

## **Annex III**

Annex III contains five Tables, one text Section and one Figure, in the order that they are referred to in the body of the thesis, followed by the references. The Tables describe the analyzed ecosystems or report numerical results; the text Section describes the indicators that were compared to the *SDB* exponent; the Figure shows two additional examples of the consumption-biomass scaling.

Table A3.1. List of the 56 trophic flow network models analyzed on Chapter 7.

Ecosystem Number and Name	Model ref.	Period	Latitude	Surface (km <sup>2</sup> )	Depth (m)	Water temperature (°C)	Salinity	Total PP (t km <sup>-2</sup> y <sup>-1</sup> )	Total biomass (t km <sup>-2</sup> )
Oceanic ecosystems									
1 Newfoundland	Heymans, 2003	1995-1997	43°N-55°N	495000 (Heymans and Pitcher, 2002)	0-1000 (Heymans and Pitcher, 2002)	5.9 (POET, 2010) {1995-1997}	saline water	4458.28	329.74
2 Western Bering Sea	Aydın et al., 2002	1981-1990	56°N-65°N	254200	about 0-200	3.7 (POET, 2010) {1985-1990}	saline water	3510.00	568.54
3 Barents Sea	Blanchard et al., 2002	1990	68°N-85°N	1400000	from 0 to > 2300	4.6	saline water	1100.04	118.80
4 Barents Sea	Blanchard et al., 2002	1995	68°N-85°N	1400000	from 0 to > 2300	4.6	saline water	1100.04	118.95
Continental shelves									
5 West Florida Shelf	Okey et al., 2004	1990's (Okey and Mahmoudi, 2002)	24°N-30°N (Okey and Mahmoudi, 2002)	170000	0-200	22.2 (Okey and Mahmoudi, 2002)	saline water	6986.95	717.61
6 Northern British Columbia	Ainsworth et al., 2002	2000	50°N-55°N (Ainsworth, 2006)	70000	10-4032 (more than 2/3 of the area > 200; Ainsworth, 2006)	9.4 (POET, 2010) {2000}	saline water	2777.75	131.68
7 West Coast of Sarawak	Garces et al., 2003	1972	1°N-7°N	76668	10-60	29.4 (POET, 2010) {1985-1990}	saline water	3592.05	71.25
8 Gulf of Nicoya	Wolff, 2006	1993-1994	9°N-10°N	1530	0-200	28.7 (POET, 2010) {1993-1994}	saline and brackish water	1162.00	132.12
9 Southern Gulf California	Salcido-Guevara, 2006	1994-1997	22°N-24°N	6250	20-140	27.1 (POET, 2010) {1994-1997}	saline water	3492.95	343.52
10 Central Gulf of California	Arreguin-Sánchez et al., 2002	1978-1979	25°N-29°N	27900	5-65	21.1 (Luch-Cota et al., 2000) {1982-1992}	saline water	1735.60	68.80
11 Campeche Sound	Zetina-Rejón and Arreguin-Sánchez, 2002	1988-1994	18°N-20°N	65000	0-200	26.0 (M. J. Zetina-Rejón, personal communication)	saline water	4668.70	104.31
12 East China	Jiang et al., 2008	1997-2000	23°N-33°N	770000	370 on average	22.4 (POET, 2010) {1997-2000}	saline water	2183.24	50.24
13 North Sea	MacIntosh, 2001	1880's	51°N-62°N	570000	about 90 on average (maximum 400)	10.0	saline water	3593.75	285.39

Ecosystem Number and Name	Model ref.	Period	Latitude	Surface (km <sup>2</sup> )	Depth (m)	Water temperature (°C)	Salinity	Total PP (t km <sup>-2</sup> y <sup>-1</sup> )	Total biomass (t km <sup>-2</sup> )
14 North Sea	Mackinson and Daskalov, 2007	1973	51°N-62°N	570000	about 90 on average (maximum 400)	10.0	saline water	2150.00	562.88
15 North Sea	Mackinson and Daskalov, 2007	1991	51°N-62°N	570000	about 90 on average (maximum 400)	10.0	saline water	2150.00	553.16
16 South Brazil Bight	Gasalla, in prep.	1977	23°S-28°S	59000	20-100	23.3 (POET, 2010) {1985-1990}	saline water	2907.49	111.53
17 South Brazil Bight	Gasalla and Spinkosky, in prep.	2001	23°S-28°S	59000	20-100	24.1 (POET, 2010) {2001}	saline water	3584.60	110.57
18 Northern Adriatic Sea, aggregated version	Barausse et al., 2007	1996-1998	43°N-45°N	32000	29 on average	14.5	saline water	2224.91	160.62
19 Northern Adriatic Sea, disaggregated and modified version	Barausse et al., 2009	1996-1998	43°N-45°N	32000	29 on average	14.5	saline water	2382.18	163.88
20 Northern Gulf of California	Morales-Zárate et al., 2004; Lercari, 2006	1990's	29°N-32°N	36000	200 on average	20.7 (Luch-Cota et al., 2000) {1982-2000}	saline water	7484.02	165.47
Upwelling ecosystems									
21 Central Chile	Neira et al., 2004	1992	33°S-39°S	50042	about 0-4000	15.0 (POET, 2010) {1992}	saline water	13412.29	281.64
22 Southern Benguela	Watermeyer et al., 2008a	1600	26°S-35°S	220000	0-500	18.1 (POET, 2010) {1985-1990}	saline water	11974.94	234.14
23 Southern Benguela	Watermeyer et al., 2008a	1900	26°S-35°S	220000	0-500	18.1 (POET, 2010) {1985-1990}	saline water	11962.17	219.59
24 Southern Benguela	Watermeyer et al., 2008a	1960	26°S-35°S	220000	0-500	18.1 (POET, 2010) {1985-1990}	saline water	11951.19	191.14
25 Southern Benguela	Shannon et al., 2003	1980's	29°S-35°S	220000	0-500	18.4 (POET, 2010) {1985-1989}	saline water	11879.23	197.62
26 Southern Benguela	Shannon et al., 2003	1990's	29°S-35°S	220000	0-500	18.4 (POET, 2010) {1990-1999}	saline water	11879.23	203.19
27 Southern Benguela	Watermeyer et al., 2008a	2000-2003	26°S-35°S	220000	0-500	18.3 (POET, 2010) {2000-2003}	saline water	10611.26	273.49
28 Northern Benguela	Watermeyer et al., 2008b	1600	15°S-29°S	179000	0-500	17.0 (POET, 2010) {1985-1990}	saline water	7397.04	532.26
29 Northern Benguela	Watermeyer et al., 2008b	1900	15°S-29°S	179000	0-500	17.0 (POET, 2010) {1985-1990}	saline water	7397.04	484.75

