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Spatial and Temporal Distribution of Some Commercially Important Fish Species in the Southeast and Southwest Arms of Lake Malawi: A Geostatistical Analysis

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SPATIAL AND TEMPORAL DISTRIBUTION OF SOME COMMERCIALLY IMPORTANT FISH SPECIES IN THE SOUTHEAST AND SOUTHWEST ARMS OF LAKE MALAWI: A GEOSTATISTICAL ANALYSIS

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Abstract

The spatial and temporal distribution of the following fish species; *Alticorpus mentale*, *Bucochromis lepturus, Copadichromis virginalis, Diplotaxodon elongate,* and *Oreochromis* spp. in the southeast and southwest arms of Lake Malawi were analysed using bottom trawl catch per unit effort (CPUE) data collected during the bi-annual demersal monitoring surveys of 1995 and 1999. Geostatistical techniques were used to (i) model and estimate the spatial structure of abundance and (ii) ordinary kriging to predict local abundance.. Small-scale intra-area variation that was detected was used to model the spatial structure. Experimental variograms were calculated and fitted using spherical variogram model. Southwest and southeast arms of the lake were treated as separate regions due to differences in productivity and geographical orientation.

Generally the structure of the variograms varied with population density. The results indicate that *A. mentale* mainly occurs in deep waters of southwest arm. In southeast arm there was localised occurrence in deep waters of Area C with abundance increasing slightly over the past four years from 684 kg in 1995 to 1046 kg in 1999 in southeast arm and from 1933 kg in 1995 to 5834 kg in 1999 in southwest arm. *C. virginalis* principally occurs along the inshore waters of southeast arm especially in Area C off Makanjila and in Area B off Masasa and Nkhudzi Bay on the western shore and off Kadango on the eastern shore. The species has declined in abundance in Area C. The total biomass in southeast arm decreased from 19602 kg in 1995 to 8724 kg in 1999. *D. elongate* was distributed widely occurring in offshore waters of southeast arm from Area A to Area C in relatively high densities. The species occurs in highest densities in Area B, the distribution in Area C is not as wide as it used to be. The biomass has declined from 103437 kg in 1995 to 35365 kg in 1999. *Oreochromis* spp. occur mainly in Area A and to a smaller extent in shallow inshore waters of Area B. Abundance and distribution patterns have greatly decreased showing evidence for contraction. *B. lepturus* is evenly distributed in shallow waters of both southeast and southwest arms. The 1999 distribution pattern indicates that the species has slightly declined in abundance in the south eastern part of Area C and Area A. Biomass figures have not been provided for the shallow water species because of problems in distinguishing the water boundary from land during the kriging process.

Although sampling was not originally designed specifically for geostatistics, these results indicate that geostatistics can be successfully used to detect changes in the spatial and temporal distribution of fish stocks or species in lake Malawi using the existing data.

1 Introduction

Lake Malawi, situated in the African rift valley between $9^o30"S$ and $14^o30"S$ and bordered by Malawi, Mozambique and Tanzania, is the third largest lake in Africa with an average depth of 292 m (Patterson & Kachinjika, 1995). The shallow areas are the most productive and are found in the southeast and southwest arms of the lake.

The fisheries on Lake Malawi are mainly distinguished by their degree of mechanisation and are classified into traditional and commercial components. The commercial fisheries which are relatively mechanised and capital intensive are dominated by stern and pair trawlers (Banda & Tomasson, 1996). Of all the fishing gears, bottom trawl nets are the most important. Pelagic trawl nets and pulse seine nets are seldom used.

The commercial fishery was established in 1968 after successful experimental trials revealed the existence of large demersal stocks in the southern portion of the lake (Turner, 1976). All commercial fishing now occurs in the southern portion of the lake.

As the trawl fishery intensified, large changes in species composition were observed. Large cichlid species mostly belonging to the genus *Lethrinops,* the clariid catfishes and *Bagrus meridionalis* have declined in abundance. This decline was followed by a corresponding increase in small cichlids most of which were *Otopharynx* spp. and *Pseudotropheus* spp. (Turner, 1976). Several follow-up projects like the "Demersal Fisheries Re-assessment Project (1989-1994)" were initiated in 1991 and one of the main findings of this project was that there was a 50-70% decline in biomass estimates in Areas A, B and C (Figure 1) were noticeable between 1989 and 1994. Some changes in species composition were also noted, particularly in area B where the relative contribution of some of the larger cichlid species to the catch had decreased (Turner *et al*, 1995).

In view of these developments, the government of Malawi through the fisheries department introduced standardised demersal surveys in 1994 to monitor the status of the stocks in the two arms of the lake. These surveys were initially conducted on quarterly basis but due to logistical problems and lack of adequate funding the frequency was reduced to two surveys a year. Recent information from these surveys and other sources indicate that the chambo (*Oreochromis* spp.) stocks in Lake Malawi have declined to the lowest level ever and as such it was proposed that all gears targeting Chambo be banned in area A. Declining catch per unit effort (CPUE) is also observed for the stocks of bombe (*Bathyclarias* spp), kampango (*Bagrus meridionalis*) and utaka (*Copadichromis* spp.) but the fisheries for usipa (*Engraulicypris sardella*) and kambuzi (small non-catfish spp.) have remained relatively stable. The findings also indicate that despite the decline of some individual stocks, the overall CPUE for the deep-water stocks has remained relatively stable (Bulirani *et al*, 1999).

The fact that the overall CPUE has remained relatively stable, despite the decline in CPUE of the large species suggests that the small species are gradually increasing in abundance at the expense of the larger ones. Unfortunately these small species fetch low market prices. Due to low catch rates of commercially important species and the increasing abundance of small species, most trawlers and other fishermen have resorted to targeting specific areas in the lake where most of the species are caught in reasonable quantities. At present the species that are highly sought after are chambo (*Oreochromis* spp.), utaka (*Copadichromis* spp.), ndunduma (*Diplotaxodon* spp.), ncheni (*Rhamphochromis* spp.), kampango (*Bagrus* spp.) and bombe (*Bathyclarias* spp).

Concentrating fishing effort on a particular stock can have serious management implications especially in cases where the stock involved is localised and has a low fecundity. For instance, most mouth brooders produce relatively few offspring because of limited brooding space. Most of the Malawi cichlids fall into this category. In situations of intense fishing pressure and the use of small-meshed gears, chances of such stocks being depleted are high. At this point, it is worth noting that the 38 mm cod-end currently in use on the Lake Malawi trawl fishery is too small, with most of the demersal species being caught immature (Kanyerere, 1999). Such factors have undoubtedly contributed to the depletion of stocks in the lake.

The decline of some stocks within the southern portion of the lake suggests that the fishery is already facing serious problems, which might include intense and localised fishing pressure, growth over-fishing and recruitment failure. It is imperative that regulatory management procedures such as closed seasons and aggregate quotas, controlled area fishing and restrictions on fishing gears and technology be instituted where necessary. However, identification and formulation of such regulations require that;

i) areas or localities where significant reduction in CPUE and species abundance has occurred be identified.

ii) those areas where commercially important species are found and what changes the species might have undergone be identified.

iii) temporal changes of abundance for species with wide distributions and those with localised distributions in relation to area, depth and time are assessed.

iv) maps of species abundance by area, depth and time are produced.

The spatial and temporal distribution of commercial species needs to be assessed over a suitable time period. This can only be accomplished through the use of geostatistics as no traditional method is suitable for such assessments. Geostatistics takes the spatial autocorrelation between samples into consideration and through kriging, allows the analysis and modelling of the variability of a population in space (Matheron 1971 in Freire 1992). Ignoring spatial patterns when using catch per unit effort (CPUE) data to estimate stock abundance can sometimes lead to inaccurate assessments (Pelletier and Parna, 1994).

As geostatistics is a relatively new technique to the Malawian fisheries, this study is preliminary and will investigate the feasibility of using geostatistics:

-to model the abundance, spatial and temporal distribution of *Alticorpus mentale, Buccochromis lepturus, Copadichromis virginalis, Diplotaxodon elongate* and *Oreochromis* spp. and

-to assess if the existing sampling locations meet the requirements of geostatistical analysis.

2 Materials and Methods

2.1 Sampling sites

The data were collected onboard the research vessel, *R.V. Ndunduma* using demersal trawl gear. A total of 54 and 43 fixed stations are sampled bi-annually in the south east and south west arms of Lake Malawi (Fig. 2). The southeast arm is divided into areas A, B and C and the southwest arm into areas D, E and F for management purposes (Fig.1). A Global Position System (GPS) was used for fixing the position of shooting and hauling for each station, with each trawl lasting 30 minutes.

