Preliminary Estimates of Community Response to Fishing Using Trophic Box Models: The Beach Seine Fishery along the Northwestern Coast of Yucatán

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ABSTRACT

Trophic box models are potentially an important tool for ecosystem management. Exploited resources are often studied independently of their functional role (in the trophic sense) in the community. Therefore, the effects of perturbations such as fishing activity on the community is practically unknown.

Using a predator-prey matrix obtained from stomach contents studies and biomass estimates, the ECOPATH II model was used to assess the affect of simulated decrements in biomass on some of the most important species of the community of the northwestern coast of Yucatán, simulating the extant beach seine fishery.

Decrements in biomass of the most important species tend to reduce efficiency, size and organization of the ecosystem. These changes are measured through the effects on respiration which are represented by losses of energy/biomass. The top predators play an important role in this scenario in that they constitute the most important species for the fishery.

KEY WORDS: trophic model, ecosystem, fisheries, ECOPATH II.

INTRODUCTION

Knowledge of ecosystem food webs is basic to their managemen, and trophic box models constitute a powerful tool to quantify energy flow through the ecosystems. Often, the dynamics of exploited resources (*i.e.*, species) are studied independently of other species without considering interactions within the community. It is reasonable to expect cascading effects such that the extraction of one resource may affect the whole ecosystem. Yet, a comprehensive study of this question is a difficult task.

However, it is possible to simulate the trophic chain behavior of communities with analytical methods. The ECOPATH II model (Christensen and Pauly, 1990) has proven to be an efficient method to evaluate various flows of energy within the food web of an ecosystem. In this paper, the ECOPATH II model has been applied to the artisanal beach seine fishery in the area of Celestun, Yucatán, Mexico to determine the impact of such a fishery on the local biota.

The artisanal fishery, which operates from February to August, results in a catch of more than 50 species with 13 of them representing 95% of the total 6000 metric tones (t.) catch, though the potential yield has been estimated as 10000 t. year (Arreguín -Sánchez *et al.*, 1987a,b).

Vega *et al.* (in press) have studied the trophic structure of this community using the ECOPATH II model (Polovina and Ow, 1983; Christensen and Pauly, 1990) and this information was used as baseline data in the present study.

METHODS

The approach used in this paper was to subject the original community as described by Vega *et al.* (in press) (Tables 1 and 2) to various fishing rates represented by losses in biomass, and determine the change in community structure by measuring changes in the energy flow within the simulated ecosystem. The stresses applied to the system were: (1) to totally remove some species, one at a time; and (2) to reduce by 20% and 40% the total biomass of the same species as (1). Energy flows under the different scenarios were determined using the ECOPATH II model after the stressed system reached steady state conditions. The basic assumptions for this model are: (1) the community is at equilibrium (steady state), and (2) that interdependences can be described by deterministic and linear equations as follows:

$B_i (P_i /B_i)EE_i - (S_j B_j (Q_j /B_j)DC_{ij}) - EX_i = 0$
where B_i = biomass of species i
P_i /B_i = Production/Biomass ratio of species i
EE_i = Ecotrophic Efficiency of species i
Q_j /B_j = Consumption/Biomass ratio of species j (predator)
C_{ij} = fraction of prey (species i) within the predators average diet
EX_i = Export out of the system from species i (including catches when i-th species is exploited)

The expression between brackets, $(S_j B_j (Q_j /B_j)DC_{ij})$, expresses the total biomass of species i consumed by all predators.

Trophic relationships were derived from a predator/prey matrix showing the average diets for all the species/groups. Stomach content data used by Vega *et al.* (in press) were collected directly from fishes obtained from commercial catches (Table 1). Biomass and Production/Biomass (P/B) ratio for the commercially important species were determined from studies on their population dynamics (Arreguín -Sánchez *et al.*, 1987a), while catch data come from statistical records compiled by the regional office of the Ministry of Fisheries. All units were standardized to g m^{-2} year^{-1} of dry weight.

