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Assessing Sustainable Fishing Yields Using Length-based Analytical Models: A Case Study with Nile Tilapia in Lake Hawassa (Ethiopia)

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Abstract

Nile Tilapia, *Oreochromis niloticus*, is one of important commercial fish in Africa and other tropical regions. In Ethiopia, it accounts for more than 60% of the total annual landings. In Lake Hawassa, one of the rift valley lakes in Ethiopia, it even mounts to more than 85%. However, recently, the yield in the lake dropped to about 50% of its historical maximum, indicative of a dwindling population size resulting from overfishing. This research aimed at assessing the sustainable potential yield of tilapia in Lake Hawassa. Data were collected for one year, on a daily basis, from the commercial fishery. The growth parameters (L_∞ and K), the total population (N) and the fishing mortality (F) were estimated using FiSAT II. The maximum sustainable and economic yields (MSY & MEY) and the corresponding fishing effort were determined using the length-based Thompson & Bell bio-economic model. Accordingly, the MSY was estimated at 466.3 tonnes per year. Our findings will be instrumental to prepare a fishery management plan for the lake. The procedure can also be applied to assess the fish stock of the other rift valley lakes.

Keywords: Fish stock assessment; Fishery management; Lake Hawassa; Maximum sustainable yield; Nile Tilapia; Overfishing

Introduction

Freshwater fisheries play an important role in the provision of affordable animal protein, income and employment in many parts of Asia, Africa and South America [1]. Despite their ecological and socio-economic importance, many freshwater lakes and ponds in these regions are impacted by anthropogenic activities such as water abstraction, introduction of alien species, industrial effluents and overexploitation [2,3]. These water bodies received only minor consideration, for they are often considered as low economic value, inexhaustible and/or self regulating resources [4]. As a result many of them are polluted, overfished and/or vulnerable to habitat and biodiversity degradation [5].

Ethiopia has about 7,444 km^2 of inland waters from which potentially about 51,481 tonnes of annual fish yield can be harvested [6]. The fishery of the country, however, remains underdeveloped with a current production of not more than 30% of its estimated potential. The major commercial species contributing to more than 95% of the national fish yield are Nile tilapia (*Oreochromis niloticus* (Linnaeus 1758)), Labeo (*Labeo forskalii* (Ruppell 1835)), African catfish (*Clarias gariepinus* (Burchell 1822)), barbs (*Labeobarbus* spp.), and Nile perch (*Lates niloticus* (Linnaeus 1758)) [7].

Nile tilapia, a member of the Cichlidae, is native to many freshwaters of East Africa [8]. It adapts to a wide range of environmental conditions. For this reason, the species has been introduced into many tropical and subtropical inland waters and culture systems. It contributes considerably to global freshwater fish production. The species is by far the most dominant and economically valuable fish in Ethiopia [9-12] contributing to more than 60% of the annual fish yield [13].

The commercial fishery of Lake Hawassa is primarily concentrated on Nile tilapia that contributes to more than 85% of the total catch [14-16]. *Clarias gariepinus* and *Labeobarbus intermedius* contribute only 7-8% and 2-3%, respectively [14,15]. Fishing is conducted almost exclusively by the use of gillnets, set and hauled from small non-motorized wooden boats. Only few fishermen use long-lines for catfish. The fishery of Lake Hawassa started at a commercial level in the 1950s [14], when fishing was mainly carried out by concessionaires of limited capacity. Starting from the early 1990s, the fishery was in a continuous expansion with a rise in the number of fishermen and fishing gears. Following this progressive increment of the fishing effort, the annual fish yield in early 1990s reached to utmost of about 900 tonnes [14]. The fisheries have, however, undergone drastic changes in recent years. The yield has been continuously declining and reached to about 50% of the maximum record. This is indicative of a dwindling population size, probably resulting from overexploitation in the last two decades [13,14]. The estimates of the maximum sustainable yield (MSY) made for the fishery of the lake in recent years also show a similar trend [16-18] indicating the instability of the stock size and a reduction of its capacity to recruit.

A new and accurate assessment of the fish stocks in Lake Hawassa is urgently needed. Updated information on the status of the stocks and sustainable yields is important, especially in the light of the changing environmental conditions and for a science-based management of the fishery. Despite the many biological and limnological studies, only limited efforts have to date been made to assess the status of tilapia stock in Lake Hawassa. The objective of this study was therefore

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to estimate the maximum sustainable yield (MEY) and maximum economic yield (MEY) with the corresponding level of fishing effort (fMSY and (fMEY).

Material and Methods

Site descriptions

Lake Hawassa is located at 6⁰33' - 7⁰ 33' N and 38⁰22' - 38⁰29' E, in southern Ethiopia at an altitude of 1680 m above sea level (Figure 1) [11,15,19]. The lake is one of the Ethiopian rift valley lakes and has a surface area of about 90 km^2 [20]. The maximum and mean depths of the lake are 22 m and 11 m, respectively [19]. It is an endorheic lake with no visible outlet [21] and receives most of its water from the Tikur Wuha River [22].

Unlike the other southern rift valley lakes in Ethiopia, Lake Hawassa harbors low fish species diversity [23]. Only six species are currently known: Nile tilapia, *Oreochromis niloticus;* African catfish, *Clarias gariepinus; Labeobarbus intermedius* (Ruppell 1835)*; Barbus paludinosus* (Peters 1852)*; Garra quadrimaculata* (Ruppell 1835) and the black lampeye, *Aplocheilichthys antinorii* (Vinciguerra 1883). Only the first three species are commercially exploited while the rest have no commercial value [15,19,24].

There are two landing sites, Amora Gedel and Tikur Wuha (Figure 1). Fishermen, operating in the southern part, fish in about one third of the lake area and land their catch at Amora Gedel. Others operating in the north, fish the northern one third and land their catch at Tikur Wuha. The fishing grounds of the northern and southern fishery do not overlap and a free zone exists in-between them. While small and medium sized tilapias dominate the landings of the southern fishery, the proportion of catfish and large size tilapia is relatively substantial in the northern fishery. The species composition, however, is totally same.

