (mortfish + mz + mort + mortomni + mortpara - outdet - detfed - omni5) \times dtINIT\ detr = 16$	9
Inflows	
$mortfish = 0.02 \times carnivore$	9.1
$mz = 0.2 \times herbivore + 0.04 \times carnivore \times (herbivore - 0.1)/(1 + herbivore)$	9.2
$mort = 0.25 \times producer + 0.17 \times (producer - 0.1) \times herbivore/(producer + 2)$	9.3
$mortomni = 0.034245 \times omnivore$	9.4
$mortpara = para \times 0.03$	9.5
Outflows	
$outdet = detr \times (qv + 0.9)$	9.6
$detfed = (0.1 \times detr) + ((IF\ (waterlevel > 10)\ THEN\ (waterlevel \times detr/3)\ ELSE\ (detr/3)))$	9.7
$omni5 = omnivore \times detr \times 0.0176$	9.8
$detritivore(t) = detritivore(t - dt) + (detfed - detexcr - detcarn - omni4 - para5 - rdetri) \times dtINIT\ detritivore = 0.6$	10
Inflows	10.1

Equations	**No**
$detfed = (0.1 \times detr) + +((IF\ (waterlevel < 10)\ THEN\ (waterlevel \times detr/3)\ ELSE\ (detr/3)))$	10.2
Outflows	
$detexcr = (0.1 \times detritivore) + +((IF\ (waterlevel < 10)\ THEN\ (waterlevel \times detritivore/3)\ ELSE\ (detritivore/3)))$	10.3
$detcarn = 0.33 \times carnivore \times 0.17 \times detritivore/(detritivore + 1)$	10.4
$omni4 = 0.04 \times (detritivore - 0.1) \times (0.1 \times omnivore)/(detritivore + 1)$	10.5
$para5 = detritivore \times para \times 0.00001$	10.6
$rdetri = 0.09 \times detritivore$	10.7
$herbivore(t) = herbivore(t - dt) + (gr - pred - mz - rz - omni2 - para2) \times dtINIT\ herbivore = 10$ (11)	11
Inflows	
$gr = IF\ (producer > 30)\ THEN\ (0.4 \times herbivore \times (producer - 1)/(2 + producer))\ ELSE\ (1)$	11.1
Outflows	
$pred = IF\ (herbivore > 3)\ THEN\ (0.1 \times carnivore \times (herbivore - 0.1)/(1 + herbivore))\ ELSE\ (0)$	11.2
$mz = 0.2 \times herbivore + 0.04 \times carnivore \times (herbivore - 0.1)/(1 + herbivore)$	11.3
$rz = 0.125 \times herbivore$	11.4
$omni2 = 0.04 \times (herbivore - 0.1) \times (0.2 \times omnivore)/(herbivore + 1)$	11.5
$para2 = herbivore \times para \times 0.00001$	11.6
$nutr(t) = nutr(t - dt) + (input + detexcr - upt - outn) \times dtINIT\ nutr = 1.6$	12
Inflows	
$input = (nutin \times qv) + +((IF\ (waterlevel < 10)\ THEN\ (waterlevel \times nutin/3)\ ELSE\ (nutin/3)))$	12.1
$detexcr = (0.1 \times detritivore) + +((IF\ (waterlevel < 10)\ THEN\ (waterlevel \times detritivore/3)\ ELSE\ (detritivore/3)))$	12.2
Outflows	

Equations	**No**
$upt = (IF\ (nutr > 0.2)\ THEN\ (1.0 \times producer \times (nutr - 1)/(5 + nutr))\ ELSE\ (0)) + ((IF\ (waterlevel < 10)\ THEN\ (waterlevel \times nutr/3)\ ELSE\ (nutr/3)))$	12.3
$outn = qv \times nutr$	12.4
$omnivore(t) = omnivore(t - dt) + (omni1 + omni2 + omni3 + omni4 + omni5 - mortomni - pred1 - para4 - romni) \times dtINIT\ omnivore = 1.5$	13
Inflows	
$omni1 = 0.04 \times (producer - 0.1) \times (0.2 \times omnivore)/(producer + 2)$	13.1
$omni2 = 0.04 \times (herbivore - 0.1) \times (0.2 \times omnivore)/(herbivore + 1)$	13.2
$omni3 = 0.04 \times (carnivore - 0.1) \times (0.2 \times omnivore)/(carnivore + 2)$	13.3
$omni4 = 0.04 \times (detritivore - 0.1) \times (0.1 \times omnivore)/(detritivore + 1)$	13.4
$omni5 = omnivore \times detr \times 0.0176$	13.5
Outflows	
$mortomni = 0.034245 \times omnivore$	13.6
$pred1 = 0.1 \times carnivore \times (omnivore - 0.1)/(0.5 + omnivore)$	13.7
$para4 = para \times omnivore \times 0.00001$	13.8
$romni = 0.02 \times omnivore$	13.9
$para(t) = para(t - dt) + (para1 + para5 + para4 + para3 + para2 - mortpara - rpara) \times dtINIT\ para = 1$	14
Inflows	
$para1 = para \times producer \times 0.00001$	14.1
$para5 = detritivore \times para \times 0.00001$	14.2
$para4 = para \times omnivore \times 0.00001$	14.3
$para3 = carnivore \times para \times 0.00001$	14.4
$para2 = herbivore \times para \times 0.00001$	14.5
Outflows	
$mortpara = para \times 0.03$	14.6
$rpara = 0.001 \times para$	14.7

Equations	**No**
$producer(t) = producer(t - dt) + (upt + uptc - gr - mort - out\_ph - omni1 - para1 - rpro) \times dtINIT\ producer = 35$	15
Inflows	
$upt = (IF\ (nutr > 0.2)\ THEN\ (1.0 \times producer \times (nutr - 1)/(5 + nutr))\ ELSE\ (0)) + ((IF\ (waterlevel < 10)\ THEN\ (waterlevel \times nutr/3)\ ELSE\ (nutr/3)))$	15.1
$uptc = 9 \times upt$	15.2
Outflows	
$gr = IF\ (producer > 30)\ THEN\ (0.4 \times herbivore \times (producer - 1)/(2 + producer))\ ELSE\ (1)$	15.3
$mort = 0.25 \times producer + 0.17 \times (producer - 0.1) \times \frac{herbivore}{producer + 2}$	15.4
$out\_ph = producer + qv + 0.1 \times producer$	15.5
$omni1 = 0.04 \times (producer - 0.1) \times (0.2 \times omnivore)/(producer + 2)$	15.6
$para1 = para \times producer \times 0.00001$	15.7
$rpro = 0.02 \times producer$	15.8
$Dissipation = rdetri + refi + romni + rpara + rpro + rz$	16
$Exergy = (producer \times 32) + (herbivore \times 35) + (omnivore \times 41) + (carnivore \times 47) + (detr \times 1) + (detritivore \times 30) + (para \times 2.4)$	17
$Residence\_Time = TST/TSS$	18
$Specific\_Dissipation = Dissipation/TSS$	19
$Specific\_Exergy = Exergy/TSS$	20
$TSS = carnivore + detritivore + herbivore + omnivore + para + producer$	21
$TST = detcarn + detexcr + detfed + gr + mort + mortfish + mortomni + mortpara + mz + omni1 + omni2 + omni3 + omni4 + omni5 + para1 + para2 + para3 + para4 + para5 + pred + pred1 + upt$	22