Ecosystem Number and Name	Model ref.	Period	Latitude	Surface (km <sup>2</sup> )	Depth (m)	Water temperature (°C)	Salinity	Total PP (t km <sup>-2</sup> y <sup>-1</sup> )	Total biomass (t km <sup>-2</sup> )
30 Northern Benguela	Heymans and Sumaila, 2007	1956	15°S-29°S	179000	0-500	17.0 (POET, 2010) {1985-1990}	saline water	21624.07	583.45
31 Northern Benguela	Watermeyer et al., 2008b	1967	15°S-29°S	179000	0-500	17.0 (POET, 2010) {1985-1990}	saline water	7650.01	500.59
32 Northern Benguela	Roux and Shannon, 2004; Watermeyer et al., 2008b	1995-1999	15°S-29°S	179000	0-500	17.5 (POET, 2010) {1995-1999}	saline water	7270.81	621.13
33 Gulf of Ulloa	Del Monte-Luna et al., 2007	1980's-1990's	25°N-26°N	10000	about 0-1400	21.5 (POET, 2010) {1985-1999}	saline water	68089.42	4114.10
34 Senegambian continental shelf	Samb, 2007	2000-2004	12°N-16°N	27600	0-200	24.6 (POET, 2010) {2000-2004}	saline water	11490.93	275.78
Mangrove ecosystems									
35 Caeté mangrove estuary	Wolff et al., 2000	N/A	1°S	220	0-10	26.1 (annual mean daily air temperature)	saline and brackish water	3134.00	13135.15
36 Celestun lagoon	Vega-Cendejas, 2003	N/A	20°N	28	0.5 on average	24.2 (Luch-Cota et al., 2000) {1982-2000}	brackish water	1.60	1.25
Coral reefs									
37 Moorea Barrier Reef	Arias-González et al., 1997	1971-1989	17°S	0.86	<2.5	27.6 (POET, 2010) {1985-1989}	saline water	19787.12	2421.10
38 Moorea Fringing Reef	Arias-González et al., 1997	1971-1989	17°S	0.44	0.15-1.5	27.6 (POET, 2010) {1985-1989}	saline water	17788.10	2359.07
39 Great Barrier Reef	Gribble, 2001	1993-1994	11°S-12°S	10000	N/A	26.6 (POET, 2010) {1993-1994}	saline water	2846.24	263.30
Rivers									
40 Upper Parana River Floodplain	Angelici and Agostinho, 2005	1992-1995	22°S-26°S	N/A	N/A	N/A	freshwater	513.84	49.67
41 Rivers Inlet	Watkinson and Pauly, 1999	1991-1995	51°N	1000	0-325	10.2 (POET, 2010) {1991-1995}	saline and brackish water, freshwater	31009.20	312.25
42 Garonne Lakes	Palomares et al., 1993b	1990-1991	43°N	0.005	1.7 on average	12.2	freshwater	2115.66	46.72

Ecosystem Number and Name	Model ref.	Period	Latitude	Surface (km <sup>2</sup> )	Depth (m)	Water temperature (°C)	Salinity	Total PP (t km <sup>-2</sup> y <sup>-1</sup> )	Total biomass (t km <sup>-2</sup> )
43 Lake Victoria	Moreau et al., 1993	1971-1972	0°S-1°S	4200	about 0-60 (International Lake Environment Committee, 2009)	about 23°C-26°C (International Lake Environment Committee, 2009)	freshwater	1902.01	85.94
44 Lake Parakrama Samudra	Moreau et al., 2001	1970's	8°N	25	5 on average	N/A	freshwater	9670.34	271.77
45 Laguna de Bay	Delos Reyes, 1995	1820	14°N	911 (Delos Reyes, 1993)	2.8 (Delos Reyes, 1993)	27.9 (International Lake Environment Committee, 2009) {1976}	freshwater (saline water intrusion)	24425.17	269.55
46 Laguna de Bay	Delos Reyes, 1995	1920	14°N	911 (Delos Reyes, 1993)	2.8 (Delos Reyes, 1993)	27.9 (International Lake Environment Committee, 2009) {1976}	freshwater (saline water intrusion)	24425.17	264.46
47 Laguna de Bay	Delos Reyes, 1995	1950	14°N	911 (Delos Reyes, 1993)	2.8 (Delos Reyes, 1993)	27.9 (International Lake Environment Committee, 2009) {1976}	freshwater (saline water intrusion)	22211.20	210.34
48 Laguna de Bay	Delos Reyes, 1995	1968	14°N	911 (Delos Reyes, 1993)	2.8 (Delos Reyes, 1993)	27.9 (International Lake Environment Committee, 2009) {1976}	freshwater (saline water intrusion)	22194.70	190.84
49 Laguna de Bay	Delos Reyes, 1995	1980	14°N	911 (Delos Reyes, 1993)	2.8 (Delos Reyes, 1993)	27.9 (International Lake Environment Committee, 2009) {1976}	freshwater (saline water intrusion)	8950.30	133.47
50 Laguna de Bay	Delos Reyes, 1995	1990	14°N	911 (Delos Reyes, 1993)	2.8 (Delos Reyes, 1993)	27.9 (International Lake Environment Committee, 2009) {1976}	freshwater (saline water intrusion)	9862.79	124.94
51 Lake Ontario	Halfon and Schito, 1993; Incofish project WP4, 2009	1971-1991	43°N-44°N	19500	86.0 on average	9.1 (International Lake Environment Committee, 2009) {1904-1968}	freshwater	11012.05	66.60
52 Lake Chad	Palomares et al., 1993a	1970-1972	12°N-14°N	25000	4.0 on average	27.5 (International Lake Environment Committee, 2009) {1956-1960}	freshwater	2821.25	2062.50
Bays									
53 Kuosheng Bay	Hsing-Juh et al., 2004	1998-2001	25°N	8	15 on average	27.0 (POET, 2010) {1998-2001}	saline water	6709.64	167.48