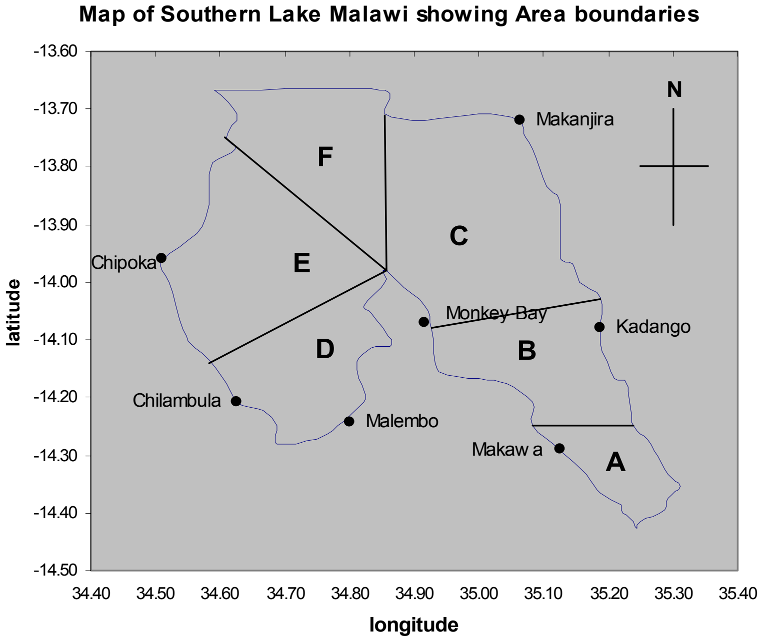

Figure 1. Area boundaries for both southeast and southwest arms of lake Malawi.

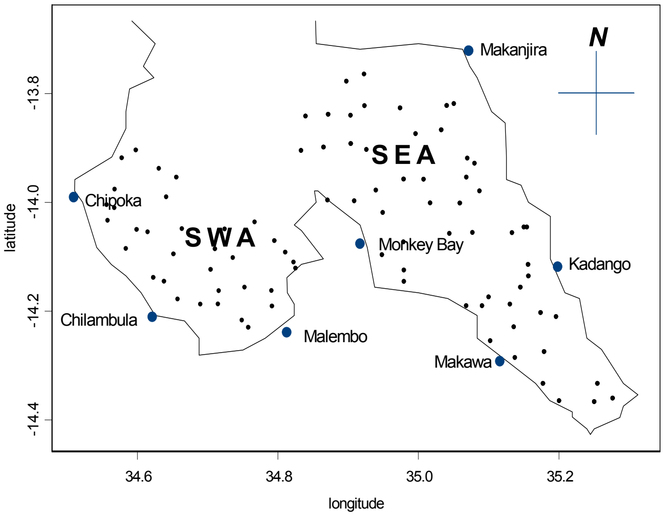

Figure 2. Map of southern lake Malawi showing sampling stations in southeast (SEA) and southwest (SWA) arms.

2.2 Data Collection

All trawling was conducted during the day (between 6 am and 5 pm) and for each station depth (m), trawling speed, actual time trawled and position at start and end of each haul (latitude and longitude) were recorded. A total of eight surveys covering the southeast and southwest arms of lake Malawi have been conducted between 1995 and 1999. Data for only 1995 and 1999 was, however, used in this analysis.

The sampling and recording of the catch closely followed guidelines outlined by Sparre *et al*, (1989). All catfish of the genera *Bathyclarias, Clarias* and *Bagrus* as well as extremely large cichlid and non-cichlid species were sorted out of the main catch. Thereafter the catch was sub-sampled; the fraction of which depended on the quantity of catch landed. The catch was then divided on deck into four categories namely; Small fish (mainly cichlids but also including *Synodontis njassae*), *Bagrus meridionalis*, Clariid catfishes and all large cichlid and non-cichlid fishes. Each category was sorted into species, length measured and weighed.

3 Data analysis

3.1 Geometric mean

From the trawl data, estimates of the percentage composition and catch per unit effort (CPUE) for *A. mentale, B. lepturus, C. virginalis D. elongate and Oreochromis* spp. were obtained. The geometric mean (GM) was used to calculate mean CPUE. This estimation was chosen over the arithmetic mean because preliminary analysis showed that the data had an asymmetric right-skewed distribution. It was therefore assumed that abundance was also log-normally distributed. The GM was obtained by calculating the mean across stations of the log-transformed values and back transforming (Rosner, 1995) such that;

$$GM = 10^{\frac{1}{n}\sum_{s=1}^{n} \log\left(CPUE_S + 1\right)} - 1$$

where $CPUE_s$ is the catch per unit effort of station *s*.

3.2 Biomass estimates

Biomass was calculated estimated using the swept area method and ordinary kriging. For the swept area method, biomass is estimated from the mean CPUE of several half-hour hauls in each depth stratum (0-50m, 51-100m and 101-150m) multiplied by the ratio of total fishing area to area covered by the trawl, using the swept area method such that (Sparre *et al*, 1989):

Area swept per standard haul, $a = D \times h \times x_2, D = V \times t$

where V is velocity of the trawl over the ground when trawling, h is head rope length, t is trawling time, x_2 is that fraction of the head-rope which is equal to the width of the path swept by the trawl, the 'wing spread', $h \times x_2$. For the *R.V. Ndunduma*, the above variables are shown in Table 2.

Table 2. Variables for the *R.V. Ndunduma* used in the Area Swept method.

Variable	**Value**
Velocity	3.5 nm hr^{-1}
Trawling time	0.5 hr
Head rope length	0.0124 nm
Fraction (x_2)	0.639
Area per haul	0.0139 nm^2

3.3 Geostatistical analysis

The abundance of a species measured at fixed locations in a lake or ocean is known as random field data and such data is suitable for geostatistical analysis. Geostatistical data often exhibit small-scale variation that may be modelled as spatial correlation and incorporated into estimation procedures. Spatial variability is modelled as a function of the distance between the sampling sites, where the sites closer together in space have more similar data values than those that are far apart. The variogram provides a measure of such correlation by describing how sample data are related with distance and direction (Kaluzny *et al*, 1998).

3.31 Exploratory data analysis

In two-dimensional space, a sampling location is defined by a longitude and latitude position. In order to successfully model an underlying random spatial process it must be assumed that:

i) the observation and the spatial process differ only through white-noise measurement error and that

ii) the spatial distribution of the species in question was stable throughout the survey period so that all CPUE observations reflect the same underlying spatial process (Pelletier and Parma, 1994).

Although fish movement might make the second assumption difficult to satisfy, Lake Malawi fishes are typically resident and therefore, at a broader spatial scale, their distribution can be considered relatively stable. The spatial process in geostatistical data can be decomposed into a large-scale deterministic component and a small-scale stochastic component with the random field in this case not having a constant mean. As the existence of the variogram is based on a process with a constant mean and variance defined only through the magnitude of distance**,** then a variogram based on a random field with both large-scale trend and small-scale random variation will not meet the necessary assumption (Kaluzny *et al*, 1994). This implies that the first step in geostatistical data analysis is the detection and removal of trend from the data before using the variogram to estimate the underlying random process.

3.32 Detecting and removing spatial trends

Procedures used in this study for purposes of detecting and removing trend from data are those outlined in Kaluzny *et al* (1998). They include:

i) rotation of the longitude and latitude axes to assess spatial invariance.

ii) modelling the logged data as a smooth function of the longitude and latitude using a generalised additive model (GAM) and

iii) fitting a local regression model (loess) to the whole trend surface.

Residuals from this model are later on used to form kriging predictions.

3.321 Trend in southeast and southwest arms

In the southeast arm the major trend was generally from south east to northwest. The angle of rotation was positive and therefore towards the north (90^o) and ranged between 16^o and 45^o. In the southwest arm the major trend was generally from southeast to northwest. Rotation was towards the south (0^o) and the angle of rotation was therefore negative, ranging between -20^o and -45^o.

3.33 Variographic analysis

The empirical variogram provides a description of how the data are correlated with distance. The semi-variogram function, γ(h), is defined as half the average squared difference between points separated by a distance *h* (Matheron, 1963 in Kaluzny *et al*, 1998) and is described as:

$$\gamma(h) = \frac{1}{2|N(h)|}\sum_{N(h)}(z_i - z_j)^2$$

where $N(h)$ is the set of all pairwise Eucledian distances $h = i - j$, $|N(h)|$ is the number of distinct pairs in $N(h)$, and z_i and z_j are data values at spatial locations i and j, respectively. The letter *h* represents a distance measure with magnitude only but when direction is also considered, it becomes a vector $h^{\sim}$ (Kaluzny *et al*, 1998).

A variogram has at least three parameters namely the nugget effect, sill and range. The nugget effect represents micro-scale variation or measurement error and is estimated from the empirical variogram as the value of $\gamma(h)$ for $h = 0$. The sill is the variance of the random field while the range is the distance (if any) at which data are no longer autocorrelated.