The following are the commercially important species used to determine the

Table 1. Fish Community off Celestún Port, Yucatán México. Predator-prey Matrix.

| | PREDATOR | | | | | | | | | | | | | | | |
	ZO	AN	ML	MC	DE	OC	LR	OO	HJ	AR	CF	MO	HP	BC	AQ	OP
ZO	-	-	0.20	-	-	-	-	0.04	0.17	0.01	0.39	0.07	-	0.05	0.13	0.10
AN	-	-	-	0.20	0.10	0.11	0.06	0.01	0.01	0.24	0.03	0.09	0.32	0.08	-	-
ML	-	-	-	0.20	0.35	0.11	0.28	-	-	0.21	0.12	0.02	0.06	0.25	0.31	0.25
MC	-	0.05	-	-	0.10	0.57	0.29	0.52	0.37	-	0.09	0.60	0.31	0.14	0.04	0.15
DE	-	-	-	-	-	0.01	0.06	0.00	0.06	0.01	-	0.16	0.20	-	0.01	0.10
OC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05
LR	-	-	-	-	-	-	-	-	-	-	-	-	-	0.11	-	0.05
OO	-	-	-	-	-	-	0.15	-	-	-	-	-	-	-	-	0.10
HJ	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	0.10
AR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
CF	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MO	-	-	-	-	-	-	-	-	-	-	0.01	-	-	0.01	-	-
HP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
BC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AQ	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05
PH	0.95	-	0.35	0.30	0.05	0.07	0.10	0.11	0.36	-	0.12	0.04	0.08	0.35	0.06	0.05
BP	0.05	0.15	0.25	-	-	0.01	0.02	0.22	0.02	0.52	0.01	0.02	0.02	-	0.33	0.05
DET	-	0.80	0.20	0.30	0.40	0.13	0.04	0.10	0.01	0.01	0.20	-	-	0.02	0.12	-
TOT	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

(Row labels at left are marked **P R E Y**.)

ZO zooplankton
AN annelids
ML mollusks
MC microcrustacean
DE decapods
OC *Ocyurus chrysunus*
OO *Opisthonema oglinum*
HJ *Harengula jaguana*
AR *Archosargus rhomboidalis*
CF catfish
MO mojarra
HP *Haemulon plumieri*
BC *Bairdiella chrysoura*
AQ *Acanthostracion quadricornis*
OP other fishes
PH phytoplankton
DT detritus
BP benthic producers
LR *Lagodon rhomboides*

Table 2. Ecosystem statistics of Celestún coast community obtained with ECOPATH II.

	Base
Sum Of All Production	7657
Sum Of All Imports	1604
Sum Of All Respiratory Flows	4209
Sum Of All Flows Into Detritus	1757
Total System Throughput	15227
Mean Trophic Level Of Fishery	3.69
Input Total Net Primary Production	4107
Calculated Total Net Primary Production	2610
Contribution To Detritus From Primary Producers	1497
Full Development Capacity	44277
Full Ascendency	17542
Overhead On Input	1712
Overhead On Exports	13
Overhead On Respiration	8632
System Redundancy	16379
Internal Capacity	39069
Internal Ascendency	9807
Tribute To Other System	45
Dissipation	12838
System Redundancy	16379

impact of the various stresses (Arreguín-Sánchez *et al.*, 1987a,b; Arreguín -Sánchez, 1989a,b):

Orthopristis chrysoptera pigfish
Lagodon rhomboides pinfish
Opisthonema oglinum sardine
Harengula jaguana sardine
Archosargus rhomboidalissea bream
Cathorops spixii and *Ariopsis felis* catfish.

Results are given as community statistics according to Ulanowicz (1986), which provide a summary of ecosystem structure and energy flow (or biomass) within the food web. Results from the various scenarios were compared with the initial community structure and represented as anomalies (relative and absolute difference) to assess the impact of the perturbations; values below 5% were ignored. The relative changes (as percent) were estimated as follows:

$$RC_J = \frac{ES_{IK} - ES_{BK}}{ES_{BK}} \times 100$$

where

RC_J = relative change for J-th species

ES = ecosystem parameter

I = index for the scenario I

K = index for ecosystem parameter

B = original results without perturbation (base running). Catches were held constant for all the simulation scenarios (See Appendix 1).

Diet compositions used by Vega *et al.* (in press) are shown in Table 1 as a predator/prey matrix; catch, biomass, P/B, and Q/B ratios for species/groups are provided in Table 2; community statistics are in Tables 3 and 4.

RESULTS

Figures 1 and 2 show the relative changes in the community statistics affecting selected species for the different scenarios expressed as anomalies per unit of the statistic, as absolute anomalies, and in percent, respectively.

The relative changes in community statistics underlie global changes in the community because all flows are weighted to express proportional changes. Absolute anomalies are net changes in community statistics (*e.g.*, biomass or flowbits).