Ecosystem Number and Name	Model ref.	Period	Latitude	Surface (km <sup>2</sup> )	Depth (m)	Water temperature (°C)	Salinity	Total PP (t km <sup>-2</sup> y <sup>-1</sup> )	Total biomass (t km <sup>-2</sup> )
54 San Miguel Bay	Bundy and Pauly, 2001	1992-1994	13°N-14°N	1115	about 0-18	28.2 (POET, 2010) {1992-1994}	saline and brackish water	2565.00	31.75
Other ecosystems									
Coupled model: Alvarado lagoon, Veracruz - adjacent continental shelf									
55	Cruz-Escalona, 2005	1991-1996	18°N-19°N	62 (lagoon); 1000 (shelf)	0-13.5 (lagoon); about 0-50 (shelf)	26.0	saline and brackish water	3430.60	183.37
Coupled model: Campeche Sound - Terminos Lagoon									
56	Zeina-Rejón et al., in prep.	1988-1994	18°N-20°N	2500 (lagoon); 65000 (shelf)	3.5 on average (lagoon); 0-200 (shelf)	24.1 (Luch-Cota et al., 2000) {1988-1994}	saline and brackish water	5397.85	220.35

For each ecosystem, the table reports: the reference(s) for the network model; the period which the network model is referred to; the latitude, surface and depth of the area covered by the model; some hydrographic (mean annual or inter-annual water temperature, salinity) and biological (total primary production and total living biomass) characteristics of the area. Unless otherwise specified, the above information was obtained or extrapolated from the reference of the network model; the total primary production (PP) and total living biomass (i.e. excluding detritus biomass) were taken from the network models. {} indicates the period over which database information was averaged. N/A indicates that data were not available.

Table A3.2. Results from the statistical analyses of the consumption-biomass scaling in carbon- and energy-based trophic flow networks, yearly or seasonal, built with different software.

Ecosystem	Software	Time-scale and currency	$SDB$	$\log_{10} \rho$	$\rho$	p-value	$\tau$	p-value	$N$	$SDB_+$	$SDB$	$\log_{10}(Q_{MAX}/Q_{MIN})$	$\log_{10}(B_{MAX}/B_{MIN})$
1. Cypress wetland, dry (Ulanowicz et al., 1997; Bondavalli and Ulanowicz, 1999; Bondavalli et al., 2000; Heymans et al., 2002)	NETWRK	seasonal, carbon	0.770	0.989	0.956	7.4E-28	0.793	2.3E-16	51	0.845	0.670	6.98	8.01
2. Cypress wetland, wet (Ulanowicz et al., 1997; Bondavalli and Ulanowicz, 1999; Bondavalli et al., 2000; Heymans et al., 2002)	NETWRK	seasonal, carbon	0.777	0.929	0.945	2.1E-25	0.780	6.8E-16	51	0.856	0.705	7.38	8.97
3. Florida bay, dry (Ulanowicz et al., 1998)	NETWRK	seasonal, carbon	0.977	1.021	0.851	2.1E-31	0.770	3.3E-32	108	1.036	0.871	7.08	8.51
4. Florida bay, wet (Ulanowicz et al., 1998)	NETWRK	seasonal, carbon	0.938	0.874	0.854	6.8E-32	0.767	5.6E-32	108	1.014	0.847	7.27	8.48
5. Mangroves, dry (Ulanowicz et al., 1999)	NETWRK	seasonal, carbon	0.855	1.074	0.888	4.2E-30	0.718	1.3E-22	86	0.986	0.757	8.09	7.50
6. Mangroves, wet (Ulanowicz et al., 1999)	NETWRK	seasonal, carbon	0.851	0.978	0.895	3.5E-31	0.751	1.4E-24	86	0.980	0.775	8.23	7.64
7. Graminoids, dry (Heymans et al., 2002; Ulanowicz et al., 2000)	NETWRK	seasonal, carbon	0.848	0.670	0.941	1.2E-27	0.763	5.4E-17	57	0.976	0.771	5.74	6.31
8. Graminoids, wet (Heymans et al., 2002; Ulanowicz et al., 2000)	NETWRK	seasonal, carbon	0.858	0.446	0.964	2.6E-33	0.789	4.4E-18	57	0.953	0.801	8.26	8.93
9. Venice lagoon, Palude della Rosa (Carter and Opitz, 1999)	Ecopath	seasonal, energy	1.011	0.751	0.901	2.6E-05	0.701	0.0012	13	1.355	0.519	4.76	4.11
10. Venice lagoon (Pranovi et al., 2003)	Ecopath	annual, energy	1.087	1.080	0.952	1.0E-10	0.759	3.9E-06	20	1.224	0.952	6.72	5.80

For each ecosystem, the table reports the software used to build the network model (NETWRK (Ulanowicz, 2004) or Ecopath (Christensen et al., 2005)); the time-scale covered by the model (i.e. the described period); the currency; the scaling exponent estimated with the Kendall-Theil robust method ( $SDB$ ); its 95% confidence intervals ( $SDB_+$ ,  $SDB$ ); the logarithm of the power law proportionality coefficient ( $\log_{10} \rho$ , i.e. the intercept of the log-log fitting line); Pearson's correlation coefficient  $\rho$  and Kendall's  $\tau$  rank correlation coefficient, with the corresponding p-values from a two-tailed test; the number  $N$  of consumer compartments in the flow network (i.e.

excluding detritus and primary producer compartments); the orders of magnitude spanned by the scaling relationship on the axes, expressed as  $\log_{10}(Q_{MAX}/Q_{MIN})$  and  $\log_{10}(B_{MAX}/B_{MIN})$ , where  $Q_{MAX}$  and  $B_{MAX}$  represent the highest consumption and biomass among the compartments of the network, and  $Q_{MIN}$  and  $B_{MIN}$  represent the lowest consumption and biomass. For NETWRK models, data were taken from <http://www.cbl.umces.edu/~atiss/>. “Wet” and “dry”, as reported in the name of some ecosystems, refer to the season.