Data collection and summarization

Weight of total catch per boat (TW), weight of a random sample of 20 fish per boat (SW), total length (TL) of sampled fishes and number of gillnets used were recorded for all boats on a daily basis from June 2013 to May 2014 at the two landing sites of the commercial fishery. For those boats for which no full recordings could be made, the numbers of nets were registered to be used as a proxy for the catch. TW and SW from each boat were measured (in kg) using a spring balance (50 g precision). The selection of 20 tilapia specimens per sample boat was based on the order of their appearance in the fishing nets. For catches with less than 20 specimens, all fish were measured. The TL of each fish was measured to the nearest mm using a measuring board. Fish price data were obtained from both landing sites where tilapia sold under three size categories: small, medium and large. To determine the coefficients of the length weight relationship, 738 tilapias were sampled. The TL and weight were measured using a measuring board and digital balance, respectively.

To summarize some important fisheries statistics, firstly total lengths were arranged into length intervals of one centimeter and length frequency distributions calculated per day. Then the total number of nets used, the number of sampled nets and the catch of the day (kg) of sampled nets were quantified. From these values, the total yield of the day (kg) was calculated by extrapolation.

$$\text{Total yield of the day(kg)} = \frac{(\textit{total number of gillnets set X catch of samples nets}(kg))}{\textit{number of sampled gillnets}}.$$

The total catch/day (in number) was then calculated in a similar way.

$$\text{Total catch of the day}(\textit{number}) = \frac{\textit{total yield of the day}\,(kg)\,X\ \textit{number of length measured fish}}{\textit{weight of length measured fish}(kg)}.$$

To make a summary of the length frequency of the daily catch, the total catch per day (in number) calculated above was distributed into length groups in proportion to the length distribution of the sampled fishes of respective day.

A number of steps were taken to convert the length frequency data of the sampled fishes into total number and weight of fishes caught during the study period. The data was arranged per month that served as time series records in the FiSAT II (FAO-ICLARM Stock Assessment Tools) software. The average number of tilapia caught per day at each length interval was calculated, using numbers of tilapia caught on each sampling days for each month. The monthly total catch (in numbers) of each length interval was calculated by multiplying the daily average by the number of days in each month. These procedures were separately applied for the southern and northern fishery. Finally, monthly total catch at each length interval of the southern and northern grounds were merged to get the monthly length frequency of the entire lake fishery.

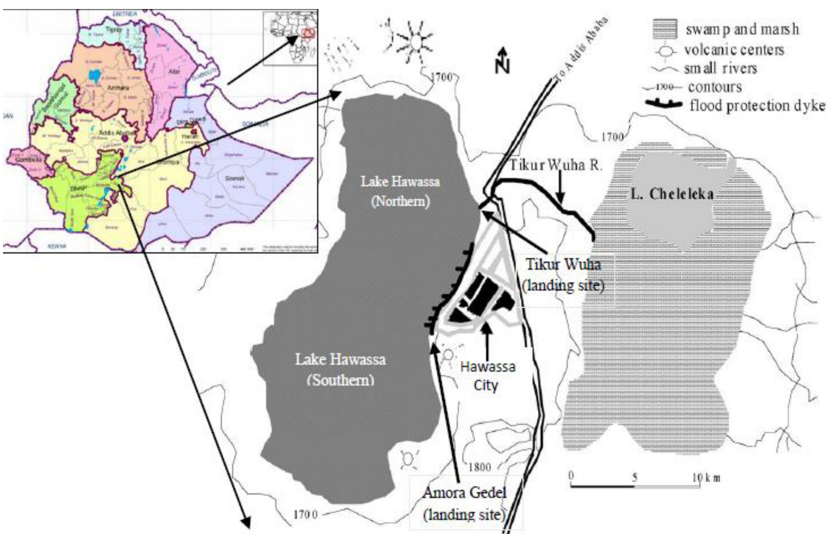

Figure 1: Lake Hawassa and the location of the landing sites on the lake.

Data analysis

To estimate the MSY, MEY and the corresponding fishing efforts, a standard length-based analytical fish stock assessment model, the absolute yield prediction model of Thompson & Bell model [25], which is commonly applied to the tropical fishery data [26-28] was used. The model also estimates the MEY and fMEY using the price of fish at landing and fishing costs as input data. N (total population) and F (fishing mortality) were used as input data. These were generated by applying [29] cohort analysis model, which in turn uses total catch arranged by length groups, the values of von Bertalanffy growth function (VBGF) parameters, the asymptotic length ($L\infty$) and growth parameter (K), average values of total mortality (Z), natural mortality (M) and average fishing morality (F) as input data. The model has been well described by Sparre and Venema [26]. Thus, our length frequency data arranged by 12 months were fed to FiSAT II and the values of N and F were estimated for the respective length groups.

The VBGF parameters were estimated by the FiSAT II software package making use of our merged length frequency data. The annual instantaneous or average rate of total mortality coefficient (Z) was also estimated using this software. In principle, Z is obtained from the linearized length-based catch curve analysis of the age frequency data [30]. In this case, it is the negative value of the slope of the graph of the age of the average length of consecutive age groups ($t\,\bar{L}$=(-1/k)*LN(1-(E3/ L_∞) plotted against the natural logarithm of the frequency in the sample catch (LN(C(L1,L2)/Δt, where Δt for length-based methods is equal to (1/k)*LN((L_∞-L1)/(L_∞-L2)) [26]. The natural mortality rate (M) was taken as 0.35 per year from the independent works [18,31,32].

