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Ecotroph: A simple model to assess fishing and trophic interactions in Lake Victoria

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Abstract
Ecotroph is a simple model that structure ecosystems as systems of energy flow surging from low to high trophic levels. Lake Victoria is the second-largest freshwater lake in the world. It is a producer of 1% of global capture fisheries and 8% producer of global inland fishery. The lake has faced overfishing and overexploitation. A pre-existing Ecopath with Ecosim model of Lake Victoria 2016, was used for data extraction, simulations, and analysis. Model outputs were juxtaposed against current biological data to determine the validity of the trends using Pearson's correlation and modelling efficiency. Fishing did not appear to have tremendous effect on the trophic interactions. Fishing at lower trophic levels negatively impacted the ecosystem than when fishing was directed to high trophic level species. The system showed resilience and stability when fishing was directed towards top predators. Lake Victoria exhibited top-down characteristics which are usually resistant to fishing.

Keywords: Ecopath, trophic level, mean biomass, mean catch, ecosystem indices

1. Introduction
Since time immemorial human communities have closely related to aquatic ecosystems. The earliest of civilizations and the beginning of settlements started around and along aquatic ecosystems [1]. Mesopotamia, the eldest of recorded civilizations was between two large rivers and Egypt always depended and developed along the great Nile. The evidence points out the crucial relations between humans and aquatic ecosystems. Humans have depended or exploited aquatic ecosystems in a myriad of ways, from navigation, fisheries, water for domestic and industrial uses to sinks for wastes and environmental pollutants.

1.1 Lake Victoria
Lake Victoria is an iconic East African lake in both its size and function. Its iconic attribute is derived both from its surface area of approximately 68,000 km^2 and the production of annual tonnage of close to 1 million metric tonnes [2]. The surface area makes it the largest freshwater lake in the tropics and the second largest in the world. Its production makes it a contributor of 1% capture fisheries produced globally and an 8% producer of inland fisheries [3]. The basin of the lake supports about 70 million people directly and transverses five East African countries [4].

For a long time, it had been believed that the aquatic resources and especially the great lakes and oceans resources are infinite. According to [5], renown scientists exclaimed that no matter the effort employed in the world's oceans, it could never diminish or deplete the resources within them. This view, however, was shot down when declines in world fisheries were reported from all over the globe [6]. Lake Victoria is not an exception. The lake has faced overfishing and overexploitation over the decades to a point that species have disappeared. Fishing affects the trophic interactions and thus has effects beyond the species level.

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1.2 Ecological Models
Models have become an integral part of understanding the functioning and processes of aquatic ecosystems [7]. They have become fundamental tools in the management of fisheries resources which are on the verge of collapse due to overexploitation and degradation [8].
Ecotroph ignores the species and instead uses the trophic spectra to describe aquatic ecosystems as functions of flow of biomass from low to high trophic levels [9]. Ecotroph, therefore, simulates the influences of different fishing scenarios and trends [10]. It is common knowledge that fishing has forces beyond the target species and therefore, the impacts of given fishing scenarios are simulated in an ecosystem concept.

2. Research Methodology
2.1 Study Area
An area covering 68900 km^2 with a spatial extent of 3.05°S to 0.55°N and 31.5°W to 34.88°E was constructed to represent the Lake Victoria ecosystem because the data presented from Ecopath to Ecotroph served biomass and catch from the whole lake.

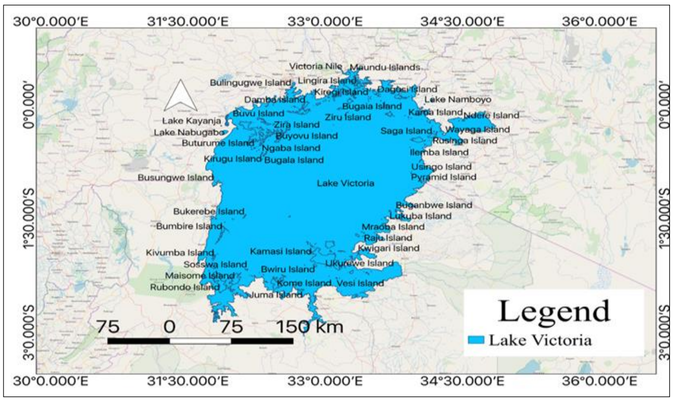

Fig 1: The study area map of Lake Victoria representing the spatial extent of the model

2.2 Modelling Framework
Ecopath with Ecosim model created for Lake Victoria in 2016 [11] was used in this analysis. Ecopath with Ecosim version 6.5 software was used for all simulations and outputs were analysed using excel.
The framework involved an Ecopath model created for the whole lake [12]. The ecosystem biomass was partitioned into different functional groups in accordance with their roles in ecology and interactions in feeding.
The functional groups of the model are piscivorous birds, the Nile crocodile, 15 fish groups taken as a group concerning the similarity of feeding, history or habitat or as individuals, 3 different invertebrate groups, 2 producer groups and a detrital group.