### Section A3.3. Description of food web indicators and ecosystems attributes.

The food web indicators and ecosystem attributes that were correlated with the *SDB* exponent, as reported in the Table 12 of Chapter 7 and in Table A3.6, are described here. Ecopath software (Christensen et al., 2005) version 5.1 was used to calculate indicators and ecosystem attributes for all the models, including those models originally built with older Ecopath versions. This choice was made to ensure the consistency of the analyzed data, since in some cases the algorithms used by Ecopath to calculate indicators or to solve the mass-balance equations have changed during the development of the software (e.g. when a bug was reported). In few cases, models originally built with older Ecopath versions and imported in Ecopath version 5.1 displayed different outputs when compared to the outputs of the older Ecopath versions. For example, balancing was no more achieved, or the balancing yielded different estimates of unknown input parameters (Christensen et al., 2005), possibly because of numerical issues, such as differences in rounding methods or significant digits between the Ecopath versions, as also suggested by the following considerations. Before the analyses, when necessary to achieve balancing and to be consistent with the original models, such differences were eliminated by doing minor modifications to input data (e.g. slight changes to diet matrices): such modifications did not sensibly affect the estimates of other food web indicators, ecosystem attributes, compartment biomasses and compartment flows. When they did, in the case of few models, those models were excluded from the present analysis.

For each trophic flow network model, the following indices, whose unit is reported in parentheses (in all cases, tonnes represent wet weight), were collected. The total living biomass ( $\text{t km}^{-2}$ ) is the sum of the biomasses of all the network compartments but the detritus ones. Detritus biomasses are generally not reliably estimated or so high that they could overshadow the sum of the biomasses of the living compartments. Absolute flows ( $\text{t km}^{-2} \text{ y}^{-1}$ ) include the total primary production in the network, the sum of all consumption flows, of all export flows, of all respiration flows, of all production, of all fishery catches (for models including the exploitation of marine resources as a flow directed outside the ecosystem). The sum of all the flows in the network, termed total system throughput, is a measure of the total system activity and energetic size, i.e. in terms of flows (Ulanowicz, 1986; Christensen et al., 2005). The net system production is the difference between total primary production and total respiration flows, and should approach zero as ecosystems mature and the energy fixed by primary producers is counterbalanced by ecosystem respiration (Odum, 1969; Odum, 1983; Christensen et al., 2005).

The cycled throughput represents the flows cycling in the food web, i.e. passing more than once through the same compartment, and the cycled throughput to total system throughput ratio is called the Finn's cycling index (dimensionless; Finn, 1980; Latham II, 2006), which represents the fraction of

the network flows that are recycled and should increase as ecosystems mature and their dependency on external resources decrease (Odum, 1969; Finn, 1980; Odum, 1983; Ulanowicz, 1986; Ulanowicz, 2004; Christensen et al., 2005; Latham II, 2006).

Other collected flow-flow and flow-biomass ratios include the total primary production to total living biomass ratio ( $y^{-1}$ ) and the total respiration to total living biomass ratio ( $y^{-1}$ ), known as the Schrödinger ratio, which are expected to decline as biomass accumulate in later succession stages (Odum, 1969; Odum, 1983; Christensen et al., 2005); the total primary production to total respiration ratio (dimensionless), expected to be higher than 1 (or lower than 1, in case of organic pollution) in developmental communities, and to approach 1 as the energy inputs are balanced by the maintenance costs of accumulated biomass (i.e. respiration) in more mature ecosystems (Odum, 1969; Odum, 1983; Christensen et al., 2005); the total living biomass to total system throughput ratio ( $y$ ) represents the living biomass sustained by a unit of energy flow (here, per unit of biomass flow) in the ecosystem, and should reach a maximum in mature ecosystems reflecting the accumulation of organic matter, the shift from smaller, r-selected organisms to bigger, K-selected organisms with lower metabolism per unit body mass and the increased efficiency and organization of energy transfers in the food web (Odum, 1969; Odum, 1983; Peters, 1983; Schmidt-Nielsen, 1984; Christensen, 1995; Brown et al., 2004; Christensen et al., 2005); the gross efficiency of fishery, i.e. the ratio of fishery catches to total primary production (dimensionless), which was analyzed in order to describe the exploitation in the ecosystem, taking higher values when lower (more abundant) trophic levels are exploited, and lower values if stocks are underexploited or fishing is targeting higher trophic levels (Christensen et al., 2005).

