

## Spatial Modelling of Trophic Interactions and Fisheries Impacts in Coastal Ecosystems: A Case Study of Sakumo Lagoon, Ghana

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### Abstract

A trophic model of a small West African coastal lagoon (Sakumo Lagoon, near Tema, Ghana), consisting of 14 interacting functional groups, was constructed using the Ecopath approach and software, based on field data gathered in the early 1970s, and reflecting an early stage in the development of this now much-modified ecosystem. This trophic model, after some test runs with Ecosim, was used as basis for an application of the 'Ecospace' routine of Ecopath, recently developed by Carl Walters, Fisheries Centre, University of British Columbia. This generates plots of the relative biomasses of functional groups onto a grid map, while accounting for their trophic interactions, their movements towards preferred habitats and the distribution of fishing effort. This example illustrates an approach that may be widely used to represent and analyse the coastal and marine ecosystems of the Gulf of Guinea, and other areas where 'ecosystem-based management' is required, while data are sparse.

### Introduction

There is, among decision-makers and scientists, wide agreement that present practices in fisheries and coastal development are unsustainable, and should be replaced by 'ecosystem-based' approaches. There is, on the other hand, much less of a consensus as to the integrative conceptual and/or software tools that may be used to implement such approaches. Also, many scientists claim that "there is not enough data" for integrative approaches of any sort, and this is one of the reasons why many decision-makers have lost patience with us.

This loss of patience is understandable, given that making this claim is, with many scientists, a reflex that kicks in every time they are confronted with the task of integrating the immense amount of largely un-analyzed data that publicly-funded research has been allowed to accumulate over the last decades.

This author and his colleagues have argued elsewhere that, at least as far as aquatic ecosystems are concerned, models explicitly accounting for trophic interactions, and structured around the principle of mass-balance, allow for rigorous integration of much of what we know about aquatic ecosystems. This approach also allows the embedding of fisheries, and their resources, base into the ecosystems that sustain them (Christensen and Pauly 1992, 1993; Pauly and Christensen 1995).

Critics of this approach, and of Ecopath, the software developed for its implementation (Christensen and Pauly 1992; Pauly and Christensen 1995, and see [www.ecopath.org](http://www.ecopath.org)), have mainly concentrated on three points:

- a) it did not include an explicit procedure for considering uncertainty in input parameters;
- b) it did not consider temporal dynamics, and thus did not allow asking 'what if questions?'
- c) it did not include a spatial structure, though spatial processes are crucial to trophic interactions.

Item (a) was accommodated by including a semi-Bayesian resampling routine (Ecoranger) into Ecopath, which allows consideration of prior distributions of Ecopath inputs, and the output of their posterior distributions, besides distributions of estimates, a procedure found suitable by practitioners (see contributions in Pauly 1998).

Item (b) was accommodated through the development of Ecosim (Walters *et al.* 1997), whose latest version, incorporated into Ecopath with Ecosim (available from [www.ecopath.org](http://www.ecopath.org)) includes, for split pools, a version of the delay-difference model of Deriso (1980).

Item (c) was recently resolved, again by Carl Walters, through the development of Ecospace, a spatially-structured version of Ecopath documented in Walters *et al.* (1999), and whose first tests by a wide range of users are documented in Pauly (1998).

This contribution presents an application of Ecospace, now a routine of Ecopath with Ecosim (see above), to Sakumo Lagoon, a small (1 km<sup>2</sup>) water body near Tema, Ghana, West Africa, which the author studied in 1971, and which may be seen as representing many other coastal lagoons along the coast of the Gulf of Guinea. Since it was originally studied, Sakumo Lagoon has been much modified by overfishing, pollution and other injuries (Ntimoa-Baidu 1991; Koranteng *et al.* 1998), a topic not followed upon here.

## Materials and methods

The data used for this study stem mainly from three earlier contributions describing the ecology of Sakumo Lagoon, and the adaptations of its dominant fish species, the cichlid *Sarotherodon melanotheron* (Pauly 1975, 1976; Pauly *et al.* 1988). This was complemented with data from (models of) similar systems, mainly adapted from contributions in Christensen and Pauly (1993).