Finally the MSY and MEY and the corresponding numbers of fishing gear were predicted using the Thompson & Bell yield prediction model. The model first predicts yield and revenue and then estimates the cost of fishing and profit derived at different levels of fishing intensity (F-factor) [26]. The aim is to firstly understand the relationship between the level of fishing effort and yield [33] and secondly to estimate the MSY, MEY and the corresponding fishing effort. The model has been well described by Sparre and Venema [26].

Results

More than two third of the tilapia catch comes from the southern fishing ground (Table 1). This may be attributed to the number of fishing nets deployed and the extent of the fishing area. While the proportion of large sized fish was relatively high in northern fishery, the abundance of small sized fish was comparably high in southern (Table 2).

Using FiSAT II, $L\infty$ and K were estimated to be 36.23 cm and 0.33 per year, respectively. For comparison, the merged data were fed to the FISHBASE length frequency analysis wizard of *O. niloticus* [33,34]. The

Operation measures	Southern fishery	Northern fishery	Whole lake fishery
Total number of fishermen in operation	270	50	320
Average number of boats operated /day	51	13	64
Total gillnets set /year	160439	89533	249972
Average gillnets set /day	440	245	685
Total number of fish caught/year	1579008	472132	2051140
Total weight of the catch/year (tonnes/yr)	330.2	132.2	462.4
Catch/day (number)	4326	1294	5620
Weight of catch/day (kg)	904.7	384.2	1266.9
Catch/gillnet/day (number)	9.8	5.3	8.2
Weight of catch/gillnet/day (kg)	2.1	1.5	1.8

Table 1: Summary of statistics of the tilapia fishery operated at the southern and northern fishing grounds, and for the whole of Lake Hawassa.

	Southern fishery		Northern fishery		Whole lake fishery	
Length group	Catch/year in number	Contribution (%)	Catch/year in number	Contribution (%)	Catch/year in number	Contribution (%)
15-16	240	0.02	20	0	260	0.01
16-17	2635	0.17	11918	2.52	14553	0.71
17-18	11122	0.7	4077	0.86	15199	0.74
18-19	45237	2.86	22070	4.67	67307	3.28
19-20	123607	7.83	19048	4.03	142655	6.95
20-21	253995	16.09	57212	12.12	311207	15.17
21-22	288323	18.26	37678	7.98	326001	15.89
22-23	306397	19.4	44977	9.53	351374	17.13
23-24	246280	15.6	48574	10.29	294854	14.38
24-25	164107	10.39	37548	7.95	201655	9.83
25-26	71386	4.52	36756	7.79	108142	5.27
26-27	34756	2.2	31347	6.64	66103	3.22
27-28	17764	1.13	19506	4.13	37270	1.82
28-29	6808	0.43	25309	5.36	32117	1.57
29-30	3068	0.19	12919	2.74	15987	0.78
30-31	1806	0.11	29226	6.19	31032	1.51
31-32	839	0.05	14000	2.97	14839	0.72
32-33	239	0.02	10342	2.19	10581	0.52
33-34	200	0.01	6827	1.45	7027	0.34
≥ 34	199	0.01	2778	0.59	2977	0.15
Total	**1579008**	**100**	**472132**	**100**	**2051140**	**100**

Table 2: Estimated annual catch by length group (in cm) of tilapia caught by the fishery operated in the southern and northern parts and in total for Lake Hawassa.

values of the stated parameters were estimated similarly at 36.6 cm and 0.35 per year respectively, where maximum TL=35 cm.

The length frequency data of the southern, northern and whole lake fishery, arranged according to a time series of 12 months, were fed to FiSAT II separately. The corresponding values for Z for the three fisheries were estimated at 2.18, 0.74 and 1.06 (Figure 2).

The ascending left and right limbs (open data points) represent length groups which were either not fully recruited or were too small to be totally vulnerable to the fishing gear. Those at the right limb of the graph (also represented by open data points) were considered to be close to asymptotic length. Both were excluded from the regression analysis. Those in the middle part represent size/age groups that are fully vulnerable to the fishing gear.

N and F values of the cohort analysis (Table 3) were used as inputs for yield prediction. First the current yield and the revenue generated were calculated using the values of a and b from the length-weight relationship ($W=aL^b$, where W=weight (g) and L=total length (cm)) and the average fish price. Using TL and weight of 738 tilapia samples, the values of a and b were estimated to be 0.0389 and 2.7601, respectively with R^2=0.8943. These values were applied to calculate the mean weight of average length of fish (in kg), (W(L1,L2)/2) corresponding to each mean length ((L1+L2)/2) as (W(L1,L2)/2)=(a((L1+L2)/2 $)^b$)/1000.

The mean weight of each length group (W(L1,L2)/2) was again multiplied by the number of fish in each length interval to get the production or yield, Y(L1,L2), of fish in each length interval in tonnes (Table 4). Adding up the yield obtained per year from each length group gives the current total annual yield of that particular site.

Yield (tons) Y(L1,L2)=Number of fish*mean weight in kg/1000.

The current annual yield is the sum of the annual yield of all sites (=ΣY(L1,L2)).

Data collected on the length range of small, medium and large size tilapia from the fish market and their corresponding price, P(L1,L2), has been summarized (Table 5). The revenue generated from each length group, R(L1,L2), and the current total annual revenue were calculated as follows.

R(L1,L2)=number of fish* P(L1,L2) and current annual revenue=ΣR(L1,L2).

Yield, revenue, cost and profit of the fishery were estimated using the Thompson & Bell yield prediction model. The model assumes that

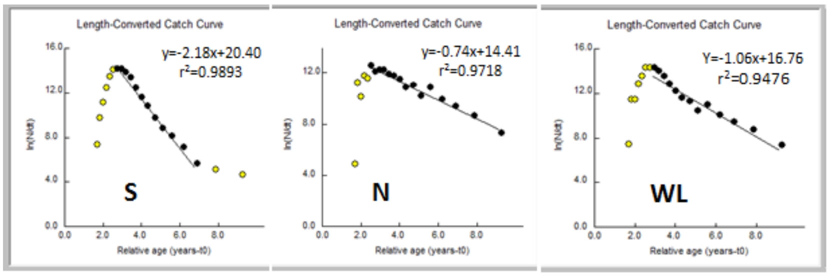

Figure 2: Estimates of the average total mortality coefficient (Z=value of slope) of the fishery operated at southern (S) and northern (N) part and whole of Lake Hawassa (WL) using FiSAT II.

