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A COMPARATIVE STUDY OF A FAMILY OF ESTIMATORS FOR THE COMMON MEAN OF SEVERAL NORMAL POPULATIONS

Abebe Tessera

Department of Statistics, Faculty of Science, Addis Ababa University
PO Box 1176, Addis Ababa, Ethiopia

ABSTRACT: A new approach of estimating the common mean of several different normal populations is introduced. It is shown that this approach yields the most commonly used estimators as special cases. An empirical comparative study of these estimators and three new ones is made through computer simulation. The results of the study show that for small samples and also when the population variances are very different the performance of the new estimators is better than that of the commonly used estimators.

Key words/phrases: Estimator, mean-squared error, mixed likelihood function, precision, relative efficiency

INTRODUCTION

The problem of making inference about the common mean of several normal populations, when the variances are unknown, was first treated by Bartlett (1936). Since then the problem has attracted the attention of many researchers. Most of the papers on this topic deal with estimation of the common mean: In this paper we shall first present some of the suggested estimators and then discuss an estimation procedure that includes these estimators as special cases. Finally a comparison of some of these estimators and other new ones is made by using the Monte-Carlo approach.

THE PROBLEM AND SOME COMPETING ESTIMATORS

Suppose there are k normal populations with the same mean μ and unknown and possibly different variances σ_i^2, $i=1,2,3, \ldots k$. The objective here is to estimate the common mean μ. For this purpose we take independent random samples of sizes n_i, i=1,2,3, . . k. We shall denote the sample means and variances by $\bar{X}_i$ and S_i^2; i.e.,

$$\bar{X}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} X_{ij} \qquad S_i^2 = \frac{1}{n_i-1}\sum_{j=1}^{n_i}(X_{ij}-\bar{X}_i)^2.$$

Some of the competing estimators of μ are listed below.

i) The Unweighted Estimator (UWE): The simplest estimator one can think of is the unweighted estimator which is given by:

$$UWE = (\sum_{i=1}^{k} n_i)^{-1}\sum_{i=1}^{k}\sum_{j=1}^{n_i} X_{ij} = (\sum_{i=1}^{k} n_i)^{-1}\sum_{i=1}^{k} n_i\bar{X}_i$$

ii) The Weighted Estimator (WTE): If the population variances, σ_i^2 i=1,2,...k, are known the best estimator for μ is given by

$$\hat{\mu} = (\sum_{i=1}^{k} n_i/\sigma_i^2)^{-1}\sum_{i=1}^{k}\frac{n_i}{\sigma_i^2}\bar{X}_i .$$

If we replace σ_i^2 by its unbiased estimator S_i^2 we obtain the weighted estimator.

$$WTE = (\sum_{i=1}^{k} n_i/S_i^2)^{-1}\sum_{i=1}^{k}\frac{n_i}{S_i^2}\bar{X}_i .$$

iii) The Maximum Likelihood Estimator (MLE): The maximum likelihood estimator is derived by maximizing the likelihood function given below.

$$L = \prod_{i=1}^{k}(2\pi\sigma_i^2)^{-\frac{n_i}{2}}\exp[-\frac{1}{2\sigma_i^2}\sum_{j=1}^{n_i}(X_{ij}-\mu)^2] .$$

The MLE is the solution of the estimating equation

$$\sum_{i=1}^{k}\frac{n_i^2(\bar{X}_i-\hat{\mu})}{(n_i-1)S_i^2 + n_i(\bar{X}_i-\hat{\mu})^2} = 0 .$$

iv) The Neyman-Scott Estimator (NSE): Neyman and Scott (1948) studied a more general version of the above estimating equation and reached the conclusion that the estimator which emerges as the solution of

$$\sum_{i=1}^{k} \frac{(n_i-2)n_i(\bar{X}_i-\hat{\mu})}{(n_i-1)S_i^2 + n_i(\bar{X}_i-\hat{\mu})^2} = 0$$

is generally more precise than the MLE. We shall call this estimator the Neyman-Scott estimator. From the estimating equation of the NSE one can see that samples of size 2 make no contribution to the estimation and this may be an undesirable property of the estimator.

v) The Kalbfleish-Sprott Estimator (KSE): Kalbfleish and Sprott (1970) obtained an estimator for the common μ by using the conditional likelihood approach. The KSE is the solution of the estimating equation

$$\sum_{i=1}^{k} \frac{(n_i-1)n_i(\bar{X}_i-\hat{\mu})}{(n_i-1)S_i^2 + n_i(\bar{X}_i-\hat{\mu})^2} = 0 .$$

This estimator is an improvement over the NSE in that samples of size 2 make a contribution to the estimation. There is a similarity among the estimating equations for the MLE, NSE and KSE, and from this we may expect these estimators to have similar properties.

Comparative studies of some or all of these estimators have been made by, among others, Levy (1970), Levy and Mantel (1974), Rao (1980), and recently by Gebre-Egziabher Kiros (1990). Levy compared the MLE and WTE and found the MLE to be generally more precise than the WTE. Levy and Mantel studied the relative efficiencies of the UWE, WTE and MLE relative to the best unbiased estimator when the variances are known. Their study suggests that

1) the UWE has a better relative efficiency than the other two when the population variances are nearly equal;
2) the WTE performs better than the MLE when the sample sizes are equal; and
3) the performance of the MLE is superior in all other cases.

Rao investigated empirically the relative efficiencies of the MLE and KSE and other estimators, and concluded that the MLE is less efficient than the KSE. Gebre-Egziabher compared all these estimators when $3 \leq k \leq 10$ and n_i's are not large using the Monte-Carlo approach. He recommends the use of the WTE because of its computational simplicity and high efficiency unless k is large and/or the n_i's differ considerably.

MIXED (OR WEIGHTED) LIKELIHOOD FUNCTION APPROACH

Since we know that the independent random samples come from k normal populations with the same mean but possibly different variances, we may construct the likelihood function as a mixed (or weighted) likelihood function of k likelihood functions; i.e.,

$$L = \sum_{i=1}^{k} p_i (2\pi\sigma_i^2)^{-\frac{n_i}{2}} \exp[-(2\sigma_i^2)^{-1} \sum_{j=1}^{n_i} (X_{ij} - \mu)^2]$$

where p_i's are the mixing probabilities (or weights) and are independent of μ and σ_i^2's, but could depend on functions of X_{ij}'s. The maximum likelihood estimator of μ is then the solution of the estimating equation

$$\sum_{i=1}^{k} p_i \frac{n_i(\bar{X}_i - \hat{\mu})}{(2\pi e \hat{\sigma}_i^2)^{(n_i/2)+1}} = 0$$

where $\hat{\sigma}_i^2 = \frac{1}{n_i} \sum_{j=1}^{n_i} (X_{ij} - \hat{\mu})^2$

For different choices of p_i we get different estimators. The previous five estimators can be obtained through this estimation procedure by appropriately selecting p_i as can be seen from Table 1. Even though the number of estimators one can obtain through this process is limitless, only three new estimators are studied here. These estimators which are labelled NE1, NE2 and NE3 are selected because of their respective similarities to the MLE and the WTE. A comparative study of these estimators will be discussed in the following sections. The MLE and the NSE were found to have more or less similar behaviour, and because of this the NSE was dropped from further consideration.

Table 1. Some special cases of the estimation procedure.

P_i	Estimator or estimating equation	Notation
$p_i \propto (2\pi e\hat{\sigma}_i^2)^{\frac{n_i}{2}+1}$	$\hat{\mu} = \frac{1}{\sum n_i}\sum_{i=1}^{k} n_i\bar{X}_i$	UWE
$p_i \propto (S_i^2)^{-1}(2\pi e\hat{\sigma}_i^2)^{\frac{n_i}{2}+1}$	$\hat{\mu} = \frac{1}{\sum n_i/S_i^2}\sum_{i=1}^{k}\frac{n_i}{S_i^2}\bar{X}_i$	WTE
$p_i \propto (2\pi e\hat{\sigma}_i^2)^{\frac{n_i}{2}}$	$\sum_{i=1}^{k} n_i^2(\bar{X}_i-\hat{\mu})/\sum_{j=1}^{n_i}(X_{ij}-\hat{\mu})^2 = 0$	MLE
$p_i \propto \frac{(n_i-2)}{n_i}(2\pi e\hat{\sigma}_i^2)^{\frac{n_i}{2}}$	$\sum_{i=1}^{k}\frac{(n_i-2)n_i(\bar{X}_i-\hat{\mu})}{\hat{\sigma}_i^2} = 0$	NSE
$p_i \propto \frac{(n_i-1)}{n_i}(2\pi e\hat{\sigma}_i^2)^{\frac{n_i}{2}}$	$\sum_{i=1}^{k}\frac{(n_i-1)n_i(\bar{X}_i-\hat{\mu})}{\hat{\sigma}_i^2} = 0$	KSE
$p_i \propto (2\pi e\hat{\sigma}_i^2)^{\frac{(n_i+1)}{2}}$	$\sum_{i=1}^{k}\frac{n_i(\bar{X}_i-\hat{\mu})}{\hat{\sigma}_i} = 0$	NE1
$p_i \propto (S_i)^{-1}(2\pi e\hat{\sigma}_i^2)^{\frac{n_i}{2}+1}$	$\hat{\mu} = \frac{1}{\sum n_i/S_i}\sum_{i=1}^{k}\frac{n_i}{S_i}\bar{X}_i$	NE2
$p_i \propto (2\pi e\hat{\sigma}_i^2(S_i^2)^{-1})^{\frac{n_i}{2}+1}$	$\hat{\mu} = \frac{1}{\sum n_i/(S_i^2)^{n_i/2+1}}\sum_{i=1}^{k}\frac{n_i}{(S_i^2)^{n_i/2+1}}\bar{X}_i$	NE3

METHOD OF COMPARISON

The comparison of the seven estimators analytically is very difficult and because of this the comparison was made by using the Monte-Carlo approach. The common mean μ was set at zero in order to simplify the computations involved and this has no effect on the conclusions reached. To compute values of the estimators a computer program having several sub-programs was written in Pascal. The sub-programs and their functions are given in Table 2.

Table 2. Sub-programs and their functions.

Name of sub-program	Function
Uniform	Generates uniform random variables by using the Wichmann-Hill algorithm. (See Gebre-Egziabher Kiros, 1992).
Generate	Converts the uniform random variables to normal random variables by using the Polar-Marsagalia method.
Statistics	Computes sample sums, means, sum of squares and variances.
Func1, Func2, Func3 and Regula Falsi	These are used to estimate the MLE, KSE and NE1.
Main Program	Reads the number of populations, population variances and sample sizes, estimates UWE, WTE, MLE, KSE, NE1, NE2 and NE3, and writes them in that order. It also writes the number of times each iteration failed to converge.

The performance of an estimator depends on the number of populations under consideration (k), the population variances (σ_i^2), the sample sizes (n_i) and the pattern in which the n_i's and σ_i^2's are combined. Because real life comparisons may not involve more than 12 populations, three values of k (i.e., 3, 7, 12) were selected. The ratios σ_i^2/σ_j^2 $i \neq j$ rather than the actual magnitudes of the variances affect the relative performance of the estimators, and because of this the σ_i^2's were selected in such a way that $\sum_{i=1}^{k} \sigma_i^2 = 1$ and $\delta = \max\ \delta_i^2/\min\ \delta_i^2$ equals 4/3, 2, 5, 10, 50, 100 and 1000. The quantity δ was used as a measure of heterogeneity in the σ_i^2's. The sample sizes selected were of three types; viz. small ($3 \le n_i < 10$), medium ($10 \le n_i \le 30$) and large ($n_i > 30$). The actual sample sizes for the different values of k are given in Table 3. Two different combination of sample sizes and population variances were used:

1) n_i's and σ_i^2's having the same rank order;

2) n_i's and σ_i^2's having the reverse rank order.

For each combination of k, n_i and σ_i^2 the program was run 1000 times and 1000 estimates were computed for each estimator.

Table 3. **Selected sample sizes.**

Type	K		
	3	7	12
Small	4,7,9	3,4,5,6,7,8,9	3,4,4,5,5,6,6,7,7,8,8,9
Medium	15,19,26	13,15,17,19,24,26,28	11,13,15,16,17,19,21,23,24,25,27,29
Large	31,38,47	33,35,37,39,44,46,48	31,33,35,37,39,41,43,45,47,49,51,53

To obtain the estimates for the MLE, KSE and NE1 the Newton-Raphson method was firstly tried. However, on several occasions it was observed that the iterative method failed to converge for the MLE and KSE, especially when the sample sizes were small. To see if this problem could be overcome and also because of its better effectivity index (see Froberg, 1970) the method was changed to Regula Falsi. Even with this iterative procedure the problem could not be overcome, and in the program a value of 99.99 was given to the estimator on such an occasion. This has the effect of exaggerating the estimates for the mean and the mean-squared error.

A second program, also in Pascal, was written to make the comparative study. The mean- squared error of the estimates about the true common mean zero was used as a measure of precision. The comparison was made by computing these mean-squared errors.

RESULTS AND DISCUSSION

For the unweighted estimator it can be shown that

$$Var(UWE) = \frac{1}{(\Sigma n_i)^2}\sum_{i=1}^{k} n_i\sigma_i^2$$

and expressions for the asymptotic variances of WTE, MLE, NSE and KSE are available. The above variance for the UWE is an exact result and may be used to check the validity of the simulation program. Before running the entire program ratios of the empirical and theoretical variances were computed for different combinations of k, n_i's and σ_i^2's and were found to be close to 1. This was taken as a validation of the simulation process.

Table 4 gives the precision of the different estimators relative to the estimator with the smallest MSE For each value of k the first seven rows refer to combinations in which n_i's and σ_i^2's have the same rank order, and the next seven rows to combinations in which n_i's and σ_i^2's have the reverse rank order.

One can observe from the table that the precision of these estimators depends, to a large extent, on the n_i's and δ. For δ =4/3 and small and medium sample sizes the best estimator was found to be the UWE for all values of k. This is not surprising when one notes that for $\delta = 1$ (i.e., the variances are all equal) the unweighted estimator is the best estimator. The result is also in conformity with suggestion (1) of Levy and Mantel. However, for large sample sizes and δ =4/3 NE1 and NE2 were found to be relatively more efficient than the UWE. For δ =2 and small samples the UWE and NE1 were found to be superior to the other estimators, but for medium and large samples the performance of NE1 and NE2 were found to be relatively better.

Table 4. Precision of the estimators relative to the best among the set.

K	Est.	Small							Medium							Large						
		δ							δ							δ						
		4/3	2	5	10	50	100	1000	4/3	2	5	10	50	100	1000	4/3	2	5	10	50	100	1000
3	UWE	100✓	101	137	171	662	1273	11936	100✓	106	164	219	789	1500	13419	101	107	150	250	792	1405	14918
	WTE	134	127	113	111	110	119	105	107	103	102	101	101	101	100	102	100	100✓	100	100✓	100	100✓
	MLE	127	*	*	*	*	*	*	107	103	100	100	100	100✓	100✓	102	100	100	100	100	100	100✓
	KSE	*	*	*	*	*	*	*	107	103	100✓	100✓	100✓	100	100✓	102	100	100	100✓	100	100✓	100✓
	NE1	106	100✓	100✓	100✓	138	164	239	101	100✓	114	118	150	174	207	100✓	100✓	106	124	143	163	224
	NE2	111	106	107	113	160	196	264	101	100	115	120	153	175	211	100	100	107	125	143	164	223
	NE3	208	175	113	106	100✓	100✓	100✓	198	177	120	119	109	103	100	217	182	139	134	116	105	101
	UWE	100✓	100	120	155	550	994	9531	100✓	105	139	210	712	1405	12703	101	106	141	197	740	1365	13440
	WTE	136	122	106	100✓	100✓	100✓	100✓	109	104	100	100✓	100✓	100✓	100✓	103	101	100	100	100✓	100	100
	MLE	*	*	*	*	*	*	*	109	104	100✓	100	100	100	*	103	101	100	100✓	100	100✓	100✓
	KSE	*	*	*	*	*	*	*	109	104	100	100	100	100	*	103	101	100✓	100✓	100	100	100✓
	NE1	106	100✓	103	105	190	288	1927	102	100✓	108	123	169	227	488	100✓	100	109	117	166	202	346
	NE2	109	101	100✓	100	149	191	359	102	100	107	120	159	203	317	100	100✓	109	116	163	193	307
	NE3	228	206	181	152	144	145	108	243	223	168	150	123	109	101	238	226	159	152	120	108	100
7	UWE	100✓	100✓	114	124	284	490	5640	100✓	107	126	139	367	636	5108	100✓	109	127	153	351	667	5763
	WTE	213	189	160	169	197	186	124	109	105	102	101	101	101	101	104	100	100✓	100	100✓	100✓	100✓
	MLE	145	144	*	117	*	*	*	107	104	100	100	100	100	100	104	100	100	100	100	100	100✓
	KSE	*	137	*	*	*	*	*	107	104	100✓	100✓	100✓	100✓	100✓	104	100✓	100	100✓	100	100	100✓
	NE1	107	103	100✓	100✓	129	138	594	101	100✓	102	101	154	172	371	101	100	103	108	149	177	380
	NE2	121	117	114	119	173	183	480	102	101	104	103	155	172	333	101	100	103	108	148	175	350
	NE3	393	323	234	220	100✓	100✓	100✓	373	355	248	249	125	116	100	429	408	282	251	138	127	104
	UWE	100✓	102	111	133	176	312	1914	100✓	106	117	159	297	544	3871	100	108	123	153	324	629	4867
	WTE	195	179	158	145	102	100✓	100✓	108	107	103	101	100✓	100✓	100✓	103	101	100✓	100	100	100	100✓
	MLE	*	*	*	*	*	*	*	107	107	102	100	100	100	100	103	101	101	100	100✓	100✓	100
	KSE	*	*	*	*	*	*	*	107	107	102	100✓	100	101	100	103	101	101	100✓	100✓	100	100
	NE1	108	100✓	100✓	100✓	107	150	829	101	100	100	105	154	200	728	100	100	102	107	151	196	530
	NE2	118	110	104	103	100✓	124	324	101	100✓	100✓	104	147	186	446	100✓	100✓	102	106	150	192	429
	NE3	424	389	394	377	304	317	398	435	482	479	512	180	142	103	568	476	389	368	145	134	103

Table 4. (Contd.)

12	UWE	100√	100√	106	155	328	400	4126	100√	100	115	188	354	680	4948	100	103	118	175	397	667	4852
	WTE	235	261	186	160	252	113	407	112	106	102	102	101	101	101	104	102	101	100	100	101	100√
	MLE	*	144	128	*	100√	*	*	112	106	100	100	100√	100	100√	103	102	100	100√	100√	100	100√
	KSE	*	*	125	105	*	*	*	112	106	100√	100√	100	100√	100√	103	102	100√	100	100√	100√	100√
	NE1	108	105	100√	100√	146	100√	329	103	100√	100	115	145	166	318	100√	100√	103	112	159	170	320
	NE2	122	132	114	118	194	120	489	102	100	102	117	147	168	306	100	100	104	113	159	171	308
	NE3	552	604	301	244	139	114	100√	660	608	287	363	162	159	123	795	714	376	393	172	172	130
	UWE	100√	100√	105	133	176	307	2028	100√	102	108	163	272	505	3606	101	103	115	177	329	554	3503
	WTE	211	207	178	147	105	100√	100√	112	108	109	101	100	100√	100	103	102	100	101	100	100√	100
	MLE	*	153	*	*	*	*	*	110	107	106	100√	100√	100	100√	103	102	100√	100	100√	100	100√
	KSE	*	*	*	*	*	*	*	110	107	105	100	100	100	100	103	102	100	100√	100	100	100√
	NE1	106	107	100√	100√	111	124	501	101	100	100	113	152	178	596	100	100	103	116	164	169	401
	NE2	117	115	108	103	100√	110	288	101	100√	100√	112	148	171	456	100√	100√	103	115	162	167	370
	NE3	676	751	667	600	532	399	287	767	801	871	607	581	354	194	797	835	883	474	191	238	133

√, Indicates the estimator with the smallest MSE. *, Indicates non-convergence.

When the sample sizes are small and $2<\delta\leq 10$ NE1 seemed to perform the best. The iterative procedure for obtaining the MLE and KSE failed to converge for small sample sizes on several occasions. A count was made of such events and it was observed that it could go to as high as 419 in 1000 runs. For medium and large samples the study indicated that the performance of the KSE was better than that of the rest.

For $50\leq\delta\leq 1000$ and small sample sizes the WTE and NE3 performed better than the other estimators. For medium and large samples the KSE, WTE and MLE had relatively higher precision than the others.

Even though there were indications that increasing the values of k favoured the KSE and MLE, the effect of k on precision was not marked. This could be because of the selected values of k which were all small and, therefore, could not clearly show the effect of k on precision.

CONCLUSION

The results of the study suggest that:

1) The relative precision of the estimators depends, to a large extent, on the sizes of the samples and δ, the measure of heterogeneity in σ_i^2's.
2) For δ near 1 and small and medium samples the UWE is relatively most efficient.
3) For $\delta=2$ and medium and large samples and for $2<\delta\leq 10$ and small samples the performance of NE1 seems to be the best.
4) For $2<\delta\leq 10$ and medium and large samples the KSE is relatively better than the rest.
5) For $50\leq\delta\leq 1000$ and small samples NE3 seems to perform well, but for medium and large samples the WTE is the best because of its relative precision and computational simplicity.

The indiscriminate use of the MLE is to some extent supported by theory. For large samples and under certain regulatory conditions the MLE has optimum properties of being approximately unbiased, consistent and efficient. But as the results of this study and also of other authors (for example Neyman and Scott and Rao) show there are circumstances when the MLE is less efficient than competing estimators. Therefore, when confronted with a new problem, one should carefully examine if the conditions are satisfied before applying the MLE.

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DIET COMPOSITION, LENGTH-WEIGHT RELATIONSHIP AND CONDITION FACTOR OF *BARBUS* SPECIES RÜIPPELL, 1836 (PISCES: CYPRINIDAE) IN LAKE AWASSA, ETHIOPIA

Demeke Admassu[1] and Elias Dadebo[2]

[1] Department of Biology, Addis Ababa University
PO Box 1176, Addis Ababa, Ethiopia

[2] Department of Animal Sciences and Rangelands Management
Awassa College of Agriculture, PO Box 5, Awassa, Ethiopia

ABSTRACT: Length-weight relationship, condition factor and composition of the diet of *Barbus* sp. in Lake Awassa were studied from monthly samples taken between December 1987 and September 1988. Total length and total weight of the fish were curvilinearly related (b = 3.14). Fulton's as well as relative condition factors did not vary between months and between sexes. *Barbus* sp. in Lake Awassa was considered to be polyphagous, because its diet was found to be composed of a diverse group of food items. Insect larvae (mainly chironomids), fruits, fish (mainly *Oreochromis niloticus)* and molluscs were the major food items of the fish whereas crustacean zooplankton, ostracods, nematodes and hydracarines were minor food items. Detritus and sand grains were also ingested by several individuals. The dominance of benthic food and the presence of sand in the gut indicate that the fish feeds mainly near the bottom. Although the fish is generally polyphagous, there were seasonal, individual and size-based differences in food and feeding habits. Thus, insects contributed more to the diet in the dry season whereas fruits, fish and molluscs contributed more in the wet season. This could probably reflect seasonal differences in availability between the food items. In addition, some individuals appeared to feed selectively on particular food items which could be a mechanism by which competition for food is minimised. Furthermore, individuals between 20.5 and 32.0 cm in length fed similar amounts of the major food items except that insects were taken at a relatively larger proportion. Fish larger than 31.5 cm appeared piscivorous. The degree of piscivory found in *Barbus* sp. in Lake Awassa was unexpectedly high, but as is the case in other cyprinids, it is believed to be due to the absence of specialised piscivores in the lake. The results of the study may also suggest that, as is the case in Lake Tana, the large *Barbus* of Lake Awassa may contain more than one morphotype, possibly more than one species. Thus, detailed taxonomic study is needed.

Key words/phrases: *Barbus* sp., bottom feeder, Lake Awassa, piscivory, polyphagous

INTRODUCTION

The genus *Barbus* (Fam. Cyprinidae) is widely distributed in African freshwaters (Cambray, 1983). In Ethiopia, the genus occurs in the River Awash and in several other rivers in the basins of Omo-Turkana, Chew-Bahir, Abaya--Chamo, Wabi-Shebelle and the Nile (Shibru Tedla, 1973; Golubtsov and Krysanov, 1993; Dgebuadze *et al.*, 1994). It also occurs in almost all of the lakes of the country. The most diversified *Barbus* fauna in Ethiopia is found in Lake Tana where 14 distinct morphotypes have recently been distinguished based on differences in external morphology and feeding habit (Nagelkerke *et al.*, 1994, 1995). Whether or not these are isolated species is yet unsettled, however, it seems probable that all of them originated from *B. intermedius* (Nagelkerke *et al.*, 1994).

Barbs are important components of the fisheries of Ethiopia (Mebrat Alem, 1993). The current annual total fish landing from the major waters of Ethiopia is about 6380 t from which 365 t is due to *Barbus* (LFDP, 1995). About 92% of the *Barbus* catch is from Lake Tana, and is composed of the various morphotypes. In addition, the annual catch of *Barbus* sp. from the other lakes ranges from 5 t (Lake Zwai) to 12 t (Lakes Koka and Awassa) (LFDP, 1995). Thus, this species is being exploited to a considerable degree in Ethiopia.

Matthes (1963) suggested that the genus *Barbus* can be split into distinct groups based on studies on feeding morphology and feeding habit. Therefore, a study on the food and feeding habit of this genus is an important development. Cyprinids do not have a true stomach (Matthes, 1963). However, the region of the gut between the oesophagus and the first bend in the tract contains food items that can easily be identified (Donnelly, 1982). Therefore, knowledge on the food habit of this fish is based on examination of the contents in this region of the gut.

In general, *Barbus* species are facultative feeders having distinct preferential diets, but they are also able to change their feeding habit (Matthes, 1963). Insect larvae and pupae form by far the most important food of several species (Donnelly, 1982; Cambray, 1983; Lowe-McConnell, 1987; Nagelkerke *et al.*, 1994). However, species like *B. altianalis* in Lake Victoria principally feed on gastropods (Corbet, 1961). Other items ingested by various species include Crustacea, Ostracods, Bivalvia, fish and macrophyte fruits and shoots (Corbet, 1961; Donnelly, 1982; Lowe-McConnell, 1987; Nagelkerke *et al.*, 1994). Filamentous algae, diatoms and desmids are, to a limited extent, ingested by certain *Barbus* spp. (Corbet, 1961; Cambray, 1983). Sand and detritus are also ingested by several species indicating a bottom feeding habit (Corbet, 1961; Mraja, 1982; Cambray, 1983; Nagelkerke *et al.*, 1994). Moreover, the diet of *Barbus* spp. varies seasonally and according to the size of the fish (Corbet, 1961; Donnelly, 1982; LoweMcConnell, 1987).

Piscivory is rare in cyprinids in general (Matthes, 1963), but it seems to occur in waters where other specialised piscivores are rare or absent (Matthes, 1963; Nagelkerke *et al.*, 1994). Nagelkerke *et al.* (1995), for instance, found that among the 14 Barbus-morphotypes of Lake Tana, 8 are mainly piscivorous.

Barbus sp. is believed to be abundant in Lake Awassa; next only to the dominant *Oreochromis niloticus*. Thus, the Barbus-fishery in Ethiopia in general and in Lake Awassa in particular is believed to develop in the future. Therefore, knowledge on some aspects of its biology will be useful to utilise the stock properly, and also to understand the role of the fish in the ecology of the lake. Hence, the specific objectives of the present study were: (1) to investigate the length-weight relationship and the condition factor, and (2) to study the food and feeding habits of the fish, and to investigate if these vary seasonally and with the size of the fish.

Lake Awassa (Lat.: 6°33′ to 7°33′N; Long.: 38°22′ to 38°29′E) is the smallest (surface area: 88 km^2; mean depth: 11 m) of a series of seven natural rift valley lakes in southern Ethiopia. The region where Lake Awassa is located is characterised by a short dry season (November to February) and a long rainy season (March to October) (Daniel Gamatchu, 1977). Electrical conductivity (K_{20}) of the lake varies between 730 and 825 μmhos cm^{-1}, with an increase in the dry season and a decrease in the wet season (Elizabeth Kebede and Amha Belay, 1994). Nitrate appears to be the nutrient that most limits phytoplankton productivity in Lake Awassa (Elizabeth Kebede and Amha Belay, 1994). The dominant phytoplankton species in Lake Awassa are *Lyngbya nyassae*, *Botryococcus braunii* and *Microcystis* spp. (Elizabeth Kebede and Amha Belay,

1994) whereas the dominant zooplankton species are *Mesocyclops aequatorialis, Thernwcyclops consimilis* and *Diaphanosoma excisum* (Seyoum Mengistou and Fernando, 1991). Chironomids, ostracods and oligochaetes are numerically among the dominant members of the benthic fauna in Lake Awassa (Tilahun Kibret, 1985). Fish species inhabiting the lake are *O. niloticus, Clarias gariepinus, Barbus sp., B. amphigramma, Garra* sp. and *Aplocheilichthys sp.*

MATERIALS AND METHODS

Monthly samples ranging in number from 23 to 47 were taken using a fleet of gill nets during the period December 1987 to September 1988 (except in March). The fleet was 152 m long and 2.4 m deep, and consisted of six gill nets whose stretched mesh sizes ranged from 50.0 mm to 112.5 mm by increments of 12.5 mm. The fleet was set, mostly between 1600 and 0900 h, at the surface of the lake (depth about 3 m) at a fixed site throughout the study.

Total length (TL) and total weight (TW) were measured from a total of 267 fish. The sex of each specimen was identified by inspecting its gonads, and sex ratio in each sample was calculated. Length-weight relationship was calculated using least squares regression analysis. Fulton's condition factor was calculated as TW in percent of TL^3 (Le Cren, 1951), and relative condition factor was calculated as TW divided by (aTL^b), where 'a' is the intercept and 'b' is the slope of the length-weight regression (Bagenal and Tesch, 1978). Length-weight relationship and condition factor were calculated for fish between 11.1 and 56.0 cm and between 10.5 and 2000.5 g. The values of condition factors were statistically tested (ANOVA, Sokal and Rohlf, 1981) to determine if they varied between sexes and between months.