The Connectance index (dimensionless) is defined in Ecopath as the ratio of the number of existing trophic links to the number of possible links in the food web (Christensen et al., 2005). Feeding on detritus by detritivores is included in the count while the opposite links, representing flows to detritus from living compartments, are disregarded (Christensen et al., 2005). This index should measure the complexity of the food web structure, but it is strongly dependent on the number of compartments and hence on the degree of aggregation of the trophic flow network model (Christensen et al., 2005), and does not take into account the relative magnitude of the connections, i.e. of the flows (Christensen et al., 2005). Consequently the Connectance index is not as fit for the comparison of different food web models as the System Omnivory Index (dimensionless), which is defined as the average Omnivory Index of the consumer compartments in the network, weighted by the logarithm of their consumption, where the Omnivory Index of a consumer compartment is defined as the variance of the trophic level of its preys (Christensen et al., 2005). A high System Omnivory Index indicates a web-like network, hence this index is expected to increase as trophic interactions change from linear (because of low diversity) to web-like (e.g. more feedbacks and cycling), during the successional stages of an ecosystem (Odum, 1969; Odum, 1983; Christensen et al., 2005). Finn's mean path length is the

number of compartments that a unit of inflow passes through on the average before leaving the network, and it can be calculated as the ratio of total system throughput to the sum of export and respiration flows (Finn, 1980; Christensen et al., 2005; Latham II, 2006). Finn's mean path length is expected to be higher in mature ecosystems, mirroring the increased diversity of flows, cycling and complexity in the food web (Odum, 1969; Odum, 1983; Christensen et al., 2005). Finn's straight-through path length has a meaning closely related to Finn's mean path length, as it represents the number of compartments that a unit of inflow passes through on the average before leaving the network, but without considering cycles, i.e. it is the ratio of the total system throughput passing straight through the system (i.e. total system throughput subtracted the cycled throughput) to the sum of export and respiration flows (Finn, 1980; Christensen, 1995).

Finally, indices based on information theory were collected, namely Ulanowicz's indices, based on the notions of ascendancy, development capacity and overhead (Ulanowicz, 1986; Ulanowicz and Norden, 1990; Ulanowicz, 1997; Ulanowicz, 2004; Christensen et al., 2005; Latham II, 2006), which now are briefly explained.

Ascendancy is the product of the average mutual information of the flow network and its total system throughput, thus it is meant to provide a measure for both the development (i.e. organization) and growth (i.e. activity) of the ecosystem (Ulanowicz, 1986; Ulanowicz and Norden, 1990; Ulanowicz, 1997; Ulanowicz, 2004; Christensen et al., 2005; Latham II, 2006).

Development capacity (Ulanowicz, 1986; Ulanowicz and Norden, 1990; Ulanowicz, 1997; Ulanowicz, 2004; Christensen et al., 2005; Latham II, 2006) represents the mathematical upper bound of ascendancy and is the product of the diversity (Ulanowicz, 2004; or, statistical uncertainty; Latham II, 2006) of the flows in the network and the total system throughput.

Overhead (Ulanowicz, 1986; Ulanowicz and Norden, 1990; Ulanowicz, 1997; Ulanowicz, 2004; Christensen et al., 2005; Latham II, 2006) represents the difference of development capacity and ascendancy and is the product of the residual diversity (Ulanowicz, 2004; or, conditional uncertainty; Latham II, 2006) of the flows and the total system throughput. Overhead is meant to gauge the disorder and freedom of the network flows, i.e. the unrealized development potential of the system and its capability to adapt to perturbations. Thus, as an ecosystem matures, a trade-off arises between its "propensity" to move towards an efficient and resistant network configuration with few dominant flows (high ascendancy) and the vulnerability to disturbances resulting from such "brittle" configuration (development capacity subtracted a high ascendancy means a low overhead; Ulanowicz, 1986; Ulanowicz, 1997; Ulanowicz, 2004; Christensen et al., 2005).

Each of these three indices is measured in flowbits, i.e.  $t \text{ bits km}^{-2} \text{ y}^{-1}$ , and can be split into four additive contributions due to internal flows (i.e. the trophic exchanges among the network compartments), dissipation (i.e. respiration flows), imports into and exports from the system

(Ulanowicz, 1986; Ulanowicz and Norden, 1990; Ulanowicz, 1997; Ulanowicz, 2004; Christensen et al., 2005; Latham II, 2006). The values of the above indices are largely determined by the magnitude of the flows in the network: for example, in the case of ascendancy, the total system throughput can vary much more than the average mutual information (Fath et al., 2001). Thus, in order to avoid biases due to different network sizes in term of flows when comparing different ecosystems, it was chosen to analyze the following rescaled, dimensionless indices (also their non-rescaled counterparts were analyzed, but only to highlight the higher usefulness of rescaled indices, see Table 12 on Chapter 7 and Table A3.6).

The ascendancy-development capacity ratio is the fraction of the potential system organization that is realized, and it is a useful index for comparing ecosystems since it is not influenced by the total system throughput, which disappears after the division being a scale factor in both terms (Baird et al., 1991; Ulanowicz, 1997; Ulanowicz, 2004; Latham II, 2006). The internal ascendancy-internal capacity ratio (the two terms are, respectively, the contribution to ascendancy and to development capacity from internal flows) is the fraction of the potential internal organization of the system that is realized, and has been proposed as a measure of the maturity, efficiency and resistance (as opposed to resilience) of the system (Baird et al., 1991; Ulanowicz and Norden, 1990; Ulanowicz, 1997; Ulanowicz, 2004; Latham II, 2006). The internal overhead-development capacity ratio (where the former term is the contribution to overhead from internal flows and is also called redundancy since it is related to the number of parallel trophic connections within the network) has been proposed as a measure of the resilience of the system and of its capability to adapt to disturbances (Baird et al., 1991; Ulanowicz and Norden, 1990; Ulanowicz, 1997; Ulanowicz, 2004; Latham II, 2006).