	Southern fishery			Northern fishery			Whole lake fishery		
Length group	Catch/ year	N(L1,L2)	F (L1,L2)	Catch/ year	N (L1,L2)	F (L1,L2)	Catch/ year	N (L1,L2)	F (L1,L2)
15-16	240	2536138	0.001	20	1138863	0	260	3653826	0.001
16-17	2635	2409388	0.007	11918	1082031	0.074	14553	3471299	0.028
17-18	11122	2280697	0.031	4077	1013789	0.026	15199	3275420	0.03
18-19	45237	2144300	0.129	22070	954002	0.141	67307	3080286	0.133
19-20	123607	1975865	0.368	19048	877179	0.125	142655	2836074	0.294
20-21	253995	1734768	0.851	57212	804832	0.396	311207	2523667	0.707
21-22	288323	1376319	1.187	37678	697057	0.28	326001	2058464	0.87
22-23	306397	1003011	1.724	44977	612287	0.359	351374	1601341	1.17
23-24	246280	634425	2.167	48574	523512	0.427	294854	1144837	1.309
24-25	164107	348366	2.607	37548	435097	0.366	201655	771148	1.233
25-26	71386	162223	2.179	36756	361611	0.399	108142	512233	0.885
26-27	34756	79372	1.975	31347	292618	0.385	66103	361319	0.687
27-28	17764	38455	1.923	19506	232738	0.268	37270	261532	0.471
28-29	6808	17457	1.365	25309	187758	0.396	32117	196590	0.488
29-30	3068	8904	1.025	12919	140086	0.233	15987	141457	0.288
30-31	1806	4788	0.995	29226	107717	0.661	31032	106064	0.724
31-32	839	2347	0.783	14000	63018	0.441	14839	60024	0.499
32-33	239	1133	0.337	10342	37900	0.456	10581	34774	0.52
33-34	200	646	0.41	6827	19616	0.476	7027	17075	0.595
≥ 34	199	275	0.915	2778	7764	0.195	2977	5912	0.355
Total	**1579008**	**16758877**		**472132**	**9589475**		**2051140**	**26113342**	

Table 3: Estimates of total annual catch of tilapia, population number (N) and fishing mortality coefficients (F) by length group using FiSAT II software.

		Southern fishery		Northern fishery		Whole lake fishery	
Length group (cm) (L1,L2)	**Mean weight (kg) W (L1,L2)**	**Current catch (number) C (L1,L2)**	**Current yield (tonnes/year) P (L1,L2)**	**Current Catch (number) C (L1,L2)**	**Current yield (tonnes/year) P (L1,L2)**	**Current catch (number) C (L1,L2)**	**Current yield (tonnes//year) P (L1,L2)**
15-16	0.08	240	0.02	20	0	260	0.02
16-17	0.09	2635	0.24	11918	1.06	14553	1.3
17-18	0.1	11122	1.17	4077	0.43	15199	1.59
18-19	0.12	45237	5.53	22070	2.7	67307	8.23
19-20	0.14	123607	17.48	19048	2.69	142655	20.18
20-21	0.16	253995	41.24	57212	9.29	311207	50.53
21-22	0.19	288323	53.39	37678	6.98	326001	60.37
22-23	0.21	306397	64.33	44977	9.44	351374	73.77
23-24	0.24	246280	58.3	48574	11.5	294854	69.8
24-25	0.27	164107	43.58	37548	9.97	201655	53.55
25-26	0.3	71386	21.17	36756	10.9	108142	32.07
26-27	0.33	34756	11.46	31347	10.34	66103	21.8
27-28	0.37	17764	6.49	19506	7.13	37270	13.61
28-29	0.4	6808	2.74	25309	10.2	32117	12.95
29-30	0.44	3068	1.36	12919	5.73	15987	7.09
30-31	0.49	1806	0.88	29226	14.21	31032	15.09
31-32	0.53	839	0.45	14000	7.44	14839	7.89
32-33	0.58	239	0.14	10342	5.99	10581	6.13
33-34	0.63	200	0.13	6827	4.3	7027	4.43
≥ 34	0.68	199	0.14	2778	1.9	2977	2.03
Total		**1579008**	**330.23**	**472132**	**132.2**	**2051140**	**462.43**

Table 4: Estimates of mean weight, annual catch and total yield of tilapia by length group.