Scenario 1, when one species was totally removed, was tested for two species. When *Orthopristis chrysoptera* were removed, many ecosystem statistics increased over 10%, except overhead on respiration, contribution to detritus from primary producers, and sum of all productions. Changes over 5% were observed in system redundancy (internal), overhead on exports, and full ascendency were observed. Removal of *Harengula jaguana*, also resulted in positive changes with exception of the overhead on respiration and the contribution to detritus from primary producers. Positive changes of 5% were observed for the system redundancy, internal ascendency, and internal capacity. Overhead on exports changed 10%.

When biomass was reduced 20% (Scenario 2), only minor changes in community structure of less than 5% were observed, except where *Opisthonema oglinum* was removed which resulted in a reduction in overheads on exports.

The greatest changes were observed under Scenario 3, where biomass was reduced 40%. *O. chrysoptera* removal resulted in a considerable reduction in the development capacity as a consequence of reduction in overheads on exports (38%) and in tribute to other systems (30%). System redundancy and the sum of all productions also decreased over 5%. Where *H. jaguana* was removed, the contribution to detritus from primary producers was reduced 100%. *O. oglinum*
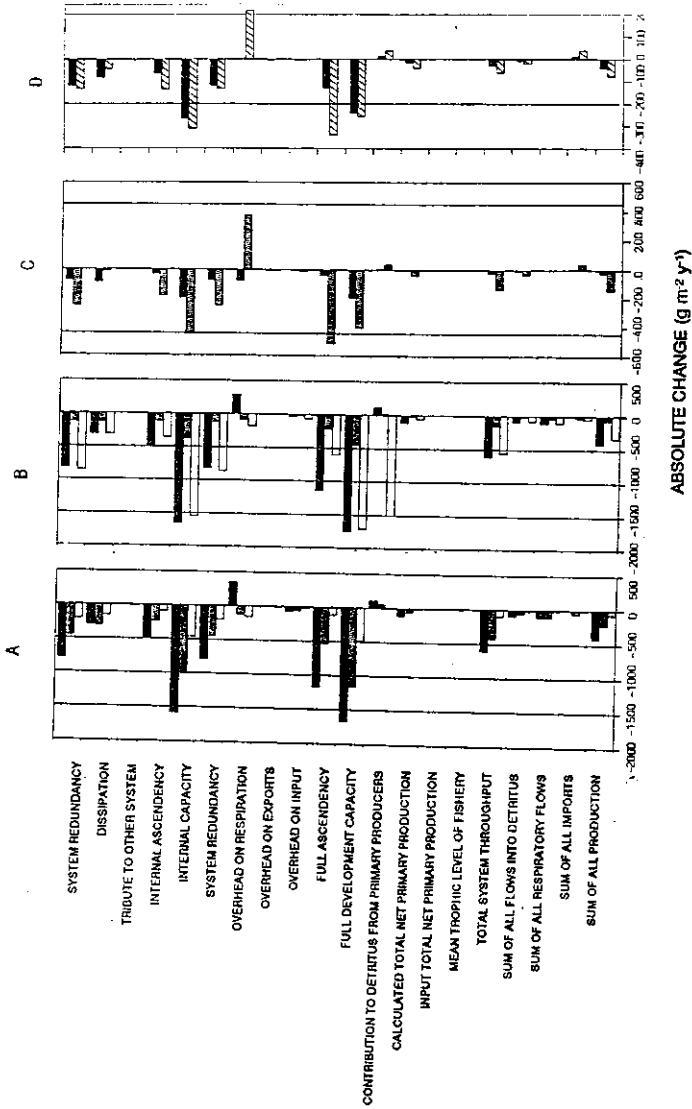
Figure 1. Community statistics of four species (a) *Orthopristis chrysoptera*, (B) *Harengula jaguana*, (C) *Opisthonema oglinum* and (D) *Lagodon rhomboides* expressed as statistic anomaly ($ES_{IK} - ES_{BK}$ from equation 2). White bar, when species was totally removed; dashed bar, with 20% of biomass removed; dark bar, when 40% of biomass was removed.
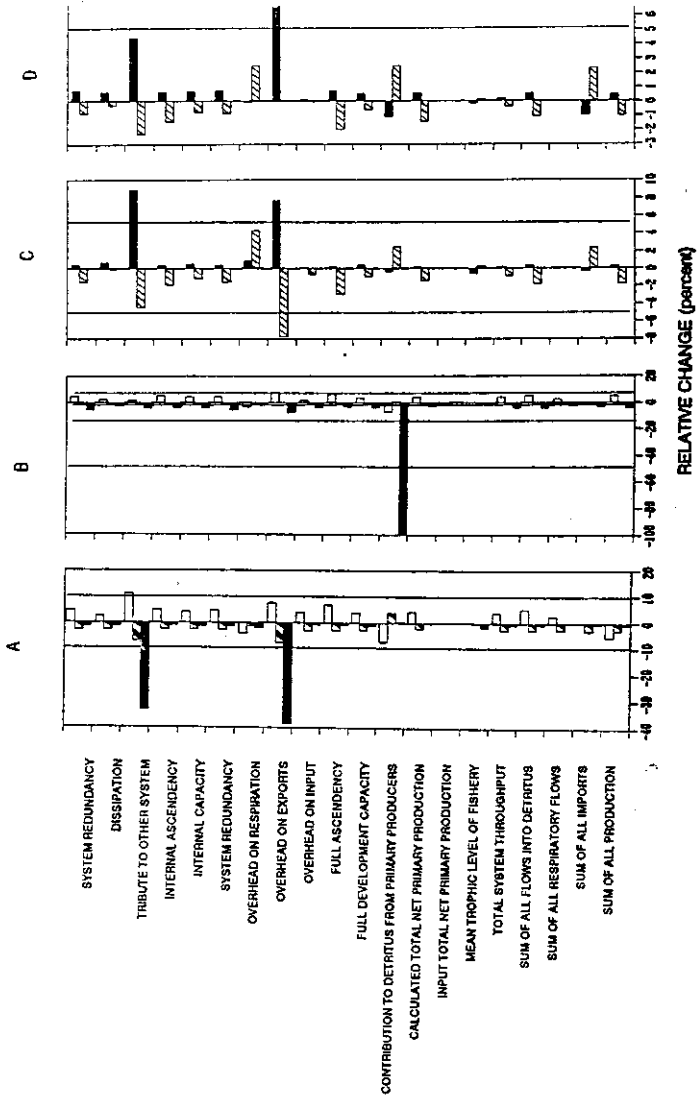
Figure 2. Community statistics of four species (a) *Orthopristis chrysoptera*, (B) *Harengula jaguana*, (C) *Opisthonema oglinum* and (D) *Lagodon rhomboides* expressed as specific anomaly (from equation 2). White bar, when species was totally removed; dashed bar, with 20% of biomass removed; dark bar, when 40% of biomass was removed.