The data requirements of an Ecopath model are expressed by its mass-balance equation, which for each of its functional group *i* demands that

$$B_i * (P/B)_i * EE_i = Y_i + \sum B_j * (Q/B)_j * DC_{ij} \quad \text{Eq. 21-1}$$

where  $B_i$  and  $B_j$  are biomasses (the latter pertaining to *j*, the consumers of *i*);  $P/B_i$  their production/biomass ratio, equivalent to total mortality under most circumstances (Mertz and Myers 1998);  $EE_i$  the fraction of production ( $P = B * (P/B)$ ) that is consumed within, or caught from the system  $Y_i$  is equal the fisheries catch (i.e.,  $Y = F * B$ );  $Q/B_j$  the food consumption per unit biomass of *j*; and  $DC_{ij}$  the contribution of *i* to the diet of *j*.

Fourteen functional groups were found appropriate, given the data at hand, to represent the interacting species of Sakumo Lagoon. They are defined in Table 21-1, which also gives the values of  $B$ ,  $P/B$ ,  $Q/B$ , and  $EE$  either entered into (with sources), or output by

the Ecopath parameterization routine, which solves (1) through a robust matrix inversion (MacKay 1981).

Table 21-2 presents the diet matrix (the  $DC_{ij}$ ) used, based on field data for the fish, on the known ecology of the invertebrates groups, on the mass-balance requirement implied in (Eq. 21-1) and on several runs of Ecosim (Walters *et al.* 1997) to verify that the system was dynamically stable.

Group Name	TL	Biomass (t·km <sup>2</sup> )	P/B (year <sup>-1</sup> )	Q/B (year <sup>-1</sup> )	EE	Preferred habitat
Adult tilapias	2.00	3.50	4.0	35.1	0.986	I,R.
Juv. Tilapias	2.80	0.20	6.0	20	0.840	I,R
Penaeids	2.31	0.03	3.5	15	0.960	C
<i>Ethmalosa</i>	2.30	0.06	2.0	16	0.423	All
Mar. carn.	3.36	0.05	2.0	15	0.508	C
<i>Callinectes</i>	2.81	0.05	2.0	10	0.500	C
<i>Clibanarius</i>	2.35	0.01	2.0	15	0.500	C
<i>Tympanotonus</i>	2.21	0.05	2.0	10	0.500	I,R
Oysters	2.10	5.00	1.0	20	0.500	I,R
Misc. benthos	2.05	0.15	5.0	50	0.908	All
Zooplankton	2.00	1.00	50.0	250	0.271	All
Phytoplankton	1.00	1.00	400.0	0	0.740	All
Detritus	1.00	10.00	-	-	0.894	All

**Table 21-1** Basic inputs of Ecopath model of Sakumo Lagoon (see text for sources), and outputs (in bold characters). Habitats are C (Coastal); I (Interior), R (Rivers), or All.

Prey No.	Prey/Predator	1	2	3	4	5	6	7	8	9	10	11
1	Adult tilapias	-	-	-	-	-	0.6	-	-	-	-	-
2	Juv. Tilapias	-	-	-	-	0.010	-	-	-	-	-	-
3	Penaeids	-	-	-	-	0.001	-	-	-	-	-	-
4	<i>Ethmalosa</i>	-	-	-	-	0.001	-	-	-	-	-	-
5	Mar. carnivores	-	-	-	-	0.001	-	-	-	-	-	-
6	<i>Callinectes</i>	-	-	-	-	-	-	-	-	-	-	-
7	<i>Clibanarius</i>	-	-	-	-	-	-	-	-	-	-	-
8	<i>Tympanotonus</i>	-	-	-	-	-	-	-	-	-	-	-
9	Oysters	-	-	-	-	-	-	-	-	-	-	-
10	Misc. benthos	-	-	0.2	-	0.001	0.2	0.1	0.2	-	0.05	-
11	Zooplankton	-	0.8	0.1	0.3	0.001	-	-	-	0.1	-	-
12	Phytoplankton	-	0.2	0.1	0.1	0.001	-	-	-	0.7	-	0.9
13	Detritus	1	-	0.6	0.6	-	0.2	0.2	0.8	0.2	0.95	0.1
14	Import	-	-	-	-	0.984	-	0.7	-	-	-	-

**Table 21-2** Diet matrix used for construction of Sakumo Lagoon ecosystem model. Most inputs are from Pauly (1975, 1976); other inputs are based on basic biology, then refined by back-calibration.