Table 1: Functional groups used in the Lake Victoria EwE model

Common name	Species included
Birds	Piscivorous birds
Crocodiles	*Crocodylus niloticus*
Nile perch	*Lates niloticus*
North African catfish	*Clarias gariepinus*
Semutundu	*Bagrus docmak*
Marbled lungfish	*Protopterus aethiopicus*
Squeakers	*Synodontis victoriae, S. afrofisheri*
Snout fishes	Predominantly *Momyrus kanume*
Silver catfish	*Schilbe intermedius*
Rippon barbel	*Labeobarbus altianalis*
Small barbs	*Enteromius* spp.
Robbers	*Brycinus jacksoni, B. sadleri*
Ningu	*Labeo victorianus*
Haplochromines	Phytoplanktivorous, Benthivorus Piscivorous
Silver cyprinid	*Rastrineobola argentea*
Nile tilapia	*Oreochromis niloticus*
Other tilapias	*O. esculentus* and *O. variabilis*
Freshwater shrimp	*Caridina nilotica*
Insects and molluscs	Macroinvertebrates, Benthic filter feeder, Shallow filter feeder, Deep filter feeder Microphtybenthos
Zooplankton	Microzooplankton, Mesozooplankton,
Phytoplankton	Macroalgae, Large phytoplankton, Dinoflagellates, Pico-phytoplankton
Detritus	Labile and refractory detritus

2.3 Data extraction from Ecopath
The functional groups presented in Table 1 above, developed in the Ecopath model were transformed and presented as flows of biomass through the trophic levels. The first step was to derive trophic spectra representing the distribution of the ecosystem biomass, across the trophic levels. The trophic spectra are the curves relating to the sum of biomass for all groups. The biomass of each group was distributed over a range of trophic levels [13]. The current kinetic trophic spectrum was derived from biomass and production trophic spectra for all groups and the ones that are accessible [14].

2.4 Simulating fishing scenarios
The Ecotroph module was used to simulate different fishing scenarios using the ET-Diagnose routine in R package. The natural loss rate was assumed to be unchanged no matter the fishing mortality magnitude of the ecosystem. Using the ET-diagnose routine in Ecotroph variations of fishing mortality with common multipliers ranging from 0-5 were used for all trophic levels [15]. A value of 0 simulated a virgin ecosystem, values ranging between 1 and 2 reflected a decreased fishing mortality and values above 2 were used to indicate an increase in the fishing mortality [16].
This ET-Diagnostic Ecotroph routine was used to calculate the fishing mortality, the fishing loss rates, the biomass flow and kinetics across the trophic levels and finally the biomass and the catch by use of the different appropriate equations [17]. Fishing effort multipliers were imposed on haplochromines, Nile perch and the dagaa because they are the most important fisheries of the lake.

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[16] Gonza *et al*.
[17] Gonza *et al*.

2.5 Mean trophic level of biomass

Ecotroph enables the calculation of different ecosystem indices such as the ecosystem characterization indices which focus on the size of the ecosystem in relation to the flow of biomass, fisheries indices which include the mean trophic level of catch and mean trophic level biomass, trophic ecosystem biodiversity which are defined by the mean trophic level of biomass and accessible biomass, finally the maturity indices. These Indices provide insights into the trophic functioning and structures of ecosystems that are simulated.

The mean trophic level of biomass was used to measure the degree of trophic level change in feeding relationships among the target species. The mean trophic level of catch was used to determine the changes in the trophic level of catch in regard to changing fishing pressures.

To determine biomass and catch trend changes in trophic levels, the mean trophic level of biomass and catch was done using the formulae below

$$\overline{I}_i b = \frac{\Sigma_i(\overline{I}_i x B_i)}{\Sigma B_i}$$

where *ti* is the trophic level, *b* is the biomass of that specific trophic level and *B* is the sum of biomass in all trophic levels.