Table 3. Ecosystem statistics of Celestum coast community obtained with ECOPATH II modified from base run with 20% less biomass and catch of these species. For key number see Table 2.

	BASE	OC	LR	OO	HJ	AR	CAT
1	7657	7443	7581	7518	7593	7657	7657
2	1604	1555	1641	1641	1574	1604	1604
3	4209	4103	4209	4209	4170	4209	4209
4	1757	1709	1739	1725	1743	1757	1757
5	15227	14810	15170	15094	15079	15227	15227
6	3.69	3.68	3.69	3.70	3.68	3.69	3.69
7	4107	4107	4107	4107	4107	4107	4107
8	2610	2552	2573	2573	2601	2610	2610
9	1497	1555	1534	1534	1506	1497	1497
10	44277	43126	44022	43876	43829	44273	44274
11	17542	17010	17204	17029	17326	17539	17541
12	1712	1663	1711	1701	1693	1712	1712
13	13	12	13	12	13	13	13
14	8632	8513	8850	9006	8548	8631	8631
15	16379	15928	16246	16127	16250	16378	16377
16	39069	38069	38757	38622	38698	39064	39066
17	9807	9568	9671	9626	9696	9806	9807
18	45	42	44	43	44	44	44
19	12838	12531	12796	12826	12709	12836	12837
20	16379	15928	16246	16127	16250	16378	16377

BASE	base running	HJ	*Harengula jaguana*
OC	*Orthopristis chrysoptera*	AR	*Archosargus rhomboidalis*
LR	*Lagodon rhomboides*	CAT	catfish
OO	*Opisthonema oglinum*		

removal caused a 9% decrement in the tribute to other systems. *Lagodon rhomboides* removals created an increase in the tribute to other systems (5%) and in overhead on exports (9%).