Additional parameters used in this study to customise the variograms were the maximum distance over which the variogram is calculated, minimum number of pairs used for calculating the variogram of which 30 is the minimum, lag and number of lags. The variograms were estimated using the robust variogram estimation method as it has the advantage of reducing the effect of outliers without removing specific data points from a data set (Kaluzny *et al*, 1998). The robust estimation method is based on the fourth power of the square root of absolute differences as follows:

$$\overline{\gamma}(h) = \frac{\{\frac{1}{2|N(h)|}\sum N(h)^{|z_i - z_i|^{1/2}}\}^4}{0.457 + 0.944/|N(h)|}$$

3.34 Modelling the Empirical Variogram

Anisotropy occurs when the spatial autocorrelation of a process changes with direction. A variogram from an anisotropic process is not purely a function of the distance ***h***, but is a function of both the magnitude and direction of $h^{\sim}$ (Kaluzny *et al*, 1998)**.** An anisotropic variogram is geometrically anisotropic if:

$$2\gamma(h) = 2\gamma^{o}(\|\boldsymbol{A}h\|), \quad h \in \Re^{d}$$

where ***A*** is a *d* x *d* matrix and $2\gamma^{0}$ is a function of a real variable.

In this situation, the Eucledian space is not appropriate for measuring distance between locations, but a linear transformation of it is (Cressie, 1993). Since variograms are only valid for an isotropic process, anisotropy has to be corrected for before fitting a theoretical model to the empirical one. In this study geometric anisotropy (range of the variogram changing in different directions, while sill remains constant) was identified by using directional variograms and was subsequently corrected by a linear transformation of the lag vector $h^{\sim}$.

After estimating the parameters of the empirical variogram, a theoretical model is then fitted to it. This is necessary because it ensures that the variance of predicted values is positive. This study makes use of the spherical model. Other models tested besides the spherical were exponential, gaussian, linear and power. Its choice was mainly based on the observation that it was the one that fitted well with the shape of the empirical variogram. Besides this, Freire *et al* (1992) state that the spherical model is the most common in the analysis of animal populations and geostatistics in general. According to Cressie, (1993) the spherical model has the form:

$$\gamma(h;\theta) = \begin{cases} 0, & h = 0 \\ C_O + C_S\,\{(3/2)(\|h\|/a_s) - (1/2)(\|h\|/a_s)^3\}, & 0 < \|h\| \le a_s, \\ C_O + C_S & \|h\| \ge a_s \end{cases}$$

where $\theta = (\mathbf{c_o},\mathbf{c_s},\mathbf{a_s})'$, $\mathbf{c_o} \ge 0$, $\mathbf{c_s} \ge 0$, $\mathbf{a}_s \ge 0$ and C_0 is the nugget effect, due to the variability between samples, the microstructure which remains undetected because of the size of the sample, or errors in measurement or location. C_s represents the sill-nugget effect, where the sill is the asymptotic value of semivariance, reached with a value of $h = a$, the range, which represents the maximum distance at which spatial effects are detected.

The spherical model was fitted to the empirical variogram by minimising the residual sum of squares between the theoretical model and the empirical variogram using the weighted least-squares estimation as follows:

$$\sum_{j=1}^{K} | N(h(j)) | \left\{ \frac{\overline{\gamma}(h(j))}{\gamma(h(j);\theta)} - 1 \right\}^2$$

where K is the number of lags, $\theta = (c_o, c, a)$, $\gamma(h(j))$ = spherical variogram model and $\overline{\gamma}(h(j))$ = empirical variogram.

A summary of variogram parameters that were used in this analysis is displayed in Table 4a. The prediction process also requires the values that are used for correcting anisotropy in addition to the range, sill, and nugget. Parameters used for correcting geometric anisotropy in this study were angle and ratio. The ratio ranged from 1.25 to 2 while the angle ranged from 45^o to 180^o. These were different for each species and year.

3.35 Spatial prediction using kriging

Kriging is a linear interpolation method that allows predictions of unknown values of a random function from observations at known locations. Kriging incorporates a model of the covariance of the random function when calculating predictions of the unknown values. There are two categories of kriging namely universal and ordinary (Kaluzny *et al*, 1998). Ordinary kriging uses a random function model of spatial correlation to calculate a weighted linear combination of available samples, for prediction of abundance and standard errors for unsampled locations. Weights for this model are chosen to ensure that the average error for the model is zero and that the modelled error variance is minimised.

In this analysis, ordinary kriging was used to predict the value of the spatial process S(x) for every location ***x*** (latitude, longitude) in the area, from a linear combination of the observed values $\{Z(x_i), i = 1,\ldots,g\}$. Based on the assumption that Z(x) and S(x) differ only through measurement error (Pelletier and Parma, 1994), it is possible to model the spatial covariance of Z(x) directly instead of that of S(x). Ordinary kriging requires the stationarity of the first differences of Z(x) as demanded by the intrinsic hypothesis of Matheron (Cressie, 1993) such that:

$E(Z(x + h^{\sim}) - Z(x)) = 0,$

$V(Z(x + h^{\sim}) - Z(x)) = 2\gamma(h)$

where $h^{\sim}$ is a vector of length $h = |h|$. The first equation means that Z(x) has the same expected value over the whole area regardless of location. In ordinary kriging, this value is assumed to be unknown. In the second equation, the variance of the difference is a function of $h^{\sim}$ only. If second-order stationarity is assumed (as is usual for kriging) such that:

$$\mathrm{Cov}(Z(x + h), Z(x)) = C(h),$$

the covariance between two points is only a function of their relative position, the semivariogram can then be expressed in terms of the spatial covariance as:

$$\gamma(h) = \delta^2 - C(h)$$

where the sill δ^2 is the variance of Z(x) in the model (Journel and Huijbregts, 1978 in Pelletier and Parma, 1994).

Thus the spatial correlation structure of Z(x) is characterised by the variogram, γ(h). The kriging variable was the residuals from the spatial loess model, while spatial locations were the rotated coordinates. The spatial correlation was modelled as spherical covariance based on the spherical variogram model fitted to the empirical variogram. The sill used was specified as the sill minus the nugget effect.

4 Results

4.10 Observed CPUE and catch composition

Presented in Table 2 is a summary of CPUE for all five species.

Table 2: CPUE (kg. $0.5\mathrm{hr}^{-1}$) for each of the species in SE and SW arms in lake Malawi for 1995 and 1999.

	South East Arm (CPUE- kg 0.5 hr^{-1})		Southwest Arm (CPUE -kg $0.5\mathrm{hr}^{-1}$)	
Species	**1995**	**1999**	**1995**	**1999**
A. mentale	0.93	1.00	1.60	2.12
C. virginalis	7.79	2.18	3.78	0.37
Oreochromis spp.	1.58	0.59	2.51	1.19
B. lepturus	0.54	0.61	1.10	0.93
D. elongate	2.65	4.65	1.63	0.95

In Table 3 is a summary of the percentage composition for each species presented separately for each area.

Table 3: Percentage composition in the total catch for each of the species in southeast arm of lake Malawi.

	A		B		C	
Species (% Comp.)	**1995**	**1999**	**1995**	**1999**	**1995**	**1999**
A. mentale	0.00	0.00	0.06	0.20	1.55	2.1
C. virginalis	0.10	15.26	30.87	14.50	28.74	0.91
D. elongate	0.32	4.28	7.01	21.46	1.48	8.80
Oreochromis spp.	31.22	11.78	0.51	0.29	0.02	0.00
B. lepturus	0.10	0.41	0.36	0.48	0.24	0.53

4.20 Variograms

4.21 Southeast arm

Table 4 presents summaries of variogram parameters for both the southeast and southwest arms of lake Malawi respectively.

Table 4:Variogram parameters for species analysed from the southeast arm of lake Malawi for 1995 and 1999.

	Southeast Arm -1995			**Southeast Arm - 1999**		
Species	**Nugget**	**Sill**	**Range**	**Nugget**	**Sill**	**Range**
A. mentale	0.005	0.36	0.3	0.005	0.35	0.26
C. virginalis	0.005	5.2	0.25	0.005	0.9	0.25
Oreochromis spp.	0.005	0.14	0.2	0.005	0.032	0.4
B. lepturus	0.005	0.1	0.3	0.005	0.14	0.27
D. elongate	0.005	2.55	0.16	0.005	2.4	0.14

Table 10: Summary of variogram parameters for species analysed from southwest arm of lake Malawi for 1995 and 1999.

	South West Arm -1995			**South West Arm - 1999**		
Species	**Nugget**	**Sill**	**Range**	**Nugget**	**Sill**	**Range**
A. mentale	0.005	1.25	0.19	0.005	1.35	0.135
C. virginalis	-	-	-	-	-	-
Oreochromis spp.	0.005	1.45	0.18	0.005	0.43	0.25
B. lepturus	0.005	0.45	0.14	0.005	0.35	0.23
D. elongate	-	-	-	-	-	-

Table 11: Percentage composition in the total catch for each of the species analysed from southwest arm of lake Malawi.