The contents of the gut of each specimen were preserved in 5% formaldehyde solution for a later microscopic examination in laboratory. Gut content samples were not taken from fish caught in February, April and May. In the laboratory, the food items were identified to the lowest taxa possible using descriptions from various sources (Mamaril and Fernando, 1978; Pennak, 1978; Edington and Hildrew, 1981). The relative importance of each food item was analyzed using the frequency of occurrence, numerical abundance and the points methods

(Hynes, 1950; Windell and Bowen, 1978). The points method was used only for the main food items after they were classified into major groups, i.e., insects, fruits, fish and molluscs. The points method, first described by Hynes (1950), was used as modified by Frost (1977) and Donnelly (1982). Points were assigned to each food item based on a visually determined contribution of the item relative to the degree of fullness of the gut. A half-full stomach, for instance, contained an estimated 1/2 insects, 1/4 fruits, 1/4 molluscs and no fish. The allotted points were 50, 25, 25 and 0 for insects, fruits, molluscs and fish, respectively. The points were then divided by 100 and multiplied by fullness index which was determined before dissection by assigning semi-quantitative indices, viz. 100 = full, 75 = 3/4 full, 50 = 1/2 full, 25 = 1/4 full, 12 = 1/8 full and 6 = traces of food. In the half-full stomach (fullness index = 50) mentioned above, the points relative to the fullness index of the gut were 25, 12.5, 12.5 and 0 for insects, fruits, molluscs and fish, respectively.

A combination of frequency of occurrence and the points method was also used by grouping the percentage points of each food item in 10% classes (i.e., 0-10%, 10-20%, etc.), and plotting this value together with the frequency of occurrence in a combined frequency distribution.

Results from the points method were statistically tested for seasonal and fish size differences (G-test, Sokal and Rohlf, 1981). The relationship between feeding habit and fish size was investigated based on results obtained from the points method.

RESULTS

A total of 131 females and 136 males were caught throughout the study. Sex ratio in the total catch and in monthly catches did not vary significantly from 1:1 (Chi-square test, $p < 0.05$). Length composition and sample size of the fish used in this study are shown in Fig. 1. From a total of 127 fish dissected for gut content analysis, 23 (18.1%) had empty guts.

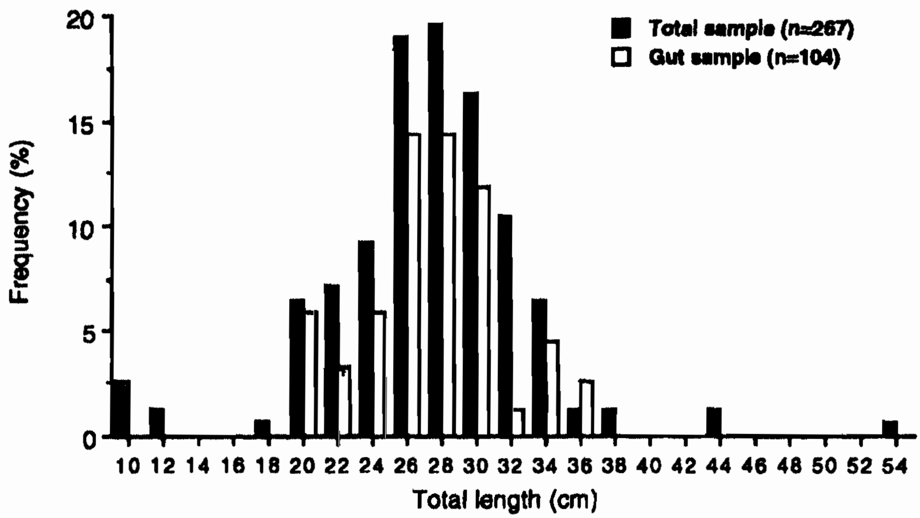

Fig. 1. Length-frequency (%) of *Barbus* sp. from Lake Awassa in the total sample and in the sample taken for gut content study.

Length-weight relationship and condition factor

The length-weight relationship of *B. intermedius* in Lake Awassa was significant (ANOVA, $p=0.001$), and curvilinear (Fig. 2). Both Fulton's and relative condition factors of the fish did not vary significantly between months or between sexes (ANOVA, $p>0.05$). The values for the sexes were combined. Monthly values (mean $\pm$ standard error) of Fulton's condition factor ranged from 0.89 ± 0.15 to 0.98 ± 0.13, whereas that of relative condition factor ranged from 0.96 ± 0.13 to 1.02 ± 0.22 (Table 1). Condition factors did not vary significantly (ANOVA, $p>0.05$) between the dry (December-January) and the wet (February-September) seasons. Fulton's condition factor was 0.95 ± 0.13 in the dry season and 0.85 ± 0.18 in the wet season. Relative condition factor was 0.99 ± 0.22 in the dry season and 1.00 ± 0.19 in the wet season.

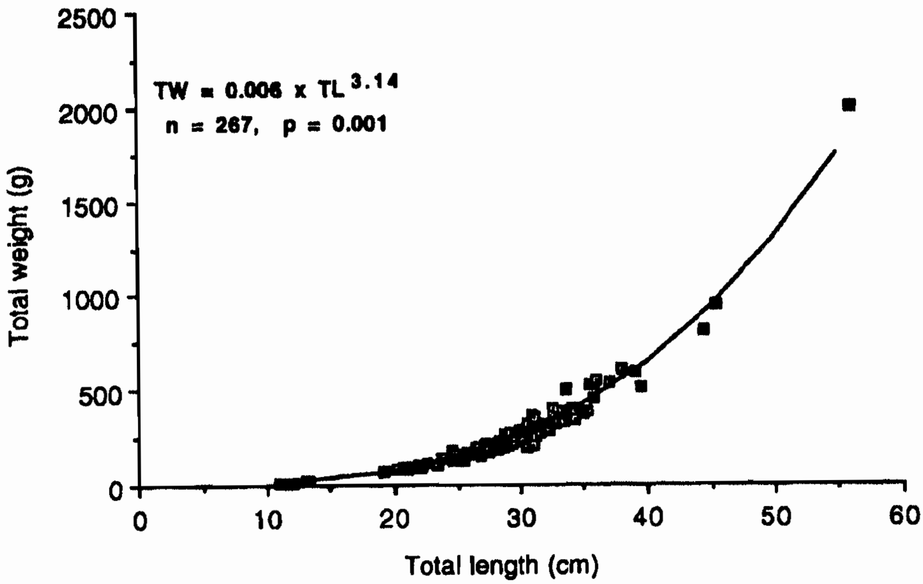

Fig. 2. Length-weight relationship of *Barbus* sp. in Lake Awassa.

Table 1. Mean monthly values of Fulton's (FCF) and relative (RCF) condition factor of *Barbus* sp. in Lake Awassa. SE is standard error and n is sample size.

Month	FCF±SE	RCF±SE	n
December	0.96±0.11	0.99±0.21	23
January	0.97±0.13	1.00±0.22	26
February	0.91±0.21	0.98±0.15	27
April	0.94±0.21	0.96±0.13	28
May	0.98±0.13	1.01±0.14	29
June	0.93±0.11	0.98±0.13	30
July	0.96±0.15	1.01±0.15	26
August	0.89±0.15	0.96±0.16	31
September	0.91±0.21	1.02±0.22	47

Composition of the diet

The diet of *Barbus* sp. in Lake Awassa was composed of diverse groups of organisms (Table 2). Algae were not found in the gut except two genera of diatoms which were rare. Crustaceans were represented by the cladoceran *Diaphanosoma excisum* and by unidentifiable copepods. Nematodes were found in the gut of some specimens, but it was not possible to determine whether they were ingested as food or they were parasites to the fish. Insects were the most diverse organisms in the diet of the fish, and were represented by young stages and adults belonging to six major groups (Table 2). Shells of gastropod snails, of which three genera were identified, were also found in several specimens. Other fish were also ingested by several *Barbus* individuals, but most of them were partly digested and unidentifiable. However, *O. niloticus* appeared the most common fish ingested by *Barbus* sp. Some of the unidentifiable fish looked like the cyprinodont *Aplocheilichthys* sp. The other important food items of *Barbus* sp. in Lake Awassa were fruits. Detritus and sand grams were also ingested by several specimens.

Generally, insects, macrophyte fruits, fish and molluscs were the major food items whereas the others were minor food items of the fish. Based on the frequency of occurrence method, the main items in descending order of importance were insects (93.2%), macrophyte fruits (63.5%), fish (34.6%) and molluscs (28.8%) (Table 3). Frequency of occurrence for the other items ranged from 3.9% (hydracarines, crustaceans and ostracods) to 9.6% (nematodes). Numerically, insects and macrophytes contributed each to about 48% of the food items. The numerical importance of each of the remaining items was considerably low: molluscs < 3%, fish < 1%, and the minor items < 2% (Table 3). Based on the points method insects, fish, molluscs, fruits and the minor items contributed 44, 29.8, 18.5, 6.7. and 1% of the bulk of the food-ingested by *Barbus sp.*, respectively.

Among insects, chironomid larvae were the most important food of *Barbus sp.* in Lake Awassa, because they were encountered in 81.7% of the specimens and constituted more than 30% of the total number of the food items. Although the corresponding values for the other insects were much lower, Ephemeroptera and Trichoptera were the second important insects in the diet (Table 3).

Table 2. Food items identified from the gut of Barbus sp. from Lake Awassa.

Algae
Bacillariophyceae (rare)
Navicula sp., *Cymbella* sp.
Crustacea
Cladocera (*Diaphanosoma excisum*)
Copepoda (unidentified)
Ostracoda
Nematoda
Insecta
Chironomidae larvae
Ephemeroptera nymphs
Tricoptera larvae & pupae
Odonata nymphs
Coleoptera
Hemiptera
Hydracarina
Mollusca (gastropods)
Bulinus sp., *Physa* sp., *Anisa* sp.
unidentified
Pisces
Oreochromis niloticus
unidentifiable (probably *Aplocheilichthys* sp.)
Macrophytes (fruits, shoots & roots)
Detritus
Unidentifiable animal remains
Sand grains (abundant)

Table 3. The relative importance of various food items to the diet of *Barbus* sp. in Lake Awassa. O, frequency of occurrence; N, numerical abundance; n, number of fish in which the items were found.

Food Items	O(%)	N(%)	n
Chironomid larvae	81.7	32.6	85
Ephemeroptera nymphs	58.7	6.4	61
Trichoptera larvae & pupae	55.8	7.8	58
Odonata nymphs	31.7	1.3	33
Coleoptera	3.9	<1.0	4
Hemiptera	3.9	<1.0	4
Hydracarina	3.9	<1.0	4
Copepoda	3.9	<1.0	4
Cladocera	3.9	<1.0	4
Ostracoda	3.9	1.2	4
Nematoda	9.6	<1.0	10
Mollusca	28.8	2.3	30
Fish	34.6	<1.0	36
Macrophyte fruits	63.5	48.5	66

Frequency distribution of percentage points is an indirect indication of the number of fish feeding on a particular food item, and also the relative volumetric contribution of the food items (Fig. 3). Thus, insects constituted 90% of the bulk of the food for 14% of the barbs examined, and were the sole food (i.e., 100% of the food bulk) for 23% of the sample. Also, it is evident from Fig. 3 that molluscs were 90% of the food bulk in 4.5% of the fish, but they were not 100% of the bulk in any specimen. Moreover, fish were found to be 90% and 100% of the food bulk in 3% and 25% of the sample, respectively. Fruits of macrophytes were the only food items (100%) in 11.0% of the fish.

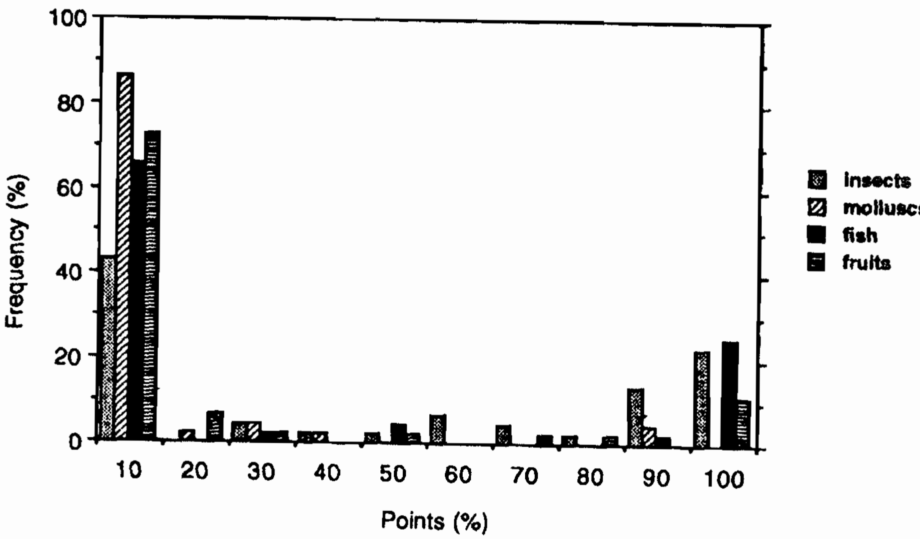

Fig. 3. Percentage frequency distribution of points (upper class limit) awarded to the main food items of *Barbus* sp. in Lake Awassa.

The percentage points of the major food items varied significantly between the dry and the wet seasons (G-test, $p < 0.05$). Insects contributed more in the wet than in the dry season whereas fruits, fish and molluscs contributed more in the dry than in the wet season (Fig. 4a).

Barbus sp. between 20.5 and 32.0 cm TL were found to feed on the various food items at approximately equal proportions, but insects appeared to be dominant (Fig. 4b). In contrast, individuals larger than 31.5 cm were found to be mainly piscivorous, but small amounts of insects and fruits were also eaten by a few individuals. The minor food items (crustaceans, hydracarines, ostracods and nematodes) were not ingested by fish larger than 30.5 cm (Fig. 4b).

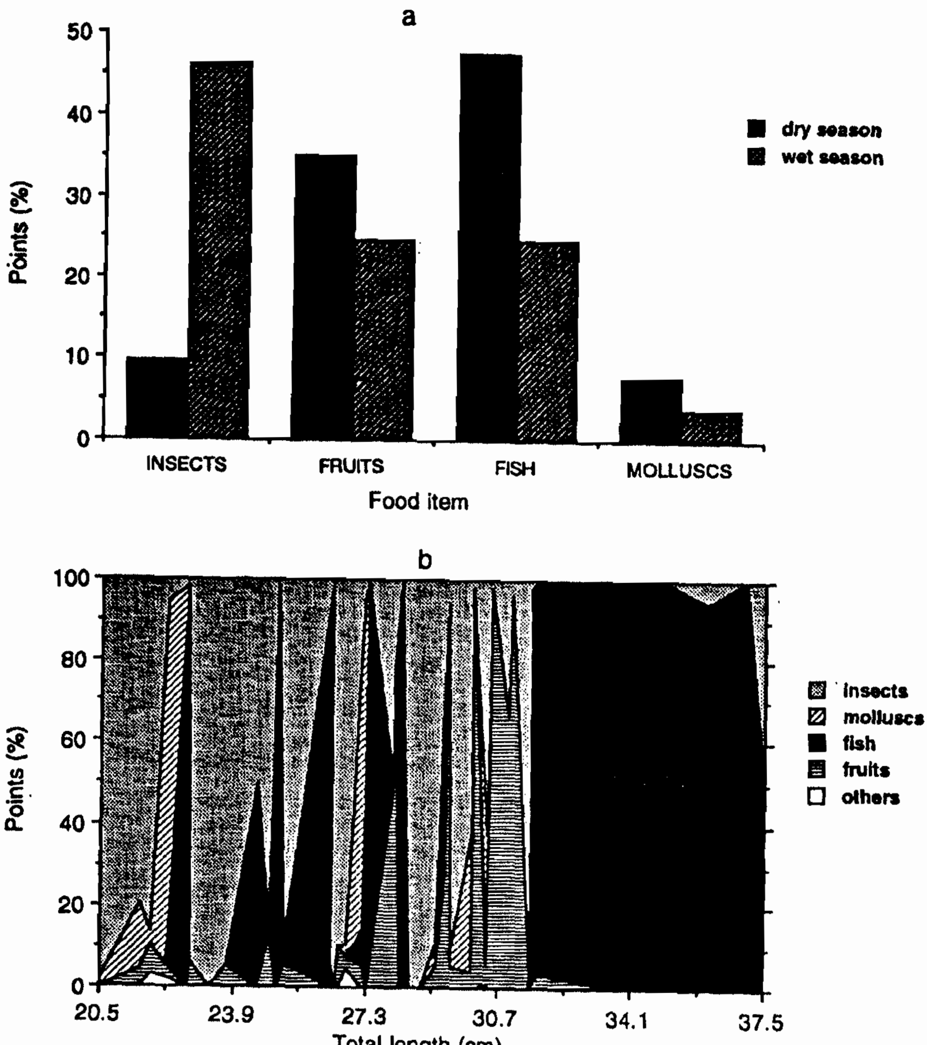

Fig. 4. **Variation in composition of the food of *Barbus* sp. in Lake Awassa between the dry and the wet seasons (a), and with total length of the fish (b).**

DISCUSSION

The length-weight relationship (b = 3.140) of *Barbus* sp. in Lake Awassa indicates that the fish grow nearly isometrically (Ricker, 1975). The value of b calculated in this study is comparable to those reported for some of the morphotypes of *Barbus* in Lake Tana (Nagelkerke *et al.*, 1994).

The study showed that *Barbus* sp. in Lake Awassa feeds on a variety of food items, and it can thus be considered as polyphagous. Polyphagy is typical for cyprinid fishes (Matthes, 1963; Cambray, 1983; Sibbing, 1991), and this may have contributed to the highly adaptable nature of *Barbus* spp in Africa, which in turn must have resulted in explosive speciation whenever conditions are favourable (Matthes, 1963). Polyphagy has also been reported by Nagelkerke *et al.* (1994) for some of the morphotypes in Lake Tana.

The frequent occurrence of sand and the dominance of benthos (i.e., insect larvae and pupae, molluscs and macrophyte fruits) in the gut of *Barbus* sp. indicate that the fish is mainly a bottom feeder. This could also be the reason why diatoms, which settle to the bottom in calm water conditions (Wetzel, 1983), were the only algae found in the gut of some fish. However, as is the case for *B. anoplus* in Lake Le Roux, South Africa (Cambray, 1983), the rare occurrence of diatoms in the gut may indicate that they were ingested accidentally when the fish were feeding on the bottom.

Donnelly (1982) found zooplankton and ostracods to be important food for juvenile *B. mattozi* in Mtsheleli Dam, Zimbabwe. Similarly, ostracods are the most important food of *B. bynni* in Lake Turkana (Mraja, 1982) and *B. anoplus* in Lake Le Roux (Cambray, 1983). These food items are of minor importance for the barbs of Lake Awassa. In addition, oligochaetes are important food for some barbs elsewhere (Spataru and Gophen, 1987), but were not encountered in this study. Furthermore, Tilahun Kibret (1985) reported that ostracods and oligochaetes are among the dominant members of the benthic fauna of Lake Awassa. Thus, it appears that some of our results may have been influenced by the lack of small fish in the study which in turn could be due to sampling fish from a single location using one type of fishing gear. Nevertheless, our results are not surprising as fish diet can vary even within a lake depending on feeding ground, season and fish size (Lowe-McConnell, 1987).

The study showed that composition of the diet of *Barbus* sp. in Lake Awassa varies with its size and between the dry and the wet seasons (Figs. 4a and 4b). Within the size range studied, the fish is omnivorous at sizes between 20.5 and 32.0 cm, but it appears to be piscivorous at larger sizes. Similarly, *B. mattozi* is planktivore when juvenile and an omnivore at sizes between 12.0 and 25.0 cm whereas entirely a piscivore at larger sizes (Donnelly, 1982). Other species showing a shift in diet with increase in size include *B. altianalis* in Lake Victoria (Corbet, 1961) and *B. longiceps* in Lake Kinneret, Israel (Spataru and Gophen, 1987).

Among the 104 individuals examined in this study, 34.6% of them had ingested other fish, and fish were the sole food in 25% of the specimens. The same has been reported for the majority of the Barbus-morphotypes in Lake Tana (Nagelkerke *et al.*, 1994). Since cyprinids lack oral teeth, they are morphologically limited to eat other fish, and hence, piscivory is rare in cyprinids (Matthes, 1963; Sibbing, 1991). Thus, the extent of piscivory in large (>32 cm TL) *Barbus* sp. in Lake Awassa appears unexpectedly high, as it is in Lake Tana (Nagelkerke *et al.* 1994 & 1995). Piscivorous cyprinids however, seem to occur where other specialised piscivores are rare or absent (Matthes, 1963; Sibbing, 1991). In Lake Awassa, *C. gariepinus* feeds on other fish, but it is an omnivore and not a specialised piscivore (Elias Dadebo, 1988). Thus, the absence of specialised piscivores in the lake could have favoured *Barbus* sp. to include fish as a major component of its diet.

The diet of a fish depends on the availability of the food in the environment. Thus, the seasonal difference in the relative contribution of the major food items of *Barbus* sp. in Lake Awassa could reflect seasonal differences in their availability. Vegetative growth of macrophytes in Lake Awassa is extensive during and immediately after the rainy season (personal observation). Thus, fructification and the eventual shedding of fruits may take place at the beginning of the dry season, hence fruits becoming more available in the dry season. In addition, other fish, particularly *O. niloticus,* appear to be relatively more available in the dry season, because recruitment of juvenile *O. niloticus* in Lake

Awassa is intensive between January and March and less intensive between July and September (Yosef T-Giorgis and Casselman, 1995; Demeke Admassu, 1997). There is no seasonal difference in the abundance of insects in Lake Awassa (Tilahun Kibret, 1985). Thus, their decrease in the diet of *Barbus* sp. in the dry season could be due to the inclusion of larger quantity of macrophyte fruits, other fish and molluscs in the diet. Information on seasonal abundance of molluscs in Lake Awassa is not available.

Macrophyte fruits, insects and other fish are each the sole food for a large number of barbs. These food items are ingested by fish of similar length range, and also both in the dry as well as in the wet seasons (Fig. 4). Thus, there appears to be a selection of a specific food item by some individuals which could be a mechanism by which competition for food is reduced among individuals. In addition, the results also suggest that the taxonomic status of the barbs of Lake Awassa may be more complicated than expected. It is also possible that the barbs of Lake Awassa may contain more than one morphotype and/or species as has been shown to be the case for Lake Tana barbs by Nagelkerke *et al.* (1994). A similar study is recommended on the barbs of Lake Awassa.

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BREEDING SEASON, FECUNDITY, LENGTH-WEIGHT RELATIONSHIP AND CONDITION FACTOR OF *OREOCHROMIS NILOTICUS* L. (PISCES: CICHLIDAE) IN LAKE TANA, ETHIOPIA

Zenebe Tadesse

Department of Biology, Bahir Dar Teachers' College
P0 Box 79, Bahir Dar, Ethiopia

ABSTRACT: The breeding season, fecundity, length-weight relationship and condition factor of *Oreochromis niloticus* from Lake Tana, Ethiopia, were studied from monthly samples collected using a bottom trawl between March, 1992 and March, 1993. In Lake Tana *Oreochromis niloticus* spawns throughout the year, with a high activity between April and August peaking in June and July. The peak spawning coincided with the onset of the rainy season. There was a curvilinear relationship between fecundity and total length (TL) (logF = -0.01 + 2.O1LogTL, r=0.86, p<0.001) and a linear relationship between fecundity and body weight (W) (F = 234.65+1.51TW, r=0.84, p<0.001) and gonad weight (GW) (F = 394.55+29.1GW, r=0.67, p<0.001). The length-weight relationship was less than a cube, LogTW = -1.373+2.742LogTL, n=680, r=0.97, p<0.001 indicating allometric growth of the fish. The length-weight regression coefficients for both males (2.748) and females (2.747) were almost the same. A significant seasonal fluctuation (ANOVA, p<0.001) was observed in the condition of the fish. The relatively low values during April to August may be due to the high energy cost of spawning.

Key words/phrases: Allometric growth, breeding season, Fulton's condition factor, fecundity, *Oreochromis niloticus*

INTRODUCTION

Tilapia (Cichlidae) are widely distributed in tropical and sub-tropical waters of Africa, South America and Asia (Fryer and Iles, 1972). The tilapia, *Oreochromis niloticus*, occurs in almost all the lakes and streams of Ethiopia (Shibru Tedla, 1973), and accounts for about 60% of the annual commercial fishery (LFDP, 1995).

Reproductive biology of *O. niloticus* from Ethiopian Rift Valley Lakes was studied by Zenebe Tadesse (1988) and Demeke Admassu (1994; 1997). Food and feeding habits were studied by Getachew Teferra (1987), Getachew Teferra and Fernando (1989), Eyualem Abebe and Getachew Teferra (1992), Getachew Teferra (1993) and Zenebe Tadesse and Getachew Teferra (1997) and age and growth was studied by Demeke Admassu (1989) and Yosef Tekle-Giorgis (1990).

O. niloticus is a maternal mouth brooding species that breeds continuously throughout the year in the Rift Valley Lakes, Ziway (Zenebe Tadesse, 1988) and Awassa (Demeke Admassu, 1997). There are peak breeding months where spawning is intensive and these months are associated with changes in environmental factors such as rainfall, temperature, and photoperiod (Zenebe Tadesse, 1988; Demeke Admassu, 1997).

Most studies of *O. niloticus* have been limited to the Rift Valley Lakes Ziway, Awassa and Chamo. By contrast, very little is known about this important fish of the non-rift valley lake, Lake Tana. Earlier reports about the fish fauna and limnology of this lake are very old and incomplete (Talling and Rzoska, 1967; Rzoska, 1976). However, recent studies have described 14 distinct morphotypes of large barbs (*Barbus* spp.) from Lake Tana based on differences in general morphology, distribution and feeding habit (Mina *et al.*, 1993; Nagelkerke *et al.*, 1995a). Mina *et al.* (1993) suggested that these morphological differences are evident after the fish attained sexual maturity. In contrast, Nagelkerke *et al.* (1995b) reported the possibility of distinguishing between most of the morphotypes at an earlier stage (< 12 cm fork length). Eventhough, their taxonomic status is still uncertain.

Oreochromis niloticus is the preferred fish for consumption by the local population and accounts for about 37% of the commercial fishery of Lake Tana (LFDP, 1995). Proper management and rational utilization of this resource requires basic biological knowledge on the fish such as feeding, reproduction and growth. However, such basic data are not available for *O. niloticus* from Lake Tana. Thus, studies on the basic biology and ecology of this fish are essential.

The main objectives of this study were to assess fecundity rate and breeding season of the fish and to estimate the length-weight relationship and condition factor of *O. niloticus in* Lake Tana.

DESCRIPTION OF THE STUDY AREA

Lake Tana (12°N, and 37°20'E) is located at an altitude of 1829 m in the north-western part of Ethiopia. It is the largest lake in the country and covers an area of 3150 km^2. It has a maximum depth of 14 m and a mean depth of 8.9 m (Rzoska, 1976). The lake was probably formed during the late Pliocene or early Pleistocene as a result of volcanic action which uplifted the surrounding mountains (Rzoska, 1976). The diel temperature varies from 23 to 30° C during the day time and falls below 10° C in the night (Fig. la). The annual rain fall may reach up to 2000 mm: the main rainy season extends from June to October peaking during June to August (Rzoska, 1976).

Among the 60 rivers that flow into the lake, the little Abbay, the Rib and the Gumera rivers are the largest. Lake Tana is the source of the River Abbay (the Blue Nile) which outflows at the south-eastern corner of the lake. The shores are partly rocky but especially at the mouth of affluent rivers there is an extensive macrophyte vegetation including *Cyperus*, *Scirpus*, *Paspalidium*, *Phragmites*, *Ceratophylum* and *Nymphea*. The vegetation provides spawning and nursery grounds for *O. niloticus*.

The bicarbonate plus carbonate, calcium, magnesium and sodium ions dominate the water chemistry of the lake. In contrast, nitrate-nitrogen is very low reaching below detection level (Talling and Rzoska, 1967). The major genera of phytoplankton in the lake include *Microcystis*, *Anabaena*, *Melosira*, *Surirella*, *Staurastrum* and *Pediastrum* (Talling, 1976). The known genera of zooplankton are *Mesocyclops*, *Thermocyclop*, *Diaphanosoma*, *Bosmina*, *Daphnia*, *Keratella*, *Brachionus* and others (Tesfaye Wudneh, pers. comm.). In addition to the 14 barbus-morphotypes (Nagelkerke *et al.*, 1995b) the fish fauna of Lake Tana is composed of *O. niloticus*, *Clarias gariepinus*, *Varicorhinus beso*, *Gara quadrimaculata* and *G. dembeensis*. The most important fish species which account for about 98% the fishery are *O. niloticus*, *Barbus* spp. and *C.* gariepinus (LFDP, 1995).

MATERIALS AND METHODS

Monthly samples from two sites were collected between March 1992 and March 1993 with a bottom trawl of a code end mesh size of 40 mm. Trawling was done for about 30 minutes during each sampling occasion. All fish collected were mixed and a random sub-sample of 30 to 60 fish were taken for analysis. Total length (TL) and total weight (TW) of each fish were measured to the nearest 0.1 cm and 0.1 g, respectively. Sex of each fish was determined by examination of gonads and the weight of gonads was recorded to the nearest 0.1g. Gonado-somatic index (GSI), gonad weight as a percentage of total body weight, was calculated for each fish. Maturity of the gonads was determined according to Siddiqui (1977) and Babiker and Ibrahim (1979). Fecundity was determined by counting all ripe eggs in ovaries that were preserved in Gilson's fluid (Synder, 1983). Length-weight relationship was constructed using least squares regression fitted to log transformed length and weight data, i.e., LogTW = loga + blogTL, where a and b are constants fitted by least squares regression.

Fulton's condition factor was calculated (Le Cren, 1951; Bagenal and Tesch, 1978). Fulton's condition factor = (TW/TL3) x 100 where, TW is in grams and TL is in centimetres.

A chi-square test was employed to determine if the sex-ratio varied between months and with fish size. Fluctuations in Fulton's condition factor as well as in GSI values were statistically (ANOVA) tested if they varied in samples between months (Sokal and Rohlf, 1981).

RESULTS

A total of 680 *O. niloticus* individuals were examined in 13 sampling occasions. Males were more numerous than females (chi-square, $p < 0.05$) in the total catch as well as in samples from April, May and June (Table 1). There was also a preponderance of males in length-groups that were larger than 27.0 cm TL (Table 2).

Table 1. The number of males, females and sex-ratio in monthly samples of *O. niloticus* caught from Lake Tana. The last column shows chi-square values. *, Significant (p<0.05).