	Southern fishery			Northern fishery			Whole lake fishery		
Length group (cm) (L1,L2)	**Current catch (number) C (L1,L2)**	**Price per fish (USD) P (L1,L2)**	**Current revenue (USD/year) R (L1,L2)**	**Current catch (number) C (L1,L2)**	**Price per fish (USD) P (L1,L2)**	**Current revenue (USD/year) R (L1,L2)**	**Current catch (number) C (L1,L2)**	**Price per fish (USD) P (L1,L2)**	**Current revenue (USD/year) R (L1,L2)**
15-16	240	0.24	56.81	20	0.19	3.88	260	0.22	55.99
16-17	2635	0.24	623.71	11918	0.19	2312.12	14553	0.22	3134.03
17-18	11122	0.24	2632.62	4077	0.19	790.95	15199	0.22	3273.15
18-19	45237	0.24	10707.76	22070	0.19	4281.63	67307	0.22	14494.75
19-20	123607	0.24	29258.22	19048	0.19	3695.35	142655	0.22	30721.16
20-21	253995	0.24	60121.53	57212	0.19	11099.25	311207	0.22	67019.31
21-22	288323	0.24	68247.09	37678	0.19	7309.61	326001	0.22	70205.24
22-23	306397	0.24	72525.28	44977	0.19	8725.63	351374	0.22	75669.39
23-24	246280	0.35	86339.46	48574	0.19	9423.46	294854	0.27	80285.27
24-25	164107	0.35	57531.71	37548	0.19	7284.39	201655	0.27	54908.28
25-26	71386	0.35	25026.1	36756	0.32	11626.21	108142	0.33	36058.98
26-27	34756	0.35	12184.56	31347	0.32	9915.3	66103	0.33	22041.45
27-28	17764	0.35	6227.6	19506	0.32	6169.9	37270	0.33	12427.35
28-29	6808	0.55	3757.72	25309	0.32	8005.43	32117	0.43	13943.03
29-30	3068	0.55	1693.4	12919	0.75	9752.83	15987	0.65	10446.53
30-31	1806	0.55	996.83	29226	0.75	22063.32	31032	0.65	20277.52
31-32	839	0.55	463.09	14000	0.75	10568.9	14839	0.65	9696.38
32-33	239	0.55	131.92	10342	0.75	7807.39	10581	0.65	6914.04
33-34	200	0.55	110.39	6827	0.75	5153.85	7027	0.65	4591.72
≥ 34	199	0.55	109.84	2778	0.75	2097.17	2977	0.65	1945.29
Total	**1579008**		**438745.67**	**472132**		**148086.54**	**2051140**		**538108.86**

Table 5: Estimates of annual revenue obtained from tilapia in Lake Hawassa.

changes in the fishing effort (decrease or increase) impacts the fishing mortality level and the fish yield. A change in the fishing effort was made using the F factor 0.1-2.0 to obtain the fishing mortality level that gives the highest production level, MSY and MEY. The resulting predicted yield and revenue were recorded for the changes made in F. Fishing costs were estimated from our survey of labor, boat and fishing net costs during this study (Table 6). The profit derived at different levels of F was the difference between the revenue and costs.

The total annual yields (current yield) during our study period for the southern, northern and whole lake fishery in tonnes were 330.23, 132.20 and 462.43, respectively (Table 4). The fishing effort used and revenue generated are indicated in Tables 1 and 5, respectively.

Based on the intermediate values generated above; the MSYs, MEYs and the corresponding profit were estimated (Table 7 and Figure 3). Accordingly, the MSYs for the southern and northern and for the

Item	Southern fishery	Northern fishery	Whole lake fishery
Rowing wooden boat			
Cost of fishing boat (USD/boat)	158.15	158.15	158.15
Service year	5 years	5 years	5 years
Annual Depreciation cost (USD/boat)	31.63	31.63	31.63
Average number of boat operated/day	51	13	64
Total cost of boat per year (USD)	1613.13	411.19	2024.32
Gillnet			
Cost of net making (USD/gillnet)	52.72	52.72	52.72
Service year	1year	1year	1year
Annual depreciation cost (USD/gillnet)	52.72	52.72	52.72
Average number of gillnet set per day	440	245	685
Total cost of gill net per year (USD)	23196.8	12916.4	36113.2
Labor			
Labor cost (USD/ man power/day)	2.64	2.64	2.64
Operating person per boat	4	4	4
Average number of boats operated/day	51	13	64
Total labor cost/day (USD)	538.56	137.28	675.84
Total labor cost per year (USD)	196574.4	50104.2	246681.6
Total cost of fishing operation/year (USD)	**2,21,384.33**	**63431.79**	**2,84,819.12**

Table 6: Estimated cost of fishing for the fishery operated at the southern, northern and whole Lake Hawassa.

F-factor	Southern fishery		Northern fishery		Whole lake fishery	
	Predicted total annual		Predicted total annual		Predicted total annual	
	Yield (tonnes)	Profit (USD)	Yield (tonnes)	Profit (USD)	Yield (tonnes)	Profit (USD)
0.1	178.13	186006.49	32.11	31580.16	158.15	149509.76
0.2	260.79	269098.72	56.75	53976.71	261.71	238927.49
0.3	300.56	302758.42	75.79	69475.34	330.44	289603.97
0.4	319.77	311200.2	90.58	79764	376.51	314886.17
0.5	328.73	306225.08	102.15	86098.47	407.6	323290.8
0.6	332.44	293870.55	111.24	89419.35	428.63	320347.13
0.7	333.44	277338.58	118.41	90435.45	442.82	309698.16
0.8	333.04	258379.13	124.09	89683.91	452.3	293774.52
0.9	331.92	237975.6	128.6	87573.88	458.51	274215.62
1	330.46	216696.27	132.2	84418.38	462.43	252137.63
1.1	328.86	194879.14	135.07	80457.91	464.74	228306.58
1.2	327.23	172731.35	137.35	75877.91	465.92	203251.78
1.3	325.62	150383.57	139.17	70821.82	466.28	177341.15
1.4	324.06	127920.57	140.61	65400.85	466.07	150831.58
1.5	322.57	105398.59	141.75	59701.46	465.46	123903.17
1.6	321.14	82855.55	142.64	53790.93	464.57	96682.51
1.7	319.79	60317.24	143.32	47721.68	463.49	69258.73
1.8	318.5	37801.15	143.84	41534.54	462.28	41694.66
1.9	317.28	15318.95	144.22	35261.35	460.99	14034.56
2	316.11	-7121.9	144.49	28926.83	459.64	-13690.48
2.1	315	-29516.91	144.66	22550.18	458.28	-41458.66
2.2	313.94	-51863.86	144.75	16146.25	456.91	-69254.81
2.3	312.94	-74162.1	144.78	9726.45	455.54	-97068.44
2.4	311.97	-96412.2	144.75	3299.48	454.19	-124892.42
2.5	311.05	-118615.54	144.68	-3128.07	452.87	-152721.98

Table 7: Annual yield and net profit obtained from the tilapia fishery, Lake Hawassa.

whole lake fishery were estimated as 333.44, 144.78 and 466.28 tonnes attained at F-factors 0.7, 2.3 and 1.3, respectively.