	D		E	
Species (% composition)	**1995**	**1999**	**1995**	**1999**
A. mentale	1.24	2.38	1.18	3.53
C. virginalis	7.74	1.74	3.12	0.07
D. elongate	5.16	2.05	2.18	0.50
Oreochromis spp.	12.37	3.84	11.48	3.58
B. lepturus	1.77	0.88	0.83	0.38

Omnidirectional variograms were calculated separately for each of the two arms of the lake. Results presented correspond to the isotropic variograms.

A. mentale

A. mentale attains a maximum size of about 25 cm TL and attains maturity at a relatively large size. It occurs in water depths of between 60 and 128 m (Turner, 1996). It is of significance to deep water bottom trawling where it contributes about 2% to the total catch in Areas C and D, and over 3% in Area E (Tables 2, 11). The 1995 and 1999 variograms for *A. mentale* differ (Fig.3a, Table 4). The range at which the data are no longer spatially correlated is slightly higher for 1995 (0.3 nm) than for 1999 (0.26 nm).

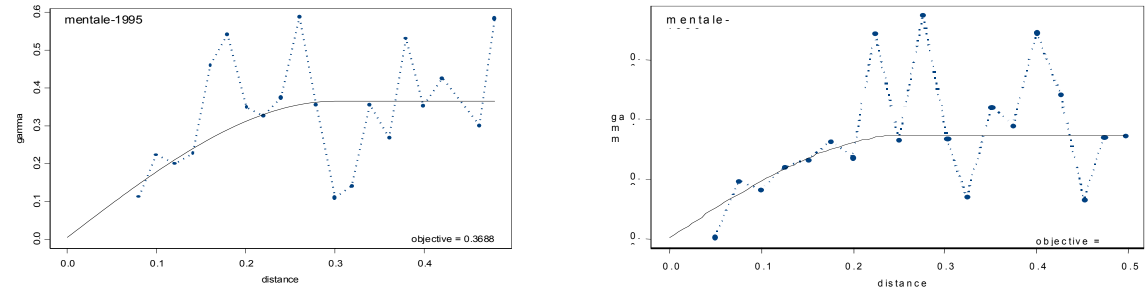

Figure 3a: Variograms for *A. mentale* in the southeast arm of lake Malawi.

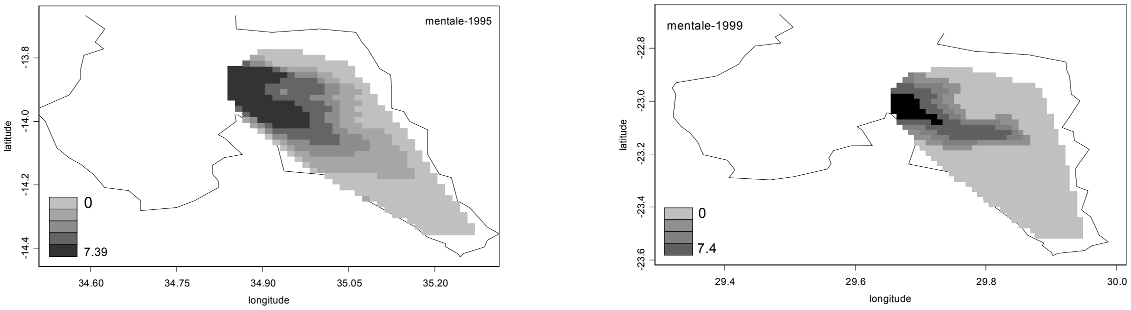

Figure 3b: *A. mentale* abundance and distribution patterns during 1995 and 1999 in the southeast arm of lake Malawi.

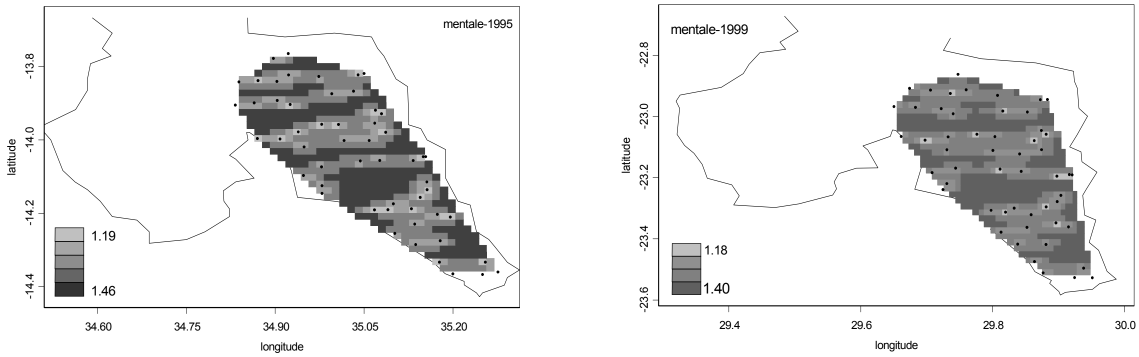

Figure 3c: *A. mentale* kriging prediction errors for 1995 and 1999.

Table 5: Biomass estimates (kgs) for *A. mentale* in southeast arm.

1995		1999	
Swept Area	**Kriging**	**Swept Area**	**Kriging**
88730.81	683.76	87842.74	1046.13

The spatial covariances for 1995 (0.36) and 1999 (0.35) were not considered different. As indicated in Table 2, the CPUE for 1999 (1kg $0.5hr^{-1}$) is slightly higher than that of 1995 (0.93kg $0.5hr^{-1}$). The percentage composition in the total catch has increased from 1.55 in 1995 to 2.1 in 1999 in Area C (Table 3). Examination of the distribution maps in Figure3b indicates that *A. mentale* is found mainly in area C and the distribution seems to have generally shrunk in 1999. The 1999 results indicate that the species has increased in abundance both in area B and C. The biomass obtained by kriging increased from 683.76 kg in 1995 to 1,046.13 kg in 1999 (Table 5). The highest density attained for both years was about 7.4 kg $0.5hr^{-1}$. Prediction errors for both years showed little difference between each other (Fig. 3c). Biomass estimates whilst similar using the swept area method, were different from a geostatistical perspective (Table 5).

C. virginalis

C. virginalis is a small shoaling species that is very abundant on steep rocky coasts or submerged rock reefs of Lake Malawi. The species attains a maximum size of about 11-15 cm TL. It has been recorded at depths ranging from 9 m to 74 m. It is a very important species to a variety of mechanised and artisanal fisheries (Turner, 1996).

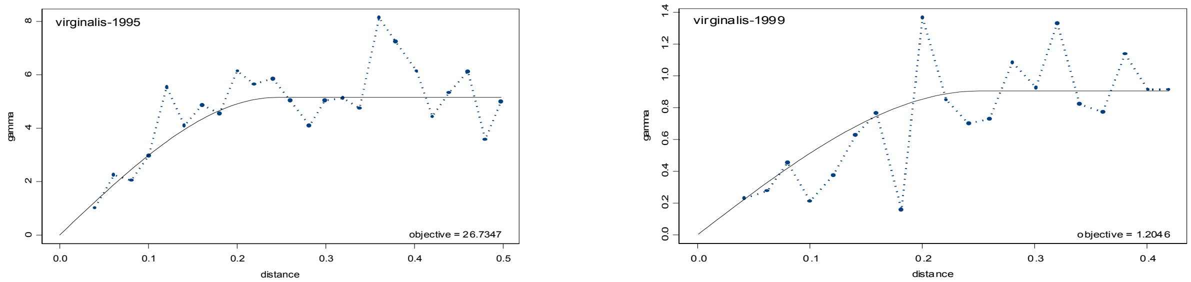

Figure 4a: Variograms for *C. virginalis* in the southeast arm of lake Malawi

.The 1999 variogram for *C. virginalis* differs from that of 1995 in that it has a spatial covariance of 0.9 against 5.2 for 1995. This in itself indicates that the species has decreased in abundance over the years. The range at which the data are no longer spatially correlated was 0.25 nm for both years (Fig. 4a, Table 4). The 1995 CPUE (7.79 kg $0.5hr^{-1}$) is much higher than that of 1999 (2.18 kg $0.5hr^{-1}$) as observed from Table 2.

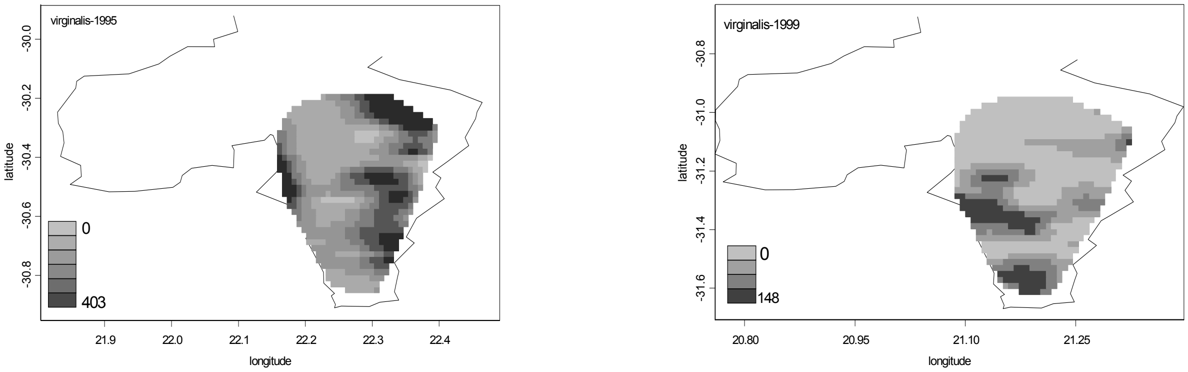

Figure 4b: *C. virginalis* distribution pattern and abundance during 1995 and 1999.