In order to include also a rescaled measure of capacity, the internal capacity-development capacity ratio was analyzed. Since the former term is the sum of internal overhead and internal ascendancy (Ulanowicz and Norden, 1990), this ratio (which to my knowledge has not been analyzed elsewhere) may reflect to some degree both the efficiency and resilience of the network of trophic exchanges within the ecosystem, hence the ecosystem “health” and “integrity” or, better, optimal status (Baird et al., 1991; Ulanowicz, 1997; Ulanowicz, 2004), as long as internal overhead is not much higher than internal ascendancy, and vice versa. However, a high value of the internal capacity-development capacity ratio indicates that the magnitude of the trophic flows exchanged among the network compartments (i.e. within the system) dominates the total system throughput, i.e. internal flows are much higher than the input flows entering the system and the output flows leaving it. Indeed, such a system must be weakly dependent on exogenous inputs and consequently resources must be internalized and intensely cycled, leading to a high Finn’s cycling index and to an internal overhead much higher than the internal ascendancy (since internal overhead is positively related to cycling, see Christensen (1995) and the correlation of the internal overhead-development capacity ratio with Finn’s

cycling index for the 56 networks here, yielding Spearman  $r_s = 0.83$ ,  $p < 0.0001$ ,  $n = 56$ ). Such interpretation was confirmed by the positive correlation that was identified between the internal capacity-development capacity ratio and Finn's cycling index ( $r_s = 0.91$ ,  $p < 0.0001$ ,  $n = 56$ ), and by the fact that the positive correlation of the internal capacity-development capacity ratio with the internal overhead-development capacity ratio ( $r_s = 0.86$ ,  $p < 0.0001$ ,  $n = 56$ ) was stronger than its correlation with the internal ascendancy-development capacity ratio ( $r_s = -0.10$ ,  $p = 0.48$ ,  $n = 56$ ). Following its positive relationship with cycling, it was assumed that the internal capacity-development capacity ratio will be higher in later succession stages, in agreement with the above interpretation of the Finn's cycling index (Odum, 1969; Odum, 1983; Christensen et al., 2005).

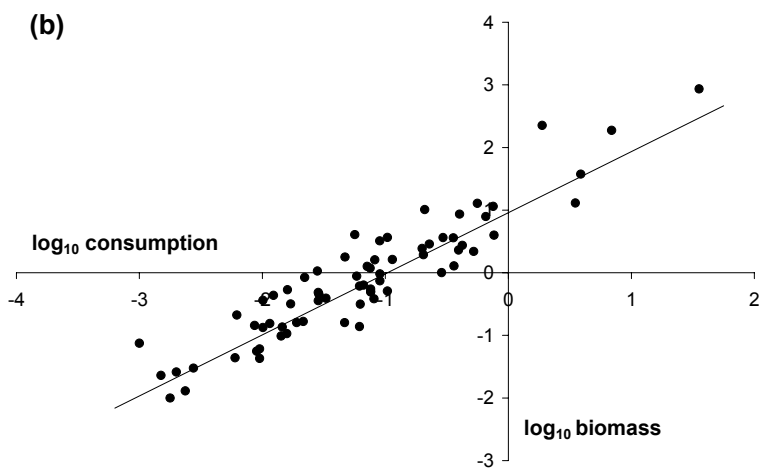
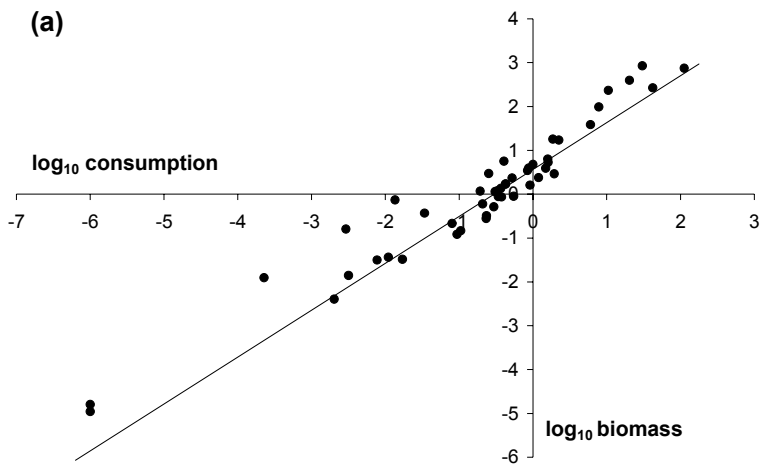


Figure A3.4. Further examples of the consumption-biomass scaling relationship. The line represents the power law fitted (a) to the 48 consumer compartments of the food web model of the Newfoundland marine ecosystem ( $\log_{10}Q_{in} = 1.07 \cdot \log_{10}B + 0.56$ ,  $Q_{in}$  is consumption,  $B$  is biomass;  $R^2 = 0.93$ ; Heymans, 2003), and (b) to the 71 consumer compartments of the food web model of the Campeche Sound and Terminos Lagoon, Mexico ( $\log_{10}Q_{in} = 0.98 \cdot \log_{10}B + 0.96$ ;  $R^2 = 0.86$ ; Zetina-Rejón et al., in preparation). Full circles represent compartments.

Table A3.5. Results from the statistical analyses of the consumption-biomass scaling in the 56 trophic flow networks.