Discussion

The tilapia fishery of Lake Hawassa is vital to support the livelihood and well-being of the fishing communities and maintain the supply of food to the local communities and the growing population and visitors of Hawassa city. It is a source of livelihood for 16,000 people and many entrepreneurs [16,21]. Furthermore, the fishery and the lake as a whole also serve as an attraction and destination for many local and foreign visitors [10]. Currently, however, the fish yield is progressively diminishing resulting likely from intense exploitation in the past couple of decades.

Length-based fish stock assessment models have progressively been applied for tropical fishery in comparison to age-based methods that are more employed for temperate waters [26,28]. Moreover, in contrast to the difficulty in acquiring age estimates, it is much easier to collect length data [35,36]. In the current analysis, we developed three models for sustainable tilapia utilization that apply for the fishery conducted in the southern and northern parts and the whole lake. We estimated the

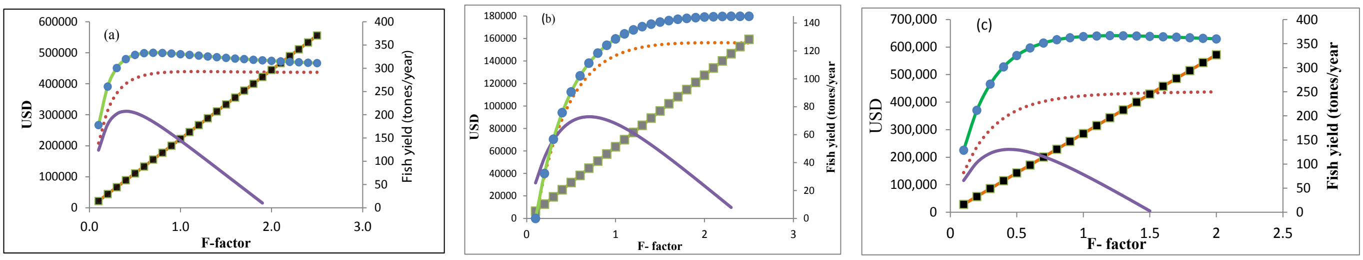

Figure 3: Predicted total annual yield, revenue, cost and net profit at different values of F-factor for the tilapia fishery in Lake Hawassa. (a) southern part of lake; (b) northern part of lake; (c) whole lake. Predicted revenue, predicted total cost, predicted net profit, predicted yield.

sustainable annual yield of the species and the corresponding fishing effort by using length-based models of fish stock assessment. The method established for the lake can also be applied to other tropical lakes where long-term (at least one year) fish length data is available.

Three major information were derived from the summary of our data: length composition of the catch, fish yield and the corresponding effort, and market value of the fish caught. The first two were utilized as input data to estimate the VBGF parameters which were in turn utilized as input data during cohort analysis. Finally, the estimates of fishing mortality coefficients, the parental stock size and market data were analyzed using the Thompson & Bell model to predict the MEY, MSY and the corresponding fishing effort. Our estimated values of the growth parameters L_∞ and K were 36.23 cm and 0.33 per year, respectively. These estimations are in agreement with those of previous authors. Based on the early works of Demeke and Yosef [31,32], Tadesse and Seyoum) [16] estimated L_∞ and K for adult tilapia of Lake Hawassa to be 40 cm and 0.5 per year, respectively. It is possible that the change in the values of these parameters is due to fishing pressure [37] exerted during the last couple of decades. According to these authors, data resources and physiological conditions related to environmental conditions may also be probable factors.

The annual instantaneous rate of mortality (also called average rate of total mortality) (Z) derived from the length converted catch curve for the southern and northern fishery were 2.18 and 0.74 per year, respectively (Figure 2). If there is no fishing and natural mortality, which is not the case under natural environment, Z is simply 0. Relatively high value of Z means high rate of total mortality and the cohort subjected in that fishery decrease faster in numbers [26]. The Z value corresponding to the southern fishery is about three times higher than the Z value inflicted by the northern fishery indicating relatively high fishing pressure in this portion of the lake. The value of Z for the whole lake fishery was 1.06 per year. Based on data collected from previous fishery, Tadesse and Seyoum [16] estimated Z (for the whole lake fishery) at 1.8 per year. The current low value of Z of the whole lake illustrates a relieve in the intensity of fishing pressure resulted from the reduction in the number of gillnets. This value of Z (1.8) is lower than our present value of Z of the southern fishery indicating the population and its replenishing capacity has already been diminished. Even though the number of gill nets was high in the former fishery; the population of the fish was also in a better condition. Thus, the present level of fishing nets is comparably higher to current population of fish than the former fishing effort on the population of that time.

As indicated in Table 2, the catch in the whole lake was dominated by length groups 18-27 cm. About 92 % of the catch in the southern fishery comes from length groups 19-26 cm while 90 % of the catch in the northern fishery comes from the length groups 18-31 cm (Table 2). Even fish larger than 30 cm were prominently seen in the catches of the northern fishery but such large-sized tilapia is seldom found in the catches of the southern fishery. The cohort analysis (Table 3) also shows that the fishing mortality (F) in the fishery of the southern part of the lake is generally high at length groups ranging between 19-30 cm and peaking at 24-25 cm. In comparison, F was generally low in the north reflecting relatively low fishing pressure. The F of the northern fishery was highest for length groups between 21-31 cm, with two peaks at 23-24 cm and at 30-31 cm. These observations might be due to intensive fishing conducted for a long period of time at the southern part of the lake.

Because their yield is decreasing, fishermen reduced the mesh size of their gill nets to compensate by increasing the number of small fishes. Currently, more than 80% of the gill nets used in Lake Hawassa have a stretch mesh size of 7-10 cm [38]. The recommended minimum mesh size for the lake is 8 cm [14]. Most fishermen in the north use relatively large mesh-sized gillnets as large fishes which fetch a better price per piece are still abundant in this part of the lake. Some fishermen, however, also use small mesh-sized gillnets just like fishermen in the southern part of the lake. Smaller fishes are needed in the market for filleting while big ones are utilized for whole frying.