In 1995, *C. virginalis* occurred in high densities in Area C just off Makanjila, and Area B off Masasa and Kadango fishing villages (Fig. 4b). The percentage composition of the species decreased from 30.87% (1995) to 14.5% (1999) in area B, and 28.74% (1995) to 0.91% (1999) in area C (Table 3). The catch rate was highest in 1995 (403 kg $0.5hr^{-1}$) as compared to 1999 (148 kg $0.5hr^{-1}$) and the biomass decreased from 19602.47 kg in 1995 to 8724.10 kg in 1999 (Table 6). From Figure 4c it is observed that prediction errors were higher in 1995 (1.60 - 4.5kg) than in 1999 (1.25 - 1.50 kg). This difference can be attributed to the much higher density and wider distribution of the species in 1995 than in 1999.

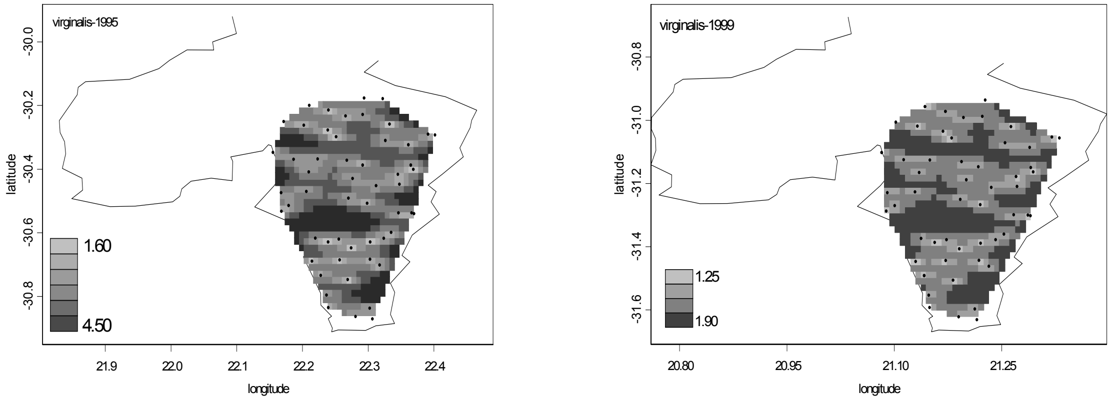

Figure 4c: C. *virginalis* prediction errors for 1995 and 1999 in the southeast arm of lake Malawi.

Table 6: Biomass estimates (kgs) for *C. virginalis* in southeast arm of lake Malawi.

1995		**1999**	
Swept Area	**Kriging**	**Swept Area**	**Kriging**
472793.80	19602.47	120821.0	8724.10

***Oreochromis* spp.**

In lake Malawi, the genus *Oreochromis* is composed of four species of which three are endemic to the lake. The endemic ones are *O. squamipinnis* (37 cm TL), *O. karongae* (38 cm TL) and *O. lidole* (37 cm TL) while *O. shiranus* (37 cm TL) is the only non-endemic species (Turner, 1996). They occur mainly in shallow waters and have been recorded at depths ranging from 2 m to 50m although they are most abundant at depths greater 20 m (Palsson *et al,* 1999).

As observed from Figure 5a and Table 4, variograms for the two years differ considerably. The spatial covariance for 1995 (0.14) is much higher than that of 1999 (0.032) while the range for 1999 (0.4 nm) is higher than that of 1995 (0.2). The CPUE data indicates that catches of *Oreochromis* spp. were much higher in 1995 than in 1999. In 1995 the CPUE was about 1.58 kg $0.5hr^{-1}$ while in 1999 the catch rate dropped to about 0.59 kg $0.5hr^{-1}$ (Table 2). This is further confirmed by the observation in Figure 5b which indicates that catch rate was highest in 1995 (148 kg 0.5 hr^{-1}) as compared to 1999 (20 kg $0.5hr^{-1}$). This group of species occurs mostly in southern most tip of the southeast arm of the lake (Figure 5b) especially Area A and parts of Area B. The biomass dropped from 3219.20 kg in 1995 to 489.45 kg in 1999. Figure 5c indicates that prediction errors are higher for 1995 (1.16-1.35 kg) than for 1999 (1.09 -1.13 kg). The very low density observed in 1999 and sharp decline in percentage composition from 31.22% in 1995 to 11.78% (Table 3) in 1999 indicates that the fishery is in a critical state.

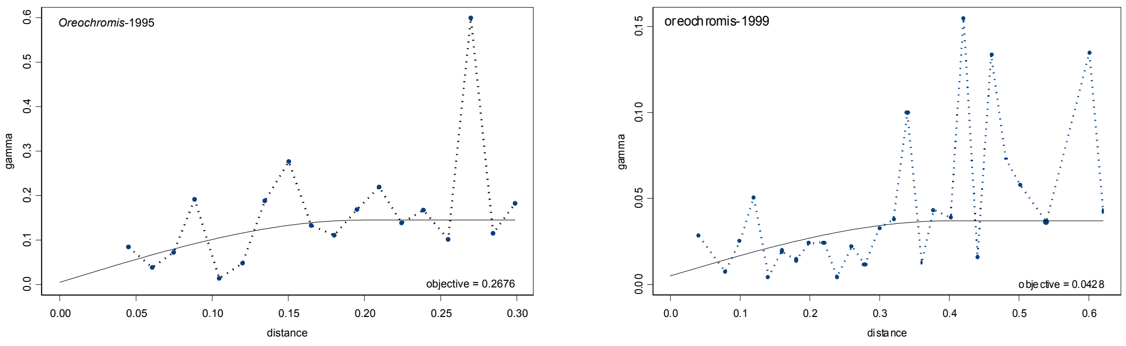

Figure 5a: Variograms for *Oreochromis* spp in the southeast arm of lake Malawi.

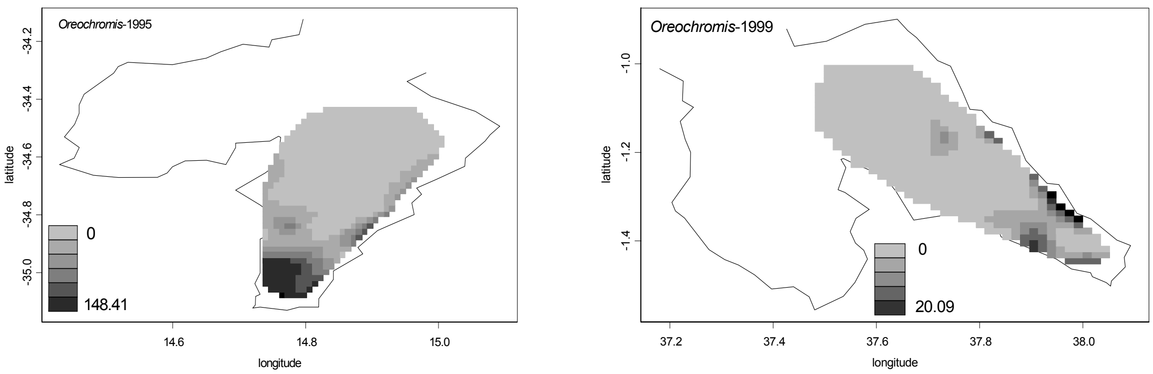

Figure 5b: *Oreochromis* spp. abundance and distribution patterns during 1995 and 1999.

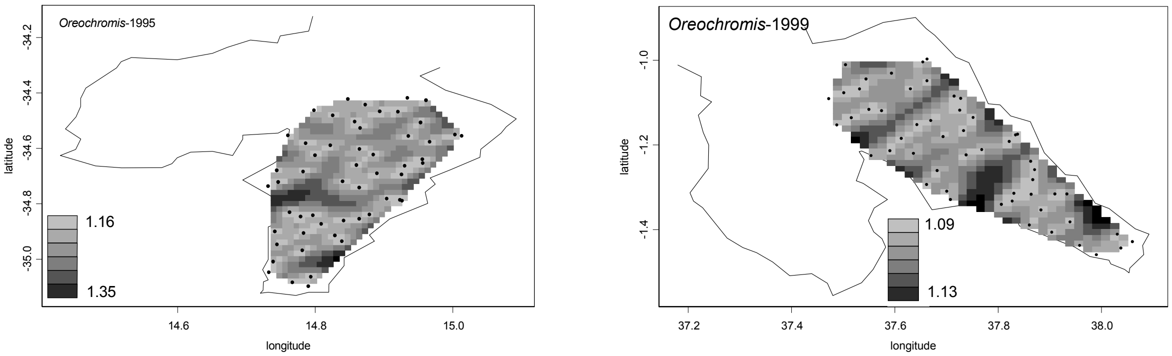

Figure 5c: *Oreochromis* spp. prediction errors for 1995 and 1999.