Ecosystem number	$SDB$	$\log_{10}a$	$\rho$	p-value	$\tau$	p-value	$N$	$N_{SD}$	$N_{SKEW}$	$SDB+$	$SDB$	$\log_{10}(Q_{MAX}/Q_{MIN})$	$\log_{10}(B_{MAX}/B_{MIN})$
1	1.069	0.563	0.962	1.2E-27	0.833	7.6E-17	48	8	3	1.186	0.950	7.89	8.05
2	0.984	0.671	0.959	5.7E-18	0.786	2.0E-13	32	1	2	1.099	0.877	4.21	4.10
3	1.151	0.577	0.875	2.8E-12	0.713	1.0E-09	36	3	0	1.328	0.975	4.05	3.42
4	1.129	0.624	0.862	1.4E-11	0.715	9.5E-10	36	6	0	1.320	0.907	3.87	3.42
5	1.091	1.406	0.948	5.5E-26	0.833	6.8E-18	51	9	0	1.192	0.991	5.73	5.44
6	1.024	0.512	0.873	5.7E-16	0.692	4.4E-12	48	7	2	1.239	0.799	4.71	5.54
7	1.119	1.081	0.896	5.9E-10	0.769	4.5E-08	26	6	0	1.322	0.999	4.29	3.28
8	1.458	1.179	0.834	3.2E-05	0.687	1.7E-04	17	3	0	1.901	1.000	3.40	2.38
9	1.096	0.954	0.843	4.1E-10	0.708	5.1E-11	34	2	2	1.378	0.810	3.08	3.08
10	1.032	0.857	0.883	1.1E-08	0.775	1.5E-09	24	7	0	1.413	0.828	4.08	3.19
11	1.135	0.957	0.908	5.1E-09	0.839	6.0E-08	22	5	0	1.364	0.850	3.99	4.51
12	1.101	1.153	0.953	2.1E-22	0.844	-2.4E-16	42	3	4	1.221	0.976	5.99	4.52
13	1.175	0.691	0.932	9.0E-19	0.833	2.0E-14	41	10	0	1.301	0.999	5.48	4.53
14	1.055	0.671	0.939	1.3E-29	0.831	1.7E-21	62	11	0	1.139	0.989	5.31	5.18
15	1.045	0.620	0.937	4.1E-29	0.809	1.9E-20	62	11	0	1.129	0.976	5.31	5.18
16	1.000	0.830	0.910	3.2E-12	0.769	2.8E-09	30	4	0	1.217	0.797	4.55	4.57
17	0.863	0.687	0.901	1.2E-11	0.715	6.1E-10	30	4	0	1.039	0.686	4.60	4.59
18	1.095	1.276	0.895	1.9E-08	0.706	4.7E-07	22	4	4	1.256	0.874	4.84	3.49
19	1.063	0.805	0.891	4.1E-11	0.747	5.1E-11	30	8	0	1.196	0.911	4.79	3.63
20	1.217	0.694	0.892	1.6E-11	0.776	1.5E-12	31	3	0	1.505	0.906	5.50	3.85
21	1.249	1.193	0.957	1.4E-10	0.860	1.1E-09	19	3	1	1.457	1.028	4.22	3.39
22	1.067	0.802	0.835	1.8E-08	0.734	3.3E-10	29	4	0	1.268	0.900	4.31	3.21
23	1.050	0.731	0.841	1.1E-08	0.759	4.8E-11	29	5	1	1.267	0.901	4.48	3.81
24	1.031	0.811	0.814	8.1E-08	0.754	7.2E-11	29	4	2	1.264	0.892	4.11	3.40
25	0.999	0.758	0.781	4.2E-06	0.727	1.4E-08	25	4	3	1.198	0.696	4.00	3.57
26	1.000	0.898	0.767	7.7E-06	0.747	4.1E-09	25	4	2	1.295	0.790	4.02	3.67
27	1.064	0.824	0.843	9.9E-09	0.744	1.6E-10	29	4	0	1.249	0.899	4.43	3.63
28	1.100	0.940	0.854	1.1E-07	0.681	3.8E-07	24	7	0	1.346	0.840	4.65	3.51
29	1.103	0.862	0.872	2.8E-08	0.667	7.7E-07	24	8	0	1.386	0.843	4.73	3.65
30	0.853	0.760	0.880	3.1E-10	0.732	2.8E-08	29	6	0	1.045	0.652	5.28	4.20
31	1.100	0.949	0.854	1.1E-07	0.674	5.4E-07	24	8	0	1.375	0.863	4.72	3.42
32	1.021	0.970	0.852	1.3E-07	0.768	2.4E-09	24	5	0	1.243	0.830	4.70	4.79
33	0.983	0.613	0.945	1.1E-11	0.763	8.7E-09	23	4	0	1.140	0.776	5.92	5.01
34	1.177	0.667	0.938	2.7E-08	0.868	9.6E-09	17	2	0	1.353	1.016	4.90	3.71
35	0.906	1.221	0.747	8.8E-04	0.420	2.7E-02	16	6	0	1.661	0.236	2.69	2.41
36	1.027	1.142	0.905	1.5E-06	0.797	2.6E-05	16	5	0	1.141	0.750	2.91	2.67
37	0.886	1.689	0.706	5.0E-07	0.529	2.8E-06	39	3	0	1.180	0.605	4.16	3.17
38	0.907	1.693	0.767	4.9E-08	0.567	1.2E-06	36	3	2	1.191	0.686	5.08	3.73
39	1.000	1.005	0.898	3.3E-08	0.800	6.0E-09	21	5	0	1.295	0.741	5.00	3.65

Ecosystem number	$SDB$	$\log_{10}a$	$\rho$	p-value	$\tau$	p-value	$N$	$N_{SD}$	$N_{SKEW}$	$SDB_+$	$SDB_-$	$\log_{10}(Q_{MAX}/Q_{MIN})$	$\log_{10}(B_{MAX}/B_{MIN})$
40	1.050	1.198	0.937	4.2E-17	0.790	1.5E-11	36	3	3	1.196	0.920	4.38	4.22
41	1.153	0.988	0.925	7.1E-13	0.811	7.6E-10	29	3	5	1.335	0.998	5.01	3.82
42	1.195	1.029	0.998	4.9E-07	1.000	4.0E-04	7	2	0	1.326	1.000	3.20	2.68
43	1.123	1.379	0.952	5.1E-07	0.615	2.7E-03	13	4	0	1.492	0.625	5.14	3.89
44	1.220	1.454	0.737	6.3E-03	0.569	1.3E-02	12	3	0	2.932	0.563	2.28	1.99
45	1.277	0.990	0.926	4.7E-12	0.748	5.3E-08	27	4	0	1.435	1.062	5.25	3.55
46	1.158	0.867	0.794	6.0E-06	0.605	1.9E-05	23	5	0	1.490	0.708	3.71	3.56
47	1.225	0.979	0.818	3.3E-05	0.699	1.2E-05	18	2	0	1.900	0.923	3.38	2.24
48	1.174	1.279	0.771	4.7E-04	0.644	6.1E-04	16	3	0	1.799	0.632	3.42	2.18
49	1.360	1.298	0.888	2.0E-06	0.809	2.7E-07	17	0	2	1.866	1.000	4.09	2.46
50	1.382	0.929	0.854	1.3E-05	0.750	3.7E-06	17	3	0	1.964	0.968	3.84	2.83
51	1.412	0.916	0.955	1.3E-06	0.840	2.1E-04	12	2	0	1.883	1.061	3.80	2.30
52	1.634	1.096	0.783	2.6E-03	0.485	3.1E-02	12	2	0	2.634	0.203	2.33	0.97
53	1.383	0.442	0.909	6.9E-06	0.868	5.5E-07	14	7	0	2.174	1.000	3.83	2.16
54	1.144	1.370	0.730	3.0E-03	0.604	2.0E-03	14	4	0	1.602	0.409	2.28	1.91
55	1.090	0.777	0.935	2.3E-27	0.816	6.9E-20	59	7	2	1.214	0.975	4.42	4.33
56	0.975	0.960	0.927	4.3E-31	0.751	2.5E-20	71	4	0	1.082	0.875	4.93	4.55