2.6 Methods of data analysis

The model outputs were examined and analysed using excel 2016 version to determine the mean trophic level of biomass, the mean trophic level of catch, the changes in catch trends and the changes in trophic levels in different fishing scenarios. The mean trophic level of biomass was deduced by excel graphics and illustrated appropriately.

Bar graphs were used to illustrate changes in ecosystem biomass across trophic levels. Line graphs were used to illustrate trends in biomass flow across trophic levels. The graphs depicted only changes in trophic levels since the biomass was seen as flowing low to high trophic levels.

3. Results

3.1 The current state of the ecosystem

The total biomass for the ecosystem derived from the Ecopath model and expressed by the Ecotroph summary is 274.7147 t km^{-2} with 164.7448t km^{-2} being the accessible biomass. The highest biomass that can be extracted from the ecosystem using the highest exploitation effort multiplier of 5 is 8.9316 t km^{-2}

The first trophic level is made up of phytoplankton, macrophytes and a detritus group. Haplochromines, the Nile tilapia, other tilapias, shrimp, insects and molluscs are in trophic level 2. Dagaa is in trophic level 3 together with most of the species regarded as high trophic species. Nile perch, *Clarias gariepinus* and *Bagrus docmak* are above trophic level 3, while *Barbus sp*, *Momyridae sp* and *Protopterus aethiopicus* are in trophic level 3. Birds are in trophic level 3 and only the crocodiles are in trophic level 4 functional group as depicted by Table 2

Table 2: The functional groups of Lake Victoria documented in Ecopath and expressed by Ecotroph

Group name	Trophic Level	Biomass	P/B	Accessibility	Omnivory index	Others Landings	Small seines Landings	Gillnets Landings	Long lines Landings
Birds	3.533859	0.005	0.3	0	0.1541713	0	0	0	0
Crocodiles	4.091322	0.001	0.3	0	0.30672	0	0	0	0
Lates	3.334084	2.0584	2.539	0.8	0.03646339	1.06E-05	2.57E-08	2.40E-05	2.38E-05
Clarias	3.324343	0.3918459	0.395	0.8	0.00760397	0.007720359	0	0.0145829	0.02573453
Bagrus	3.358609	0.577	1.2	0.8	0.01258661	0.01712494	0	0.03234711	0.05708314
Protopterus	3.104005	0.439	0.442	0.8	0.3463205	0.01451613	0	0.03290322	0.01258065
Squeakers	3.451617	0.638	0.106	0.8	0.01401623	0.000214407	0	0.01076503	8.93E-06
Momyridae	3.181378	0.1	0.3	0.8	0.2806715	0.000328985	0	0.01651777	1.37E-05
Shilbe	3.332234	0.05	0.281	0.8	0.004234358	0.00467442	0	0.00701163	0
Rippon barbel	3.044787	0.4	0.23	0.8	0.289854	0.003924419	0	0.00588663	0
Small barbs	3.052632	0.025	2.49	0	0	0	0	0	0
Alestidae	3.20002	0.05	0.258	0.8	0.03701294	0.000889535	0	0.0013343	0
Ningu	2	2	0.175	0.8	0	0.04351164	0	0.06526746	0
Haplochromines	2.300228	8.191396	3.15	0.8	0.228705	0.005478272	0.02873407	0.00778774	0.008915618
Dagaa	3.052632	2.08	2.51	0.8	0	0.000104395	0.000695605	0	0
Nile tilapia	2.45792	0.12	0.9	0.8	0.3950846	0.000400778	0	0.00068257	3.13E-06
Other tilapias	2	2.172	0.369	0.8	0	0.1125126	0	0.1916229	0.000879004
Shrimp	2.526316	0.7	11.4767	0	0.2770083	0	0	0	0
Insects and mollusks	2.31589	1.5	14.3235	0	0.232787	0	0	0	0
Zooplankton	2.052632	3.5	50.2186	0	0.05263158	0	0	0	0
Phytoplankton	1	4.5	160	0	0	0	0	0	0
Macrophytes	1	6	15	0	0	0	0	0	0
Detritus	1	10	0	0	0.3917667	0	0	0	0

3.2 The smooth Function

Figure 2 depicts biomass distribution and flow along the trophic levels. The biomass is highest in the lower trophic levels where there are high production and recycling than in the higher trophic levels which are mostly made up of top predators such as Nile perch and *Bagrus docmak.* The highest peak is observed at trophic level 2 due to the abundance of plankton in the ecosystem. There are also two peaks at trophic level 2.5 and trophic level 3.5. The peak at trophic level 2.5 is made up of mid-lower trophic species such as the dagaa and the haplochromines. The tilapias are also considered lower trophic species because they mostly feed at lower trophic species which include the plankton.