Table 7: Biomass estimates (kgs) for *Oreochromis* spp. in southeast arm.

1995		**1999**	
Swept Area	**Kriging**	**Swept Area**	**Kriging**
627373.90	3219.20	55630.52	489.45

B. lepturus

B. lepturus like all other members of the genus is a large heavily-built species that attains a maximum total length of about 42 cm. It is a shallow water species, and has often been sampled from depths ranging from 10 to 26 m (Turner, 1996). It is probably one of the most delicious fishes of the lake although it is not found in large numbers.

Variograms for *B. lepturus* for the two years differ slightly (Fig. 6a, Table 4). The range at which the data is spatially correlated is higher in 1995 (0.3 nm) than 0.27 nm for 1999. The spatial covariance is slightly higher for 1999 (0.14) than for 1999 (0.1). The 1999

CPUE of about 0.61 kg 0.5hr^{-1} is higher than that of 0.54 kg 0.5hr^{-1} for 1995 (Table 2). The species seems to be evenly distributed in shallow waters of both Areas B and C. The distribution pattern map of 1999 indicates that there is a decline in abundance in the southern most tip of the lake (Area A) and the eastern part of area C (Fig 6b). However, overall the species seems to have slightly increased in abundance in most parts of the southeast arm.

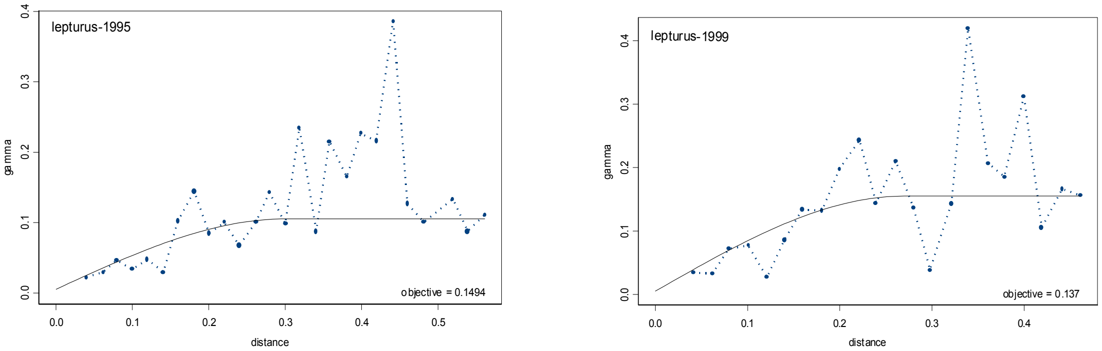

Figure 6a: Variograms for *B. lepturus* in the southeast arm of lake Malawi.

This is evidenced by the general increase in percentage composition of the species in the total catch in 1999 as compared to that of 1995 (Table 3) and the catch rate is highest in 1999 (20 kg 0.5 hr-1) as compared to 7.4 kg 0.5hr^{-1} in 1995 (Fig. 6b). The biomass also increased from 884.55 kg in 1995 to 1160.92 kg in 1999 (Table 8).

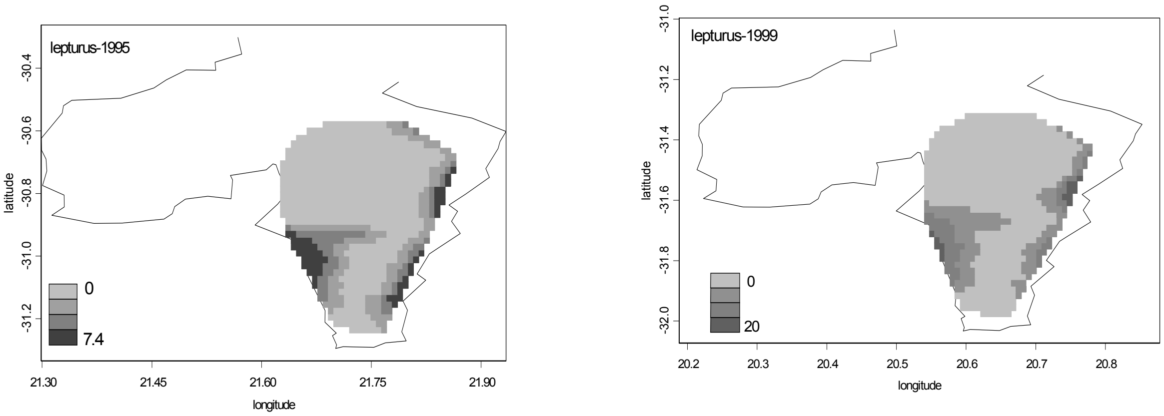

Figure 6b: *B. lepturus* abundance and distribution patterns during 1995 and 1999 in the southeast arm of lake Malawi.

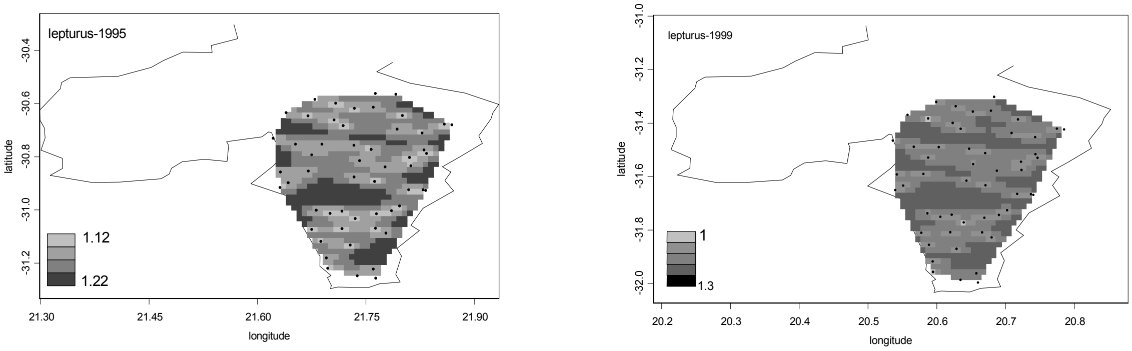

Figure 6c: *B. lepturus* prediction errors for 1995 and 1999 in the southeast arm of lake Malawi.

Table 8: Biomass estimates (kgs) for *B. lepturus* in southeast arm of lake Malawi.

1995		**1999**	
Swept Area	**Kriging**	**Swept Area**	**Kriging**
22546.01	884.55	34045.08	1160.92

Prediction errors are relatively higher for 1999 (1.0 - 1.3 kg) than for 1995 (1.12 - 1.22 kg) as indicated in Figure 6c. Generally biomass estimates obtained through the swept area method are much higher than those of kriging.

D. elongate

Members of the genus *Diplotaxodon* belong to the "Ndunduma" group of fishes that are principally deep-water piscivores and zooplanktivores with upwardly angled mouths. *D. elongate* and its relatives are truly pelagic zooplankton feeders, which occupy the feeding niche of the "Utaka" (*Copadichromis*) in offshore waters. The species attains a total length (TL) of about 19 cm. It has been recorded throughout the pelagic zone of the lake from the surface to a depth of at least 220 m (Turner, 1996). Commercially, it is also an important species to both the commercial and artisanal fisheries.

Figure 7a and Table 4 indicate that the spatial covariance was higher for 1995 (2.55) than 2.4 for 1999. The ranges for the two years are also different. The 1995 range was 0.16 nm while that of 1999 was 0.14 nm. The 1999 CPUE of about 4.65 kg $0.5hr^{-1}$ is also much higher than that of 1995 (2.65 kg $0.5hr^{-1}$) as indicated in Table 2.