Ecosim is structured around the reinterpretation of Equation (1) as a system of coupled differential equations:

$$dB/dt_i = [B_i * (P/B)_i * EE_i - F_i * B_i + \sum a_{ij}] \quad \text{Eq. 21-2}$$

where  $dB/dt_i$  is the growth rate of groups  $i$  in terms of its biomass,  $a_{ij} = Q_{ij}/(B_i * B_j)$  is the Lotka-Volterra mass-action term, and all other terms are defined as in (Eq. 21-1). However, the biomasses, in Ecosim do not strictly follow Lotka-Volterra dynamics:

- a) the  $B_i$  are divided into vulnerable and invulnerable components (Walters *et al.* 1997), and it is the transfer rate between these two components (adjustable by the user) which determines if control is top-down (i.e., Lotka-Volterra), bottom-up (i.e., donor-driven), or intermediate (as used here);
- b) in case of split pools (juveniles vs. adults of the same species), account is kept of the numbers that recruits from the juvenile to the adult stages (using a delay-difference model, which allows stock-recruitment relationships (not further discussed here) to be among the Ecosim outputs. (Split pools are used here only for the tilapia *Sarotherodon melanotheron*, which dominates the biomass of Sakumo Lagoon, and which undergoes at about 4 cm a strong ontogenic diet shift, from plankton to detritus (Pauly 1976, and see Table 21-2).

Ecospace is a dynamic version of Ecopath, incorporating key elements of Ecosim (including a & b above), and which allocates biomass across a grid map (usually 20 x 20 cells, as used here, but more are possible), while accounting, among other things, for:

- 1) symmetrical movements from a cell to its four adjacent cells, of rate  $m$ , modified by whether a cell is defined as 'preferred habitat' or not (running means over sets of five cells allows for smooth transitions between habitat types);
- 2) increased predation risk (here by a factor of 1.5 for all groups) and reduced feeding rate (here by a factor of 0.5 for all groups) in non-preferred habitat;
- 3) a level of fishing effort that is proportional, in each cell, to the biomass of the target group in that cell, and whose distribution can also be made sensitive to costs (e.g., of sailing to certain areas).

Based on Pauly (1975), three habitat types can be distinguished within Sakumo lagoon:

- 1) *Coastal*, near the mouth of the lagoon, which is kept permanently open by a sluice, and in which therefore allows coastal organisms to swim, or to be washed into the lagoon, especially at high tide;
- 2) *Interior*, referring to the much larger, interior part of the lagoon, in which the dominant process is the deposition at a mean depth of 50 cm, of the terrigenous and planktonic detritus that is the food of adult *S. melanotheron*; and
- 3) *Rivers*, referring to the small areas covered by the mouths of small rivers connected to the *Interior*, and which contain, at least following the raining season, residues of a freshwater fauna.

The assignment of the 14 functional groups to either of these three preferred habitat, or to 'all' for groups with uniform distribution, are given in Table 21-1. The defaults movement rates ( $m$ ) assumed for the various groups were used. These values are tentative, but similar results (i.e., distribution maps, see below) were obtained using different values.

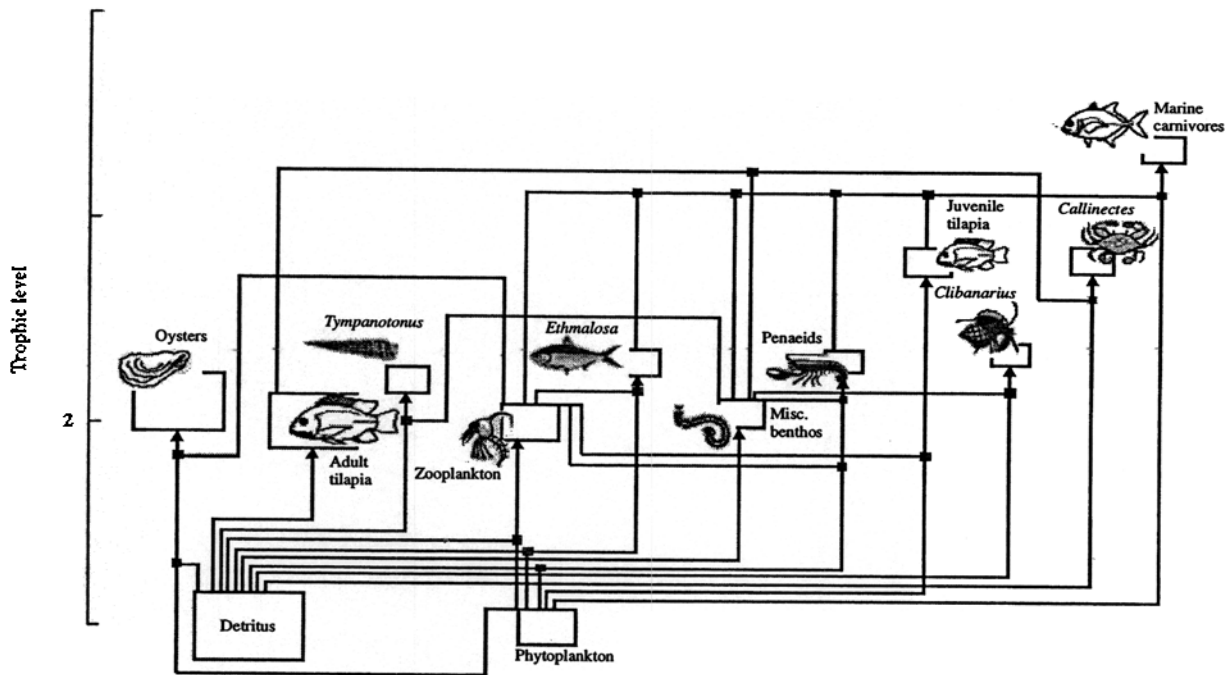
Based on field observation (Pauly 1975), the fishery was assumed to be distributed uniformly with regards to the habitat types, i.e., it is only the distribution of the organisms (mainly