Month	Males	Females	Sex ratio (male: female)	Chi-square
Mar. '92	22	17	1:0.77	0.64
Apr.	44	15	1:0.34	14.25*
May	36	21	1:0.58	3.95
Jun.	42	17	1:0.41	10.59*
Jul.	25	22	1:0.88	0.19
Aug.	23	26	1:1.13	0.18
Sep.	17	16	1:0.94	0.03
Oct.	31	23	1:0.74	0.19
Nov.	25	22	1:0.88	0.19
Dec.	25	36	1:1.44	1.98
Jan. '93	28	26	1:0.93	0.07
Feb.	32	29	1:0.91	0.15
Mar.	33	28	1:0.85	0.41
Total	383	297	1:0.78	10.88*

The gonado-somatic indices varied significantly (ANOVA, $p < 0.001$) between months. GSI values of females ranged from 0.43 ± 0.03 to 2.45 ± 0.25 (mean $\pm$ SE) whereas those of males ranged from 0.09 ± 0.01 to 0.99 ± 0.08. High GSI values were evident between April and August for both sexes. The peak occurred in June for females and in June and July for males (Fig. lb). The values were generally low during the rest of the sampling period except for the slight increase that was observed between January and March, 1993. This increase was more pronounced in males than females (Fig. lb). However, sex by month interaction was insignificant (ANOVA, $p = 0.068$) suggesting that the pattern of seasonal fluctuation on GSI was similar in both sexes.

Oreochromis niloticus with ripe gonads were caught throughout the year, however, their frequency in the catch varied seasonally (Fig. 1c). Ripe females were more frequent during April to August than during the rest of the year. However, the frequency of ripe males slightly increased between January and March in 1993 (Fig. 1c). The results from seasonal fluctuation in GSI and the frequency of ripe fish suggest that *O. niloticus in* Lake Tana breeds intensively between April and August, but some individuals may breed throughout the year.

Table 2. The number of males, females and sex-ratio in samples of *O. niloticus* caught from Lake Tana. Samples were grouped in 2.0 cm length classes. The last column shows chi-square values. *, Significant ($p<0.05$).

Length (cm)	Males	Females	Sex-ratio (male: female)	Chi-square
13	3	1	1:0.33	1.00
15	7	4	1:0.57	0.82
17	16	7	1:0.44	3.52
19	33	47	1:1.42	2.45
21	44	61	1:1.39	2.75
23	73	52	1:0.68	3.53
25	78	62	1:0.79	1.83
27	53	44	1:0.83	0.84
29	38	12	1:0.32	13.52*
31	22	5	1:0.23	10.70*
>32	16	2	1:0.13	10.89*
Total	383	297	1:0.78	10.88*

Fecundity of *O. niloticus* in Lake Tana ranged from 495 to 1243 eggs for females whose length was between 21 and 31.5 cm and weight was between 190 and 570 g. The mean fecundity was 730 eggs (standard deviation = 168, n=45). Fecundity was curvilinearly related with TL (Fig. 2a), and linearly related with TW (Fig. 2b) as well as with gonad weight (Fig. 2c).

There was a significant ($p < 0.001$, $n = 680$) curvilinear relationship between TL and TW of *O. niloticus* in Lake Tana. The regression equation which was fitted for fish between 12 and 34.8 cm TL and 40 and 743 g TW was as follows:

Males: $\text{Log}TW = -1.383+2.748\text{Log}TL$ ($r=0.974$, $p<0.001$, $n=383$).
Females: $\text{Log}TW = -1.377+2.747\text{Log}TL$ ($r=0.965$, $p<0.001$, $n=297$).
Males and females: $\text{Log}\,TW = -1.373+2.742\text{Log}\,TL$ ($r=0.971$, $p<0.001$, $n=680$).

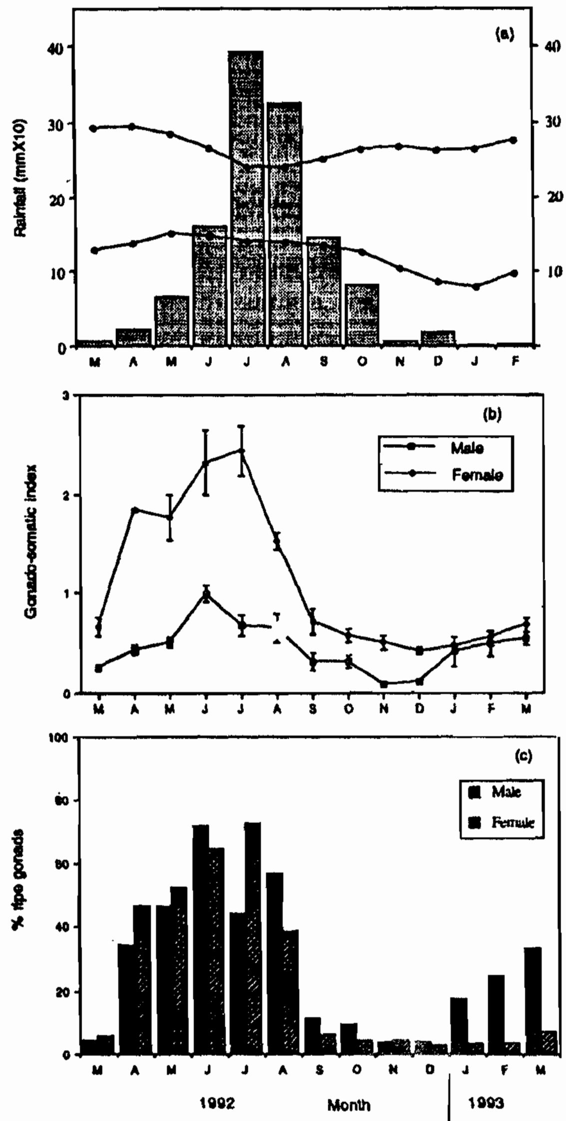

Fig. 1. Monthly mean total rainfall (bar) and air temperature (line) around Lake Tana between 1979 and 1988 (a), seasonal variation in gonado-somatic index (b) and frequency of ripe gonads (c) of *Oreochromis niloticus*. Vertical bars indicate standard error of the mean.

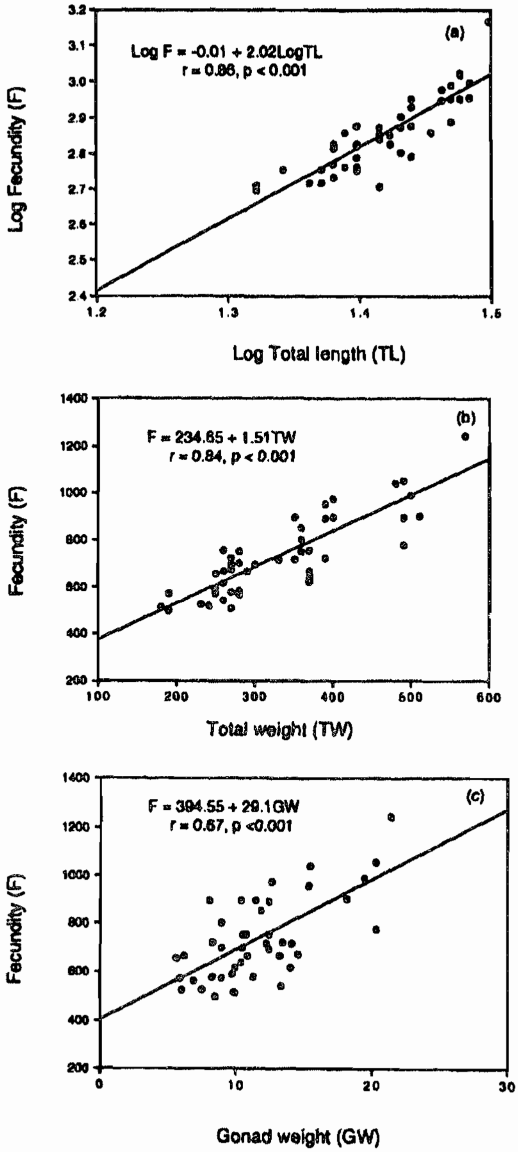

Fig. 2. Relationship between fecundity and total length (a), fecundity and total weight (b) and fecundity and gonad weight (c). n=45.

Fulton's condition factor of the fish ranged from 1.47 to 2.29 for females and from 1.44 to 2.37 for males. The values were found to be significantly different between months (ANOVA, $p < 0.001$). Thus, the values were relatively lower between May and August (Fig. 3) which seem to coincide with the peak breeding season of the fish (cf. Figs 1b and 1c).

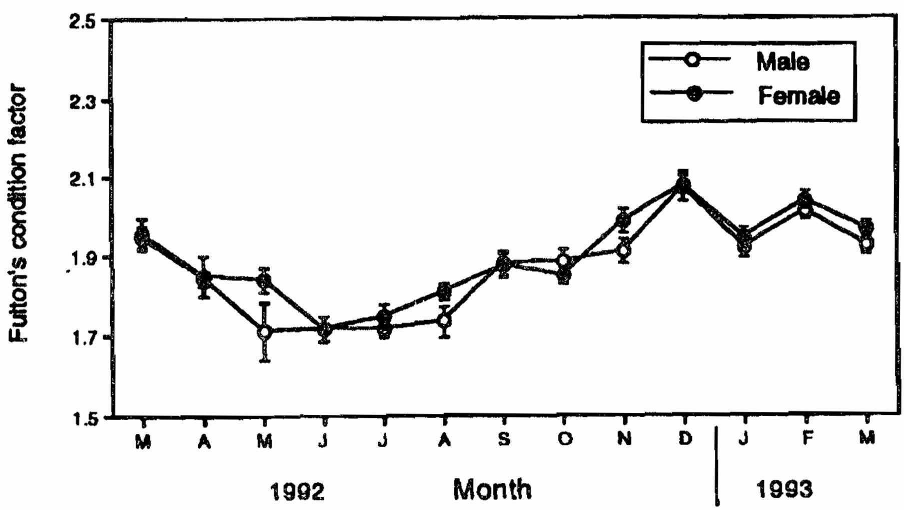

Fig. 3. Seasonal variation in the Fulton's condition factor of *Oreochromis niloticus*. Vertical bars represent standard error of the mean.

DISCUSSION

This study demonstrates that males predominated in the catch that was taken during the peak spawning period of the fish and this could be one of the reasons why males were more numerous than females in the total catch as well as in size groups above 27 cm TL (Tables 1 and 2, Figs 1b and 1c). The preponderance of males over females in the catch taken during the peak breeding season may be explained by the interactive effects of the reproductive behaviour of the fish and the sampling gear. During the spawning season, male tilapia build their spawning nests at the bottom and guard them against intruders

(Lowe-McConnell, 1958; 1959). In addition, the males are polygamous and thus stay at their breeding nests to court several females (Lowe-McConell, 1958; 1959). The females, on the other hand, move to their brooding sites in the vegetation zones up in the water column immediately after fertilization (Lowe-McConell, 1958; 1959). Thus, the males stay longer at the bottom of the water making them more vulnerable than the females to be caught by the gear used in this study (bottom trawl). This may also be the reason why males dominated over the females particularly in sexually mature fish (> 27 cm TL). In contrast, gill nets set at the water surface are likely to catch more females than males. This was reported by Demeke Admassu (1994) who found a preponderance of females over males in *O. niloticus* from Lake Awassa in gill net catches taken during the peak fish breeding seasons. He also attributed his results to the breeding behaviour of the fish and to the type of gear he used. Sex-ratio in favour of males has been reported to the related mouth brooding species *T. leucostica* in Lake Naivasha (Siddiqui, 1977). Lowe-McConnell (1959) has also suggested that in tilapia a preponderance of males in catches may indicate peak breeding season.

Oreochromis niloticus in Lake Tana breeds intensively during April to August (Figs 1b and 1c). However, some breeding activity may take place at other times of the year as well. Environmental factors such as temperature and photoperiod influence gonadal development in tilapia (Balarin and Hatton, 1979), but this is only possible in the temperate regions where there is a marked seasonal fluctuation in these factors. In the tropics however, seasonal fluctuations in temperature and photoperiod are generally very low, and this might be favourable for some tropical fish to spawn at any time of the year (Lowe-McConnell, 1982). Similarly, this may be the reason why breeding *O. niloticus* in Lake Tana were present throughout the year. Other species of *Tilapia* were also found to spawn year round (Siddiqui, 1977; 1979). Rainfall is another environmental factor associated with spawning in tropical fish in general and in tilapia in particular (Zenebe Tadesse, 1988; Demeke Admassu, 1997). The rainy season at Lake Tana was coincident with the peak spawning activity of *O. niloticus* (Figs la,b and c). Evidently, rainfall increases production (phytoplankton, zooplankton) of waters because of the resulting nutrient load by run off (Elizabeth Kebede *et al.*, 1994). This in turn insures the availability of sufficient food for better growth and survival of the off-springs of tilapia fish

(Jalabert and Zohar, 1982). In addition, the quality of the available food may also be improved after the rainy season. A study that was conducted concurrently with the present (Getachew Teferra pers. comm.), for instance, showed that the food ingested by *O. niloticus* in Lake Tana after the rainy season contained high levels of organic matter and protein and low levels of hydrolysis resistant organic matter. In addition, rainfall increases water level which in turn provides suitable spawning grounds for adults and feeding and nursery grounds for the young (Jalabert and Zohar, 1982). Since the macrophyte vegetation of Lake Tana grows extensively following the rainy season, the juvenile *O. niloticus* would be provided with suitable shelter and minimize the risk of predation by piscivores. Thus, rainfall appears to be an important environmental cue associated with the intensive spawning activity of *O. niloticus* in Lake Tana between April and August (Fig. 1a).

Similar studies (Zenebe Tadesse, 1988; Tudorancea *et al.*, 1988; Demeke Admassu, in press) have shown that the fish in the rift valley lakes of Ethiopia spawn throughout the year. However, breeding was intensive between December and March in Lake Ziway (Zenebe Tadesse, 1988) and during January to March and July to September in Lake Awassa (Tudorancea *et al.*, 1988; Demeke Admassu, 1997). Stewart (1988) also reported that the species in Lake Turkana breeds continuously but peak breeding occurs during March to July. Peak spawning activity of *O. niloticus* in the above studies has been attributed to rainfall and to factors associated with it, and agree well with the present study.

Fecundity of *O. niloticus* in Lake Tana was related nearly to the square (b = 2.01) of fish length (Fig. 2a). This is low when compared with substrate spawners where fecundity is related to the cube of their length (Simpson, 1951; Lowe-McConnell, 1959). The low fecundity of *O. niloticus* could be due to the mouth brooding behaviour of the fish as the number of spawn will be limited by the size of the buccal cavity (Lowe-McConnell, 1955; Babiker and Ibrahim, 1979). Moreover, Lowe-McConnell (1955) stated that mouth-brooding tilapia tend to produce large but few eggs due to better parental care they provide for their offspring. A comparably low fecundity has been reported for the same species from Lakes Ziway (b=2.16) Zenebe Tadesse (1988), Lake Awassa (b=2.39), Demeke Admassu (1994) and from the White Nile (b=2.02) Babiker and Ibrahim (1979) supporting the result obtained in this study. Siddiqui (1977) also reported a low value (b=2.17) of fecundity for the related mouth brooding *T. leucostica*. Fecundity was linearly related to total weight (Fig. 2b) as well as to gonad weight (Fig. 2c). Similar relationships were also reported by other workers for the same species (Demeke Admassu, 1994), and the related *T. leucostica* (Siddiqui, 1977). The relatively weak correlation (r = 0.67) between fecundity and gonad weight might be due to differences in the size of ripe oocytes. Large ovaries were found to contain fewer oocytes (Welcomme, 1967), and this might account for the poor correlation observed between fecundity and ovary weight.

The curvilinear relationship between weight and length of *O. niloticus* in Lake Tana was less than a cube (b = 2.74) for both sexes. This coefficient is expected to be near three since growth in weight represents an increase in three dimensions whereas length measurements are taken in one dimension (Bwanthondi and Pratap, 1981). However, the apparently low value of the coefficient might be because of shortage of food (phytoplankton) available for the fish in the lake. In a similar study, a value close to cube was obtained from the Rift valley lakes, Ziway (b=3.03 (Zenebe Tadesse, 1988)) and Awassa (b=3.01 (Demeke Admassu, 1990)) for the same species. These two lakes contain a relatively high algal biomass (Awassa 18.3 $\mu g(l)^{-1}$; Ziway, 154.2 $\mu g(l)^{-1}$ (Elizabeth Kebede *et al.*, 1994)) when compared with Lake Tana (3.7 $\mu g(l)^{-1}$ (Talling, 1976)). Thus, although food is seldom limiting under natural conditions, the relatively low algal biomass in Lake Tana, might be less than sufficient for optimum growth of the fish.

The condition factor of the fish varied significantly (ANOVA, $p < 0.001$) between months (Fig. 3). Low condition factor of *O. niloticus* in Lake Tana is coincident with the peak spawning season of the fish. Spawning drains metabolic resources for the production of sperm and eggs (Fryer and Iles, 1972). In addition, in species such as *O. niloticus* females brood their young in the buccal cavity and the males are actively engaged in building and guarding nests and in fertilizing several females (Lowe-McConell, 1958, 1959). Thus, feeding intensity of *O. niloticus* may be reduced if the fish is actively engaged in breeding activities. This could be the reason why the condition factor of *O. niloticus* in Lake Tana was relatively low during the fish peak breeding season. Similar conclusions were made for the same species from Lakes Ziway (Zenebe Tadesse, 1988) and Lake Awassa (Demeke Admassu, 1994). Stewart (1988) also correlated the decreased condition of *O. niloticus* during the peak breeding period in Lake Turkana with increased reproductive activity of the fish which causes erratic feeding and depletion of bodily reserves.

Studies on the breeding season, fecundity and related parameters have practical significance for *O. niloticus* fishery. The legal minimum mesh size (stretched) of the gill net for the tilapia fishery of Lake Tana and of most other lakes in Ethiopia is 100 mm. This gill net at Lake Awassa for instance, is reported to catch a considerable number of spawning fish during their breeding period (Demeke Admassu, 1994). In addition, the length of 50% maturity of *O. niloticus* in Lake Awassa, i.e., 18.8 cm for females and 19.8 cm for males (Demeke Admassu, 1994), is similar to the fish in Lake Tana, i.e., 18.1 cm for females and 20.7 cm for males (Tesfaye Wudneh pers. comm.). Thus, it is highly probable that the gill net being used at Lake Tana may remove a significant number of spawning fish during their peak breeding season. Hence, it is essential to investigate the effect of commercial gill netting on the *O. niloticus* stock of Lake Tana so that appropriate management actions can be taken to sustain the yield.

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MAGMA-CRUST INTERACTION DURING EMPLACEMENT OF CENOZOIC VOLCANISM IN ETHIOPIA: GEOCHEMICAL EVIDENCE FROM SHENO-MEGEZEZ AREA CENTRAL ETHIOPIA

Gezahegn Yirgu

Department of Geology and Geophysics, Addis Ababa University
PO Box 1176 Addis Ababa, Ethiopia

ABSTRACT: The Ethiopian Cenozoic volcanic province constitutes a thick succession dominated by fissural basalts and subordinate silicic products spread over an area measuring several hundred thousand square kilometres. Major and trace element analyses are presented for a suite of basic to acid rocks from sections around Sheno-Megezez area, north-east of Addis Ababa. The analyzed basic rocks belong to the plateau-forming Aiba Formation, sampled near Sheno village, and the shield-forming Termaber Formation, sampled at Megezez mountain. The silicic samples, stratigraphically found between the two basaltic formations, represent the Alaji Rhyolite Formation. The basalts exhibit variable degrees of evolution and are generally transitional between tholeiitic and alkaline. They display comparable major element compositions but show significant internal variations in some incompatible element ratios such as Rb/Nb and Rb/Ba. The data presented in this work is best interpreted in terms of magmatic processes involving combined fractional crystallization (FC) and interaction with a component of acid composition (AFC). The acidic products appear to be derived from parental basaltic magmas by fractional crystallization. The component of acid composition interacting with mantle-derived basaltic magmas could derive either from rhyolitic melt generated by FC or from material of crustal origin. It, therefore, appears that mantle-derived magmas could have undergone important geochemical modifications at intracrustal levels. This observation, together with similar findings from other regions in the Ethiopian volcanic province, puts significant constraints on utilizing geochemical signatures of basalts to infer mantle source heterogeneity before critically evaluating the effects of crustal interaction.

Key words/phrases: Basalt, crust, Cenozoic, Ethiopia, geochemistry, fractional crystallization

INTRODUCTION

Continental flood basalt volcanism is often associated with rifting, as in the case of the Afar-Red Sea-Gulf of Aden area. Ideas on the origin of these basalts have developed rapidly during the last two decades.The erupted volcanics in these areas display compositional variations both in time and space, which are now believed to reflect largely the involvement of different mantle sources beneath the regions of magmatic activity (e.g., Hart *et al.*, 1989, Deniel *et al.*, 1994). However, a number of other authors argue that some of the geochemical variations in the mafic magmas may be the result of low-pressure evolutionary processes not directly related to source heterogeneity (Cox and Hawkesworth, 1988; Huppert and Sparks, 1985; Devey and Cox, 1987). It is, therefore, necessary that the role of evolutionary processes in modifying magma compositions be assessed before inferring the nature of the mantle source from basalt geochemistry. One of the possible processes that may impose modifications on mantle-derived magmas is crustal contamination as magmas make their way through continental crust.

The Ethiopian Cenozoic volcanic province constitutes one of the largest intracontinetal magmatic provinces. It developed entirely during Cenozoic with emission of huge amounts of flood basalts and interbedded ignimbrites. The flood lava sequence is overlain, in part, by shield volcanoes of the so-called Termaber formation. The complex evolution of magmatism in space and time makes this region a favourable area to investigate the origin and evolution of large-volume volcanics. In this work new major and trace element data are presented on a suite of basic to acid volcanic rocks collected from the Ethiopian Central Plateau and a shiled volcano in the region of Debre-Berhan town. The aim of this study is to report new analytical data on the Cenozoic volcanics and investigate on possible processes responsible for the geochemical characteristics of the erupted magmas, with particular emphasis on the role of continental crust in the petrogenesis of the volcanics.

Geological setting

The Ethiopian volcanic province, which covers an area of greater than 600, 000 km^2, is dominated by up to 300,000 km^3 of generally fissure-fed basaltic lavas forming the volcanic plateaus that bound the Afar and Ethiopian Rifs (Mohr, 1983; Ebinger *et al.*, 1993). The volcanic products lie directly on metamorphic rocks of Precambrian age or on Mesozoic sedimentary sequence. A number of studies in this province have contributed to the understanding of the major tectonic and magmatic events and deep mantle processes responsible for them (Zanettin *et al.*, 1974; Merla *et al.*, 1979; Davidson, 1983; Mohr, 1983; Hart *et al.*, 1989, among others). These authors have provided valuable data on stratigraphy, radiometric ages and petrological and geochemical composition of the Ethiopian volcanics.

These studies have allowed to recognize two major phases of magmatic activity. A first phase was responsible for the eruption of lavas that built thick successions, up to nearly two kilometres, of fissural basalts (known as Ashange and Aiba Basaltic Formations) and later emplacement of a thick series, up to 500 meters, of silicic lavas mainly in the form of ignimbritic sheets (Alaji Rhyolitic Formation). This fissural magmatic stage was followed by the building up of huge shield-like volcanic complexes from central vents with the predominance of basalts over evolved volcanics (Termaber Basalt Formation). Earlier K/Ar radiometric age determinations reported by several authors in the Ethiopian Northern Plateau region (see Merla *et al.*, 1979; Mohr and Zanettin, 1988; for review) indicate an age of about 55 Ma for the emplacement of the oldest Ashange basalt flows, an age of 34 to 13 Ma for the Alaji Formation and an interval of 28 to 5 Ma for the Termaber Formation. These results are now being revised in light of much recent data from carefully studied sections using better and modern techniques. Preliminary age determinations, based on $^{40}Ar/^{39}Ar$ method, complemented by palaeomagnetic studies, indicate that the main fissural outpourings on the Ethiopian Central Plateau region occurred at about 30 Ma and were probably emplaced in a short time interval (Hoffman *et al.*, 1995).

A second phase of magmatic activity in the Ethiopian region was mainly located in the Afar depression and along the Main Ethiopian Rift, where it is active at present (Gibson, 1974; Di Paola, 1972; Barberi *et al.*, 1980). This activity is associated with the opening of the interconnected Red Sea- Afar- Gulf of Aden young oceanic rift system and the continental East African rift.

Sampling and petrography

The studied area is located about 80 km northeast of Addis Ababa, in the region of the town of Debre-Berhan, to the south and east of Sheno village (Fig. 1). The outcropping rocks in this area belong to the Aiba, Alaji and Termaber Formations, according to Merla *et al.* (1979). The plateau flood basalts of the Aiba formation have been sampled along the Inkoy river and Amari Wiha river gorges (tributaries of Kesem river), south of the town of Sheno. The samples of the Termaber formation have been collected from various localities on the Megezez shield volcano. The silicic rocks of the Alaji formation have been sampled both from the top of the plateau series (overlying Aiba basalts) and from the base of the Meghezez volcano (underlying the shield-forming basalts).

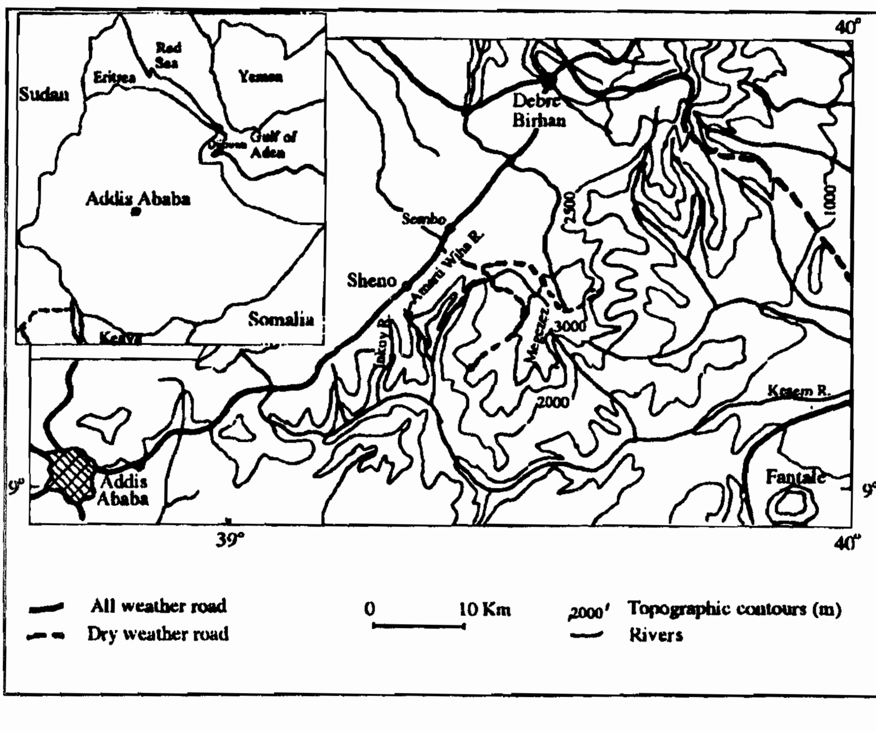

Fig. 1. Location map of the studied area.

The analyzed rocks range petrographically from basalt to rhyolite. Aiba samples from Sheno are all basaltic while those of Megezez consist of basalts and intermediate varieties. Basic and intermediate rocks are variably porphyritic with total phenocryst contents ranging from about 40% to less than 5% of the total rock volume. Plagioclase is invariably the main phenocrystal phase and is accompanied by minor clinopyroxene and, in a few cases, by scarce olivine and magnetite microphenocrysts. Aiba basalts are commonly aphyric and rarely porphyritic or glomero-porphyritic while those of Megezez are characterized by the presence of up to 5 mm large plagioclase phenocrysts and less common aphyric basalts. Plagioclase shows complex zoning and in some cases is strongly resorbed. Some phenocrysts show evidence of secondary transformation. Clinopyroxene is present in well preserved euhedral crystals. Olivine occurs as small altered crystals. The groundmasses of basalts and intermediate rocks are generally microphytic or intergranular and consist of the same mineral phases as the phenocrysts, with opaque minerals (Fe-Ti oxides) and some altered glass.

The Alaji acid rocks, found mainly in the form of ignimbritic sheets, are generally scarcely porphyritic with phenocrysts of sanidine, and quartz set in a cryptocrystalline groundmass. Rare alkali amphiboles, and aegerine-augite are sometimes present. Fe-Ti oxides commonly occur as microphenocrysts and in the groundmass. Phenocrysts are generally broken and strongly fractured. Sanidine is commonly euhedral while quartz is often resorbed with rounded margins and embayed edges. Groundmasses are devitrified and, in some cases, show phantoms of eutaxitic texture.

GEOCHEMISTRY

Analytical methods

Major and trace elements have been determined at the Institute of Earth Sciences, University of Messina, Italy. Major elements have been analyzed by combined wet chemical methods and X-ray fluorescence (XRF) procedures (Franzini *et al.*, 1972). The trace elements Cr, V, Ni, Co, Rb, Sr, Y, Nb, La, Ce, Ba and Zr have been analyzed by XRF on pressed powder pellets. Several international rock standards have been used for curve calibration. Precision is better than 10% for all the trace elements, except Rb and Sr which have precisions better than 5%. Some selected samples have been analyzed by Instrumental Neutron Activation Analysis (INAA) for the Rare Earth Elements (REE), Sc, Cr, Co, Th, U, Cs, Ta and Hf. Precision is better than 10% for most of these elements at the concentration level of the studied samples. The elements obtained by both INAA and XRF compare quite well, except for La, Ce and Co which show consistently higher values in XRF determinations.

Major and trace elements

Abundances of major and trace elements are reported in Table 1. The Total Alkali-Silica (TAS) classification diagram (Le Bas *et al.*, 1986) shows that the suite of rocks analyzed range in composition from basalt through trachyandesite to rhyolite (Fig. 2). Basaltic rocks dominate over the salic ones with only few samples of intermediate compositions. Such a distribution of volcanic rocks is not an artifact of sampling but reflect the relative volumes of erupted volcanics as observed in the field. Both the plateau and the Megezez basalts plot along the boundary separating the alkaline from the sub-alkaline series of Irvine and Baragar (1971) (Fig. 2 inset) and are best characterized as transitional basalts, following the nomenclature of Piccirillo *et al.* (1979) for Ethiopian volcanics. It is important to note here that the Termaber Basalt Formation has so far been regarded as an alkalic type in previous works on Ethiopian volcanics (Mohr and Zanettin, 1988). The present data confirm that the Termaber formation also contains transitional volcanics and, thus is more variable than previously thought.