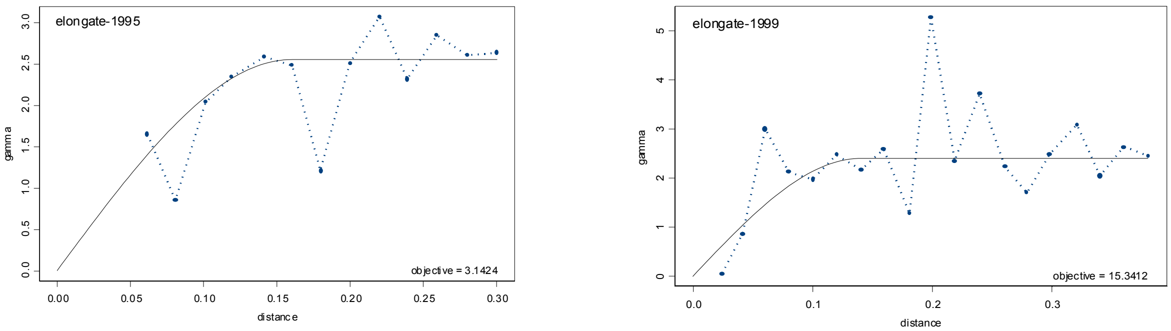

Figure 7a: Variograms for *D. elongate* in the southeast arm of lake Malawi.

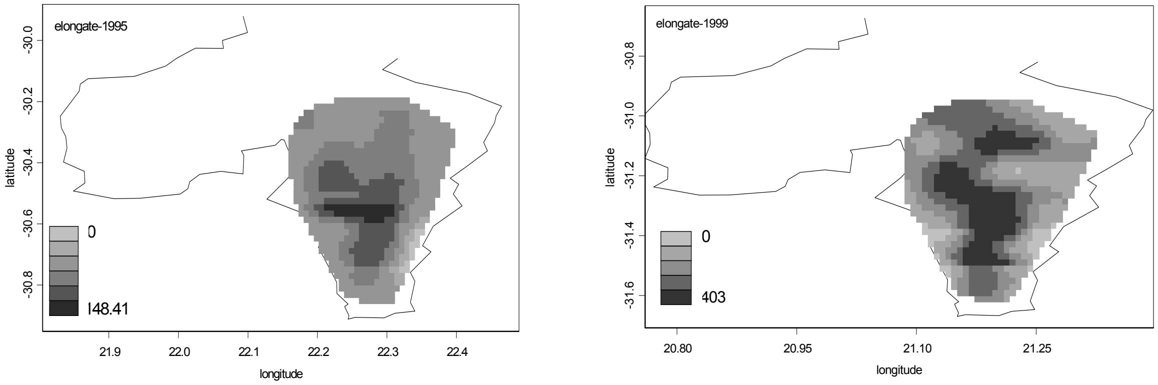

Figure 7b: *D. elongate* abundance and distribution patterns during 1995 and 1999 in the southeast arm of lake Malawi.

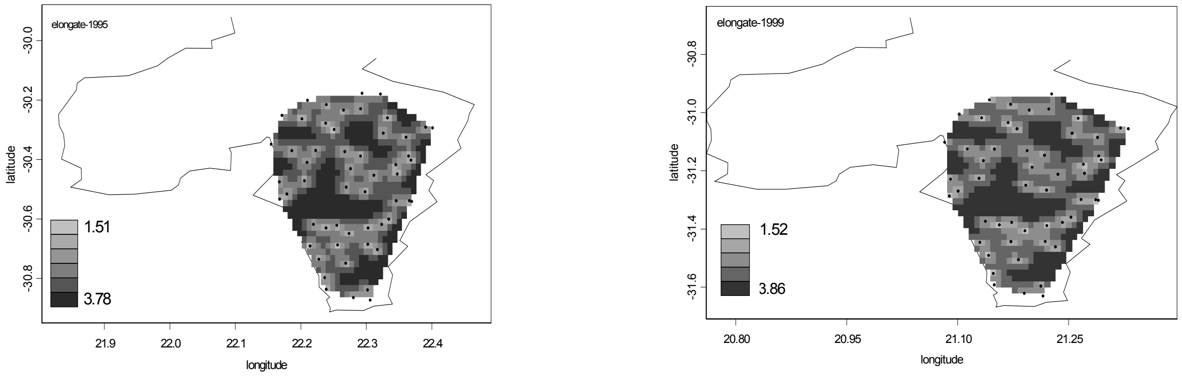

Figure 7c: *D. elongate* prediction errors for 1995 and 1999 in the southeast arm of lake Malawi.

Table 9: Biomass estimates (kgs) for *D. elongate* in southeast arm.

1995		1999	
Swept Area	**Kriging**	**Swept Area**	**Kriging**
280876.40	103436.70	501271.13	35365.51

The distribution pattern in Figure 7b indicates that *D. elongate* is found mainly in deep waters of Area B extending into south of Area C. The density was much higher in 1999 (403 kg) than in 1995 (148 kg) however the distribution range seems to have decreased in 1999 (Fig. 7b). This probably explains why the biomass for 1995 (103436.70 kg) is much higher than that of 1999 (35365.51 kg) as indicated in Table 9. Figure 7c indicates that prediction errors for 1995 (1.51-3.78 kg) are slightly lower than those of 1999 (1.52 - 3.85 kg). As indicated in Table 9, biomass estimate obtained through the swept area method increased in 1999 while that of kriging decreased. This highlights the importance of incorporating spatial distribution patterns when estimating biomass because species are seldom uniformly distributed.

4.22 South West Arm

The 1999 data for southwest arm contains a number erroneous cordinates especially for shallow water stations and as such the results for shallow water species are not accurate. However they have been presented. Due to taxonomical problems especially in 1995, *D. elongate* and *C. virginalis* have not been analysed. It is suspected that two *Copadichromis* species *C. virginalis* and *C. inornatus* were mixed in 1995. *D. elongate* seems to also have been mixed up with *D. 'intermediate'* and the 'big eye' species complex. This was identified during preliminary data analysis and these two species were therefore not analysed further.

A. mentale

Figure 8a and Table 10 indicate that the spatial covariance for 1995 (1.25) is lower than that of 1999 (1.35) while the range for 1999 (0.135 nm) is smaller than that of 1995 (0.19

nm). The CPUE is higher for 1999 (2.12 kg 0.5hr^{-1}) than for 1995 (1.60 kg 0.5hr^{-1}). The percentage composition is also higher for 1999 in both areas D and E (2.38% and 3.53% respectively) than in 1995 (1.24 and 1.18 respectively) as indicated in Table 11. The highest catch rate observed for both years is about 20 kg 0.5hr^{-1} and the abundance and distribution patterns in Figure 8b indicate that the species had increased in abundance by 1999. This is confirmed by the increase in biomass from 1932.66 kg in 1995 to 5833.89 kg in 1999 (Table 12).

As observed from Figure 8b, the species seems to occur exclusively in deep waters of the southwest arm.

Figure 8a: Variograms for *A. mentale* in the south west arm.

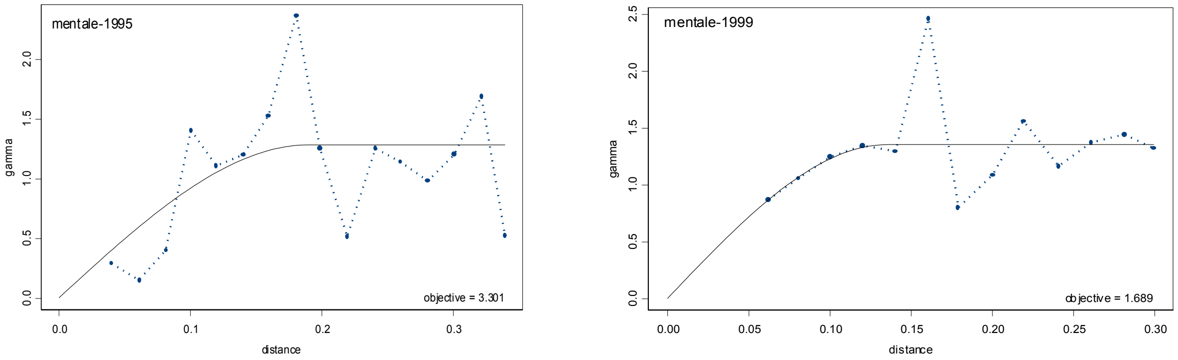

Figure 8a: Variograms for *A. mentale* in southwest arm of lake Malawi.

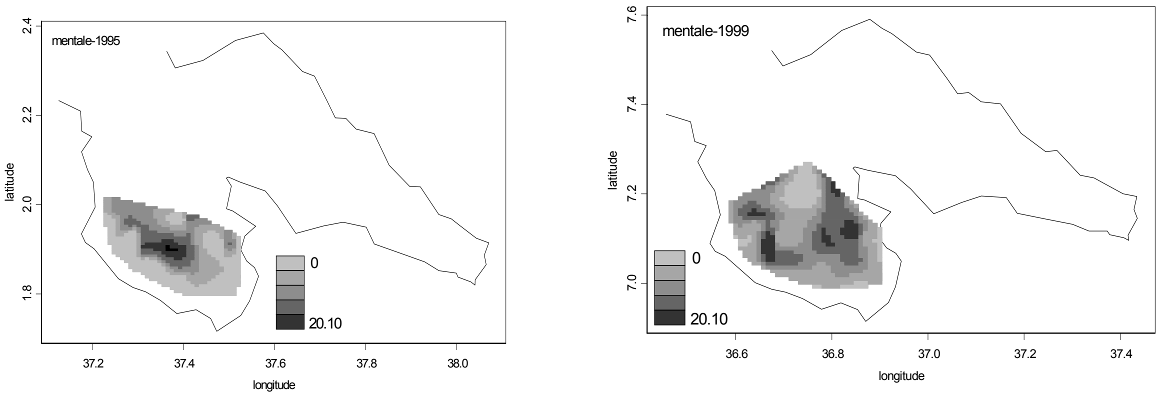

Figure 8b: *A. mentale* abundance and distribution patterns during 1995 and 1999 in southwest arm of lake Malawi.