tilapia) which determined where the fishers operate, and not costs (which can also be accommodated by Ecospace).

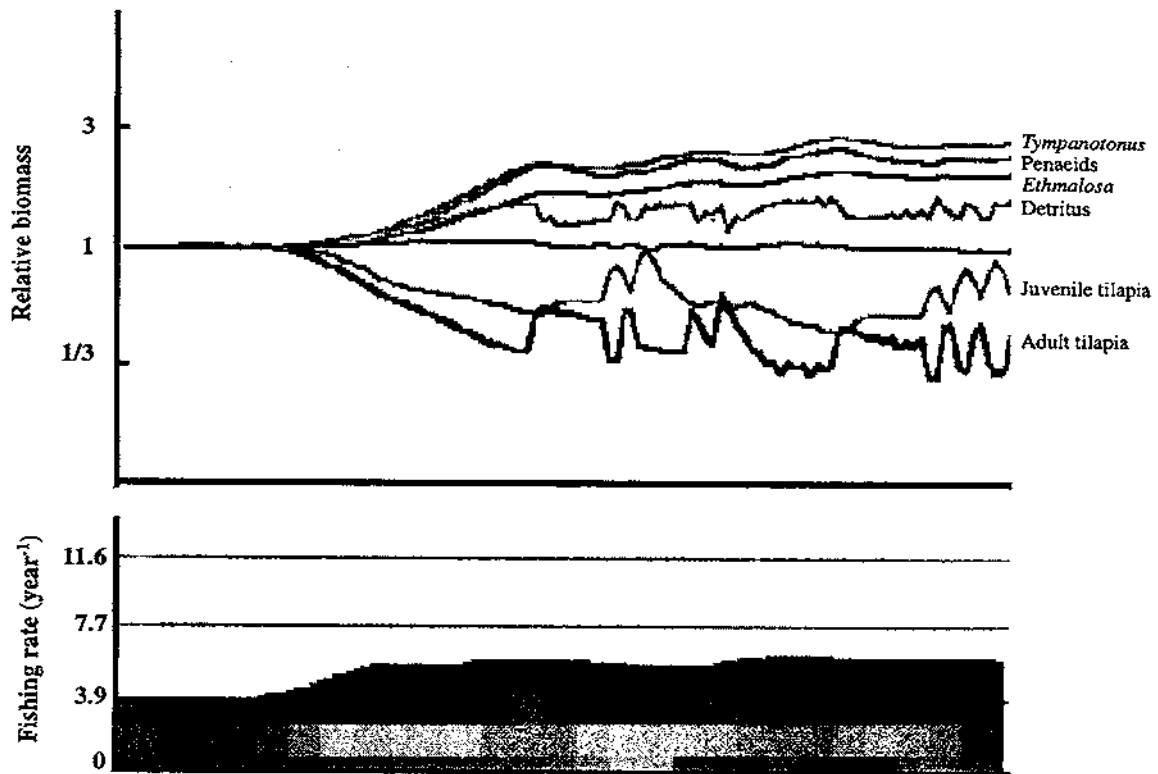
## Results and Discussion

Figure 21-1, representing the trophic interactions implied in Tables 21-1 and 21-2, complements a previous qualitative representation of these same interactions (Pauly 1975; Figure 12). As might be seen, *S. melanotheron* entirely dominates the biomass of Sakumo Lagoon. Also, its food consumption is higher than that between all other groups, except those between phytoplankton and detritus.