There were no important changes with the removal of *Archosargus rhomboidalis* and the catfishes *Cathorops spixii* and *Ariopsis felis.*

DISCUSSION

For all cases, the most important changes took place on the full development capacity through ascendency and system redundancy. Obviously, the total system throughput was also affected by the sum of all production. Another isolated, but important, change was the complete absence of the contribution to detritus from primary producers when *H. jaguana* was extirpated. These negative changes represent ecosystem losses in biomass/information/flowbits (Figure 2).

Since the development capacity measures the development potential of the

Table 4. Ecosystem statistics of Celestum coast community obtained with ECOPATH II modified from base run with 40% less biomass and catch of these species. For key number see Table 2.

	BASE	OC	LR	OO	HJ	AR	CAT
1	7657	7246	7620	7634	7244	7656	7657
2	1604	1608	1620	1609	1608	1605	1604
3	4209	4103	4209	4210	4102	4209	4209
4	1757	1664	1748	1751	1663	1757	1757
5	15227	14621	15197	15205	14617	15227	15227
6	3.6889	3.6722	3.6943	3.7108	3.6731	3.6996	3.688
7	4107	4107	4107	4107	4107	4107	4107
8	2610	2499	2594	2605	2499	2609	2610
9	1497	1608	1513	1502	1608	1498	1497
10	44277	42602	44036	44083	42535	44268	44271
11	17542	16371	17415	17503	16402	17535	17539
12	1712	1648	1710	1710	1677	1712	1712
13	13	12	12	12	12	13	13
14	8632	8985	8638	8557	8922	8633	8632
15	16379	15586	16260	16302	15551	16376	16376
16	39069	37482	38804	38869	37414	39059	39063
17	9807	9314	9745	9774	9296	9805	9806
18	45	40	43	41	44	44	44
19	12838	12542	12755	12752	12523	12834	12836
20	16379	15586	16260	16302	15551	16376	16376

BASE	base running	HJ	*Harengula jaguana*
OC	*Orthopristis chrysoptera*	AR	*Archosargus rhomboidalis*
LR	*Lagodon rhomboides*	CAT	catfish
OO	*Opisthonema oglinum*		

network, we assume that the lower negative values for ascendency and total system throughput suggest a decline in the size and organization of the ecosystem.

On the other hand, positive changes in the overhead on respiration suggest an increased loss of flowbits. Generally, when biomass of any species/group is reduced, the whole ecosystem responds to compensate for the loss. However, the opposite was true in all the cases tested here. That is, the loss of predatory species resulted in lower community complexity, diversity, and network efficiency which translated into the loss of energy/biomass available to the fishery.

Major changes were observed in the development capacity (Figure 1) as consequence of changes in the overhead on exports, and in the tribute to other systems (Figure 2). An important decline in the contribution to detritus from primary producers was observed only when *H. jaguana* was removed. These changes reflect the fact that development capacity represents the upper bound of

ascendency, assuming there were no overheads which can not be accounted for thermodynamic reasons (Ulanowicz, 1986).

When *O. chrysoptera* and *H. jaguana* were completely removed, positive changes took place in most of the ecosystem parameters, which could be interpreted as an increase in the network efficiency as a consequence of reduction in the flow diversity (*i.e.*, ecosystems simplification).