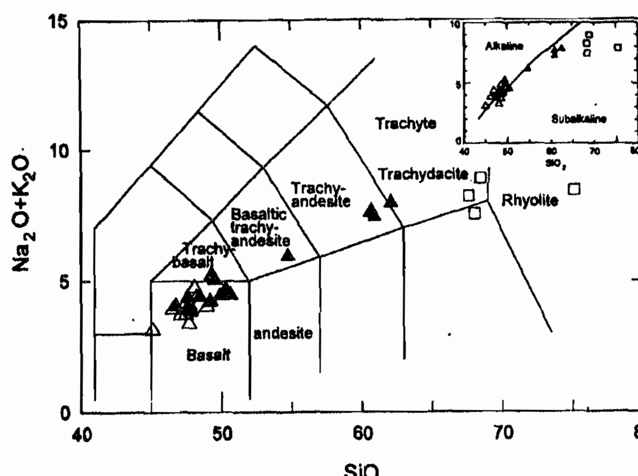

Fig. 2. **TAS classification diagram (Le Bas *et al.*, 1986) for the analyzed volcanics (recalculated on hydrous basis). Δ, fissural plateau lavas; ▲, Megezez shield volcanics; □, Alaji silicics. Inset: Plot in the alkaline-sub-alkaline diagram of Iryine and Baragar (1971).**

Variations of major elements as a function of SiO_2 wt% for the analyzed samples are shown in Fig. 3. The plateau basalts show a narrow range of silica contents but rather wide variations of some major elements, especially Na_2O, TiO_2, P_2O_5, and, to a less extent, Al_2O_3. The Megezez volcanics span a relatively wider compositional range of silica contents. The rocks from the Alaji formation are acid in composition and exhibit restricted variations. K_2O and Na_2O exhibit a regular increase with SiO_2 in the Megezez rocks, whereas MgO, CaO, FeO_{total} , Al_2O_3, P_2O_5 and TiO_2 decrease with increase in SiO_2 with some scattering in the basic samples. The Alaji acid rocks plot on the same trends as the Megezez suite, except for Na_2O, which is lower in the Alaji rocks than in the most evolved Megezez volcanics. Overall, the major element trends of the Megezez rocks mimic a liquid line of decent and are consistent with a fractional crystallization path of magma evolution. These variation trends correlate with the assemblage of minerals in the studied samples and suggest that these minerals significantly governed the compositional path of liquids during magmatic differentiation. On the contrary, the plateau lavas display marked elemental variations at a fairly constant silica content. These variations are not related to textural features of the rocks, such as the amounts of phenocrystal phases and must be considered as inherent to the composition of magmas.

Table 1. Major element (wt%) and trace element (ppm) data for the Sheno-Megezez volcanics. Asterisks indicate X-ray fluorescence trace element data. Other trace elements have been analyzed by INAA.

	SHENO SECTION (Aiba and Alaji forms)						
	M-G	TM-B	TM-J	TM-D	TM-I	TM-E	TM-K
SiO_2	45.13	46.55	47.11	47.35	47.50	47.70	47.74
TiO_2	2.43	2.62	4.14	2.48	4.19	2.63	2.48
Al_2O_3	16.87	15.58	14.54	17.32	14.49	17.06	17.62
Fe_2O_3	3.55	7.68	5.18	7.41	3.99	5.21	4.55
FeO	8.86	7.00	9.26	4.82	10.72	6.14	7.51
MnO	0.19	0.19	0.21	0.19	0.20	0.24	0.19
MgO	6.51	4.32	4.48	3.26	4.57	3.79	4.33
CaO	10.67	8.37	9.16	9.03	8.08	9.26	9.72
Na_2O	2.53	3.02	2.68	3.32	2.68	3.35	2.93
K_2O	0.60	0.88	0.99	0.69	1.02	0.71	0.43

Table 1. (Contd.)

	SHENO SECTION (Aiba and Alaji forms)						
	M-G	TM-B	TM-J	TM-D	TM-I	TM-E	TM-K
P_2O_5	0.75	0.53	0.55	0.65	0.49	0.69	0.54
LOI	2.01	3.25	1.07	3.31	1.31	2.67	1.96
Mg#	53.11	39.44	40.3	37.31	40.11	42.33	43.9
La*	11	14.8	31	11	28	10	13
Ce*	33	34	81	21	69	25	32
V*	307	334	407	290	422	293	293
Cr*	16	37	25	9	19	7	27
Co*	41	39	43	25	45	29	37
Ni*	31	18	34	12	31	13	19
Rb*	9	20	26	9	25	12	4
Sr*	580	390	470	491	468	503	480
Y*	28	46	55	34	51	36	41
Zr*	72	153	334	118	329	114	126
Nb*	11	12	44	11	41	12	10
Ba*	514	364	271	385	280	322	267
Th*	2.3	1.7	7	4.6	4.3	2.3	0.8
La		14					13
Ce		34					32
Nd		21					20
Sm		5.3					5
Eu		2.1					2
Tb		0.9					1
Yb		2.9					2.6
Lu		0.4					0.4
Cs		0.1					0.1
Th		0.9					0.8
U		0.1					0.1
Ta		0.8					0.6
Hf		4.4					3.5
Cr		37					27
Sc		35					32
Co							37

Table 1. (Contd.)

	M-AT	TM-F	TM-C	TM-M	TM-H	TM-L
SiO_2	47.84	47.91	48.12	48.26	48.98	75.05
TiO_2	2.27	2.52	2.76	2.79	3.67	0.29
Al_2O_3	17.81	16.06	18.13	17.77	15.28	10.92
Fe_2O_3	4.11	4.78	2.34	2.32	2.33	2.19
FeO	7.94	8.51	8.11	8.19	10.82	1.62
MnO	0.20	0.19	0.19	0.19	0.19	0.12
MgO	4.18	4.61	3.87	4.04	4.62	0.19
CaO	9.03	8.69	9.27	9.02	8.51	0.21
Na_2O	3.18	3.15	3.93	3.59	2.88	3.89
K_2O	0.66	0.78	0.81	0.80	1.13	4.51
P_2O_5	0.61	0.63	1.01	1.07	0.50	0.03
LOI	2.19	2.16	1.36	1.36	1.08	0.97
Mg#	42.96	43.01	44.28	47.32	42.86	9.99
La*	11	15	20	20	35.7	124
Ce*	21	32	51	42	77	213
V*	282	387	176	179	385	1
Cr*	25	31	4	5	11	0.5
Co*	32	40	23	25	44	2
Ni*	18	18	5	6	27	11
Rb*	9	8	14	13	29	115
Sr*	446	404	838	755	501	6
Y*	37	43	35	36	47	135
Zr*	119	143	122	124	296	1225
Nb*	10	13	22	20	38	128
Ba*	279	326	166	452	298	22
Th*			3	2	4	18
La					35.7	124
Ce					77	213
Nd					40	115
Sm					8.8	21
Eu					3.1	1
Tb					1	3.5
Yb					2.8	12.1
Lu					0.4	1.8
Cs					0.1	0.3
Th					4	18
U					1	1.8
Ta					2.3	7.3
Hf					6.5	29
Cr					11	0
Sc					25	5
Co					44	0.9

Table 1. (Contd.)

	MEGEZEZ (Termaber formation)							
	MZ-8	MZ-4	MZ-11	MZ-16	MZ-3	MZ-18	MZ-2	MZ-9
SiO_2	46.76	47.61	47.70	48.47	49.23	49.35	49.55	49.91
TiO_2	2.39	2.86	2.64	2.34	2.55	3.07	3.23	2.26
Al_2O_3	18.00	18.03	17.81	19.29	18.01	15.17	14.99	21.86
Fe_2O_3	7.43	4.75	5.18	3.99	5.89	3.79	8.58	1.67
FeO	5.00	6.37	6.51	6.09	5.01	8.53	3.77	5.96
MnO	0.16	0.16	0.15	0.14	0.16	0.18	0.18	0.12
MgO	3.91	3.35	3.79	3.65	3.42	4.18	3.58	2.48
CaO	8.02	9.33	9.11	8.84	9.14	7.86	6.84	9.09
Na_2O	3.08	3.26	2.99	3.35	3.02	3.58	3.46	3.47
K_2O	0.95	1.09	0.93	1.04	1.19	1.64	1.58	0.96
P_2O_5	0.45	0.59	0.45	0.55	0.50	0.76	0.65	0.55
LOI	3.25	2.06	2.75	2.25	1.61	1.89	3.58	0.87
Mg#	41.24	39.76	41.57	44.16	41.03	42.34	39.52	41.07
La*	18	18	13	16	19	30	46	17
Ce*	38	44	41	38	47	85	90	32
V*	304	228	316	197	278	249	268	173
Cr*	34	7	14	7	0	3	0	26
Co*	42	31	41	29	31	31	33	19
Ni*	37	20	26	27	17	7	8	12
Rb*	16	17	16	16	22	30	32	15
Sr*	647	765	560	776	567	499	497	918
Y*	33	34	34	29	40	34	70	26
Zr*	165	190	172	162	210	301	305	136
Nb*	18	24	14	19	26	34	37	14
Ba*	298	363	263	319	490	475	560	395
Th*	2.5	4.8	5.5				3.3	
La	18		19.2				46.8	
Ce	38		41				90	
Nd	20		23				54	
Sm	4.9		5.3				12	
Eu	1.8		2				4	
Tb	0.7		0.9				1.9	
Yb	1.9		1.8				4.3	
Lu	0.3		0.3				0.7	
Cs	0.1		0.1				0.7	

Table 1. (Contd.)

	MEGEZEZ (Termaber formation)							
	MZ-8	MZ-4	MZ-11	MZ-16	MZ-3	MZ-18	MZ-2	MZ-9
Th	1		1.8				3.3	
U	0.4		0.5				0.9	
Ta	1.1		1.1				2	
Hf	3.5		4.7				7.6	
Cr	34		14					
Sc	19		23				22	
Co	42		42				33	

Trace element variations as a function of SiO_2 are shown in Fig. 4. The plateau basalts display large variations in the compatible trace elements as well as in Ba and Sr contents against a negligible range in SiO_2. The steep trends in Cr, Co, Ni and Sc can be directly related to the removal of the mafic minerals also present in the basalts.The absence of relations between Ba and Sr on one hand and SiO_2 on the other, however, indicates that the variations did not result from a differentiation process which would have also affected silica markedly. This is supported by the absence of relation between Ba and Sr contents and the porphyricity index of the samples, that may suggest that the scattering is a product of phenocryst accumulation. Furthermore, none of the phenocrystal phases could incorporate appreciable amounts of Ba, which indicates that the observed trace element variations in the basalts are pristine geochemical characteristics of magmas. The incompatible trace elements Rb, Ba, Light Rare Earth Elements (LREE), and others exhibit positive correlations with SiO_2 in the Megezez volcanics, with scattering of Sr and Ba in the mafic range. The positive relations may be correlated with plagioclase and alkali feldspar phenocrysts abundantly found in the rocks suggesting that differentiation was significantly controlled by these minerals.The ferromagnesian elements (Co, Cr, Sc) show a sharp decrease to very low values within the Megezez mafic samples and drop down to very low concentrations in the evolved products. Ba and Sr drop to low concentrations in the Alaji acid rocks.

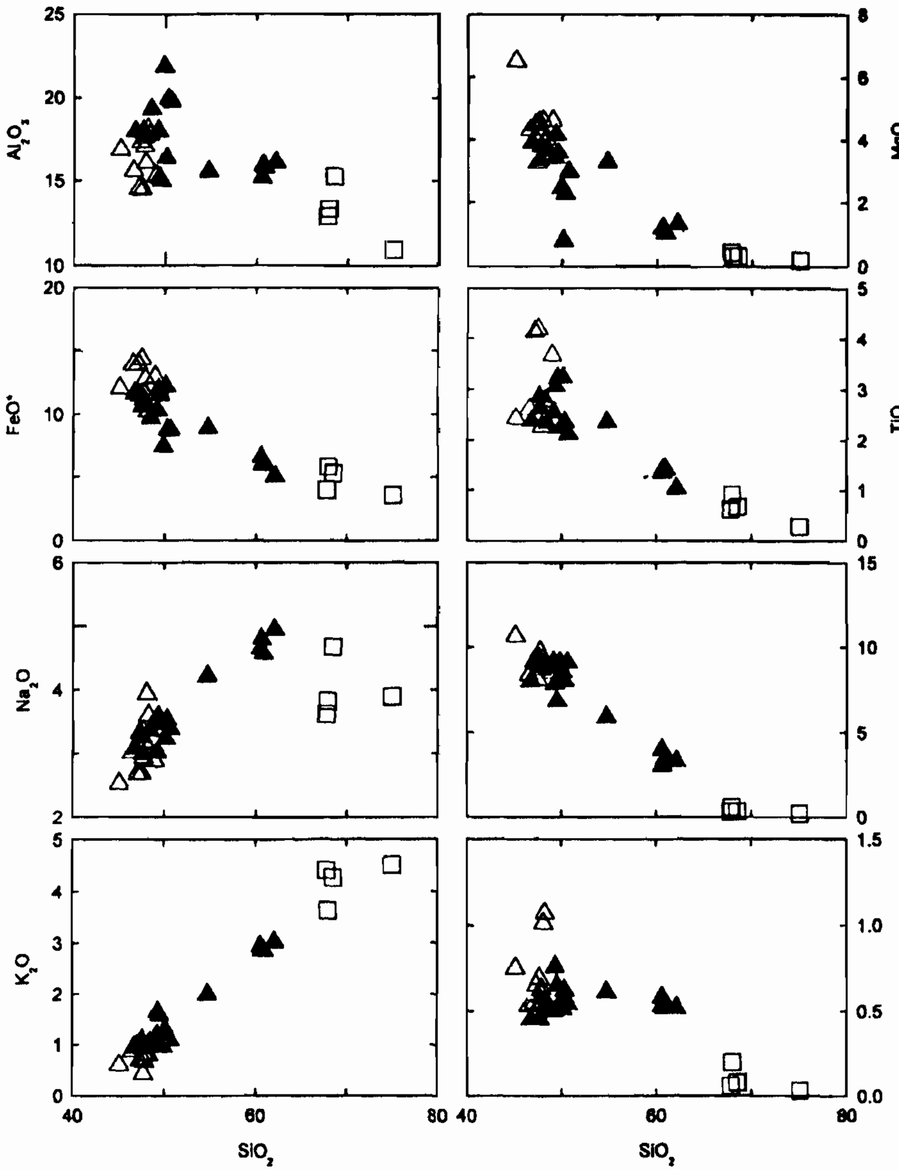

Fig. 3. **Variation diagrams of major element abundances (Wt.%) as a function of SiO_2 content.** Symbols as in Fig. 2.

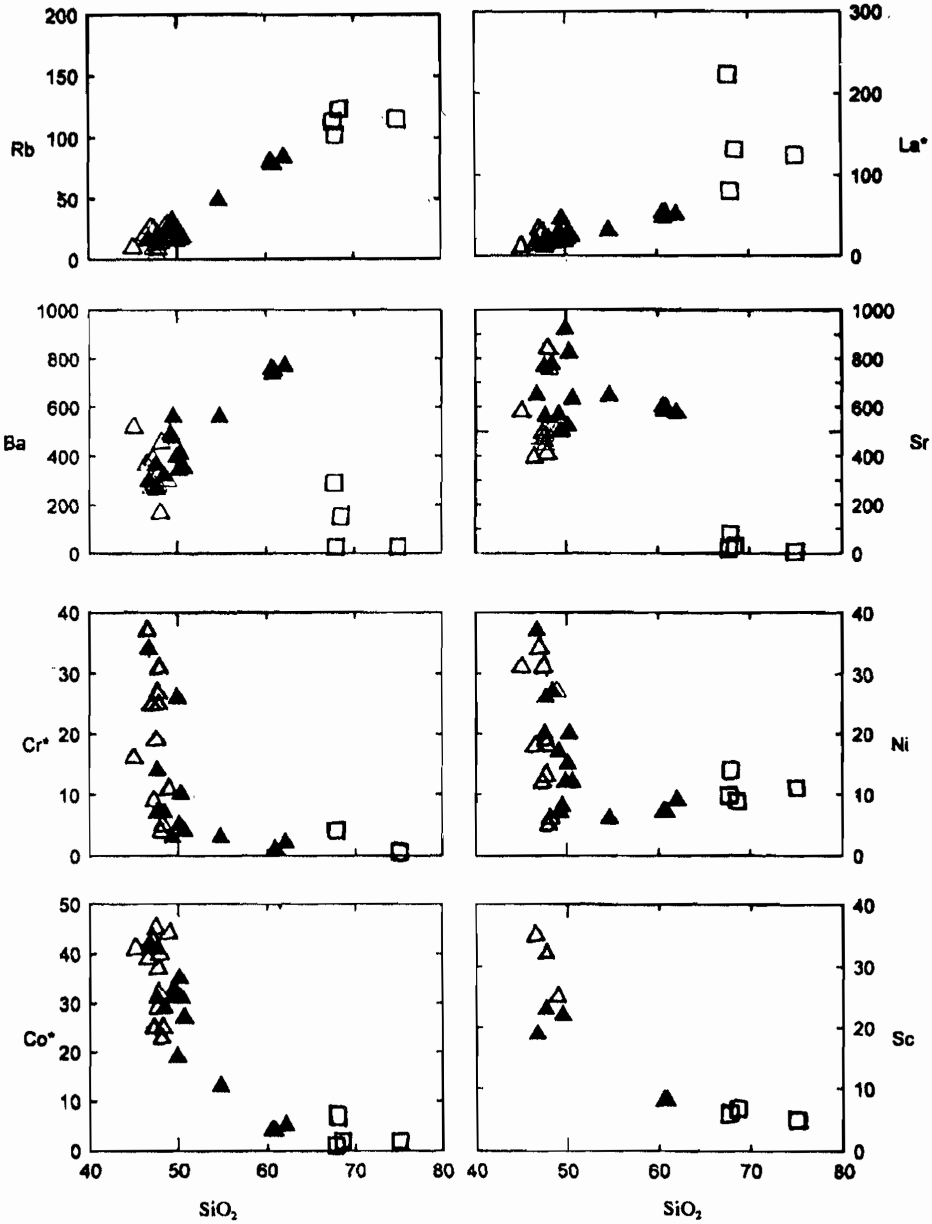

Fig. 4. Variation diagrams of trace element abundances (ppm) as a function of SiO_2 content. Symbols as in Fig. 2.

Rare earth* (REE) *and incompatible elements

The contents of the REE determined on selected rocks is reported in Table 1. REE patterns plotted by normalizing with respect to chondrites (Nakamura, 1974) are reported in Fig. 5. It can be observed that plateau and Megezez basalts exhibit very similar REE patterns both in abundance and fractionation. The Alaji silicic samples are distinctly enriched in both the LREE and the Heavy Earth Elements (HREE) relative to the basalts and are characterized by a significant negative Eu anomaly which may be related to the fractionation of plagioclase.

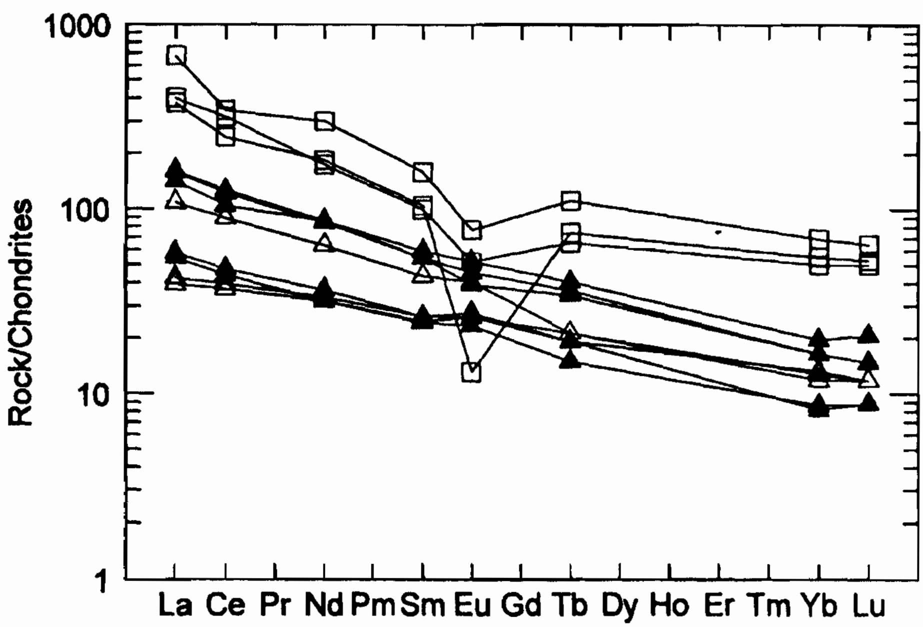

Fig. 5. Chondrite-normalized Rare Earth Element patterns for the analyzed rocks. Symbols as in Fig. 2.

Incompatible element patterns of the analyzed samples are shown in Figure 6. The plateau and the Megezez basalts display similar incompatible element patterns with relative enrichment in the highly incompatible trace elements. Some Megezez basalts show relative enrichment in Ba with respect to Rb and

Th and relative depletion in Ti. Plateau basalts are overall relatively less enriched than Megezez basalts and exhibit relative enrichment in Nb and Ba with marked negative anomalies in U in some samples.

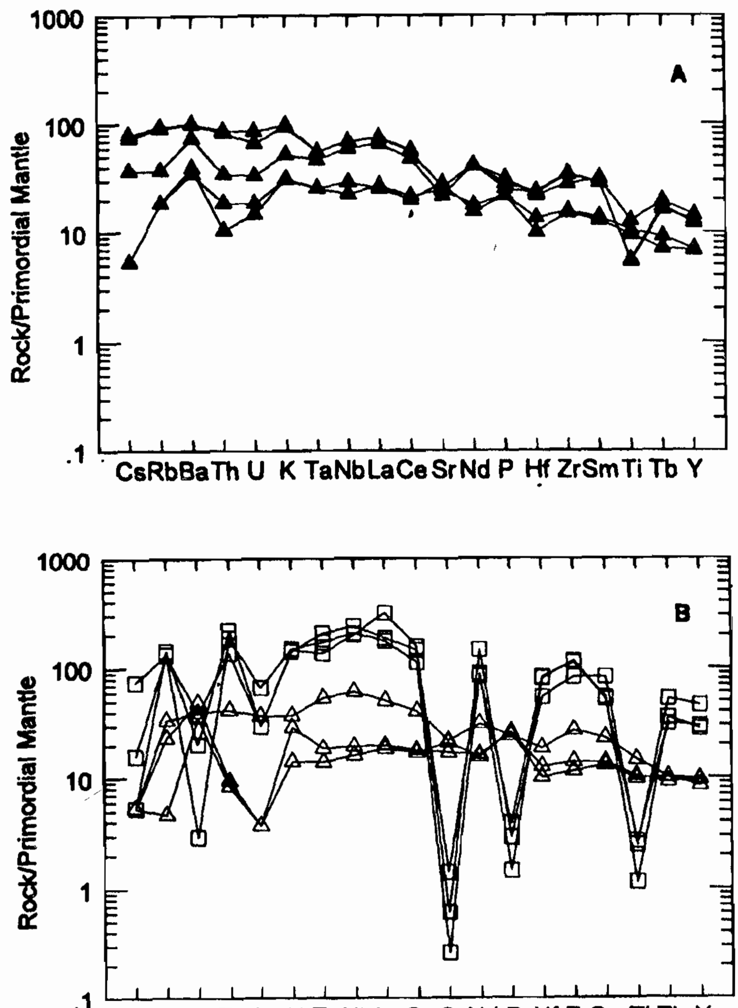

Fig. 6. Incompatible element patterns normalized to Primordial Mantle composition (Wood *et al.*, 1979). A) Megezez volcanics; **B)** Plateau and Alaji volcanics. Symbols as in Fig. 2.

The acid rocks of the Alaji formation display distinctly higher enrichment in incompatible elements, but with patterns basically similar to the plateau and Megezez basalts. However, the Alaji acid samples possess strong negative anomalies of Ba, Sr, P and Ti. These negative spikes testify the important role of plagioclase for Sr, alkali feldspar for Ba, apatite for P and Ti-magnetite forTi in the genesis and/or evolution of these rocks, in good agreement with the observed mineral assemblage in the rocks. Furthermore, the similarity of abundance patterns between basaltic terms and Alaji silicics suggests a direct genetic relationship of the acid rocks with the basalts through a differentiation process controlled by crystal fractionation, as suggested also by major and trace element abundance patterns.

DISCUSSION

Field, petrological and geochemical data on volcanic rocks from Sheno-Megezez area indicate that the plateau lavas consist only of basaltic rocks while those of Megezez volcanics consist of a larger range of compositions from basalts to intermediate-acid rocks. The two series are separated by acid volcanics of the Alaji formation. The basalts are of transitional type, with a mildly alkaline affinity in some samples, while the acidic rocks are alkaline to peralkaline, in agreement with observed petrographic features. The rock series in this area is characterized by a lack of samples with high Mg#, Ni and Cr, which indicate non-primitive geochemical characteristics. Most of the analyzed basalts have MgO < 6.51%, Mg # (42–67) and Ni (7–37 ppm), which testifies to significant differentiation during uprise to the surface. In general terms, the plateau basalts, although having a relatively small range in contents of SiO_2, record significant variations in trace and some major elements.

Some of the main observations that require thorough discussion and adequate explanations in light of the available results include:

1. Significance of the geochemical variations within the plateau and the Megezez basalts;
2. Genetic relationships between basalts and the intermediate rocks in the Megezez suite; and
3. The genesis of the Alaji acid rocks.

The plateau lavas show small variations in silica and MgO, but a large range in the abundances of several incompatible elements. In particular, TiO_2 displays a variation that allows to distinguish high-Ti and low-Ti groups of basaltic rocks within the studied samples. Such a distinction has been found in other areas of intracontinental basaltic volcanism (e.g. Paranà) as well as in similar plateau sequences in Ethiopia. In addition to TiO_2, there are significant variations of other major and trace elements, such as Na_2O, Al_2O_3, Ba, Sr, Nb, and other incompatible element abundances and ratios. The main problem related to these basalts is to understand whether these variations reflect pristine compositions of primary melts or are the effect of low pressure evolution that occurred during magma uprise to the surface.

Inter-elemental relationships demonstrate that TiO_2 is positively correlated with a number of elements and elemental ratios such as Fe, V, Zr, Nb, Y, La/Y and Rb/Sr and negatively correlated with Al_2O_3. Most of these elemental variations can be explained by fractional crystallization (e.g. Ti vs. Fe and V) while other correlations such as Ti vs. Nb and Zr require the combination of fractional crystallization and interaction with the upper crust. As the upper crust is characterized by low Ti, Zr and Nb (Taylor and McLennan, 1985), interaction between the high-Ti basaltic magma and the upper crust would result in a decrease of all these elements. This interaction should also produce a decrease in Co, Ni, Cr and other compatible elements. However, low-Ti and high-Ti basalts have comparable concentrations of Co, Cr and Ni. Moreover, positive correlations between TiO_2 and Rb/Sr ratios argue against assimilation processes. It is, hence, concluded that the variable Ti contents in the plateau basalts reflect the characteristics of primary magmas which suggest derivation from compositionally different sources. Alternatively, variable degrees of partial melting could be invoked to have produced the observed effects. However, as it will be argued later, there are other elemental variations that favour the role of evolutionary processes in modifying magma characteristics.

The Megezez volcanics have a more complex evolution than the plateau lavas, with significant elemental variations within the mafic rocks. Accordingly, it is necessary to understand 1) the processes that generated the elemental variations within the basalts, and 2) the processes that generated the evolved volcanics. A semi-quantitative geochemical modelling approach has been followed to help elucidate these problems.

Fig. 7 shows Rb vs. Rb/Nb variations within the plateau, Megezez and Alaji volcanics. It can be observed that the Megezez basalts cluster around a Rb/Nb value of unity. The intermediate Megezez volcanics, instead, have higher Rb and Rb/Nb values. Since both Rb and Nb are strongly incompatible elements, the increase in Rb/Nb cannot be due to the effect of fractional crystallization alone. Alternatively, an AFC process must be assumed. The geochemical modelling demonstrates that the intermediate rocks from the Megezez volcano can be obtained by AFC processes starting from the associated basalts and assuming moderate amounts of assimilation of upper continental crustal material (with a ratio of crystallized to assimilated material, r = 0.2–0.5).

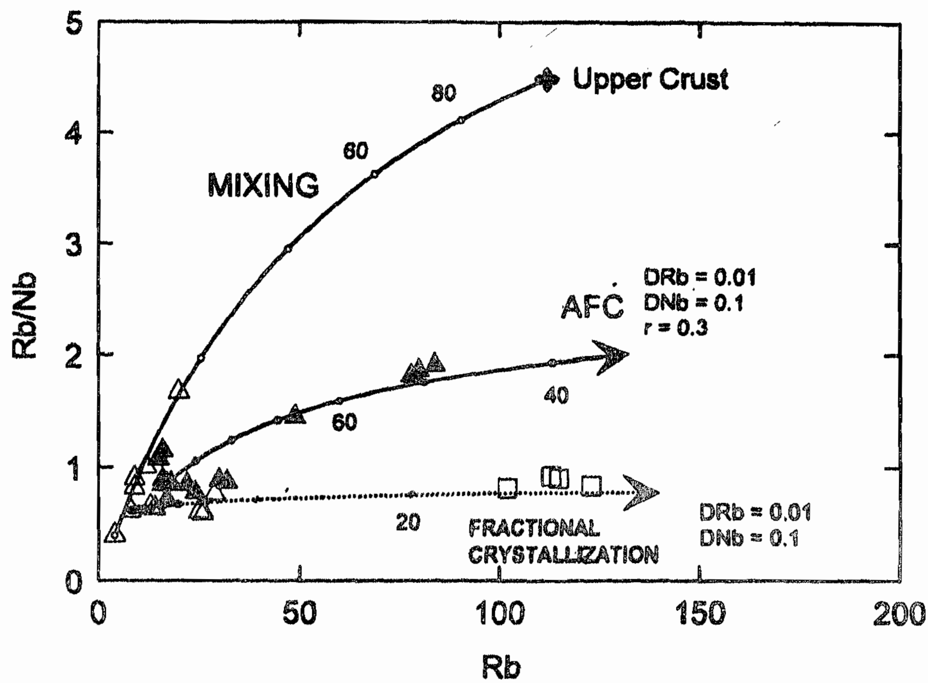

Fig. 7. Fractional Crystallization (FC) and Assimilation Fractional Crystallization (AFC) models for the investigated rocks. The letter "r" indicates the ratio between mass of assimilated and crystallized material. Numbers along the lines are the amounts of residual liquid. Cross symbol represents average upper crust composition according to Taylor and MacLennan (1985) which has been used as assimilant. Symbols as in Fig. 2.

The diagram reported in Fig. 7 further shows that the basalts from the plateau sequence also display significant variations of Rb/Nb. This variation fits a calculated trend of mixing between the least evolved analyzed plateau basalt and upper crust (Taylor and McLennan, 1985). Accordingly, Rb/Nb variations suggest that the plateau lavas have also interacted significantly with the upper crust. The Alaji rhyolites have similar Rb/Nb ratios as the basalts from both the plateau and Megezez volcano. This suggests a derivation of the Alaji acid rocks from basaltic magmas by processes dominated by fractional crystallization.