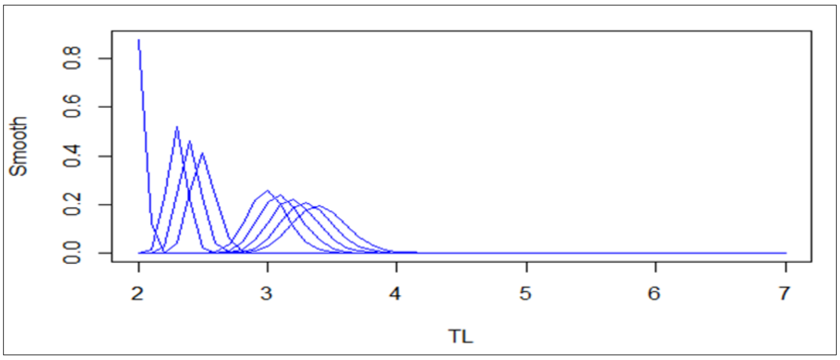

Fig 2: Biomass flow across trophic levels, in the Lake Victoria ecosystem.

3.3 Trophic Level Distribution of species

The below Figure 3, describe the distribution of all species and of each of the species. Observing the biomass by group distribution, the zooplankton form part of the lower trophic levels and the Nile perch represented by the blue colour indicate species of the higher trophic levels. Dagaa, freshwater shrimp and haplochromines occupy the intermediate trophic levels.

The haplochromines form the largest portion of biomass in the Lake Victoria ecosystem followed by dagaa, then the Nile perch and finally the tilapias in that order.

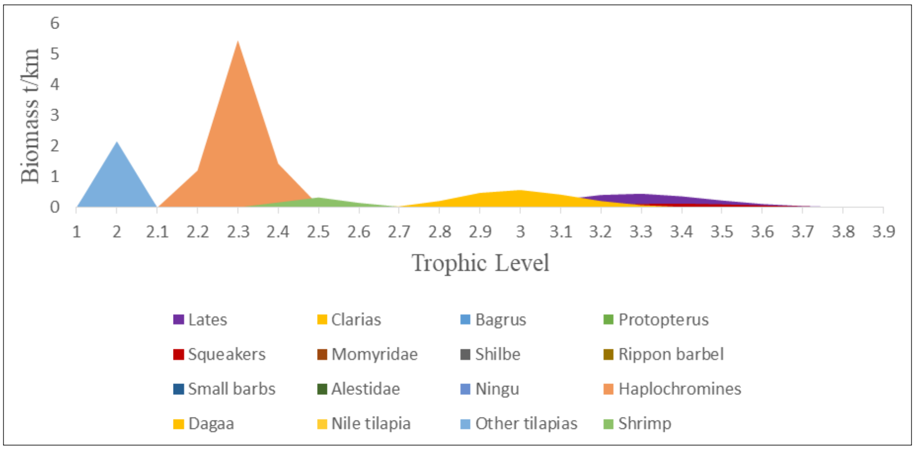

Fig 3: The distribution of species biomass across the trophic levels

Figure 4 shows that long lines target and catch species in the higher trophic levels. There are however some species in the intermediate trophic levels caught by the long lines and these might be the juveniles of the high trophic level adults of Nile tilapia and Nile perch. Other tilapias are also in the intermediate catch. Gill nets target or can be said to have a catch that is mostly in the lower trophic levels. These species are made up of the catfish, Ningu, haplochromines, juvenile Nile perch and other tilapias. The small seine catch is mainly composed of the intermediate trophic levels and these are majorly the dagaa, the haplochromines and juveniles of most of the species in the ecosystem.