The MSY and MEY of the tilapia fishery of the whole Lake Hawassa were estimated at 466.28 and 407.60 tonnes/annum, respectively (Table 7 and Figure 3). In order to attain the MSY of the lake, our result suggests (Table 7), there should be a reduction of the number of fishing nets by 30% in the south and increment by 230% in the northern fishery. This totally makes 811 nets. If the management intends to increase the profitability, the fishing nets currently used in the south and north should be 176 and 171 respectively making the total number of nets 347.

Our results clearly demonstrated overfishing in southern part of the lake. The MSY in this part of the lake will be attained only if the fishing nets are reduced. The MSYs of the southern, northern and whole lake were estimated at 333.44, 144.78 and 466.28 tonnes per year, respectively (Table 7). The estimated annual yields in the study period for the mentioned fishing grounds were 330.23, 132.20 and 462.43 tonnes per year (Table 1), which corresponds with 99%, 91% and 99% of the corresponding MSY, respectively. However one should note that attaining the MSY at F-factor of 0.7 (Table 7) means that the southern part of the tilapia stock has been overfished and that the current fishing intensity overpasses the level of effort which sustains the annual yield. Inspite of overexploitation of tilapia in the southern fishery, the annual yield is still comparable to the MSY. This is because tilapia is resilient for high level of fishing efforts which might attribute to its reproductive strategy such as early maturation which tries to counteract fishing [27].

At the current growth performance of tilapia, the production can be maintained at MSY by reducing the effort by 30%. Further reduction of the fishing effort by 60% would maintain the fishery at MEY (Table 7 and Figure 3a-3c) and attain the highest profit. Reduction of the fishing effort would give more fish the opportunity to grow and reproduce. As a consequence, the future production would rise to the intended level of production, MSY or MEY. Another option to maintain this condition is just to increase the mesh size of gillnets which in turn allows small fishes to escape and to further grow and reproduce. The introduction of either of these measures reduces the yield and income of the fishermen temporarily. In the long run, however, it improves the population, the size composition of the yield and income of fishermen.

Stunting or dwarfing of tilapia can also be a sign of overexploitation [8,27,39] in the southern fishery. Length at first sexual maturity of tilapia in Lake Hawassa is 18 cm [40]. The proportion of fishes below 18 cm in the current catch is not very alarming. However, a study conducted on the lake indicated that length at which female tilapia first matures has decreased from 18.8 cm to 15.4 cm [14]. Early sexual maturation negatively affects the growth performance of the fish, the quality of the catch and fishermen's income. It is inevitable that the decline of length of first maturity and stunting will be aggravated as the fishing pressure increases. Besides, the nets used for tilapia also catch catfish and more than 70% of the catfish caught by tilapia net are between 30 and 40 cm TL. On the other hand length at first maturity of catfish is 45 cm [18] and thus increasing the mesh size of tilapia nets would improve the reproductive efficiency of catfish in the lake too.

The situation of the fishery in the northern part of the lake was somewhat different. The current yield was about 91% of the estimated potential. However, unlike the southern part, the optimum fishing effort that gives the MSY was not yet reached and the current annual yield was lower than the estimated MSY. Hence, the northern part of the tilapia stock seems to be in a relatively better condition. The average annual fishing mortality rate of 0.39 (Z-F) also reveals that the fishing pressure was relatively low. An increment of fishing effort would raise the yield to the level of MSY. This condition, however, may lead to the depletion of large size tilapia or mega-spawners. Secondly, the profit gained by the fishermen will be less (Table 7). Our result show that the profit in this north fishery would be maximized at 70% reduction of the current fishing nets, 172 gillnets per day. In such situations some small fishes and mega-spawners would get opportunity to continue to grow and reproduce better [34]. As discussed earlier, such a condition can also alternatively be achieved by increasing the mesh size of gillnets. This will in the long run increase the proportion of well grown fish in the landings which in turn results in a better price and income. As a result the overall profitability of the fishing business could increase.

The analysis of the merged data, which represents the fishery of the whole lake, estimated the MSY to be 466.28 tonnes per year at an F-factor of 1.3 (130% increment). This suggests a possibility of raising the number of gillnets in the northern part. However, the current yield was not significantly different from the estimated MSY. Thus, maintaining the current level of fishing effort; with some adjustment in the southern and northern fishery, i.e., -132 and +132 from and to the currently used number of nets, respectively); is safe. However, if the objective of the management is to raise the profitability of fishing business, the currently used fishing nets should be reduced by 50%. This condition reduces the annual yield to 407.60 tonnes/year but raises the profitability (Table 7).

Our estimate of MSY of the lake was in line with the decreasing trend of surplus production indicating that the intensity of fishing in the past shifted the stock towards a new state of equilibrium of lower level of productivity. Before the start of the commercial fishery Atkins and Partners [17] estimated the MSY of the lake at 1000 tonnes per year. After the introduction of commercial fishery and exploitation of the resource, the potential production has shown a significant reduction. In the 1990s, it was estimated at only 440 tonnes per annum [13]. The results of recent studies also revealed the decreasing trend. Previous studies also estimated at 641 [18] and 450 [41] tonnes/annum. Similarly, Tadesse and Seyoum [16] found the annual yield of tilapia to be 6.97 t/km^2 (627.3 tonnes/year) using a mass balance ecopath model. Other recent study in this regard [42] estimated the MSY for one-third of the lake to be 192 tonnes/year, which is equal to 576 per year for the whole lake fishery.