Rb vs. Rb/Ba diagram in Figure 8 shows that the Megezez suite can be modelled by assuming an AFC process with significant amounts of assimilation of upper continental crust ($r = 0.3$). On the other hand, the Rb/Ba variations within the plateau basalts are consistent with a process of mixing between continental crust and the least evolved analyzed mafic magma. The range of Rb/Ba variations in the mafic rocks can be also explained in part in terms of mixing interaction between the least evolved plateau basalt and Alaji acid liquids.

A plot of Rb/Ba vs Rb/Nb is shown in Fig. 9. Comparison between modelled and observed patterns suggests that, most probably, mixing of primitive basaltic magma with upper continental crust as well as with differentiated acid liquids played a role in the evolution of plateau basalts. This is observed in the diagram where some of the plateau samples plot on the mixing curve between upper crust and the most mafic plateau basalt, and other samples fit the mixing line between the mafic and acid magmas. The diagram further shows that Megezez volcanics are genetically related to one another through AFC processes.

As a whole, the variations in elemental ratios considered above agree in indicating that the Alaji rhyolites were most probably derived from basalts by fractional crystallization. The steep increase in Rb/Ba in Fig. 9 testifies to the leading role played by alkali feldspar fractionation. This is in fact the only mineral that is capable to incorporate Ba and produce, at the same time, a rapid decrease in the same element during the most advanced stages of magmatic differentiation. Considering the available trace element data for the rhyolites, especially their lower Rb/Nb (< 1) (Fig. 7), compared to the higher Rb/Nb (> 10) for rhyolites inferred to have originated by crustal melting, the possibility that Alaji rhyolites originated by partial melting of the continental crust could not be favoured.

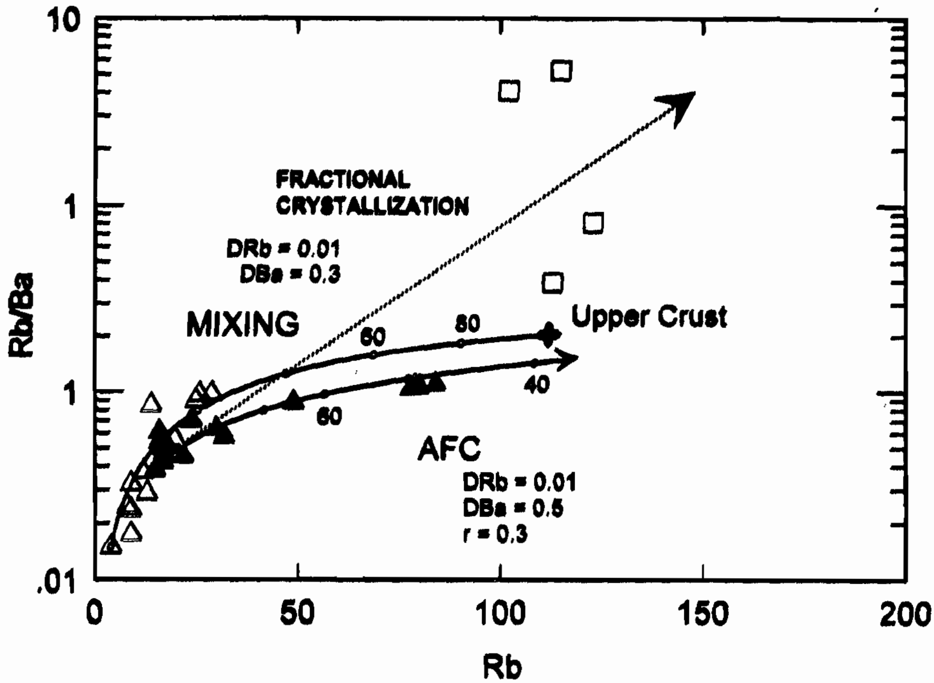

Fig. 8. Rb versus Rb/Ba FC and AFC models. The letter "r" indicates the ratio between mass of assimilated and crystallized material. Numbers along the lines are the amounts of residual liquid. Composition of upper crust is from Taylor and McLennan (1985). Symbols as in Fig. 2.

The idea that the Alaji silicic rocks could be differentiated products from basaltic parents does not, however, explain the bimodal nature of the volcanic suite. It is, therefore, suggested that these rhyolites are possibly derived by partial melting of a basaltic source material, followed by fractional crystallization. Further studies using isotopic data are required to understand better the genesis of the rhyolites as well as the scarcity of intermediate volcanics in the entire Ethiopian flood lava sequence.

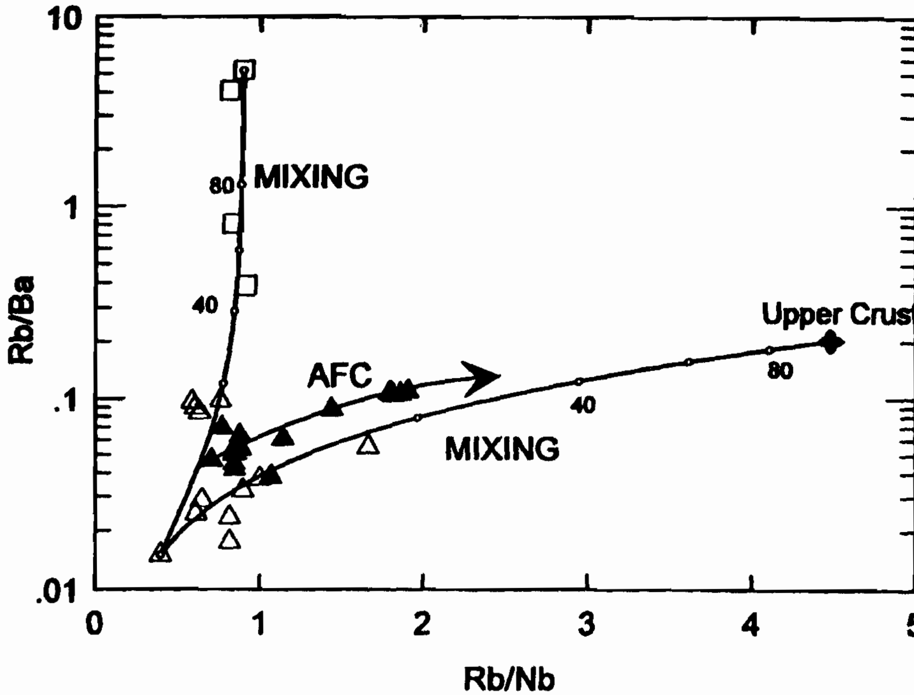

Fig. 9. Plot of Rb/Nb against Rb/Ba for the analyzed volcanics and modelled variation curves for AFC processes. D values for Rb, Nb and Ba as in Figs. 7 and 8. Numbers along the lines are the amounts of residual liquid. Upper crust composition from Taylor and McLennan (1985). Symbols as in Fig.2.

CONCLUSIONS

The present study has shown that the basaltic rock suite from the plateau sequence of the Sheno area displays compositional variability in terms of several element abundances and ratios. Based on Ti abundances, high-Ti and low-Ti varieties have been distinguished. These two groups are likely related either to compositionally different sources or to the same source affected by different degrees of partial melting. However, the investigated plateau basalts also display significant variations of elemental ratios such as Rb/Nb and Rb/Ba that indicate that these magmas have interacted significantly with the upper crust and with acid liquids having a composition similar to the Alaji acid rocks.

The rocks from the Megezez volcano range in composition from basalts to trachyandesite. Geochemical modelling suggests that this compositional range has been effected through AFC processes starting from mafic magmas.

Finally, the Alaji acid volcanics show compositional characteristics that suggest a derivation from basaltic parents by low-pressure evolutionary processes dominated by fractional crystallization. However, additional studies, especially isotopic compositions, are required to further constrain or disprove this hypothesis.

As a whole, the data presented here as well as in previous studies on Ethiopian basaltic magmas (Mohr, 1983; Mohr and Zanettin, 1988; Hart *et al.*, 1989; Gasparon *et al.*, 1993; Peccerillo *et al.*, 1995) strongly argue in favour of the possibility that marked modifications in basalt compositions could result from the involvement of a component of acidic composition during the evolution of mantle-derived basaltic magmas. The origin of the acid end- members could be rhyolitic melts formed from basalts by fractional crystallization, crustal material itself or a combination of the two. In conclusion, the available geochemical data from Sheno-Megezez rocks as well as from other Cenozoic mafic suites from Ethiopia suggest that basaltic magmas have undergone important intracrustal geochemical modifications en route to the surface. These modifications have been superimposed on primary magma variations which themselves resulted either from heterogeneous sources or from variable degrees of partial melting of a homogeneous source. It is, therefore, suggested that caution must be taken in considering basalt compositions as indicators of sub-crustal processes, and that the effects of crustal contamination and magma mixing must be critically evaluated before making inferences on source composition.

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CROP ASSOCIATIONS OF HOME-GARDENS IN WELAYTA AND GURAGE IN SOUTHERN ETHIOPIA

Zemede Asfaw and Zerihun Woldu

Department of Biology, Faculty of Science, Addis Ababa University
PO Box 3434, Addis Ababa, Ethiopia

ABSTRACT: Home-gardens of Welayta and Gurage, southern Ethiopia, were studied for possible patterns of crop association. A sample of 36 home-gardens were inspected yielding a total of 60 crop species with an average of 14.4 crops per garden. Crops included were some Ethiopian domesticates and many others belonging to various horticultural groups and life-forms. The distinctive feature of this agro-ecosystem is its polycultural nature with a universal occurrence of *enset* (*Ensete ventricosum* (Welw.) Cheesm.). The association among 30 of the most frequent crops and their positions within each garden was studied from detailed data collected in 18 of the representative home-gardens selected by systematic random sampling from among the 36. Application of Two Way Indicator Species Analysis and Principal Components Analysis on the qualitative data matrix (presence or absence of 30 crop species in 18 home-gardens) produced constellations of gardens and crops. Some crop constellations were aggregates of starchy root-crops, legumes and leafy vegetables; suggesting the optimal mix in terms of crop co-existence, nutritional complementarity and family preferences. The groupings of gardens and crops reflect on-going differentiations influenced by provenance, socio-cultural factors and the rural-urban milieu. Some crops are strongly associated with the most extensive crop (*enset*) as demonstrated by frequent co-occurrence and adjacent occurrence. Home-gardens in Welayta and Gurage have evolved through generations of gradual intensification in response to increasing human pressure and the corresponding shortage of arable land. Crop constellations produced by the analyses indicate the optimal crop mix for meeting dietary and other family needs. The home-garden is therefore realized as an important self-sustaining agro-ecosystem with the dual functions of production and on-farm conservation of the agro-biodiversity as well as the associated wild-biodiversity. It is envisaged that honouring this traditional practice and its further enhancement by optimizing its crop mix would be more rewarding.

Key words/phrases: Association analysis, co-occurrence, farming system, home-garden, optimal crop mix

INTRODUCTION

Traditional home-gardens are farming systems with an assemblage of perennial and annual crops resembling multistoreyed forest with a number of possible niches. The crops are grown in small plots around the homestead mainly for home consumption. Home-gardening is reported to have first been recorded from the third Millennium B.C. of the Near East (Brownrigg, 1985). At present, it is widespread in the tropical and subtropical ecosystems of Asia (Christanty, 1990; Marten, 1990), Central America (Caballero, 1992) and Africa (Okigbo, 1990). In recent years tropical home-gardens have attracted much interest as sustainable agricultural systems (Rico-Gray, *et al.*, 1990; Torquebiau, 1992; Wojtkowski, 1993), and as ideal avenues for on-farm in-situ crop biodiversity conservation (Esquivel and Hammer, 1992). The farming system developed through processes of intensification by adopting the strategy of mixing appropriate crops, organic manuring, diversification of the biotic components, labour intensification and space optimization (Brownrigg, 1985; Soleri and Cleveland, 1989; Berkmuller, 1992). The same trend of development of home-gardening in Ethiopia has given rise to the present polycultural-polyvariety complex (Okigbo, 1990; Zemede Asfaw and Ayele Nigatu, 1995). Traditional home-gardens found in Africa, such as those studied here, are viewed as generalized agricultural ecosystems with high diversity index (Benneh, 1974) and their sustainability has been highly credited (UNICEF, 1982; Christanty, 1990; Berkmuller, 1992).

Studies on some aspects of home-gardens in Ethiopia (Westphal, 1975; Okigbo, 1990; Zemede Asfaw and Ayele Nigatu, 1995) have given clues on the contribution of the farming system to food security and conservation of the biological diversity. The stability of the farming system largely owes to the land-holding system which has a high degree of permanence since the land must remain within the kinship.

The mid-highland areas of southern Ethiopia belong to the tropical vegeculture complex (Westphal, 1975). Welayta and Gurage, where this study was carried out, are located within this complex. These areas are widely accepted to be densely populated. In the study area a cropping pattern of diverse assemblages of root-tuber crops, vegetables, legumes, fruits, spices, beverage and medicinal plants, and many others are husbanded in integration with livestock, poultry and apiculture. The merits of such an ecosystem are better appreciated when the temporal and spatial distribution, both horizontal and vertical, are considered and when the role of the farming system is viewed in relation to its regular supply of fresh products.

There is as yet no report on the nature of crop associations in Ethiopian home-gardens. Application of numerical methods primarily developed to study natural ecosystems is hoped to furnish insight into co-occurrence of home-garden crops and their implications to nutritional profile, product range and fundamental biological processes. This paper gives results of applications of multivariate analyses, PCA (Goodall, 1964; Orloci, 1966) and TWINSPAN (Hill *et al.*, 1975; Hill, 1994), on data set collected from home-gardens in Welayta and Gurage.

THE STUDY AREA AND METHODS

Study area and data collection

A study of home-gardens was carried out in the mid-highlands of Welayta and Gurage in southern Ethiopia (Fig. 1) in the sites indicated in Table 1 during the months of August and September, 1995. This time corresponds to the period when the maximum number of crops are encountered in home-gardens of the study area in their mature state. The sites are located within the bounds of Bui in Gurage (8°22'N and 38°35'E) and Sodo in Welayta (6°49'N and 37°45'E). The average annual rainfall of the study area is 1,000 mm. Sites in Welayta are in the humid zone while those in Gurage are more on the sub-humid side. The study sites were selected on the basis of the importance of home-gardens, accessibility, urban-rural characteristics and cultural diversity.

A total of 405 homes were surveyed within the study area for presence of home-gardens and to see the proportion of different types (Table 2). Thirty-six houses of those with home-gardens were preferentially selected and studied for their crop composition yielding a total of 60 crops (Table 3). Eighteen of the representative home-gardens considered manageable for detailed data collection and analyses were selected for further study by systematic random sampling. In each of these home-gardens, the presence and exact position of each crop was indicated on a sketch map of the garden. From the sketch maps, data on presence and absence of 30 of the most frequent crops, found in at least three of the home-gardens, and adjacent occurrence of crops within the 18 home-gardens were produced. The owners of the home-gardens were interviewed using data collection format. The data on presence and absence of the 30 crops and 18 home-gardens were considered for the multivariate analyses. Ratio between adjacent occurrence and co-occurrence were calculated for crops frequently planted adjacent to those that had the highest frequency of occurrence, *enset* (*Ensete ventricosum* (Welw.) Cheesm.) and the Ethiopian kale (*Brassica oleracea* L.), as an index of non-randomness of their occurrence.

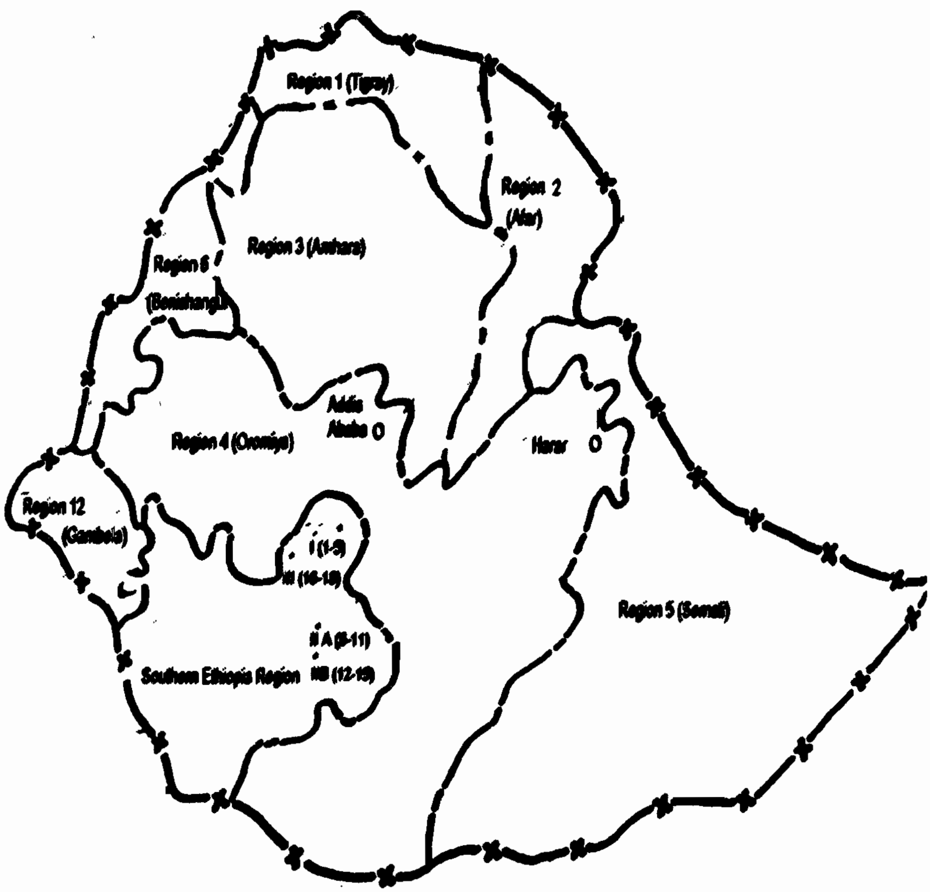


Fig. 1. Map showing the study area and location of home-gardens studied (scale 1:8,000,000). Names of places and site characteristics are given in Table 1.

and 18 home-gardens were considered for the multivariate analyses. Ratio between adjacent occurrence and co-occurrence were calculated for crops frequently planted adjacent to those that had the highest frequency of occurrence, *enset* (*Ensete ventricosum* (Welw.) Cheesm.) and the Ethiopian kale (*Brassica oleracea* L.), as an index of non-randomness of their occurrence.

Table 1. Study sites*. Bugi is 40 km from Sodo town on the way to Shashemane, Attat and Gaburi are respectively 30 and 25 km from Welkitie, other sites in Welayta are within 10 km radius from Sodo town while other sites in Gurage are within 10 km radius from Bui town.

Locality	Garden no.	Site	Setting (location)
I	1	Bui	semi-urban (Gurage)
	2	Kelad	rural (Gurage)
	3	Anati	rural (Gurage)
	4	Firshi	rural (Gurage)
	5	Bui	rural (Gurage)
IIA	6	Sodo	urban (Welayta)
	7	Sodo	urban (Welayta)
	8	Sodo	urban (Welayta)
	9	Sodo	urban (Welayta)
	10	Sodo	urban (Welayta)
	11	Sodo	urban (Welayta)
IIB	12	Geneme	rural, near Sodo (Welayta)
	13	Fate	rural (Welayta)
	14	Bugi	rural (Welayta)
	15	Bugi	semi-urban (Welayta)
III	16	Welkitie suburb	rural (Gurage)
	17	Gaburi	rural (Gurage)
	18	Attat	semi-urban (Gurage)

*, Locations of sites are shown in Fig. 1.

Data analysis

The data matrix of crops and home-gardens was subjected to multivariate analyses involving Principal Components Analysis (PCA) (Goodall, 1964; Orloci, 1966) and Two Way Indicator Species Analysis (TWINSPAN) (Hill *et al.*, 1975; Hill, 1994).

Ordination implies a summarization of the information content of a matrix whose elements define the spatial relations between entities. Summarization of the data is achieved by projection of the points into space which has less dimensions than the original matrix. The simplified geometric model obtained is interpreted in terms of major ecological gradients and the clusters of individual points. PCA in Syntax (Podani, 1988), a technique of axis construction to achieve an efficient ordination of individuals, was used for the analysis. The data were then analyzed using TWINSPAN (Hill *et al.*, 1975; Hill, 1994). This programme first constructs a classification of the samples and then uses this classification to obtain a classification of the species according to their ecological preferences. The two classifications were then used to obtain an ordered two way table that expresses the relationships of the species as clearly as possible.

RESULTS

Presence of home-gardens

Three hundred sixty two of the 405 houses inspected ((89%) had home-gardens. The proportion of backyard, front-yard, side-yard, all-round and other types of home-gardens and the sampling localities are given in Table 2.

Home-gardening is a common activity of the rural community in the study area. Both in Welayta and Gurage all homes inspected in rural settings had home-gardens, *enset* being a common element to all, albeit differences in size, quality and crop composition. In urban and semi-urban sites most homes (89%) had associated home-gardens (Table 2). About 50% of the gardens are backyard types. All round type gardens were more frequent in Welayta than in Gurage.

Crops recorded in home-gardens of the study area

A total of 60 crops belonging to 31 angiosperm families were recorded in the 36 home-gardens. The average crop per garden was 14.4 (14.8 in Welayta and 13.9 in Gurage). A total of 13 plant families (Rutaceae, Brassicaceae, Solanaceae, Poaceae, Fabaceae, Lamiaceae, Musaceae, Cucurbitaceae, Asteraceae, Alliaceae, Rosaceae, Apiaceae and Euphorbiaceae) were represented by more than one species. Most of the commonly known products of home-gardens such as root-tubers, legumes (pulses), vegetables, spices, grains and fruits belong to these families. Some of the crops (e.g., *enset*, Ethiopian kale, Welayta dinich) are Ethiopian domesticates while others are known to be domesticates from the new world and other parts. Ornamentals, weeds and other wild plants including trees were not included in the list as they are not normally considered as crops. All the crops recorded are given in Table 3.

Table 2. Home-garden frequency in the study area.

Number of	In and Around Sodo (Welayta)							In and around Bui (Sodo-Gurage)					Overall total	Overall % of houses with garden
	Catholic Village	Mariam Sefer	Aroge Arada	Gola Village	Mara-Chere	Wadu	Total	Bui	Kelad	Anati	Firshi	Total		
Houses Inspected	56	56	45	40	47	54	298	28	26	31	22	107	405	-
Houses with g	38	51	43	37	46	53	268	22	23	27	22	94	362	89.0
Backyard gardens	11	24	26	11	22	21	115	20	16	18	15	69	184	50.0
Frontyard gardens	3	0	0	5	0	5	13	0	0	4	0	4	17	4.7
Sideyard gardens	8	6	1	1	2	2	20	1	3	0	2	6	26	7.2
All round gardens	15	16	17	17	16	1	79	1	4	5	5	15	94	26.0
Other gardens	1	5	3	3	6	18	35	0	0	0	0	0	35	9.7

Table 3. Crops recorded from home-gardens in the study area.

No.	Crop name	Scientific name	Family
1	*Enset*	*Ensete ventricosum* (Welw.) Cheesm.	Musaceae
2	Ethiopian kale	*Brassica oleracea* L.	Brassicaceae
3	Pepper	*Capsicum* spp.	Solanaceae
4	Coffee	*Coffea arabica* L.	Rubiaceae
5	Maize	*Zea mays* L.	Poaceae
6	Sweet orange	*Citrus sinensis* (L.) Osbeck	Rutaceae
7	Sugarcane	*Saccharum officinarum* L.	Poaceae
8	Avocado	*Persea americana* Mill.	Lauraceae
9	Sweet potato	*Ipomoea batatas* (L.) Lam.	Convolvulaceae
10	Banana	*Musa paradisiaca* L.	Musaceae
11	Sweet basil	*Ocimum basilicum* L.	Lamiaceae
12	Rhamnus	*Rhamnus prinoides* L'Herit	Rhamnaceae
13	Taro	*Colocasia esculenta* (L.) Schoot.	Araceae
14	Rue	*Ruta chalepensis* L.	Rutaceae
15	Lime	*Citrus aurantifolia* (Christm) Swingle	Rutaceae
16	Pumpkin	*Cucurbita pepo* L.	Cucurbitaceae
17	Lippia	*Lippia adoensis* Hochst. ex Walp	Verbenaceae
18	Castor	*Ricinus communis* L.	Euphorbiaceae
19	Artemisia	*Artemisia absinthium* L.	Asteraceae
20	Onion/shallot	*Allium cepa* L.	Alliaceae
21	Papaya	*Carica papaya* L.	Caricaceae
22	Guava	*Psidium guajava* L.	Myrtaceae
23	Common bean	*Phaseolus vulgaris* (Vatke) Agnew	Fabaceae
24	Welayta dinich	*Plectranthus edulis* L.	Lamiaceae
25	Tomato	*Lycopersicon esculenta* L.	Solanaceae
26	Chat	*Catha edulis* (Vahl) Forssk. ex Endl.	Celastraceae
27	Bullock's heart	*Annona reticulata* L.	Annonaceae
28	Peach	*Prunus persica* (L.) Batsch	Rosaceae
29	Yam	*Dioscorea alata* (L.)	Dioscoriaceae
30	Sorghum	*Sorghum bicolor* (L.) Moench	Poaceae

Table 3. (Contd.)

No.	Crop name	Scientific name	Family
31	Mango	*Mangifera indica* L.	Anacardiaceae
32	Casmir	*Casimiroa edulis* LaLlave & Lex	Rutaceae
33	Passion fruit	*Passiflora edulis* Sims	Passifloraceae
34	Pomegranate	*Punica granatum* L.	Punicaceae
35	Grape fruit	*Citrus paradisi* Macfad.	Rutaceae
36	Grapes	*Vitis vinifera* L.	Vitaceae
37	Citron	*Citrus medica* (L.) Burm.f.	Rutaceae
38	Apple	*Malus sylvestris* Miller	Rosaceae
39	Potato	*Solanum tuberosum* L.	Solanaceae
40	Cabbage	*Brassica oleracea* L. var. Capitata	Brassicaceae
41	Ethiopian mustard	*Brassica carinata* A.Br.	Brassicaceae
42	Pine apple	*Ananas comosus* (L.) Merr	Bromeliaceae
43	Sour orange	*Citrus aurantium* L.	Rutaceae
44	Garlic	*Allium sativum* L.	Alliaceae
45	Common cress	*Lepidium sativum* L.	Brassicaceae
46	Funnel	*Foeniculum vulgare* Mill.	Apiaceae
47	Tabacco	*Nicotiana tabacum* L.	Solanaceae
48	Cassava	*Manihot esculenta* Cranz	Euphorbiaceae
49	Faba bean	*Vicia faba* L.	Fabaceae
50	Carrot	*Daucus carota* L.	Apiaceae
51	Cotton	*Gossypium* spp.	Malvaceae
52	Bottlle gourd	*Lagenaria siceraria* (Mol) Stardl.	Cucurbitaceae
53	Lettuce	*Lactuca sativa* L.	Asteraceae
54	Swisschard	*Beta vulgaris* L.	Chenopodiaceae
55	Otostegia	*Otostegia integrifolia* Benth	Lamiaceae
56	Lima bean	*Phaseolus lunatus* L.	Fabaceae
57	Finger millet	*Eleusine coracana* (L.) Gaertn.	Poaceae
58	Lemon grass	*Cymbopogon citratus* (D.C.) Stapf	Poaceae
59	Night shade	*Solanum nigrum* L.	Solanaceae
60	Sage	*Salvia leucanta* Car.	Lamiaceae

Principal components analysis (PCA) of the home-gardens

Application of PCA on the data from 18 home-gardens to summarize the relationships among gardens in two dimensions produced three major clusters (Fig. 2). The scatterplot of axes 1 and 3 was used to decide on the integrity of the clusters. The clusters and the main features of the clusters are shown in Table 4. Group 1 is identified by the presence of a single indicator species, Welayta dinich (*Plectranthus edulis L.*). This is a common feature of rural gardens in Welayta. Groups 2 is characterized by the co-occurrence of coffee and/or maize whereas group 3 is characterized mainly by sweet basil, onion/shallot and banana.

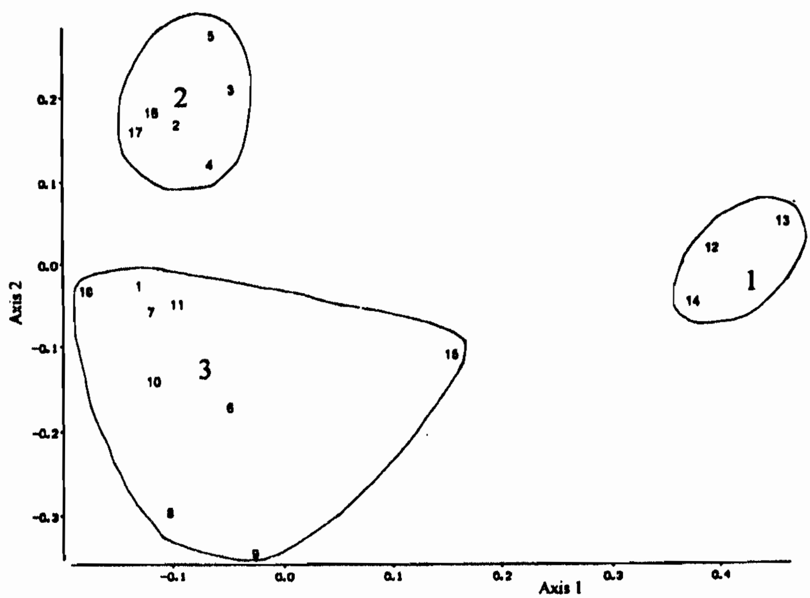


Fig. 2. **PCA scattergram of home-gardens.**

Principal components analysis (PCA) of the crops

PCA of the first 30 crops listed in Table 3 produced the four major groups shown in Fig. 3 and Table 5. The first two axes were used to plot the scattergram. The scatterplot of axes 1 and 3 was used for the same purpose as in the ordination of the gardens.

Table 4. Clusters of home-gardens.

Group	Gardens included	Main features
1	12 13 14	Welayta dinich, rural sites in Welayta
2	2 3 4 5 16 17	Coffee and/or Maize, all located in Gurage
3	1 6 7 8 9 10 11 15 18	Sweet basil-onion-banana, urban/semi-urban sites in Welayta (6-11) and Gurage (1 & 18)

The analysis produced four groups which can be summarized into two super clusters considering horticultural categories, i.e., groups 1 and 3, dominated by root-crops and groups 2 and 4, characterized by diverse categories of other horticultural elements (Table 5). Although the scattergram appears diffused in the two dimensional ordination, some of the following pattern is evident. The crop aggregation in group 1 consisted of *enset* in association with many vegetables and spices while group 3 consisted of root crops such as Welayta dinich, yam and taro. Group 1 is typical of Gurage gardens while group 3 is typical of Welayta gardens. Although groups 2 and 4 are not as discrete as the other groups, they are characterized by a common feature of being composed of mainly woody perennial elements.