This is emphasized by the matrix of mixed trophic impacts (not shown), from which one can infer that only changes in tilapia or in detritus biomass could markedly impact the fishery, or the other groups in the system. Consequently, Ecosim suggests that increased fishing on tilapia would directly or indirectly affect other groups in the systems (Figure 21-2), while increased fishing on other groups would not affect the tilapias (simulations not shown). Overall, the robust results obtained here with Ecosim suggest that the original description of Sakumo lagoon as an ecosystem driven by the detritus consumption of *Sarotherodon melanotheron* still holds.



**Figure 21-1** Flowchart of trophic interaction in the Sakumo Lagoon ecosystem in the early 1970s, as constructed using Ecopath based on the data in Tables 21-1 and 21-2. Backflows to the detritus (ungrazed phytoplankton, fecal matter, etc.) are not shown.



**Figure 21-2** Result of a run with Ecosim, the dynamic version of Ecopath (Walters *et al.* 1997) of the file representing the Sakumo Lagoon ecosystem. The scenario run here assumes an increase of about 30 % of the fishing mortality on adult tilapia (baseline). Note resulting increase of various competitors, and of detritus. Note also the oscillations induced by the delay-difference model, wherein the juvenile and adult tilapia alternate in abundance. This behavior can be suppressed, or amplified by changing the setting of Ecosim, and is presented here only for information, as it has so far not been shown to really occur in *S. melanotheron*, or any other tilapia.

The different panels of Figure 21-3 (colour plate) illustrate the key results of the present exercise, i.e., that Ecospace can reproduce the observed distribution of different functional groups in Sakumo Lagoon, while simultaneously accounting for their movements, and their interactions with their preys and predators (including the fishery). As might be seen, the distribution of all groups (except phytoplankton) reflects our definition of three habitat types through their relative equilibrium biomass (as attained after a simulation period of 10 years; see insert on lower right corner of graph).

Overall, these distributions correspond to those observed by the author (see Pauly 1975, especially Figure 11). More importantly, a few interesting predictions are made that suggests realism. Notably, the miscellaneous carnivores, of entirely marine origin, were very hard to accommodate in term of their food requirements, within or close to that small part of the lagoon here defined as having a 'coastal' habitat. Indeed, the miscellaneous carnivores declined under most scenarios (as indicated in the insert), reflecting their nature as occasional

visitors (Pauly 1975). However, we shall abstain here from 'tweaking' the model until it closely matches the observed distributions. This would be pointless, given that the model, sophisticated as it is, cannot capture the key change that appears to have occurred in the lagoon: the miniaturization (as a genetic response to constant, strong fishing pressure?) of *Sarothodon melanotheron*, which now appears to reach 5 cm at most, and to mature at an even smaller size (pers. obs., July 1998).

Rather, we shall conclude by proposing that the tools presented here – Ecopath for food web construction and analysis, Ecosim for temporal simulations, and Ecospace for spatial simulations – are well suited for studying the various subsystems of the Large Marine Ecosystem represented by the Gulf of Guinea, just as they have been shown to be useful when applied to other ecosystem types (Longhurst and Pauly 1987; Christensen and Pauly 1993; Walters *et al.* 1997, 1999). Further, the author offers to assist interested colleagues in constructing models such as presented here (see also [www.ecopath.org](http://www.ecopath.org)). The time has come to make sense of the data we have been gathering all these years.