Ecosystem numbers refer to Table A3.1. For each of the 56 trophic flow network models, the table reports the scaling exponent estimated with the Kendall-Theil robust method ( $SDB$ ); its 95% confidence intervals ( $SDB_+$ ,  $SDB_-$ ); the logarithm of the power law proportionality coefficient ( $\log_{10}a$ , i.e. the intercept of the log-log fitting line); Pearson's correlation coefficient  $\rho$  and Kendall's  $\tau$  rank correlation coefficient, with the corresponding p-values from a two-tailed test; the number  $N$  of consumer compartments in the flow network (i.e. excluding detritus and primary producer compartments); the number of outliers detected with the Stahel-Donoho ( $N_{SD}$ ) and skewness-adjusted ( $N_{SKEW}$ ) methods; the orders of magnitude spanned by the scaling relationship on the axes, expressed as  $\log_{10}(Q_{MAX}/Q_{MIN})$  and  $\log_{10}(B_{MAX}/B_{MIN})$ , where  $Q_{MAX}$  and  $B_{MAX}$  represent the highest consumption and biomass among the compartments of the network, and  $Q_{MIN}$  and  $B_{MIN}$  represent the lowest consumption and biomass.



Table A3.6. Correlations between *SDB* and additional food web indicators or ecosystem attributes, not taken into account in the Bonferroni correction in the main text and reported for information purposes.

Correlations between <i>SDB</i> and additional indices, reported for information purposes and not taken into account in the Bonferroni correction:	Spearman $r_s$	p-value	$n$
Total system throughput (t km <sup>-2</sup> y <sup>-1</sup> )	-0.03	0.801	56
Total primary production (t km <sup>-2</sup> y <sup>-1</sup> )	0.04	0.777	56
Sum of all consumption flows (t km <sup>-2</sup> y <sup>-1</sup> )	-0.07	0.618	56
Sum of all export flows (t km <sup>-2</sup> y <sup>-1</sup> )	0.17	0.217	56
Sum of all flows into detritus (t km <sup>-2</sup> y <sup>-1</sup> )	-0.01	0.959	56
Sum of all respiration flows (t km <sup>-2</sup> y <sup>-1</sup> )	-0.11	0.428	56
Sum of all production (t km <sup>-2</sup> y <sup>-1</sup> )	-0.01	0.963	56
Total fishery catches (t km <sup>-2</sup> y <sup>-1</sup> )	0.23	0.130	46
Cycled throughput (t km <sup>-2</sup> y <sup>-1</sup> )	-0.20	0.140	56
Net system production (t km <sup>-2</sup> y <sup>-1</sup> )	0.16	0.238	56
Total living biomass (i.e. excluding detritus biomass) (t km <sup>-2</sup> )	-0.26	0.0502	56
Connectance Index	0.02	0.877	56
Ascendency (flowbits)	-0.01	0.916	56
Internal ascendency (flowbits)	-0.03	0.822	56
Internal overhead (flowbits)	-0.05	0.691	56
Internal capacity (flowbits)	-0.08	0.569	56

In addition to the thirteen selected indices reported in the Table 12 of Chapter 7, the Table reports correlations between *SDB* and other indices, based on absolute flows or biomasses, or strongly dependent on the level of aggregation of the model (such as connectance, Christensen et al., 2005), and thus not fit for inter-ecosystem comparison (Baird et al., 1991), unlike the aforesaid thirteen selected indices (which are, for example, ratios). Accordingly, the indices that are reported in Table A3.6 were not expected to correlate with *SDB* and hence they were not taken into account in the Bonferroni correction of Table 12: they are reported for information purposes only and to highlight the higher meaningfulness of the thirteen selected indices of Table 12. If not specified, indicators are dimensionless. In some ecosystems there were no fisheries, so that for the “Total fishery catches” indicator the number  $n$  of valid cases is 46. A description of the food web indicators and ecosystem attributes (as well as their units of measurement) can be found in the Section A3.3.

Table A3.7. Number of compartments identified as outliers for the consumption-biomass scaling relationship (sorted into distinct ecological categories).

Ecological category	Stahel-Donoho method			Skewness-Adjusted method		
	Total	Above line	Below line	Total	Above line	Below line
Planktonic organisms (zooplankton, bacteria, fish larvae, etc.)	74	73	1	14	14	0
Zoobenthos	44	29	15	5	2	3
Sea birds	39	38	1	9	9	0
Fish	36	22	14	2	1	1
Marine mammals (e.g. cetaceans, pinnipeds, etc.)	23	23	0	4	4	0
Micro-benthic fauna (e.g. bacteria, micro-crustaceans), meiofauna	22	22	0	2	2	0
Jellyfish	11	2	9	0	0	0
Juvenile fish	3	3	0	2	1	1
Reptiles (e.g. turtles) and amphibians	3	1	2	1	0	1
Cephalopods	4	4	0	0	0	0
Other organisms	4	3	1	1	1	0

Results for the two methods used to detect outliers (the Stahel-Donoho robust multivariate outlyingness measure and a skewness-adjusted generalization of it; Hubert and Van der Veen, 2008) are reported, and outliers are divided into ecological categories. For each category, the total number of outliers in the 56 trophic flow network models as well as their position above or below the Kendall-Theil robust fitting line is reported.

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