Table 5. Clusters of the crops.

Group	Crops included	Main features
1	*enset*, Ethiopian kale, pepper, sweet orange, sugarcane, avocado, sweet basil, onion/shallot, maize and sweet potato	Food crops - mix of vegetables, spices, fruits, grains; most are herbaceous species
2	coffee, banana, *Rhamnus*, lime	Aggregate of fruits, stimulants, spices
3	pumpkin, taro, Welayta dinich, yam, sorghum, tomato, common bean, guava	Food crops - root-tuber crops well mixed with vegetables, grains and fruits
4	castor, *Lippia*, *Artemisia*, bullock's heart, peach, chat, rue	Mix of spices, fruits, stimulants and others

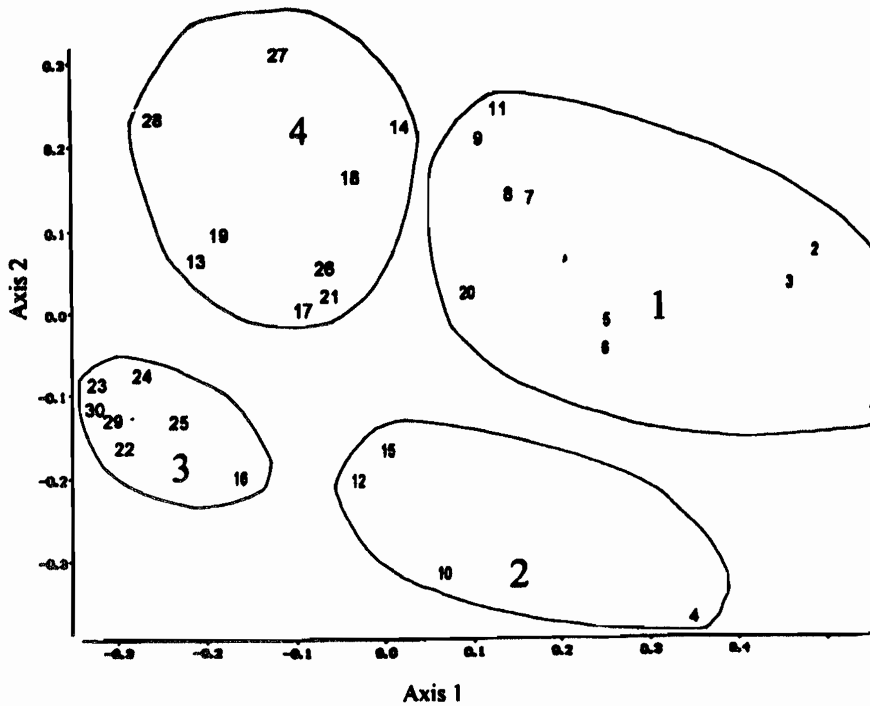
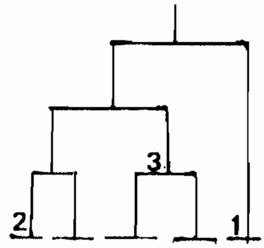
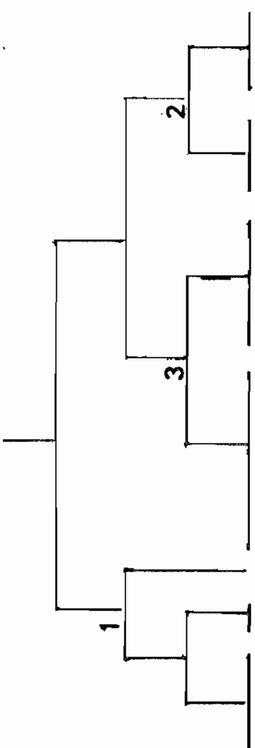


Fig. 3. PCA **scattergram of the crops.**

The result of the TWINSPAN shows three major groups of crops and three major groups of gardens based on the distinctness of the blocks (Fig. 4). The blocking is more clear in cluster 1 of the crops and cluster 1 of the gardens. The rest of the blocks are relatively more diffused. The distinctness of some groups is also reflected in the ordination scattergrams as shown by group 3 of the crops and group 1 of the gardens which are clearly corresponding.



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               Rue   --1---1--1-1-11---   000
              Lime   --11111-------1---   000
              Chat   111--------1--1---   000
   Bullock's heart   -------1---11-----   000
   Ethiopian kale    -1111-111111111-1    001
            Pepper   1-111-1111111-11-1   001
       Sweet basil   ----1--1-1111-11--   001
    Onion/shallot    ----1-11111-----1-   001
            Coffee   111111111----1111    0100
            Banana   11-111-1------1-11   0100
           Rhamnus   --1111-1-------1--   0100
             Enset   111111111111111111   0101
      Sweet orange   --1111-111-11---11   0101
            Lippia   ---11-------1-11--   0101
             Maize   11----11111-1-1111   0110
         Sugarcane   ---11--1-1-1111-11   0110
           Avocado   -----11111-11---11   0110
            Papaya   ----1--1-1----1-1-   0110
      Sweet potato   --1----11--11111-1   0111
            Castor   ------11----1-1--1   0111
         Artemisia   ------1-----1-111-   0111
             Peach   -----------11---1-   0111
              Taro   -----------1-11111   10
           Pumpkin   --11----------1111   110
            Tomato   --1-1----------11-   110
             Guava   -----1---------111   1110
       Common bean   ---------------111   1111
   Welayta dinich    --------------1111   1111
               Yam   ---------------111   1111
           Sorghum   ---------------111   1111

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Fig. 4. Two way indicator species analysis of the crop-garden data (garden numbers are as given in Table 1).

DISCUSSION

The home-gardens in the study area depicted that it is a polycultural farming system that is based on the *enset* crop. *Enset* is an indigenous root-crop cultivated and processed for human food as a major carbohydrate source only in Ethiopia (see Brandt, 1996). It is the key species in home-gardens in Welayta and Gurage. It is also used as a source of fibre and wrapping material for the processed *enset* and other products. The plant provides shade to other smaller plants and conserves moisture because of its large leaves and its spongy leaf sheathes. The special characteristics of the home-gardens studied are also governed by the biology of this plant and the culture that developed around its traditional husbandry. Monoculture home-gardens were never encountered during this study and each crop occupied relatively small land area, where the share of the major crop is relatively more, indicating that the produce is largely for household use. The study revealed that *enset* is cultivated in association with many common garden crops. The crops that are frequently maintained in the same home-garden together with *enset* are vegetables, spices, legumes and root-tuber crops. It was noted that some individual gardens had crops (e.g., chat in Gurage, sweet potato in Welayta) which are grown mainly for generating cash. In any given garden, the crop mix is generally much wider and covers many crop categories. However, there are variations which may have been due to combination of factors including availability of land, socio-economic conditions, differences in agroclimate and cultural attitudes. The system can be described as a mixed gardening where different crop types including root-tuber crops, vegetables, spices, grains, legumes, fruits, beverage and medicinal plants and other minor categories and non-cultivated food plants are integrated.

The PCA ordination indicated segregation of gardens into urban and rural types. Parallel trends, where home-gardens in cities tended to have more ornamental species and commercial fruits, have been reported for Mexican home-gardens (Rico-Gray, *et al.*, 1990). The present observation hints at the direction of home-garden evolution following demands for fruits that is coming up with the growing urbanization. Home-garden group 3 (Fig. 4) is an aggregate of 9 gardens all from urban/semi-urban sites in Welayta and Gurage, which also have fruit crops like avocado, bullock's heart and mango. While the urban gardens of Welayta and Gurage are lumped up, the rural gardens are classified separately (garden groups 1 and 2) indicating that urbanization is gradually driving gardens to uniformity that were initially different. This is further supported by the PCA ordination as evidenced by cluster 3 of Fig. 2 which is composed of homogeneously urban/semi-urban home-gardens.

Gurage gardens are based on *enset*, as a main staple crop while in Welayta carbohydrates are also obtained from various starchy root-tuber crops (sweet potato, Welayta dinich, taro, yam) complementing that of *enset*. In general the mixing of crops of different horticultural classes is a common feature of home-gardens in Welayta and Gurage. This polycultural (also polyvariety as there are many clones of *enset*, Welayta dinich and varieties of other crops) system has evolved into a useful practice through centuries of experimentation. A defined mixture or the best configuration that can be taken as a universal composition does not exist since it varies with location and the social needs. It appears that farmers consider many factors such as life forms, horticultural groups, yield factors, adaptability, market demands (rarely) and individual needs while deciding on the crop mix. The prevailing freedom of choice and the indigenous knowledge may have ultimately contributed to the diversification of the practice as well as the crops. At the outset, the variation observed in the pattern of cropping in home-gardens in Welayta and Gurage appears to be influenced partly by differences in agroclimate. Welayta which is more southwestern is relatively wetter than Gurage which is centrally located.

Certain garden crops tend to occur together in groups or constellations as seen in the association of the major crops (Tables 4, 5 and Fig. 4). Each constellation can be taken as indicative of a nutrient profile, as reported and rationalized for west Javanese home-gardens (Marten, 1990). The constellations produced by the analysis show similar ecological adaptability of the crops not withstanding the influence of household needs, preferences and cultural attachments. Marten (1990) reported an optimization study to find out the optimal mix of starchy root crops, legumes and green leafy vegetables which he referred to as nutritional calculus of home-gardening. In the present study crop groups 1 and 3 (Fig. 3) include the three basic elements in the crop aggregates, and hence approaches an optimal mix. Inspection of the TWINSPAN classification, garden 13 in Welayta and garden 15 in Gurage (Fig. 4), approach what may be considered as an optimal crop mix. The average crop per garden is higher in Welayta than in Gurage. Furthermore, the number of starchy root crops is higher in Welayta. Whether this suggests a higher value of nutritional calculus in Welayta is a topic for further investigation. However, tremendous possibilities exist for further optimization especially for some individual gardens. It would be very rewarding to apply the nutritional calculus formula (Marten, 1990) and establish a balanced mix of crops in Welayta, Gurage and other parts of Ethiopia for optimal use of the home-garden agroecosystem.

Crop pairs consistently planted adjacent to each other may indicate possible positive interactions in being mutually beneficial to each other by providing shade and substrate for growth through conversion of wastes (Berkmuller, 1992). The indicated regularities in this regard may have well founded reasons, but this requires further research.

In conclusion, it can be stated that home-gardening has a high plasticity both in terms of use and environmental constraints. Farmers of Welayta and Gurage have been slowly stretching home-gardening to its limits in order to meet their needs. Hence more efforts towards increasing the productivity and optimizing the crop mix is needed.

Tropical cultivated landscapes are regarded to be highest in biodiversity near the homes (Okigbo, 1994) suggesting that home-gardens occupy a central position in conservation. The conservation of biodiversity in farmers' fields has been considered a very important area in the Convention on Biological Diversity (CBD, 1994; Navdanya, 1993). Traditional home-gardens could be avenues for promotion of this important resolution of the Convention. Another dimension of this practice is the benefit farmers obtain from the diversity of products and their nutritional complementarity, together with the food security and regularity of supply.

A detailed study focusing on crop associations which are mutually benefiting and useful to farmers would add more to the understanding of home-gardens and the associated practices. The study would help in discovering, among others, the combination of crops with positive synergetic effects, neutral coexistence as well as those with antagonistic effects. Such knowledge on the characteristics of crops in home-gardens would be useful in the optimization of the economic and conservation benefits that accrue from this farming system and in its future enhancement.

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EVALUATION OF THE SPOILAGE POTENTIAL OF SELECTED BACTERIAL ISOLATES ON ETHIOPIAN SAUCES AND EFFECT OF TWO MAJOR SPICE FORMULATIONS ON SPOILAGE MICROORGANISMS

Mogessie Ashenafi[1]

Department of Basic Sciences, Awassa College of Agriculture
PO Box 5, Awassa, Ethiopia

ABSTRACT: The spoilage potential of *Bacillus* spp., *Micrococcus* spp., Enterobacteriaceae, *Aeromonas* spp. and other Gram positive rods isolated from spoiled traditional Ethiopian sauces was tested on legume-based, vegetable-based and meat-based Ethiopian sauces. Legume-based sauces were spoiled by all 56 test organisms within 48 h at ambient temperatures. Foul odour with or without gas production was detected at spoilage. Meat-based sauces and vegetable-based sauces were spoiled only by 14 and 12 test strains, respectively. Enterobacteriaceae were the major spoilers of most sauces in terms of foul odour and gas production. One of the major ingredients of Ethiopian sauces, the hot spice "berbere", showed stronger inhibitory property against spoilage microorganisms until 12 hours of storage.

Key words/phrases: Antibacterial effect, pepper, sauces, spoilage potential, turmeric

INTRODUCTION

Ethiopian sauces are usually hot sauces made of a variety of ingredients. Different sauces have different flavours depending on the type and amount of spices and other constituents, the extent of cooking and other factors. The sauces are basically legume-based, vegetable-based or meat-based. Legume-based sauces are usually frequented in low-income families and during fasting periods, whereas meat-based sauces are mostly luxuries for most families. In

[1] Present Address: Department of Microbiology and Immunology, Institute of Pathobiology, Addis Ababa University, PO Box 1176, Addis Ababa, Ethiopia.

most households, sauces are usually prepared early in the day and are supposed to last until dinner and frequently are kept overnight at ambient temperatures.

Spoilage of sauces is detected after 24 h and is manifested in the form of foul odour and/or gas production. As the cooking temperature is over 85° C, most microorganisms in raw materials are expected to be eliminated. Spoilage may, thus, be caused by spore formers or heat resistant types. Spoilage by heat sensitive species may be due to introduction of these microorganisms after cooking. The ingredients of the various spices may also affect the extent of proliferation of spoilage microorganisms in the sauces.

The presence of spoilage and pathogenic microorganisms in prepared foods was reported by various workers (Bryan *et al.*, 1992; Ferrer *et al.*, 1992; Khan *et al.*, 1992). There is, however, very little information on spoilage of Ethiopian foods (Mogessie Ashenafi *et al.*, 1995). The purpose of this study was to evaluate the spoilage potential of some bacterial strains isolated from spoiled sauces and to assess the effect of the major ingredients of sauce spices on the spoilage microflora.

MATERIALS AND METHODS

Test strains

Fifty six isolates which constituted the dominant spoilage flora of legume-based, vegetable-based, and meat-based sauces in a previous study (Mogessie Ashenafi, 1996) were used to evaluate their spoilage potential. The isolates consisted of *Bacillus* spp. (18), *Micrococcus* spp. (6), Enterobacteriaceae (16), *Aeromonas* spp. (3), *Pseudomonas* spp. (4) and other non-spore forming Gram positive rods (9).

Preparation of sauces

Legume-based, vegetable-based and meat-based sauces were prepared following traditional methods and the sauces were sterilized in screw cap bottles in 200 ml amounts.

Inoculation with test organisms

Test strains were grown overnight in Brain Heart Infusion Broth (Merck), centrifuged and washed repeatedly in sterilized water and were separately inoculated into the various sauces to give an inoculum level of 10^2-10^3 cfu(ml)$^{-1}$.

Inoculated sauces were kept at ambient temperature and checked periodically at 12 h intervals for signs of spoilage (foul odour or gas production).

Effect of major sauce spices on spoilage microflora

The effect of the two major spices, "berbere" and "erd", used to prepare hot or mild sauces, respectively, on spoilage microflora was studied. The traditionally prepared powdered hot spice "berbere" constituted of red mature fruits of pepper (*Capsicum annum*) (70%), *Nigella sativa* (3%), *Trachyspermum ammi* (3%), Thyme (3%), false cardamom (7%), Ginger (2%), rue fruits (2%), garlic (3%), fenugreek (0.1%) and salt (7%). Most households prepare their own "berbere", although, in urban areas, it can be purchased from vendors.

Based on the proportion used in traditional sauce making, "berbere" medium was prepared at 10% concentration in Brain Heart Infusion Broth. The mild spice "erd" consisted of turmeric and was prepared by making a 0.2% mixture of turmeric in Brian Heart Infusion broth.

Eight isolates which produced strong foul odour and/or gas in the spoilage experiment were separately inoculated in "berbere" or "erd" medium at an initial inoculum level of 10^2 or 10^3 cfu(ml)$^{-1}$. Brain Heart Infusion broth without "erd" or "berbere" served as control.

Samples were taken every two hours and plated on Brain Heart Infusion Agar to determine their growth rates.

RESULTS

The test strains had various spoilage potential in the different sauce types (Table 1). All test strains spoiled legume-based sauce within 48 h at ambient temperatures. Of these, 14 produced gas in addition to foul odour and they consisted of Enterobacteriaceae (10), *Bacillus* spp. (3) and *Aeromonas* spp. (1). These strains were originally isolated from spoiled legume-, vegetable, or meat-based sauces.

Only 14 strains were able to spoil meat-based sauces. Eight exhibited spoilage activity already within 48 h, and the remaining at 70 h. Foul odour and strong gas was produced by *Aeromonas* (1), Enterobacteriaceae (11) and *Bacillus* spp. (1).

Table 1. Spoilage pattern of the various sauces by test organisms.

Test organism	Number tested	Legume-based		Vegetable-based		Meat-based	
		Foul odour	Gas	Foul odour	Gas	Foul odour	Gas
Bacillus spp.	18	16	3	1	-	2	1
Micrococci	6	6	-	-	-	-	-
Other G^{+ve} rods	9	9	-	-	-	-	-
Entero-bacteriaceae	16	15	10	10	10	11	11
Aeromonas spp.	3	3	1	1	1	1	1
Pseudomonas spp.	4	4	-	-	-	-	-

Vegetable-based sauces were spoiled only by 12 strains, but spoilage was detected as early as 42 h in all cases. Foul odour and gas production were frequently observed in sauces inoculated with Enterobacteriaceae.

Eight Enterobacteriaceae and one *Aeromonas* isolates resulted in spoilage of sauces of all types.

Of the six Enterobacteriaceae test strains, four showed no significant difference in rate of growth in control or "erd" medium ($p < 0.1$). Significantly lower rate of growth was seen in "berbere" medium than in control in four strains ($p > 0.05$). "Berbere" medium also showed a significantly retarding effect than "erd" medium on four strains ($p < 0.025$). The single test strain of *Aeromonas* showed significantly retarded growth in "berbere" medium than in control ($p < 0.025$). No significant difference was observed in growth of *Bacillus* test strains in control and "erd" medium. Growth rate was, however, significantly lower in "berbere" medium than in control ($p < 0.025$) or in "erd" medium ($p < 0.005$). In general, "berbere" showed a stronger growth retarding effect on the test strains than turmeric (Figs 1 and 2). Final counts at 24 h were, however, not different in all media including the control.

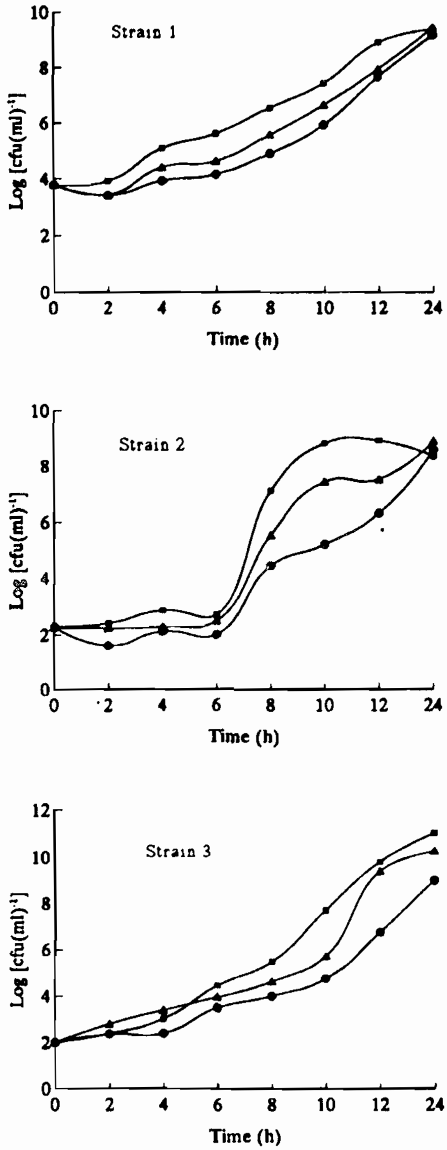

Fig 1. Growth pattern of three Enterobacteriaceae test strains in control (■), turmeric medium (▲) and "berbere" medium (●).

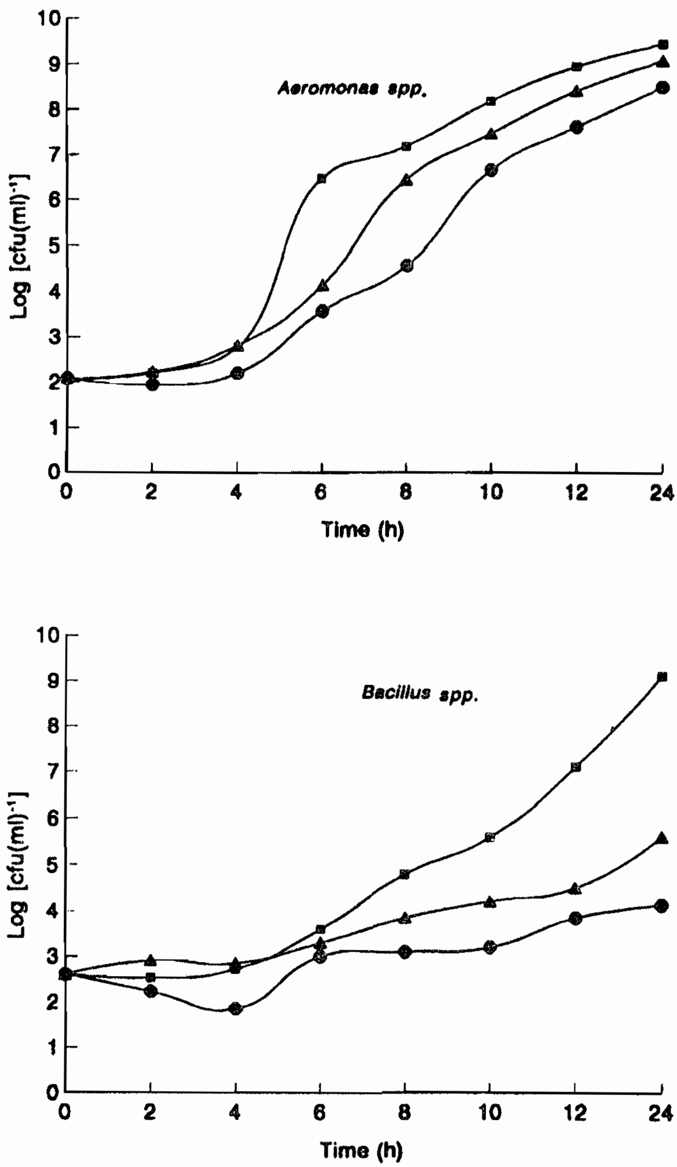

Fig 2. **Growth pattern of *Aeromonas* spp. and *Bacillus* spp. test strains in control (■), turmeric medium (▲) and "berbere" medium (●).**

DISCUSSION

Spoilage of the various traditional sauces resulted in foul odour and was of effervescent or non-effervescent type. Normally a family rejects any sauce which manifests any one of the two spoilage types. Effervescent type of spoilage was more common in legume-based sauces and the major gas producer in such sauces were Enterobacteriaceae.

Meat and vegetable-based sauces were spoiled only by a limited group of microorganisms. Enterobacteriaceae were the major spoilers of these sauces and spoilage was mainly of foul odour and effervescent type. The time/temperature combination during the cooking of all types of sauces is sufficient to kill Enterobacteriaceae, which, in this study, were found to be the major spoilers. It is, thus, evident that Enterobacteriaceae, which were introduced after cooking or during serving should be the major causes of spoilage. Microorganisms can be introduced into the sauces from serving spoons. As left-over sauces are not usually reheated and are kept at ambient temperatures until the next serving, introduced microorganisms may proliferate in the sauces and cause spoilage.

Bacillus and *Aeromonas* test strains also spoiled the three types of sauces. Only very few *Bacillus* test strains produced gas and this was in agreement with the observations of Al-Diejaili and Anderson (1991), where they caused non-effervescent spoilage in under processed foods. The Aeromonas test strains produced foul odour and gas. Aeromonas spp. were reported to contaminate a variety of food types (Barnhart and Pancorbo, 1992; Krovacek *et al.*, 1992).

Vegetable-based sauces and meat-based sauces were relatively more resistant to spoilage by a variety of spoilage microorganisms. Although various vegetables are initially contaminated with a variety of microorganisms (Khan *et al.*, 1992), the persistence of vegetable-based sauces to spoilage may be due to the occurrence of antimicrobial activities in their juices as observed by Marchetti *et al.* (1992). Meat-based sauces are usually cooked much longer than other sauce types and are strongly spiced. In addition to the effect of thorough cooking, spices may exhibit some inhibitory effect on certain microorganisms (Aureli *et al.*, 1992).

One of the major ingredients of Ethiopian hot sauces is "berbere". This ingredient has shown a stronger, but not long lasting, inhibitory property against the spoilage microorganisms. As "berbere" consists of a variety of different spices, its retarding effect may be due to the antimicrobial effect of some essential oils from the spices as observed by Aureli *et al.* (1992). However, as retardation was effective only for the first 12 hours, this ingredient may not be expected to improve the keeping quality of sauces stored overnight.

It may be difficult to use cold storage in most households in Ethiopia. However, reheating sauces satisfactorily after servings may help to improve the keeping quality of the sauces even when stored at ambient temperatures.

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BACILLUS SPP. FROM FERMENTED *TEF* DOUGH AND *KOCHO*: IDENTITY AND ROLE IN THE TWO ETHIOPIAN FERMENTED FOODS

Ayele Nigatu[1], Berhanu A. Gashe[2] and Tarekegn Ayele[3]

[1] Biodiversity Institute, PO Box 80928, Addis Ababa, Ethiopia

[2] University of Botswana, Private Bag 0022, Gaborone, Botswana

[3] PO Box 33944, Addis Ababa, Ethiopia

ABSTRACT: A significant population of Gram-positive, endospore-forming rods were isolated from fermenting *tef* dough and *kocho*. A taxonomic study showed that *Bacillus circulans*, *B. firmus* and *B. larvae* were common to both foods. The other species were, however, limited to one food or the other. *B. licheniformis* (56%) was the dominant species amongst the *tef* isolates while *B. larvae* (39.3%) was dominant in *kocho*. Most of these strains exhibited a wide spectrum of enzymatic activities and some showed antimicrobial effects against certain food-associated bacterial pathogens. Biochemical features of these bacilli led to the suggestion that they may play active metabolic roles and enrich the substrates for the succession and dominance of the lactic acid bacteria (LAB) which are essential for the characteristic fermentation of the two foods. Further studies are recommended to establish the effect of this group of bacteria and their metabolic products on human health.

Key words/phrases: ***Enset*, *injera*, *kocho*, *tef* dough, traditional lactic acid fermentations**

INTRODUCTION

In many traditional plant food fermentation processes *Bacillus* spp. breakdown starch into simple sugars which subsequently serve as substrates to initiate growth of organisms involved in fermentation, such as the lactic acid bacteria (LAB), as is the case in cassava (*Manihot esculenta*) (Adegoke and Babalola, 1988). Fermented cassava products are a major diet in Africa and Latin America (Okafor, 1992; Parada *et al.*, 1996) where strains of *B. subtilis* usually set preconditions by degrading the starch so as to give way to the LAB and yeasts which predominate in the latter periods of fermentation. In this process, *Bacillus* spp. are known to change the texture, taste, flavour, aroma and appearance of the raw cassava to a detoxified product where the enzyme linamarase breaks down the cyanogenic glucosides (linamarin and latomarin) (Oyewolle, 1992).

Bacillus spp. are also known to be actively involved in the production of other foods such as, Japanese *natto* (a side dish with rice from soya beans, fermented by *B. natto/ B. subtilis*) and Sudanese *kawal, sigda* and *furundu* fermented by *B. subtilis* from *Cassia obtusifolia* leaves, *Sesame indicium* seed cake and *Hibiscus sabdoriffa* crushed seeds, respectively (Harper and Collins, 1992). In foods, such as the Equadorian fermented rice products-*arroz fermentado, arroz amarillo* and *arroz requmando*-bacilli, particularly *B. subtilis,* play prominent role in bringing about a golden cinnamon brown colour of the rice (Pederson, 1979).

In Ethiopia, amongst the various fermented plant foods, *injera* from *tef* (*Eragrostis tef*) and bread from *kocho*, pit fermented product of *enset* (*Ensete ventricosum*), are widely consumed dietary sources (ICNND, 1959). The processes of *tef* dough and *enset* fermentations were well described as lactic acid fermentations (Berhanu A. Gashe *et al.*, 1982; Berhanu A. Gashe, 1987). In addition to the major fermenting lactic acid bacterial genera (Berhanu A. Gashe *et al.*, 1982; Berhanu A. Gashe, 1987; Ayele Nigatu, 1992), the presence of members of the family *Enterobacteriaceae*, sporeformers and yeasts in the fermenting foods is also reported (Berhanu A. Gashe *et al.*, 1982; Chaltu Gifawossen and Abraham Besrat, 1982; Berhanu A. Gashe, 1985; Meaza Girma and Berhanu A. Gashe, 1985; Berhanu A. Gashe, 1987).

However, the sporeformers in general and the species of *Bacillus* in particular, associated with these two widely consumed Ethiopian diets have not yet been described. The present study was, therefore, aimed at identifying the common species of *Bacillus* in fermented *tef* dough and *kocho*, and assessing their metabolic and fermentative roles and the possible health implications to consumers.

MATERIALS AND METHODS

Samples

Tef (*Eragrostis tef*) grain was purchased from a market in Addis Ababa and ground into flour using a local flour mill. The flour was thoroughly mixed, in a glass jar, with tap water (flour:water, 1 kg:1.8 l, w:v ratio), mouth covered with lid and allowed to ferment at room temperature (18-22° C). Fermented *kocho* dough (*Ensete ventricosum*) was also purchased from a market in Addis Ababa.