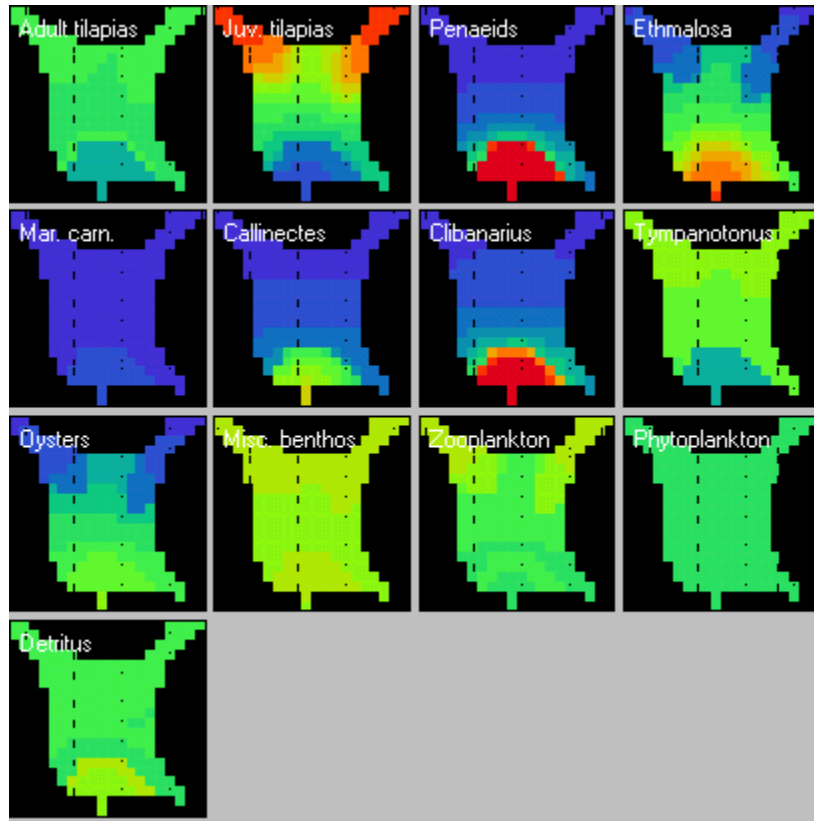
## Acknowledgments

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## References

- Christensen, V. and D. Pauly 1992 The ECOPATH II - a software for balancing steady-state ecosystem models and calculating network characteristics. *Ecological Modelling* 61: 169-185.
- Christensen, V. and D. Pauly (eds) 1993 Trophic models of aquatic ecosystems. ICLARM Conference Proceedings No. 26. 390p.
- Deriso, R.B. 1980 Harvesting strategies and parameter estimation for an age-structured model. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 268-282.
- Koranteng, K, M. Entsua-Mensah and P.K. Ofori-Danson. 1998 Comparative study of the fish and fisheries of three coastal lagoons in west Africa. *International Journal of Ecology and Environmental Science* 24: 371-382.
- Longhurst, A. and D. Pauly 1987 *Ecology of Tropical Oceans*. Academic Press, San Diego, 407p.
- MacKay, A. 1981 The generalized inverse. *Practical Computing*, September 1981: 108-110.
- Mertz, G. and R.A. Myers. 1998. A simplified formulation for fish production. *Canadian Journal of Fisheries and Aquatic Sciences* 55(2): 478-484.
- Ntiama-Baidu, Y. 1991 Conservation of coastal lagoons in Ghana: the traditional approach. *Landscape and Urban Planning* 20: 41-46.
- Pauly, D. 1975 On the ecology of a small West African lagoon. *Meeresforschung* 24(1): 46-62.
- Pauly, D. 1976 The biology, fishery and potential for aquaculture of *Tilapia melanotheron* in a small West African lagoon. *Aquaculture* 7(1): 33-49.
- Pauly, D. (ed.) 1998 *Use of Ecopath with Ecosim to evaluate strategies for sustainable exploitation of multi-species resources*. Fisheries Centre Research Reports 6(2). 49p.

- Pauly, D. and V. Christensen 1995 Primary production required to sustain global fisheries. *Nature* 374: 255-257.
- Pauly, D., J. Moreau and M.L. Palomares 1988 Detritus and energy consumption and conversion efficiency of *Sarotherodon melanotheron* (Cichlidae) in a West African lagoon. *J. Appl. Ichthyol.* 4: 150-153.
- Walters, C., V. Christensen and D. Pauly 1997 Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Reviews in Fish Biology and Fisheries* 7: 139-172.
- Walters, C., V. Christensen and D. Pauly 1999 Ecospace: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems with emphasis on the impacts of marine protected areas. *Ecosystems* 2: 539-554.



**Figure 21-3** Results of a run with Ecospace, the spatial version of Ecopath (Walters *et al.* 1999) of a file representing the Sakumo Lagoon ecosystem. Note abundance (red color) of animals with marine affinities near the mouth of the lagoon, and conversely for freshwater organisms. Note that some patterns of relative abundance are not due to primary habitat assignments, but to ‘cascade’ effects, wherein the preys of organisms abundant in certain cells are scarce in those cells, and conversely for *their* prey (see also text).