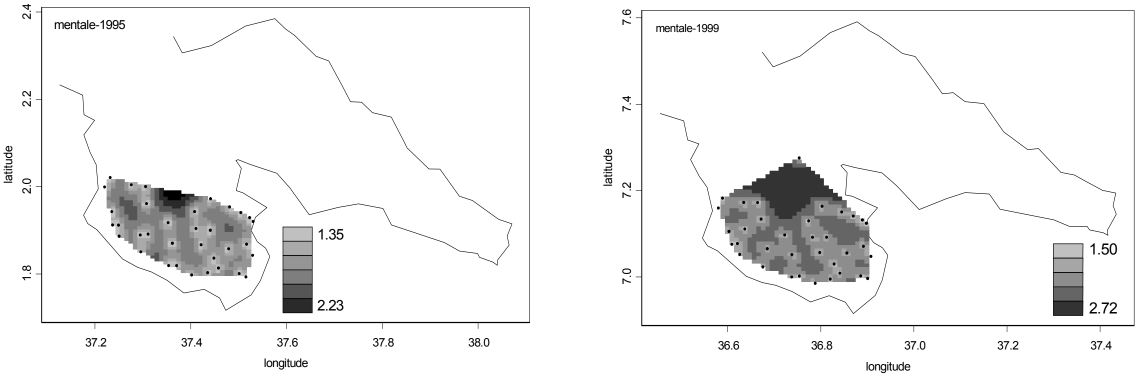

Figure 8c: *A.mentale* prediction errors for 1995 and 1999 in the southwest arm of lake Malawi.

Table 12: Biomass estimates (kgs) for *A. mentale* in southwest arm of lake Malawi.

1995		**1999**	
Swept Area	**Kriging**	**Swept Area**	**Kriging**
71002.78	1932.66	117384.03	5833.89

Biomass estimates obtained through the swept area method show the same increasing trend although they are much bigger than those obtained through kriging (Table 12).

Prediction errors are generally slightly higher for 1999 than for 1995 (Fig. 8c).

5 Discussion

Stock assessment methods that disregard spatial distribution of species may provide inaccurate information pertinent to management. This is so because such methods usually assume that the existing density areas or strata are internally homogeneous unless the sampling design is perfectly random (Freire *et al*, 1992). Having the ability to map abundance gradients and integrating them into space, geostatistics gives a more realistic view of a species distribution. This information can also be used to trace the spatial and temporal allocation of fishing effort for both effort-controlled and open-access fisheries.

All the five species assessed in this study show different distribution patterns. This is expected because distribution patterns are in most cases linked to food availability, water temperature, dissolved oxygen, bottom sediment type and other ecological factors such as presence or absence of aquatic vegetation and submerged rocky reefs. The distribution pattern can at times be highly influenced by human interference such as excessive exploitation that can bring about localised extinction of a species or group of species.

Alticorpus mentale

The results from this study indicate that *A. mentale* mainly occurs in deep waters of both the southwest and southeast arms. In southeast arm it mainly occurs in deep waters of Area C. It is however more abundant in southwest arm than in southeast arm. The restricted distribution range greatly endangers the continued existence of the species in the southeast arm because of high fishing pressure from deepwater demersal trawlers. However, the results from the same southeast arm indicate that the species has gradually increased in abundance over the period from 1995 to 1999 despite intense fishing pressure. This can only be attributed to the fact that because deepwater species have a poor market value, fishing pressure has over the years been redirected to high value shallow to medium water-depth (20-70m) species such as *C. virginalis, D. elongate* and *Oreochromis* spp. among others. The decline in the catch rates and distribution of species such as *C. virginalis, D. elongate* and *Oreochromis* spp. bears testimony to the redirection of fishing effort away from deep waters.

Copadichromis virginalis

This study has shown that *C. virginalis* occurs along the shores of the southeast arm especially in Area C off Makanjila, and in Area B off Masasa, Chirombo and Nkhudzi bay on the western shore and to a smaller extent on eastern shore just off Kadango fishing village (Fig. 1). The results based on the 1999 data indicate that the species has greatly declined in abundance in Area C but there is instead a marked increase in abundance of the species in Area A.

The decline in the abundance of this species in Areas C and B can be attributed to the uncontrolled fishing pressure that is exerted on the species from both the artisanal, commercial and semi-commercial fisheries. Fishers along the shores of the southeast arm know exactly where to fish for this species resulting into localised declines in abundance within its preferred grounds while the abundance has increased in areas that are less known to fishers. An example here is Area A.

Diplotaxodon elongate

The results from this survey indicate that *D. elongate* is a widely distributed species occurring in offshore waters of the southeast arm from Area A to Area C in relatively high densities. The species occurs in highest densities in Area B. As observed from the distribution pattern for both 1995 and 1999 respectively, the species has over the period 1995-1999 increased in abundance with much higher densities occurring in Area B and partly extending into the southern portion of Area C. However its distribution range has decreased over the period between 1995 and 1999.

D. elongate being a pelagic species, is not always available to bottom trawlers and therefore suffers relatively less fishing mortality than other species that are permanently demersal. There is also relatively less fishing pressure from the lone midwater trawler operating in Area B which occasionally lands about 53% of *D. elongate* as bycatch (Turner, 1996). Although there are indications that the current distribution is not as wide as it used to be especially in Area C, the species unlike the others, is not greatly affected by fishing activities. It seems to be more or less governed by the existing environmental conditions.

Oreochromis spp.

These species are commonly called "Chambo" and have for decades been the mainstay of both the commercial and artisanal fisheries in southern Lake Malawi. Results from this study indicate that *Oreochromis* spp. occur mostly in Area A and to a smaller extent in shallow inshore waters of Area B. The species have greatly declined in abundance and their distribution range has narrowed very much. Of concern is that these species have actually disappeared from Area A.

The drastic decline in the abundance and distribution of the species has mostly been blamed on localised and excessive fishing pressure from both commercial and artisanal fisheries over the years. Much of the blame has been laid on the light attraction fishery "Kauni", beach seines, and undersized gillnets. To redress the situation, it was recently proposed that beach seines and Kauni fisheries be banned in Area A (Bulirani *et al*, 1999).

The situation in southeast arm requires urgent intervention from the fisheries department because if nothing is done to curb the current trends in fishing practices, the remaining few pockets will also disappear.

Buccochromis lepturus

The results from this study indicate that in the South East arm, *B. lepturus* is evenly distributed in shallow waters of Areas B and C. Abundance has generally increased as manifested by the higher biomass in 1999 than in 1995. However by 1999 the species had disappeared from the eastern part of Area C and the southern most portion of the lake (Area A). Thus the distribution range has decreased. The general decline in abundance of this species in parts of Area C and Area A can be attributed to excessive fishing effort in these areas mainly because of localised fishing effort in Area A for *Oreochromis* spp. and in Area C for *C. virginalis*.

6 Conclusions

This study has demonstrated that geostatistics can be successfully used to analyse the existing CPUE data in Lake Malawi to detect changes in the spatial and temporal distribution of fish stocks. The reasonably low nugget effect (0.005 max) indicates that the micro-scale variation or measurement error is small for all the species analysed. Biomass estimates are generally good for species found offshore or in deep water. This is because during kriging, this part of the water body is analysed more thoroughly than shallow waters. However, there is another method that can be used to improve biomass estimates for shallow water species. This method was not employed in the current analysis because a lot of time is required to manually define the area to be kriged.

In order to enhance the efficacy of this new technique, the number of stations needs to be increased in southeast arm especially in Area B. The seven stations in Area A need to be evenly redistributed.

In southwest arm, the deeper waters in Areas D and E are not well covered. There is need to locate more stations in that part of the lake. At present, the Bi-annual monitoring surveys only cover Areas D and E, Area F is not covered (Fig 1). The amount and quality of data can be greatly improved if future surveys would include Area F. The existing sampling regime is suitable for geostatistical analysis. However there is need to improve the quality of the data particularly spatial cordinates.

Generally, all the species studied show localised occurrence in various areas of the lake, and as such they are very vulnerable to overfishing and are in imminent danger of facing localised extinction. To protect these stocks it is suggested that stock-specific management measures be constituted and implemented as soon as possible. Options to be considered include closed seasons and aggregate quotas, controlled-area fishing, restrictions on fishing gear and technology.

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