Isolation and maintenance of gram-positive endospore-forming rods, yeasts and molds

Twenty-five ml portions of fermented *tef* dough (72 h) or 25 g portions of *kocho* dough were diluted with 225 ml sterile 0.1% peptone water diluent in screw capped brown bottles and heat-treated at 80° C for 10 min to enrich spore formers. The bottles were then cooled to room temperature. From appropriate serial dilutions, aliquots of sample were seeded in tryptone/soya/ agar (TSA) (OXOID) in duplicate plates and incubated at 32° C for 2-5 days. Yeasts, molds and *Actinomycetes* were isolated from non heat-treated fermented *tef* dough and *kocho* samples and maintained using potato/dextrose/agar (OXOID); plates were incubated at 32° C for 2-5 days. Using morphological characteristics of well grown colonies on TSA and microscopic appearance of portions of 24 h culture in nutrient broth for Gram's reaction and possession of endospore, yeasts, molds and *Actinomycetes* were separated from the bacteria. Representative colonies of all Gram-positive, spore-forming, rod-shaped bacteria from TSA were then picked, purified and stock cultures maintained on agar slants for further identification. TSA also served for total count.

Identification of Bacillus *isolates*

Stock cultures from agar slants were subcultured into sterile nutrient broth (OXOID) and incubated at 30° C for 24 h. All isolates were further characterized using the dichotomous key of Norris *et al.* (1981).

Phenotypic tests and culture media

The following major physical and biochemical tests were employed to assign the aerobic endospore-forming rods into different species of *Bacillus*. These included Gram's reaction, size of cell, presence and position of spore, oxygen requirement for growth using anaerobic medium, growth at 50 and 65° C, growth in 7% sodium chloride, production of catalase, reduction of nitrate to nitrite, pH and reaction in Voges-Proskaur test, decomposition of casein, hydrolysis of starch, and production of acid and/or gas from glucose. All of these tests were performed in duplicate and average results of three experiments were recorded. Corning Model 140 pH meter (USA) was used to measure pH.

Media employed in phenotypic tests included: nutrient broth (OXOID) for culture maintenance and for testing growth at different temperatures and salt tolerance; MRVP medium (OXOID) for acid and Acetyl methyl carbinol production. After 3, 5, and 7 days of incubation, pH of the medium was monitored. Acetyl methyl carbinol (VP) production was detected as recommended by Collins and Lyne (1976) and Norris *et al.* (1981). Milk/agar (OXOID) was utilized for testing casein hydrolysis (Collins and Lyne, 1976). Starch/agar (DIFCO) was prepared by adding 0.5% soluble potato/starch into nutrient agar (DIFCO) and employed for testing hydrolysis of starch. Thioglycollate medium (OXOID) was used to determine anaerobic growth.

Isolation and identification of non-sporing microflora from tef *dough and* kocho

Twenty-five ml portions of fermented *tef* dough (72 h) or 25 g of *kocho* dough were diluted in 0.1% sterile peptone water from which serially diluted aliquots were seeded in plates of appropriate media. Incubation of plates for members of the family *Enterobacteriaceae* and LAB was carried out, at 37 and 32° C, for 1 and 2–5 days, respectively.

Culture media utilized for asporogenous bacteria

Culture media used for isolation, purification and maintenance of non-sporeforming bacteria from fermented *tef* or *kocho* were the following: Mac Conkey agar (OXOID) for members of the family *Enterobacteriaceae*, Rogosa agar (OXOID) for lactobacilli; dextrose/tryptone/agar (OXOID) for pediococci; sucrose/gelatin/agar (prepared as follows, $g(l)^{-1}$ of distilled water: sucrose, 10; gelatin, 20; nutrient broth, 13; agar, 15; all chemicals were from BDH, England) for *Leuconostoc* species and Slanetz and Bartley medium (OXOID) for streptococci. The LAB were isolated following procedures described earlier (Berhanu A. Gashe, 1985; 1987).

Determination of moisture content

The method described by Welcher (1975) was modified and employed as follows. Food samples (10 g) were placed in an oven desiccator at 95° C for 24 h. Moisture content was calculated based on differences in weight before and after drying.

Determination of reducing sugars

Reducing sugars were determined after Miller (1959) using dinitrosalicylic acid reagent (DNS), prepared by dissolving 8.0 g of dinitrosalicylic acid, 1.6 g of phenol, 0.4 g of sodium sulfite, 160.0 g of potassium/sodium/tartarate and 8.0 g of sodium hydroxide in 800 ml of distilled water. The reagent was kept in brown bottles until use.

To each 1 ml portion of the supernatant liquids from *tef* or *kocho* dough, 1 ml of DNS reagent was added and mixed thoroughly. This was placed in boiling water bath for 5 minutes. After cooling, 5 ml of distilled water was added and the absorbance read at 540 nm using a spectrophotometer (Spectronic 21, Bausch and Lomb, USA). The amount of reducing sugars present in the samples was extrapolated from a curve prepared using glucose as a standard.

Determination of free amino acids

Free amino acids were quantified using a modification of the method outlined by Riemeredes and Klostermayer (1976). Ninhydrin solution was prepared by dissolving 5 g of Ninhydrin in 188 ml of methyl cellosolve. This was then combined with 62 ml of 0.1% $SnCl_2$ in sodium/acetate buffer, pH 5.5. The buffer was prepared by combining 5.44 g of sodium/acetate, trihydrated, in 100 ml of distilled water and 100 ml of glacial acetic acid. The final volume was raised to one liter after pH adjustment.

To one ml aliquots of the clear supernatants (food samples) obtained by centrifuging, 1 ml of the ninhydrin solution and 1 ml of the acetate buffer were thoroughly mixed and the tube was immersed in boiling water for 10 minutes. The intensity of the colour that developed, quantified using a spectrophotometer at 570 nm, was used to estimate free amino acids using aspartic acid as a standard. In all cases mean values of three experiments were recorded.

RESULTS AND DISCUSSION

Fermented *tef* dough (72 h) and *kocho* when purchased had pH values of 4.0 and 4.3, respectively. Their nutrient composition is shown in Table 1. The predominant and important fermentative microflora isolated from these acidic foods are presented in Table 2. In this study members of the family *Enterobacteriaceae* were hardly isolated from *kocho*. The overall microbial load per gram of adequately fermented *tef* dough (fermented for 72 h) was higher than the same weight of fully fermented *kocho*. *Bacillus* spp. in both foods had lower counts than the other fermentative microflora.

A total of 25 and 28 strains of *Bacillus* were isolated from fermented *tef* dough and from *kocho* samples, respectively (Tables 3 and 4). The different strains isolated from both foods were further tested for growth under different temperatures, conditions of oxygen, concentrations of salt and utilization of various biochemicals. The isolates from *tef* were accordingly assigned into six species of *Bacillus: Bacillus licheniformis* (56%), *B. circulans* (12%) and *B. laterosporus*, *B. firmus*, *B. alvei* and *B. larvae* (each comprising 8%). On the other hand, isolates from *kocho* belonged to the following 10 species: *B. larvae* (39.3%), *B. popilliae* (14.29%), *B. sphaericus* and *B. coagulans* (each, 10.71%), *B. firmus* (7.14%) and *B. polymyxa, B. circulans, B. megaterium, B. subtilis* and *B. thuringensis* (each, 3.57%).

Table 1. Nutrient composition of fermented *tef* and kocho. The values are mean results of four food samples in triplicate experiments.

Type of food	Fermentation time	pH	Content per g dry wt of *tef* flour or *kocho*		
			Moisture (%)	Reducing sugars (mg)	Free amino acids (mg)
Tef dough	72 h	4.0	66.4±2.2	34.2±1.0	4.3±0.1
Kocho dough	Purchased fermented	4.3	44.0±3.5	0.73±0.06	5.6±0.3

Table 2. **Microbial composition of fermented *tef* and *kocho*.** Each value is a mean of four food samples from triplicate experiments. Populations of molds and other spore-formers were variable and not presented here as they are not involved as fermentative microflora.

Food type	pH	Estimated number of organisms per g dry wt of *tef* flour or *kocho*							
		Enterobacteriaceae	*Lactobacillus* spp.	*Pediococcus* spp.	*Leuconostoc* spp.	*Streptococcus* spp.	*Bacillus* spp.	Yeasts	Total count
Tef dough (72 h)	4.0	$1x10^4$	$3.5x10^7$	$3.3x10^8$	$3.7x10^6$	$1x10^5$	$2x10^5$	$1.4x10^5$	$3.7x10^8$
Kocho dough (as purchased)	4.3	—	$5.2x10^6$	$2.3x10^6$	$1.9x10^4$	<10	$1.4x10^4$	$2.8x10^5$	$7.8x10^6$

—, No growth.

The isolates from *kocho* showed larger number and greater diversity than those from *tef. B. larvae, B. circulans* and *B. firmus* were common to both of these plant-based fermented foods. Species, such as *B. licheniformis*, *B. laterosporus* and *B. alvei* were restricted to *tef* whereas *B. subtilis*, *B. sphaericus*, *B. polymyxa*, *B. popilliae*, *B. megaterium*, *B. coagulans* and *B. thuringensis* were limited only to *kocho* samples.

As shown in Table 1, fermented *tef* dough (72 h, pH 4.0) and fermented *kocho* (pH 4.3) are acidic foods mainly fermented for improved qualities. The pH values dropped arising from accumulation of non-volatile organic acids, including lactic acid (Melaku Umeta and Faulks, 1989). During the onset of fermentation, the raw foods had near-neutral pH values, wherein the case of *tef* flour it was 6.6 and in *kocho* 6.7. The final pH values of completely fermented products from both foods, not only contributed to the characteristic aroma and taste of the foods, but also to the inhibitory properties against most spoilage and food-borne bacterial pathogens (Meaza Girma *et al.*, 1989; Ayele Nigatu, 1992; Ayele Nigatu and Berhanu A. Gashe, 1994a,b).

As shown in Tables 3 and 4, however, the spectrum of the species as well as the composition and number of strains in the two foods were not the same. In whatever way they differ, both foods also shared same species of *Bacillus*, such as *B. circulans*, *B. firmus* and *B. larvae*.

Threshing of *tef* seeds is usually carried out on a dry ground plastered with cow dung, where domestic animals, such as oxen and cows, are used for trampling, to shake-off the seeds (Berhanu A. Gashe *et al.* 1982; Berhanu A. Gashe, 1987). *Kocho* on the other hand remains entirely moist throughout its processing. The fermentation conditions of the two foods and their environments also differ. *Kocho* is fermented outdoors in underground pits covered by the remaining litter from decorticated *enset* plants while *tef* is fermented indoors in partially-clean, earthen, plastic, wooden or metallic vessels. In both foods, however, the microbial constituents come mainly from starters used to initiate the fermentations, and/or the processing ground, plants and animals (Berhanu A. Gashe, 1987; Ayele *et al.*, Unpublished data).

Table 3. Species composition and characteristics of *Bacillus* isolates from fermented *tef* dough (72h).
-, all strains negative; (-), 78.5% of strains negative; +, all strains positive; ±, 50% of strains positive; (+), 91.4% of strains positive; A(F), one strain aerobic and the other facultative; F, facultative; R, rod.

Characteristics	Isolate number and properties					
	1,5,7,8,9,11,12,15,16,17,19,22,24,25	2,3,18	4,10	6,21	13,23	14,20
Gram	+	+	+	+	+	+
Shape	R	R	R	R	R	R
Catalase	+	+	+	+	+	-
Voges-Proskaur	+	-	-	-	+	±
Oxygen relationship	F	F	A(F)	A(F)	A(F)	A(F)
Growth at 50° C	+	-	-	±	-	+
Growth at 65° C	-	-	-	-	-	-
Growth in 7% NaCl	+	+	±	-	±	±
Acid & gas from glucose	-	-	-	-	-	+
Nitrate to nitrite	+	+	+	+	-	+
Hydrolysis of starch	±	+	-	+	±	+
Hydrolysis of casein	(-)	+	±	±	+	+
Rod width ≥1.0 μm	-	-	-	-	-	-
pH in V-P<6.0	(+)	+	±	-	+	+
Acid from glucose	+	+	±	+	+	+
Identified as	*B. licheniformis*	*B. circulans*	*B. laterosporus*	*B. firmus*	*B. alvei*	*B. larvae*

Table 4. Species composition and characteristics of *Bacillus* isolates from *kocho*. -, all strains negative; (-), 63.6% of strains negative; (-)*, 66.7% of strains negative; (-)**, 72.7% of strains positive; (-)***, 81.8% of strains negative; +, all strains positive; ±, 50% of strains positive; (+), 66.7% of strains positive; (+)*, 81.8% of strains positive; A, aerobic; AN, anaerobic; F, facultative; F-A, facultative to aerobic; R, rod.

Characteristics	Isolate number and properties									
	1	2,11,15	3,4,5,7, 12,13,19, 23,24,25,26	6	8,9	10,14,21,22	16	17	18,27,28	20
Gram	+	+	+	+	+	+	+	+	+	+
Shape	R	R	R	R	R	R	R	R	R	R
Catalase	+	+	-	+	+	-	+	+	+	+
Voges-Proskaur	-	-	±	-	-	±	-	-	-	+
Oxygen relationship	AN	F-A	F-A	F	A	F	F	A	F	AN
Growth at 50° C	-	-	(-)	-	-	±	-	-	-	+
Growth at 65° C	-	-	-	-	-	-	-	-	-	-
Growth in 7% NaCl	+	(+)	+	-	+	+	-	+	(+)	-
Acid & gas from glucose	-	-	-	+	-	-	-	-	-	-
Nitrate to nitrite	+	-	(-)***	-	+	+	-	-	-	+
Hydrolysis of starch	+	+	+*	+	+	±	+	+	+	-
Hydrolysis of casein	+	(-)*	+	+	-	-	-	+	+	-
Rod width ≥1.0 μm	+	+	+	+	+	+	-	+	+	+
pH in V-P<6.0	-	(-)*	(-)**	-	+	±	-	+	+	+
Acid from glucose	+	-	(-)	+	+	+	-	+	+	-
Identified as	*B. subtilis*	*B. sphaericus*	*B. larvae*	*B. polymyxa*	*B. firmus*	*B. popilliae*	*B. circulans*	*B. megaterium*	*B. coagulans*	*B. thuringensis*

The larger number and higher diversity of bacilli from *kocho* than from *tef* could be attributed to the constant contact of *kocho* with wet surfaces and soil starting from the time of cultivation until termination of fermentation. The dry and closed storage of *tef* seeds in containers, such as sacks, traditional granaries and the like for years, coupled with the thorough sifting and clearing of dust before milling as well as the clean indoor fermentation of the dough, could have minimized the chance for continuous influx and thus to the reduced diversity of these bacilli therein.

The two foods also had distinct species associated with each of them, such as *B. popilliae*, *B. sphaericus* and *B. coagulans* to *kocho* and *B. licheniformis*, *B. alvei*, and *B. laterosporus* to *tef*. This may also relate to the higher chance of *kocho* for contact with diverse groups of insects and worms during processing and fermentation as a source of nourishment as opposed to the dry *tef* seeds which interact differently with microorganisms.

Bacillus spp. can grow on a variety of substrates as the result of their diverse enzymatic activity. Most species of *Bacillus* are known to produce α amylase, (Aderibigbe *et al.*, 1990; Parada *et al.*, 1996) and may hydrolyse starch in *tef* and *kocho* in the early phases of fermentation into simple sugars (Adegoke and Babalola, 1988; Lealem Fikru and Berhanu A. Gashe, 1994).

Most of the isolates had proteolytic enzymes which might degrade the available proteins and also anabolize them into essential amino acids thereby supporting growth of the fastidious LAB. This continuous supply of free amino acid and simple sugars could apparently support growth of microorganisms, especially of those dominating in the latter stages of fermentation (Table 1) (Berhanu A. Gashe, 1985; Ayele Nigatu, 1992). This event also agrees with the fact that organisms such as *B. megaterium* are equipped with the entire enzymatic machinery necessary to make all compounds required for growth (Gottschalk, 1986). This species was common in the starchy food, *kocho*, but not in *tef*, probably enriching the low-protein food, *kocho*, with indispensable nutrients, a likely and beneficial association especially for the LAB.

Species like *B. circulans* are known to produce the antibiotic circulin; *B. subtilis* subtilin, mycobacillin, bacitracin and bacillin; *B. polymyxa* polymyxin and aerosporin (Shoji, 1978). *Tef* and *kocho* doughs may possess these metabolites.

On the other hand, though infrequently, certain species of *Bacillus*, other than the well recognized pathogens such as *B. anthracis* and *B. cereus* are known to be involved in human disease processes. In most cases, however, these bacilli are not known as causative agents and are rather found associated with infected organs (Norris *et al.*, 1981). Therefore, the status of these bacilli in traditional foods remains controversial.

Nevertheless, although no confirmatory experiments were done to assess whether our mesophilic isolates are non-pathogenic to man, the fermentation and baking processes could inactivate these endospore-forming bacilli. The absence of *B. cereus* and clostridia in both of these two traditional fermented foods may also serve as a good clue to their safety and wider consumption by millions of people.

Further work to quantify the amounts and qualify whether or not their secondary metabolites are toxic to consumers in the monotonous diet would be essential for there are indications that antibiotics produced by species like *B. licheniformis* to have a nephrotoxic effect on animals including man (Thimann, 1963).

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Feature article

THE BLUE NILE RIVER BASIN: THE NEED FOR NEW CONSERVATION-BASED SUSTAINABILITY MEASURES

Mengistu Woube

Afro-Scandinavian Service, 752 66 Uppsala, Sweden

SUMMARY: The Blue Nile *(Abay)*, one of the most famous international rivers, has its origin in the Ethiopian highlands. The river passes across different geographical zones and serves different land users in the upper and lower Nile riparian countries — Ethiopia, the Sudan and Egypt, respectively. Although the Blue Nile basin contributes 86% of the total annual discharge of the Nile, Ethiopia has not built big hydro-electric power installations or modern dams in this river basin. On the other hand, the river carries the country's valuable natural resources to the lower riparian countries while the Ethiopian people suffer from recurrent drought and famines. Ethiopia's efforts to divert its waters have brought confrontations with the lower Nile riparian states. Through the building of big dams and canals, enormous amounts of water and soil nutrients are utilised by the Sudan and Egypt. In recent years, however, farmers in Egypt have not been getting sufficient water and soil nutrients as before, due to environmental deterioration along the Blue Nile basin. Based on three selected sites, water resource development projects are proposed to be implemented in Ethiopia through conservation based sustainability measures. It is suggested that political stability, understanding and environmental rehabilitation measures taken by all countries of the Nile river basin are urgently needed if water resources are to be utilised on sustainable basis by the lower and upper Nile riparian countries alike.

INTRODUCTION

Water is one of the most important natural resources and life-supporting systems. This indispensable resource is, however, misused in many countries either through poor land-use systems and inappropriate agricultural inputs or through the process of industrialisation. Due to lack of sustainable development, water resources in the Blue Nile basin are neither planned properly nor managed carefully, which has led to the destruction of natural and human environments in the region. Upreti (1994) defines sustainable development as "the management and conservation of the natural resource-base, and the orientation of technological and institutional changes in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations".

Which countries and groups of people benefit most from the Blue Nile basin? Why has Ethiopia not diverted water from the Blue Nile and why has this river basin become the source of conflict in the region? How can water be shared among the riparians and at what price? What will be the long-term environmental consequences on the Blue Nile basin if the present land-use continues; and how can regional co-operation and understanding be established on the basis of ecological, legal, institutional and moral principles in the region? In this article, attempt will be made to answer these questions in an interrelated manner by providing some basic factors that have led to the environmental problems facing those riparian countries in the management of the Blue Nile river basin and proposing sustainable development and water resource use through the conservation of natural and human landscapes and habitat (biodiversity).

The paper is based on the author's field work in some weeks in 1984, 1991 and 1994 along the Blue Nile river basin, participation in an international course on the hydrology of the Nile river and studies of relevant literature.

THE GEOGRAPHY OF THE BLUE NILE RIVER BASIN

There are eight major rivers in Ethiopia. Six of these are either boundary and/or trans-boundary rivers while two are confined within the country. The Blue Nile is one of the most important rivers in the country. It flows north from temperate and humid Ethiopia to semi-arid and arid conditions in the Sudan and Egypt (Fig. 1). The Blue Nile originates as a small spring (called Gilgel Abay), about 100 km south of Lake Tana, in the volcanic mountains of Ethiopia that have steep relief and ridges that rise up to 3000 m altitude. Before *Gilgel Abay* reaches Lake Tana, it passes through a large flat land. Many rapids occur on smoothed and resistant rocks, conditions which are favourable for hydro-power generation.

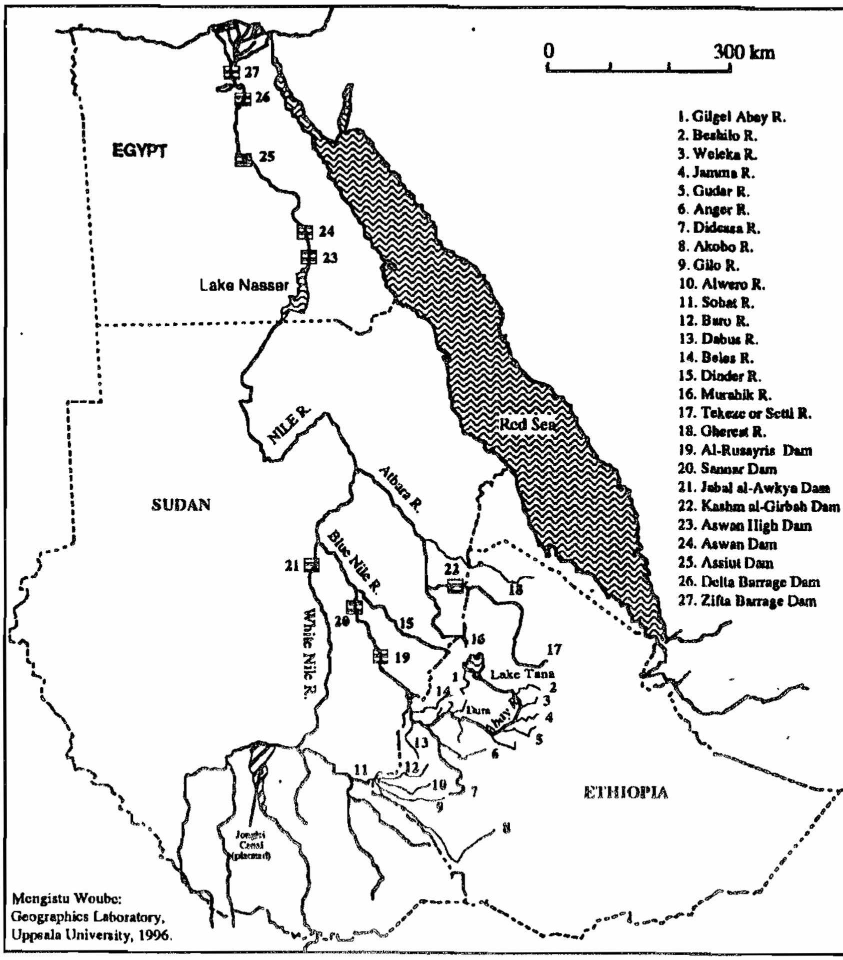

Fig. 1. Map showing the Blue Nile and White Nile river basins with existing dams and reservoirs. Neither dams nor reservoirs exist in Ethiopia.

Lake Tana is a creator lake (Ethiopia's largest) situated in the north-east part of the Blue Nile basin and it covers an area of about 3,150 km^2. The catchment area of Lake Tana sub-basin, including the Lake, is 17,500 km^2. It is 78 km long, 67 km wide with a maximum depth of 14 m. The mean annual outflow is about $4x10^9$ m^3 yr^{-1} or about 127 m^3 s^{-1} (Admasu Gebeyehu, 1989). The main tributaries, other than *Gilgel Abay* are Gumara, Ribb, Magech, Infranz and Gedla. *Zege* is one of the coffee-tree peninsulas, *Dek* and *Daga* are the main islands. Many churches and monasteries are located in these places. According to Mohr (1961), recent lavas cover the peninsulas and islands, and lacustrin sediments occur all round the Lake Tana basin. There are also lagoons and swamps on all sides of Lake Tana, that have resulted from hydrological and land-use changes.

Gilgel Abay passes over Lake Tana and outflows at Chara-Chara cataract in the eastern part of the Lake. In the outlet, the river is called Blue Nile (*Tikur Abay*). From the outlet, the river runs in a south-easterly direction. As we go down from the outlet, the river becomes wider and even deeper. Due to high vegetation density (e.g., papyrus), swamps in some places can be observed and in places where water flows in narrow topography, the velocity of the floods increases, which makes it extremely difficult to cross the river.

Thirty five kilometres from the outlet of Lake Tana, the Blue Nile river reaches *Tiss Isat* Falls or Smoke of Fire (Fig. 2). Here, the water flow goes in different directions due to the topographical characteristics and vegetation patterns. The morphology of the water flow varies considerably depending on the season. In the rainy season (June to September) when heavy rainfall falls on the region, the amount of water is much larger and covers wider areas (as seen in Fig. 2). This huge amount of water can be stored on the Blue Nile plateau to be used during the dry season before it passes *Tiss Isat* Falls and reaches the high evaporation climatic regions. During the dry season the water discharge is much reduced.

From this great and beautiful falls, the Blue Nile follows the bed of a deep gorge and borders five administrative regions. Five hundred kilometres from its source, the Blue Nile reaches an altitude of 490 m in the Sudan. It encounters on the way many rushing torrents (Fig. 1) until it finally joins the White Nile and emerges as the main Nile river in Khartoum.

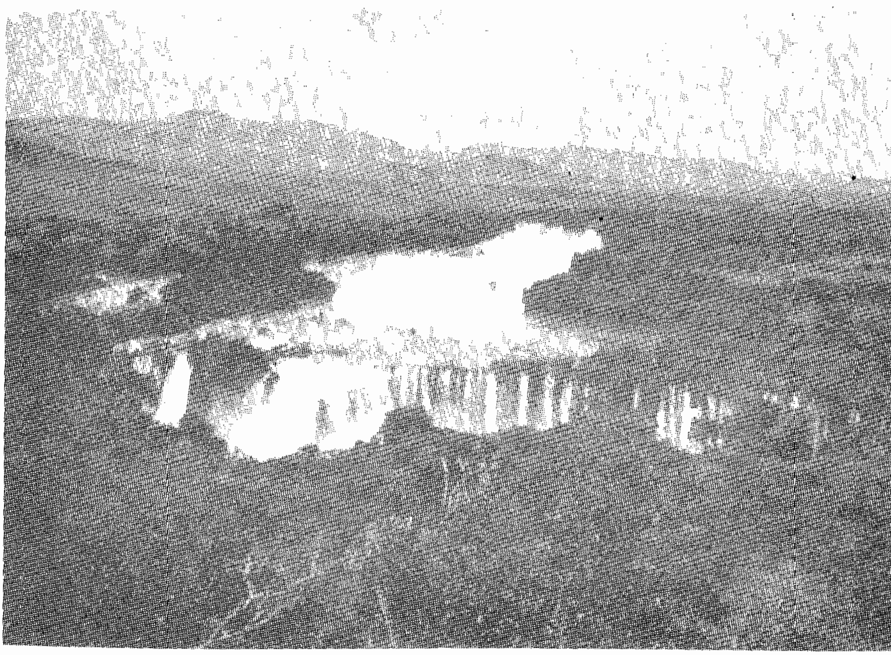

Fig. 2. ***Tiss-Isat* Falls on the Blue Nile below Lake Tana.** Photo was taken during the rainy season by the author.

The Blue Nile gorge is one of the largest and deepest in the world comparable to the Grand Canyon in the United States. It passes several rapids, tumbling through volcanic and sedimentary rocks (Fig. 3). Its river basin covers 201,346 km^2 or 16.6% of the total area of the river basins in Ethiopia (re-calculated from Zewdie Abate, 1994, p. 29). Its annual discharge amounts to 50×10^9 m^3 yr^{-1} or 1600 m^3 s^{-1} on the 935 km below the Blue Nile outlet at Rosaries (Admasu Gebeyehu, 1989). About 85% of the total annual discharge of the upper river Nile comes from the Blue Nile, Tekeze (Atbara), Baro and Akobo rivers in Ethiopia and only 15% comes from the East African source areas of the White Nile (Whittington *et al.*, 1994). The low amounts of water from the latter river is due to surface evaporation and evapotranspiration (from aquatic vegetation) losses. Also, much of the water remains in the Marchar marshes along the Jonglei canal areas (Sudd region) in Southern Sudan (Conway and Hulme, 1992). About 80% of the water passes to Khartoum during the rainy season and declines to 20% in April, before the next rainy season (Godana, 1985). The reasons for the alternate enormous torrential and shrunk flow of waters are mainly the concentration of high amounts of rainfall and low evaporation during the rainy season, low amounts of rainfall and high evaporation during the dry season (on the lower altitudes), deforestation and the high speed of the river due to topographic characteristics.

Fig. 3. Blue Nile river passing through a narrow trough-like gorge. The materials on both sides of the river are bedded various types of sedimentary rocks such as limestone, sandstone, variegated shale and gypsum. Many streams and rivers tumbledown from the mountains and hills, thundering through gorges and enter the Blue Nile river. (Photo was taken by the author during the dry season in 1991.)

THE BLUE NILE RIVER BASIN AS A SOURCE OF LIFE

At least ten ethnic groups (1.3 mill. people) live along the Blue Nile basin. They are ox-plough farmers, nomads, pastoralists, hunters, gatherers, slash and burn-cultivators, fishermen, and traders. In the alluvial soils, farmers cultivate two crops a year and perennial crop farming is also practised. During the dry season, pastoralists and nomads move their cattle along the tributaries and the Blue Nile river, which creates conflicts among the different land-users. Due to deforestation along the river basin, the Blue Nile gorge has become a major source of wood and grass for construction materials, fuel-wood and charcoal production. Most wild animals now seek refugee along this important gorge.

Due to its geographical features, the Blue Nile has been a frontier for nationalists, anti-colonialists and anti-government groups. During the Ethiopian war with Italy (1936–41) for instance, the resistance groups used the Blue Nile gorge as an important strategic place to fight the Italians. Whenever conflict emerged between the central governments and the people in the region, the Blue Nile gorge has been used for defence. Moreover, the geography of the Blue Nile basin has created cultural differences (languages, religions, ethnic groups, economic systems, etc.) and problems of infrastructural development. Although the Blue Nile provides 68 GWh yr^{-1} (average) of electricity (from the *Tiss-Isat* Falls) to the towns of Bahir Dar and Gondar, neither big hydro-electric power installations nor industries, reservoirs or modern dams are built in Ethiopia. The main reasons are financial, geographical and political constraints. In the Sudan and Egypt however, the water resources from the Blue Nile have been more exploited through modern irrigation systems and dams.