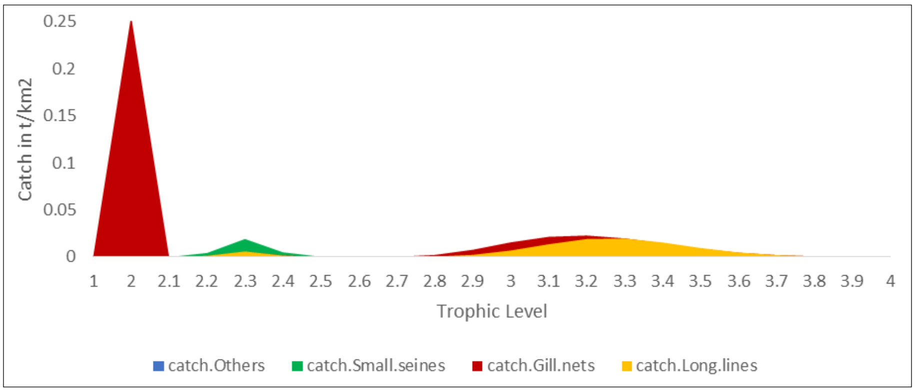

Fig 4: Biomass across trophic levels removed through fishing by different fleets which are long lines, gill nets, small seines and other fishing fleets in Lake Victoria.

3.4 Exploring the effects of fisheries

Figure 5 gives a representation of two curves, one representing the fish loss rate and the other fishing mortality relationships. Fishing mortality measures the probability of a fish to be caught and the fish loss rate represents the trophic levels currently exploited for the fishery. The fish loss rate is lower at the lower trophic levels but the fishing mortality is higher in lower trophic levels. This means that more fish in the lower trophic level is accessible to fishing but are not experiencing fish loss at a higher-level meaning that fishing is not being directed towards these low trophic level species. The fish loss increases in the higher trophic levels as does the fishing mortality which declines very higher into the higher trophic levels. The fish loss rate is higher in the high trophic levels because most of the fishing is directed here.

The fishing mortality reaches a maximum of 0.05 t km^{-2} y^{-1} at trophic level 3.4 which is majorly made up of top predators the Nile Perch. This means therefore that the fishery of Lake Victoria majorly targets high trophic species. The fishing loss rate is also higher in the trophic levels indicating that the highest rate of mortality happens in the higher trophic levels. Since the fishing loss rate indicates the impact of fishing to the ecosystem by showing the proportion of the production caught every in tons per square kilometre, it is evident that the higher trophic levels are targeted because the peak is seen at trophic level 4.9. there is however another lower peak at trophic level 3 indicating another group of species targeted by fisheries which make up the tilapia and the dagaa.

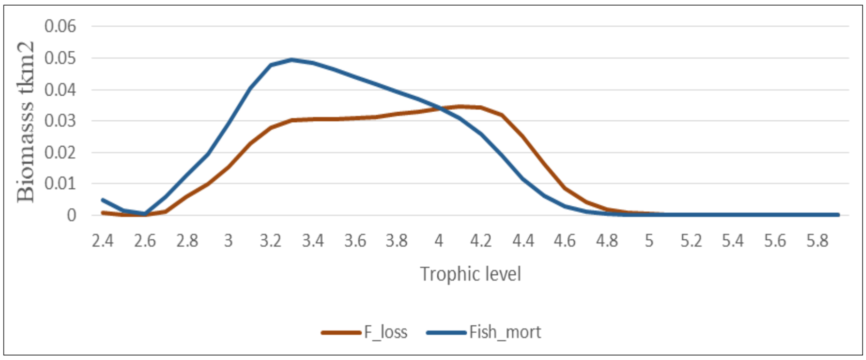

Fig 5: Fishing loss rate and the fishing mortality, the two important indices that describe the effects of fisheries on the ecosystem

3.5 Biomass changes due to fishing

As the Nile perch biomass goes down, the biomass of the lower trophic level species goes up. On increasing the fishing pressure on Nile perch and Nile tilapia, the biomass of Nile perch and Nile tilapia reduces but the biomass for the haplochromines and the dagaa and most of the mid-trophic level species increases considerably.

3.6 Influence of fishing on Catch

3.6.1 Mean trophic level of catch

It can be deduced that as the fishing effort increases the level of catches increase but not to a large extent. With continued exploitation, the catch gets to a point that it cannot increase anymore.

3.6.2 Mean trophic level of catch for Dagaa and Haplochromines

As the fishing mortality is increased in these lower trophic level species, the catch declines greatly as well as the biomass of the whole ecosystem. It gets to a point when there is only a very slight increase in caught biomass when the fishing mortality is severe. Only under overexploited conditions does the catch increase but to a very low extent. When there is increased fishing mortality on the lower trophic level the higher trophic level biomass reduces. This is the only scenario when there is an overall decline on biomass for all species in the lake.