Even though the impact of environmental factors such as climatic variability, habitat degradation, and pollution on the ecosystem as well as fish growth and reproduction in the lake is not well understood, we suggest that the declining trend in MSY and the reduction of the annual yield of the fisheries of Lake Hawassa is due to overfishing. This is a situation occurring when the rate of exploitation of the stock by fisheries is much faster than it replenish itself [34]. It diminishes the ability of the fish to reproduce (recruitment overfishing) and increases the proportion of fish that do not attain their growth potential (growth overfishing) [34]. Another common sign for the occurrence of overfishing is a reduction in the mean length of fishes in the catch [27]. Stunting or dwarfing of tilapia is a common phenomenon whenever there is high fishing pressure [39]. In line with this pattern, also the tilapia of Lake Hawassa is becoming stunted and matures at a smaller size. The total length at which female tilapia first matures has decreased from 18.8 cm [40] to 15.4 cm [14]. As a result, the current catch is dominated by small and medium-sized fishes, which is especially evident in the southern part of the lake with a relatively high fishing pressure.

The sustainable potential yield of tilapia varies in different water bodies. This might be due to environmental factors and size and trophic level of the water body. In comparison to some nearby lakes, the potential tilapia yield per unit area is highest for Lake Hawassa (Table 8). This might be due to the associated wetland which serves as an extra feeding, breeding and/or hiding ground for the species and which contribute to a better water quality. In addition, Lake Hawassa is an endorheic lake where the incoming nutrients and growing plankton biomass are not removed by the flow of an outgoing river. Aggressive predators such as Nile Perch are absent in Lake Hawassa. Such factors might explain for the relatively high tilapia yield in the lake.

On the other hand, the application of management measures related to gear manipulation is substantial to maintain the water quality. As Nile tilapia grows to adult size; it becomes entirely herbivorous, feeding on phytoplankton [43-45]. Hence, increasing the proportion of adults in the population will also have a controlling effect on algal blooms that can be toxic when caused mainly by Cyanobacteria. Thus, our

Lake	Surface area (km^2)	Safe level tilapia yield (tonnes/year)	Yield in tonnes per km^2	Reference
Hawassa	100	440	4.44	Current study
Hawassa	100	466	4.66	[13]
Ziway	434	2000	4.61	[13]
Chamo	551	1700	3.09	[13]
Koka	255	500	1.96	[13]
Tana	3500	460	0.13	[13]
Langano	225	170	0.76	[13]
Naivasha	160	889*	5.56	[43]

*Yield of all fish species in the fishery.

Table 8: Comparison of the potential of tilapia yield per unit area of some Ethiopian lakes and L. Naivasha, Kenya.

recommendation to reduce the number of fishing nets and/or increase their mesh size not only improves the landings of the fishermen and the recruitment capacity of the parental stock but also maintains the aesthetic value and the trophic state of the lake.

Conclusion and Recommendation

Estimating the potential sustainable yield and the corresponding effort of commercial fishes in a fishery is very important since management basically relies on recent values of these parameters. The present findings disclose that the tilapia stock in Lake Hawassa has been over exploited during the past two decades. For a proper recovery of fish stocks, fishing mortality must be reduced so that growth and reproduction will improve to increase the size of the parental stock. We recommend that management should focus towards the three fisheries indicators; increase the percentage of mature fish, increase the percentage of fish with optimum length (length range where maximum yield could be obtained) and reduce the percentage of mega spawners in the catch. Mega spawners and undersized fishes must be protected by imposing a mix of management measures such as limitation of annual yield, number and mesh size of gillnets and seasonal and area closure. Letting small fishes to grow and spawn improves the spawning stock and future yield. Besides to serving the stock as reservoir of genes of individual fitness, mega spawners (females) produce large number and big size eggs which is important to ensure survival of larvae and increase recruitment [34].

Efforts must be made to provide better scientific information on e.g., optimum mesh size, size at first maturity, peak breading seasons, identification of breeding grounds, assessment of water quality parameters etc and utilize the findings in the management process. Hence, regular data collection for assessing the status of the stock and exploitation of Lake Hawassa should be encouraged. Management measures should be introduced and implemented based on the information gained from such assessments. On the other hand, the management should take action to restrict open access condition by enforcement of the existing legislation.

Beside to imposing management regulations, attention should be given to seeking multiple alternatives for employment, increase income of the fishermen and satisfy the growing demand for fish. One option is to organize fishermen under a functional association, provide training and facilitate schemes such as credit facilities sothat they will be engaged in fish processing. Value added products fetch better price and improve fishermen's income. Other area where attention should focus to help create alternative job opportunities to the fishing community and increase fish yield is to carry out land-based and/or water-based aquaculture. The application of one or more of these alternatives ultimately helps to increase the fishermen's income, reduce the fishing pressure and increase fish yield.

We also recommend that the fishery on Lake Hawassa should be managed by a single management body responsible both to the fishery operated in the northern and southern part of the lake. Formation of such a management body resolves the conflict and competition among fishermen of different groups.

Limitation of the Study

Although our research has reached its aims, there were some unavoidable limitations. The first limitation concerns the source of our intemediate input data, values of the growth parameters $L\infty$ and K. These were determined using FiSAT II. For verification we used FISHBASE length frequency analysis wizard of *O. niloticus* developed by 33 Rainer Froese that needed the maximum total length as an input data (35 cm). Because we collected all our sample fishes from the fishermen's landings who normally use similarly designed gillnets that selectively catch fishes of only certain size range. Due to this reason big fishes may be missed and our recording of maximum total length could be wrong. Secondly, the catch composition in our recording would have been different if we were collecting samples using for example seine nets. Generally, very small and very big sized fishes were not satisfactorily abundant in our recording. Lastly, our estimation of MSY applies only to Tilapia yield. However, Lake Hawassa, has a potential for the production of other commercial and non-commercial fishes such as African catfish and Labeobarbus species. In this case our estimation of MSY applies only for tilapia. These limitations would have impact on our result. Future research would have been more convincing if the researchers take these factors into consideration.

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