ENVIRONMENTAL DETERIORATION

While it may be said that the Sudan benefits from the Blue Nile basin (its eastern part is totally dependent on the basin), Egypt is a creation of this great river. Without water and indispensable soil nutrients from the Blue Nile basin, the civilisation of Egypt would not have been possible. Ethiopia looses its enormous quantities of fine silts from the more largely bare mountains in the country. At the expense of the natural resources from Ethiopia, Egypt was said to be the "bread basket" of the Roman Empire. However, the present soils in Egypt are poor in Nitrogen, Iron, Zinc and Magnesium. Following population increase (about 3% per annum) and soil deterioration, Egypt is poised to reclaim more land to maintain production, but seepage, salinization and high evaporation reduce on the average 10% of the agricultural production every year (Kishk, 1986). Egypt now needs more and more water and soil nutrients for her new reclaimed arid lands to feed its rapidly growing population. However, these huge demands can not be met since the country receives little water from the White Nile. The absence of annual deposits of Nile alluvium is due to the Aswan High Dam in Egypt (Kishk, 1986 and 1993). It is also said that vegetation changes in Ethiopia and the construction of dams in Sennar, Al-Rusayris, etc. in the Sudan have reduced the amount of water and soil nutrients.

The changes in vegetation patterns result in land degradation along the Blue Nile basin, due to the collapse of sustainable environmental management systems, institutional networks and food security. These situations in turn cause unexpected floods and reduce soil nutrients both in the upper and lower Nile riparian countries. The cutting of trees for firewood and charcoal is a growing cause of deforestation. Due to population increases fallowing is no longer possible. As the result, intensive cultivation occurs (often without fertilisers) and soil nutrients are washed. Another problem is overgrazing associated with inadequate management of grazing land which is aggravated by inadequate watering points (Mengistu Woube and Sjöberg, 1994).

The root causes for the mismanagement of resources are lack of land-use planning, population increase, high taxation and poor agricultural and price policies. In order to feed themselves and the urban population, the rural people in the Blue Nile basin are increasingly forced to exploit the natural resources. In addition, due to lack of alternative energy sources, building materials, etc., the entire population in this river system is dependent on the natural vegetation of the area (Mengistu Woube, 1994). The physical and human environments in the region are, thus, in crisis. It can be concluded that vegetation changes from highland Ethiopia have brought a profound impact on the physical and human environments both within Ethiopia and in the lower Nile riparian countries.

How long can the Ethiopian physical environment provide its resources freely to the lower Nile riparians, while the Ethiopian people suffer from shortage of water and food due to severe droughts, famines and poverty? Ethiopia has been assisted with food by international communities, but none of these have given significant assistance to the country to divert its many rivers to the development of agriculture and hydro-electric power installations. Ethiopia is said to be the potential "water tower" of North-eastern Africa, but except for the Awash (one of the main rivers), almost all are yet to be exploited. The dilemma is that Ethiopia is unable to divert its water resources from the Blue Nile, Lake Tana and other rivers to the agricultural and human settlements and to construct hydro-electric power installations. Rural electrification can reduce the cutting of trees for fuel or can save the use of animal dung which otherwise could be used to improve soil fertility. Rural electrification would also provide power for agro-processing industries, water lifting for irrigation, etc.

Though a nation-wide afforestation programme was introduced in the 1970s and 1980s, it did not bring significant changes (Mengistu Woube, 1986 and 1995). Afforestation and reforestation programmes can only be implemented successfully when alternative energy sources (hydro-power, solar and wind energies) are provided to the people. Potentially, the bare land can be re-covered with vegetation quickly since the Blue Nile basin in Ethiopia has sufficient rainfall (1224 mm annually), favourable climatic and soil (mainly Nitosols, Ferralsols, Vertisols and Alluvial soils) conditions. Afforestation will increase the supply of surface and ground water, decrease sediment loads and add organic matter to the soils. As Hosier (1988) pointed out, deforestation of the Ethiopian highland, cultivation of steep slopes and erosion from them have made possible the fertile cultivation along the Nile for centuries. Due to extreme pressure on land (which led to the loss of protective vegetation skin) and erodible tropical soil characteristics, soil disappears, "the surface run-off increases and the ground water is not totally refilled since the rain water does not infiltrate in the same degree as before" (Tvedt, 1992; Olsson, 1987). As a result, abnormal floods and unexpected droughts have increased in Ethiopia, which have caused considerable loses in agriculture, dams and water reservoirs damaging the human settlements in the lower Nile riparian countries (Darkoh, 1992).

CONFLICTS ON WATER RESOURCES

Conflicts between and among nations, rich and poor people, pastoralists, nomads and farmers on water resources is a phenomenon in all parts of the world. Conflicts between and among the upper and lower Nile riparians are ancient and any type of water development project in the upper Nile source regions has been a threat to the lower riparian states. Although several agreements for the utilisation of the Nile waters were signed in 1902, 1929, 1959, 1967, 1981 and 1993 (Hurst, 1952; Godana, 1985; Collins, 1990; Pearce, 1991; Ethiopian Herald, 1993; Vesilind, 1993), none of these have ever included the Ethiopian side nor promoted Ethiopian interest or protected its natural resources.

Unless Ethiopia is supported to build its own dams and irrigation canals, assisted to rehabilitate its river basins and as long as water is not utilised on equal bases between the upper and the lower Nile riparian countries, maintaining peace and stability in the region becomes questionable. One of the five Upreti's (1994) principles for environmental conservation is equity and social justice. Without this principle it is neither possible to protect Ethiopian's natural resources nor satisfy human needs for the present and coming generations.

THE NEED FOR ENVIRONMENTAL CONSERVATION

Unfortunately, there are no well established international laws on river basins that could create understanding between the water contributors and users. Interestingly enough, Egypt and the Sudan, which do not contribute to the Blue Nile water resources, are the users, while Ethiopia's right has been denied. How much and for how long Ethiopia can afford not to harness its water resources to alleviate its own problems, which are aggravating the environment? It is estimated that Ethiopia has 0.9 mill. ha of irrigable land in the Blue Nile river basin and 1.5 mill. ha in the Baro-Akobo basin (a White Nile tributary) that could be developed under irrigation schemes (Zewdie Abate, 1992). Although Ethiopia contributes enormous amounts of water to the Nile flow, currently the country has no water allocation (Whittington *et al.*, 1994).

In contrast, Egypt utilises 3.2 x 10^9 ha. Due to shortage of farm land, Egypt is said to reclaim more than 0.58 mill. ha of desert land in the coming years (Kishk, 1993). In order to irrigate the reclaimed land, more than 10x10^9 m^3 of additional water is needed by the year 2000 (Abdu-Zeid, 1991; Kishk, 1993). Since 97% of the land in Egypt is desert each drop of water and each kilogram of silt are important. However, due to environmental deterioration and poor water management, salinization is increasing and the ground water rises up and dissolves salts up to the root zones of the plants which kills them (Olsson, 1987). The Sudan has developed 1.8 mill. ha of land. Irrigated agriculture uses 18.3 x 10^9 m^3 of water each year and it is projected to expand by 1.5 mill. ha. The annual demand of water will reach to more than 31 x 10^9 m^3 in the coming years (Zewdie Abate, 1990).

All these point out that restructuring a new agreement on the use of water resource in the three countries is a strongly felt need. Such an agreement should allow Ethiopia to use her water resource and to obtain international support to finance irrigation schemes and to rehabilitate its deteriorated environment. Ethiopia has lost regional and natural rights to divert its water resources for development purposes. The country does not have sufficient hydrometeorlogical data, capital, modern technology, trained manpower for environmental management and support from international organisations and donor countries. In contrast, Egypt has appropriate technology and information about the river basin. The country is backed by the developed countries and international organisations and the state have given top priority for the development of hydraulic technology and water control. Nevertheless, unless the water resources are redistributed (on the basis of trans-boundary water resources policy, population and resource sizes and wealth) among the Nile riparian countries, sustainable development cannot be maintained.

What is happening today in the region is that the lower Nile riparian states are demanding more water without contributing to the rehabilitation of the deteriorated environment in the Blue Nile basin. The basic problem facing Egypt is that there is not enough water available to meet the growing demands for irrigation and electricity. Currently, the Aswan High Dam supplies about 20% of the Egyptian's total power needs, which are growing by about 6% yr^{-1}. The dam may not supply more that 10% by the year 2000 (Whittington *et al.*, 1994). The main reasons are the rapid population growth and the environmental degradation in the Blue Nile source region, which need collective rehabilitation measures.

Rehabilitation measures require regional and international support and Ethiopia alone and by itself can not mitigate the deteriorated environment. In order to introduce sustainable (conservation-based) water utilisation programmes, well discussed and integrated river basin planned policies are indispensable. To begin with, the state and quality of the existing environment of the basins must be understood and the Blue Nile basin should be rehabilitated by all countries in the region before things turn to worse. As argued by Upreti (1994), "the policy-makers .... must agree in principle that the solutions for the environmental and human problems, namely of conservation of biodiversity and habitat restoration with ecosystem development, must be sought within the context of well-connected landscape ecosystem processes on a regional basis".

Based on detailed studies on the physical and human environments, well thought-out principles as guide-lines, laws and regulations must be developed in order to utilise the water resources on sustainable development basis by all riparian countries. Unfortunately, such indispensable issues are not discussed. With demand on water increasing, neither international laws and regulations nor real understanding between the Nile riparian states have been established. However, for the benefit of the lower Nile riparian countries the Blue Nile river basin must be considered as an ecological region, be utilised in an integrated, unified and co-operative manner; and Ethiopia must be allowed and be supported to utilise her water resources through conservation based sustainability measures.

THE PROPOSED PROJECT TYPES AND SITES

In order to feed its rapidly growing population, Ethiopia, sooner or later, will introduce reservoir, dam and irrigation projects along the Blue Nile river basin. Before the introduction of such projects, a) the lower Nile riparian countries must recognise Ethiopian's rights to water resources, b) the Blue Nile environmental management must be understood and c) Ethiopia must offer specific and concrete proposals. Here some environmentally sound and economically viable project types (reservoirs, dams and irrigations) and project sites (on the tributaries, Lake Tana and Blue Nile river) are proposed as follows:

The first proposed project is the development of small and medium-scale dams and irrigation systems on village or household level along the various Lake Tana and Blue Nile tributaries. These types of projects are less expensive, manageable or maintainable, efficient in saving water and energy and can increase agricultural production. Small-scale hydro-electric power stations can also be generated in most of the tributaries on community and village levels; and these in turn can save thousands of trees that are now cut every day for fuel-wood and for other purposes. These projects will not affect the water flow, rather they reduce sediment loads, which is a serious problem for the lower Nile riparian countries.

The second proposed project is the development and use of Lake Tana and its surrounding as a water reservoir. The United States Bureau of Reclamation argued as early as in 1964 that one of the numerous advantages of the construction of the Blue Nile reservoirs in Ethiopia can be the saving of huge amounts of waters that presently evaporate (through evaporation and evapotranspiration) from the lower riparian countries, specifically from the Aswan High Dam reservoirs on the White Nile. Such reservoirs can provide over-year storage and can also control the unexpected floods that also affect the Sudan and reduce large sediment loads, which presently affect agricultural output and water quality in Egypt (Whittington *et al.*, 1994). Through the construction of water reservoirs in and around Lake Tana, the alluvial plains of Fogera and Dembya in the north, Takusa in the west and Achefer in the south of Lake Tana, can be irrigated and crops can be cultivated two or three times a year, which will lead to food self-sufficiency in the Blue Nile river basin.

The third proposed project sites and types are divided into two: a) Small-scale dams and irrigation projects to be introduced on the outlet of the Blue Nile, along the Dura depression and the Sudan border (Fig. 1), b) Large, medium and small-scale hydro-electric power stations to be introduced on the various water falls sites along the Blue Nile river. Through these measures, the rural population in the region can be provided with alternative energy and Ethiopia can sell electricity to the lower Nile riparian countries. The regional water marketing system can finance Ethiopia to implement her afforestation and soil conservation programmes in the region, which is also useful to the lower Nile riparian countries.

For the establishment and implementation of such development projects: a) the willingness of the local people, b) a stable and widely supported national government, c) carefully designed plans and strategies, d) restructuring of human and agricultural settlements, e) adequate capital and experts, f) scientific understanding of the physical environment such as geological, agronomical and hydrometeorlogical environments, g) financial and moral support from the international communities are prerequisites. The implementation of the above mentioned proposals can lead to co-operation and regional-based conservation of the natural resources, and alleviate human misery and environmentally hostile conflicts among the Nile riparian countries.

If the upper and lower Nile riparian states continue arguing on the so called "national and regional rights" on waters, further environmental deterioration is imminent as nature has its own limitation to serve its users. As Rees rightly argues "true sustainability requires that we recognise the reality of ecological limits to material growth and the need to live in the interest of our remaining ecological capital. This is not an option but an absolute necessity if we are to have a sustainable future" (Rees, 1990).

CONCLUSION

Water is an indispensable resource and it has also been a source of conflicts in many parts of the world. Through the building of gigantic dams and canals, Egypt and the Sudan exploit water resources from the Blue Nile basin. Ethiopia neither utilises effectively its waters and silts nor protects these resources through effective afforestation programmes. Some of the main constraints to environmental rehabilitation are lack of: a) understanding between the upper and lower Nile riparian states; b) knowledge about the physical and human environments in the river basin; c) resources and administrative capacity; and d) short and long-term conservation-based environmental rehabilitation measures.

How can realistic and long-lasting conservation-based sustainable development programmes be introduced and implemented? National governments in the Nile riparian countries will have to have strong political determination to introduce correct land-use and environmental planning, provide people with basic education, especially ecological economics and environmental awareness. To do these, a joint committee (as a common body) for co-ordination of investigation of the Blue Nile river basin has to be established in the region. As Upreti (1994) argues, environmentally sound and socio-economically responsible planning require scientific knowledge and understanding not only of the biophysical and hydrological environments, but also of the socio-economic, ethical and moral aspects of human environment. The root causes of today's environmental degradation, ecosystem destruction, human misery and social instability result from highly egocentric attitudes and approaches of human beings towards the natural system and lack of understanding of the human institutions.

If such environmental rehabilitation and conservation measures are not introduced and implemented urgently, the upper and lower Nile riparian countries may not be able to alleviate poverty and avoid conflicts and to produce food from their farms in the future. These situations will eventually force people to change the existing agricultural and human settlement sites, increase mass migrations, diseases and deaths. For a healthy environment, increased life supporting system, secured politics and for a sustainable future in the Nile riparian countries long-lasting conservation based sustainable development programs are indispensable.

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Short communication

NEW PLANT RECORDS FOR ETHIOPIA

Tesfaye Awas, Sebsebe Demissew* and Tamrat Bekele

The National Herbarium, Faculty of Science, Addis Ababa University
PO Box 3434, Addis Ababa, Ethiopia

ABSTRACT: Three plant species, *Chazaliella abrupta* (Hiern) Petit & Verdc. (Rubiaceae), *Corchorus capsularies* L. (Tiliaceae) and *Ipomoea shupangensis* Bak. (Convolvulaceae) were recorded from Gambella as new additions to the Ethiopian Flora.

Key words/phrases: **Gambella, *Chazaliella abrupta*, *Corchorus capsularies*, *Ipomoea shupangensis***

INTRODUCTION

In the course of a study to document non-cultivated food plants and wild relatives of cultivated crops from Gambella, southwestern Ethiopia (October 14, 1995 - October 10, 1996), it was noted that among the plants collected three species *Chazaliella abrupta* (Hiern) Petit & Verdc. (Rubiaceae), *Corchorus capsularies* L. (Tiliaceae) and *Ipomoea shupangensis* Bak. (Convolvulaceae) did not match with any specimens collected from Ethiopia and deposited at the National Herbarium. It was also not possible to key out using preliminary accounts of the family Rubiaceae by Puff (in preparation), family Tiliaceae by Vollesen and Sebsebe Demissew (1995), and family Convolvulaceae by Sebsebe Demissew (in preparation). In this report we present results of a detailed study on these species which are now recognized as new additions to the Ethiopian Flora.

MATERIALS AND METHODS

The study was carried out in Gambella People's National Regional State, in southwestern Ethiopia, between latitudes 6°30′ and 8°30′ N and longitudes 33°00′ and 35°45′ E, with an area of 26,000 km^2. The region is bordered by Oromia Regional State to the north, Southern People's Nations and Nationalities Regional State to the east and Republic of the Sudan to the south and west. The northern and the eastern parts of the region have an elevation about 2,000 meters above sea level. The central part is between 500 and 600 m. Toward the western part elevation decreases gradually to an altitude of 300 m.

A reconnaissance survey of the study region was made in October, 1995 to identify vegetation types in undisturbed areas. Everest altimeter was used to measure altitude and 1:50,000 map was used to decide areas for detailed study.

Through five study trips 469 plant specimens were collected, pressed, dried for identification and mounting. Most of the specimens were identified by comparing them with already identified herbarium specimens at National Herbarium (ETH), Ethiopia and few at Royal Botanic Gardens (K), England (abbreviations according to Holmgren *et al.*, 1981), and with the help of written descriptions in the ETH. All specimens were deposited at the ETH and Institute of Biodiversity/Ethiopia.

RESULTS AND DISCUSSION

The detailed botanical descriptions of the three species including information on collectors, localities and habitats are given below.

1. Chazaliella abrupta *(Hiern) Petit & Verdc. (Rubiaceae)*

The plant species, *C. abrupta* was recorded previously from Kenya, Tanzania, Mozambique, Malawi and Zimbabwe (Verdcourt, 1976). We report here that ir also occurs in Gambella, southwestern Ethiopia as well. The taxonomic character states of the specimen also fit into the description given in Verdcourt (1976).

C. abrupta is an understorey shrub up to 3 m high. *Stem* green when young and grey and cork covered when matured. *Leaves* petiolate; petiole up to 3 mm; leaf-blade ovate, 1-2.2 x 2.5-4.5 cm, with characteristic cottony mass in the angle formed by the veins arising from the main vein (mid-rib) on the first half of the lower surface, apex acuminate, base cuneate, margins entire. *Inflorescence* many flowered. *Flowers* tubular, bright yellow, stamens attached to corolla, nectar with pleasant smell (like honey). *Fruits* drupes, dark blue. *Seeds* brown.

Specimens examined: **Ethiopia.** Gambella Region: 18 km on Phugnudo-Gog road (Gog forest), 10–04–1996, Tesfaye Awas and Okeach Odol 305 (ETH). **Kenya.** Kilifi District: Manyani, just S of Malindi Point, 3°36′ N 40°15′ E, 02–04–1981, M.G. Gilbert 6041 (ETH); Kilifi District: 33–36 km. N. of Mombasa, Gongoni Forest, 05–04–1953, Bally 8850 (K). **Tanzania.** Lushoto District: Amani, Mt. Bomole, 21–02–1950, Verdcourt 84 (K); Linidi District: Lake Lutamba, 10–12–1934, Schieben 5717 (K).

Habitat: Semi-deciduous forest dominated by *Baphia abyssinica* Brummitt., *Tapura fischeri* Engl., *Diospyros abyssinica* (Hiern.) F.White., *Milicia excellsa* (Welw.) C.C.Berg, *Malacantha alnifolia* (Bak.) Pierre., *Zanthoxylum lepreurii* Guill. & Perr., *Celtis zenkeri* Engl. and *Trichilia prieuriana* A. Juss. Friis (1992), described this forest as Dry Peripheral Semi-deciduous Guineo-Congolian Forest. The top soil is grey. Sub soil is sandy and with reddish granules. Altitude *ca.* 700 m.

2. Corchorus capsularies *L. (Tiliaceae)*

Vernacular Name: Awachuwaey (Anywaa)

Workers such as Purseglove (1968), Cobley and Steele (1976) had reported that *C. capsularies* occurs wild only in China. It was recorded as a cultivated plant in the Republic of South Africa and Tanzania (Edmonds, 1990). However, it was found to occur wild in Gambella. The taxonomic character states of the specimen fit into the description given by Edmonds (1990).

C. capsularies is an annual herb up to 1 m high. *Leaves* glabrous; petiole 4–14 mm; leaf-blade lanceolate, 0.8–3 x 2.5–12 cm; apex cuminate, margins serrate, with the lower 2-teeth elongate into auricles, 3–8 mm. *Flowers* yellow, leaf opposed, (1-3) at a point. *Capsules* globose, flattened at the top, surrounded by longitudinal ridges. *Seeds* brown to black.

Specimens examined: **Ethiopia**. Gambella Region: 12 km on Abobo-Uballa road, 24-11-1987, Mesfin Tadesse 6729 (ETH); 10 km along the road from Gambella to Bure (Karmi area), 30-11-1995, Tesfaye Awas and Okeach Odol 163 (ETH). **South Africa**. Natal: 30 to 60 miles from the sea, 2000-3000', 1856, Sutherland, s.n. (K). **Tanzania**. 6 km W of Kingupira water hole, 8°30' E, 09-05-1976, K. Vollesen 3609 (K).

Habitat: Riverine vegetation dominated by trees such as *Anogeissus leiocarpa* (A.DC.) Guill. & Perr., *Ficus sycomorus* L., *Celtis toka* (Forssk.) Hepper & Wood and *Tamarindus indica* L.; lianas such as *Combretum capituliflorum* Fenzl ex Schweinf., *Saba florida* (Benth.) Bullock and *Capparis erythrocarpus* Isert. The specimen was collected from dry river-bed growing on sand with *Corchorus aestuans* L., *Senna obtusifolia* (L.) Irwin & Barneby and *Triumfetta rhomboidea* Jacq. Altitude *ca.* 570 m.

3. Ipomoea shupangensis *Bak. (Convolvulaceae)*

Vernacular Name: Ajuwaella (Anywaa)

This species was previously recorded from Kenya, Uganda, Tanzania, Mozambique, Congo Republic, Zimbabwe and Angola (Verdcourt, 1963). The species also occurs in Gambella. The specimen was identified using the key of family Convolvulaceae given by Verdcourt (1963).

I. shupangensis is a prostrate to a twining perennial herb 4-6 m long. *Stem* and *leaves* with milky latex upon cutting. *Leaves* glabrous; petiole 1.5-4.5 cm; leaf-blade ovate, 2-6.4 cm x 2.5-9 cm, apex acute, base cordate, margins entire. *Inflorescence* 3-14 flowered. Corolla campanulate, 6-7 cm, 10-lobed with 5 interpetaline glabrous areas, pale purple with purplish centre, margin more whitish. Stamens 5, hairy at the base, 1 long, 3 short and 1 intermediate and as long as the pistil. Stigma bi-globose. *Fruits* ellipsoid, 3-locular. Milky latex seen upon dissecting young fruits. *Seeds* covered with grey hairs up to 12 mm.

Specimens examined:**Ethiopia**. Gambella Region: 24 km along the road from Gambella to Dembidollo (Solen area), 07-12-1995, Tesfaye Awas, Sebsebe

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Habitat: Open woodland dominated by *Terminalia laxiflora* Engl. & Diels, *Combretum collinum* Fresen., *Pterocarpus lucens* Guill. & Perr., *Grewia mollis* A.Juss., *Bridelia scleroneura* Muell.Arg., *Lannea fruticosa* (Hochst.ex A.Rich.) Engl., *Lonchocarpus laxiflorus* Guill. & Perr., *Crossopteryx febrifuga* (G.Don) Benth. and *Pseudocedrela kotschyi* (Schweinf.) Harms with tall grasses on sandy soil. Altitude *ca*. 750 m.

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Short communication

ESSENTIAL OILS OF FIVE *EUCALYPTUS* SPECIES GROWN IN KENYA

Pauline Muchori[1], Lawrence Mang'uro[1], Ben Chikamai[1], Ermias Dagne[2,*] and Tefera Bekele[2]

[1] Kenya Forestry Research Institute (KEFRI), PO Box 20412, Nairobi, Kenya

[2] Department of Chemistry, Faculty of Science, Addis Ababa University
PO Box 30270, Addis Ababa, Ethiopia

ABSTRACT: The leaf essential oils of five *Eucalyptus* species grown in Kenya have been analyzed using GC and GC-MS. These were: *E. globulus, E. camaldulensis, E. macarthurii, E. globulus ssp maidenii* and *E. citriodora*. The results showed that *E. globulus, E. globulus ssp maidenii* and *E. camaldulensis* were rich in 1,8-cineole (>70%) while the principal components in *E. citriodora* and *E. macarthurii* were citronellal and geranyl acetate, respectively (>80%).

Key words/phrases: ***Eucalyptus globulus, E. globulus ssp maidenii, E. camaldulensis, E. macarthurii, E. citriodora***

INTRODUCTION

The genus *Eucalyptus*, family Myrtaceae, comprises more than 700 species (Formacek and Kubeczka, 1982). In recent years many species of the genus have been introduced and acclimatized in Africa. Because of quantitative and some times even qualitative variations in the composition of the leaf constituents of many members of this genus, it is important to determine the chemical constituents of the introduced species. In this study we have investigated essential oils obtained by steam distillation from leaves of five *Eucalyptus* species that occur widely in Kenya. These are: *E. globulus* Labill., *E.*

camaldulensis Dehn., *E. macarthurii* Deane and Maiden, *E. globulus ssp maidenii* F. Muell and *E. citriodora* Hooker.

The *Eucalyptus* essential oils are generally classified into three types: Cineolic or medicinal essential oils, Perfumery essential oils and Industrial essential oils (Zrira *et al.*, 1992). The most important commercial oil rich in 1,8-cineole is derived from *E. globulus* (Zrira and Benjilali, 1996). This oil is used primarily in pharmaceutical preparations (Bauer *et al.*, 1990). *E. citriodora* and *E. macarthurii* are known to produce perfumery essential oils. The former contains citronellal, an important ingredient in perfumery, while the latter is known for producing the pleasantly aromatic oil due mainly to its high geranyl acetate content. Species such as *E. radiata* are known as sources of industrial essential oils, which are rich in compounds such as α-phellandrene, that is used in the manufacture of sanitary products.

MATERIALS AND METHODS

Sample collection

Plant materials were collected from Muguga Arboretum in Nairobi, Kenya. Voucher specimens are kept at KEFRI Herbarium with voucher numbers Wanjiku P1 (*E. globulus*), Wanjiku P2 (*E. citriodora*), Wanjiku P3 (*E. macarthurii*), Wanjiku P4 (*E. globulus ssp maidenii*) and Wanjiku P5 (*E. camaldulensis*).

Isolation of essential oils

Fresh leaves of the plants were hydro-distilled for 3 h in a Clevenger-type apparatus.

GC and GC-MS analysis

The composition of the essential leaf oils of the five *Eucalyptus* species were analyzed by GC and GC-MS. GC was performed on Varian 3700 chromatography using DB-17 fused silica capillary column (30 m x 0.25 mm i.d.). The oven was programmed at 50–210° C at a rate of 3° C$(min)^{-1}$ using N_2 as carrier gas, and injector temp was 220° C and detector temp (FID) 270° C. GC-MS was performed on Fisons GC model 8000 series chromatography coupled to MD 800 mass selective detector. The column type and the GC parameters were the same as above. The constituents were identified by matching their 70 eV mass spectra with National Institute for Standards and Technology (NIST) and Wiley databases and further confirmed by peak enhancement and GC retention time.

RESULTS AND DISCUSSION

The compounds identified from the five species are listed in Table 1 in order of their elution from a DB-17 capillary column. Total of 22 components were identified from the five species. The essential oils obtained from *E. camaldulensis*, *E. globulus* and *E. globulus ssp maidenii* exhibited high percentage of 1,8-cineole (>70 %). The absence of α- and β-phellandrene in these oils is noteworthy as a result of which these medicinal essential oils meet the European Pharmacopoeia specifications for such oils (Singh, 1994). The perfumery essential oils obtained from *E. citriodora* and *E. macarthurii* were rich in citronellal (>80 %) and geranyl acetate (>80 %), respectively.

Table 1. Constituents of the essential oils of the five *Eucalyptus* species acclimatized in Kenya.

Components*	Absolute area percentage					Confirmation
	E. camaldulensis	*E. globulus*	*E. globulus ssp maidenii*	*E. citriodora*	*E. macarthurii*	
3-hexen-1-ol	-	-	-	-	0.4	
trans-ocimene	-	-	2.8	0.1	-	
α-pinene	0.4	7.2	-	-	-	PE
β-pinene	t	0.2	0.1	0.3	-	PE
β-myrcene	0.1	0.2	0.1	t	-	PE
D-limonene	2.2	2.8	1.0	0.1	-	PE
1,8-cineole	92.5	82.1	90.0	0.4	-	PE
γ-terpinene	-	0.6	-	0.1	-	PE
terpinolene	-	-	-	0.1	-	
isoamyl isovalerate	-	-	0.1	-	-	
linalool	-	0.1	-	-	1.4	PE

Table 1. (Contd.)

Components*	Absolute area percentage					Confirmation
	E. camaldulensis	*E. globulus*	*E. globulus ssp maidenii*	*E. citriodora*	*E. macarthurii*	
isopulegol	-	-	-	3.5	-	
citronellal	-	-	-	85.1	-	PE
terpinen-4-ol	0.6	0.5	-	-	-	
cis-carveol	-	-	-	-	0.1	
α-terpineol	2.0	4.0	3.0	-	t	PE, NMR
citronellol	-	-	-	4.1	-	PE
geraniol	-	-	-	-	5.0	PE
nerol	-	-	-	-	0.1	
α-terpinyl acetate	0.4	0.2	-	0.1	-	PE
citronellyl acetate	-	-	-	4.5	-	PE
trans-caryophyllene	-	-	0.3	0.2	-	
geranyl acetate	-	0.2	-	0.1	86.0	PE
myrtenyl acetate	-	-	-	-	0.2	0.2
alloaromadendrene	-	0.5	-	-	-	-
guaiol	-	-	-	-	1.7	1.7
β-eudesmol	-	-	-	-	2.8	2.8
Percentages of total components identified	98.5	98.80	96.7	99.1	97.0	97.0

*, Components are arranged in order of their elution from a DB-17 capillary column; PE, peak enhancement; NMR, ^{1}H and ^{13}C- NMR; t, trace.

The essential oil contents of the five *Eucalyptus* species reported above are comparable with results of analyses of these species acclimatized in other countries in Africa e.g. Morocco (Zrira *et al.*, 1992), Burundi (Dethier *et al.*, 1994), South Africa (Ndou and Von Wandruszka, 1986) and Madagascar (Lawrence, 1996).

We conclude from this study that the three medicinal essential oils obtained from *E. camaldulensis*, *E. globulus* and *E. globulus ssp maidenii* acclimatized in Kenya exhibit adequate 1,8-cineole content and no α- and β-phellandrenes. This indicates that these oils are suitable commercial sources for production of medicinal *Eucalyptus* oils. *E. macarnnurii* and *E. citriodora* with their relatively high geranyl acetate and citronellal content, respectively, should be suitable for the production of perfumery essential oils.

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