4. Discussion

4.1 Lake Victoria Trophic Functioning

In most ecosystems, trophic interactions, functions and responses to human perturbations are controlled by the accessibility of biomass of that ecosystem, the biomass flow kinetics and the fishing loss rate determine the trophic functioning of an ecosystem.

In Lake Victoria only, a small proportion of the total biomass is accessible to fishing. This, therefore, makes the trophic functioning relatively stable. The exploitation of the lake mainly targets the higher trophic level Nile perch species and mid trophic level species the Dagaa. The impact of fishing on Dagaa is compensated by the huge biomass of mid trophic level species the haplochromines. The biomass flow is highest in the lower trophic levels because of the variety of the species undergoing regeneration. However, the Nile perch gives a very unique scenario of the ecosystem. Nile perch species are highly fecund and thus have a high rate of regeneration than most top predators. With enough diet from the haplochromines and the Dagaa the Nile perch has the capability of regenerating at a faster rate thus compensating for the low kinetics of biomass in the higher trophic levels. Nile tilapia and other tilapia feed lower in the trophic levels but are capable of growing to large sizes thus can be mistaken as high trophic level.

4.2 Different Fishing Scenarios

4.2.1 Impact on biomass

For the scenarios simulated, there did not appear to have a huge impact on biomass change due to fishing. As the fishing effort multiplier is increased more catch is realized but without devastating impacts to the trophic interactions. The lake seems to be a top-down ecosystem that is highly resistant to fishing impacts. When there is actually increased fishing in the higher trophic levels the ecosystem becomes even more stable because there is predatory release to the lower trophic organisms [18] which form the prey for the Nile perch the major higher trophic level predator. From a general perspective, top-down control limits the impacts on biomass due to fishing even when there is strong fishing on the top predators and as long as the lower trophic remain unexploited or underexploited [19]. The only repercussion is that the top predators are overexploited and may disappear from the ecosystem. This is attested by the re-emergence of the haplochromines that long before were thought to be extinct [20]

[18] Gascuel, Guénette, and Pauly, "The Trophic-Level-Based Ecosystem Modelling Approach: Theoretical Overview and Practical Uses."
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4.2.2 Impact on catch
The catch increased as the fishing effort multipliers were increased to depict increased fishing. This is as expected because the more effort is applied to a fishery the greater the catch but only to a certain level. Using the mean trophic level catch for Nile perch, a trend of the increasing catch was recorded but only on very thin margins from the current fishing. This means that the level of exploitation at the current moment cannot be increased to any extent to make it larger. The increase in exploitation of dagaa and haplochromines, the lower trophic level species, from the current rate, shows very drastic impacts to the species and to the ecosystem. The catch dwindles with increased exploitation pressure applied to the species. Then there is a slight increase with very intense fishing effort multipliers due to a phenomenon referred to as fishing down the marine food webs by (Pauly *et al*., 1998), fishing that targets the high trophic levels does not affect strongly the mean trophic level of biomass as when fishing is directed towards the low trophic species.

5. Conclusion and Recommendations
Ecotroph is a model that leaves the notion of species behind and only structures an ecosystem as a system of biomass flow through the trophic levels. The biomass is high in the low trophic levels and decreases higher in the trophic levels

The trophic interactions of the Lake Victoria ecosystem have been identified to be determined by the biomass flow speed referred to as kinetics, the accessibility of the biomass to fishing and the range of trophic levels. Lake Victoria has only few trophic levels reaching a maximum of TL4 where the top predators are in trophic level TL3. Most of the biomass is in lower trophic levels.

On exploring the different fishing scenarios, the system showed resistance to fishing pressure. With increasing pressure, the change in biomass was very little showing only a change of 20% in biomass. The lower trophic levels, TL2 and TL2.5 showed great resistance to fishing and this is explained by the high rate of resource recycling and production.

Fishing at low trophic species reduces the biomass of the whole ecosystem significantly in the negative. The ecosystem experiences a state of collapse. When the fishing is halted in high trophic level species the ecosystem biomass reduced significantly and as well experiences a state of collapse. Therefore, increased fishing in the high trophic level species and reduced exploitation in the lower trophic level species is a recipe for a stable Lake Victoria ecosystem.

When the biomass of high trophic level species is reduced through withdrawal by fishing, a predatory release phenomenon is created. Meaning that the lower trophic species get to increase in biomass and thus the resurgence of reduced biomass in haplochromines observed in Lake Victoria.

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