Overhead on respiration was the parameter most affected in the various scenarios. It represents the way in which the community, as a functional unit, adjusts itself to conserve energy flow stability in response to perturbations. According to Christensen and Pauly (1990) this parameter summarizes the input and output throughputs associated with a given box in the model. Thus, this process may reflect the way by which the community compensates for anomalies in total throughputs. Relative changes in respiration showed that the highest losses in respiration are directly related with trophic level; that is, the loss of energy increases with trophic level (Figure 3). Because ecosystem
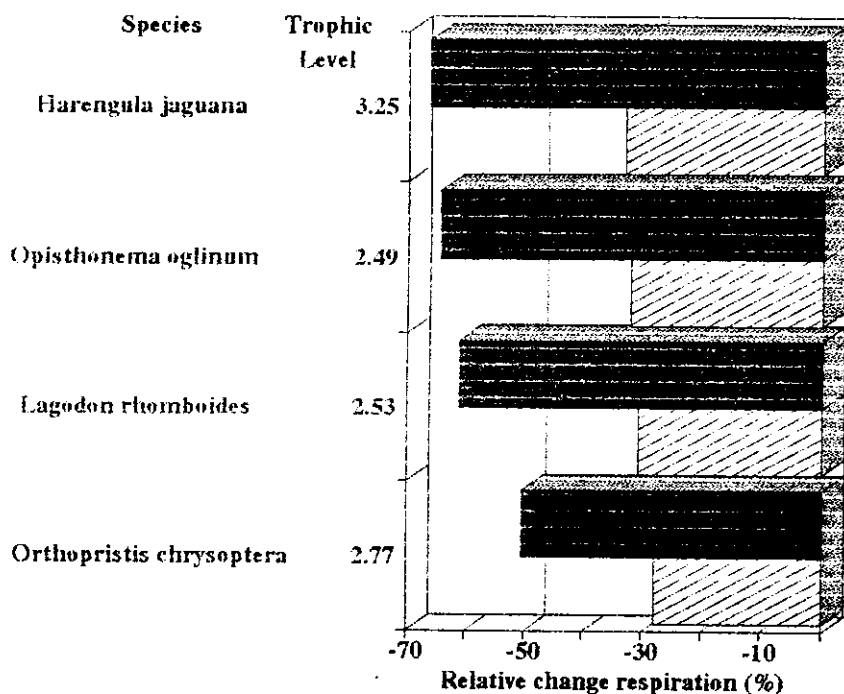
Figure 3. Relative changes in respiration for the main species off Celestún when 20% (dashed bar) and 40% (dark bar) of biomass was removed.

respiration represents unusable biomass/energy (*i.e.*, flow of mass/energy that is not directed toward, nor used by any other species/group), then increased respiration, in response to perturbation, will mean losses in ecosystem efficiency, and the availability of biomass for the fishery.

In the beach seine fishery where the most important species occupy upper trophic levels, increased fishing (*i.e.*, loss of predatory biomass) will reduce the efficiency, size, and organization of the community. These changes are due, in part, to the effects on respiration, represented by losses of biomass/energy of the top predators within the system.

Overhead respiration appears to be the best parameter to measure the impact of ecosystem stress. High impacts are associated with higher trophic levels, and in the beach seine fishery, the most important commercial species are in the upper levels of the trophic web.

ACKNOWLEDGMENTS

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APPENDIX 1

Definitions for some of the main concepts used in this contribution which describe community properties (following Ulanowicz, 1986; Field *et al.*, 1989; Kay *et al.*, 1989; Christensen and Pauly, 1990):

Total System Throughput (T): measures size or growth of the system in terms of flows through all its compartments. The term throughput represents flow of energy/matter among boxes.

Ascendency: represent both, size and organization of the flows (= product of T and diversity of flows in a system). Is a quantitative tool in diagnosing ecosystem change at the level of the whole system.

Flow diversity: measures how many interactions there are in an ecosystem. It is formulated from both, the number and evenness of flows. Measures the diversity with which components of the system are used as food resources by other living components.

Development capacity: measures the potential of a particular network to develop, given its particular set of connection and total throughput.

Trophic efficiency of a food web can be calculated from Linderman spine by comparing the inflow to a trophic category with its outflow to the next category.

Tribute to other systems: The sum of the contribution to exports from overheads and ascendency.

Overhead on exports: The loss of flowbits due to the fact that the export flows out of an ecosystem does not provide information on the boxes to

which the flow are going.

Respiration: A flow (or flows) of mass or energy that is (are) not directed toward, nor could be used by any other box(es) (Unusable mass/energy).

Exports: A flow (or flows) of usable mass/energy that is not directed toward any of the boxes explicitly included in an ecosystem model (Usable mass/energy).

System overhead: The difference between development capacity and ascendency. It is the sum of four components: overhead on inputs, on exports, on respiration, and the overhead on redundancy or System redundancy.

Overhead on respiration: the loss of flowbits due to the fact that respiratory flows do not connect boxes, and hence, do not involve any mutual information between boxes (it increases with respiration and must always be $>>0$).

Internal development capacity: Is the development capacity computed without considering external inputs.

Internal ascendency: Same as ascendency but computed without considering the contribution to ascendency of the flows related to inputs, exports and respiration.

Dissipation: The contribution of respiration to the overhead of a system and its ascendency.

Ascendency/Development capacity: A measure of ecosystem network efficiency.