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Short communication

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The variability of morphometric and meristic characteristics of Urmia chub, *Petroleuciscus ulanus* (Günther, 1899) in the Mahabd-Chai and Godar-Chai rivers, Lake Urmia basin

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ABSTRACT. In this study, for the first time, we provide morphometric and meristic data on *Petroleuciscus ulanus* from the Lake Urmia basin by comparing them in the populations of the Mahabad-Chai and Godar-Chai rivers. For this purpose, a total of 100 specimens were collected using electrofishing device and cast net during 2014 and 2015. 19 morphometric and 8 meristic traits were measured and counted, respectively. The meristic traits of the two populations showed significant differences in three characters, including branched dorsal and ventral fin rays and lateral line scales ($P < 0.05$). In addition, the morphometric analysis showed significant differences in head length, eye diameter, caudal peduncle length, dorsal fin height and base lengths, pectoral and ventral fin lengths, anal fin base and height lengths ($P < 0.05$). The finding of the current study can help to further studies on the biological features of this endemic species of Iranian inland waters.

Keywords: *Petroleuciscus ulanus*, morphological characteristics, Urmia chub, meristic traits

Introduction

Urmia chub, *Petroleuciscus ulanus* (Günther, 1899) (Cyprinidae) is the sole member of this genus in Iranian inland waters (Bogutskaya, 1996; 2002; Coad and Bogutskaya, 2010; Perea et al., 2010; Esmaeili et al., 2018). This species is recognized by having brown-green dorsum and light silver abdomen, a narrow dark stripe from the eye to end of the lateral line, the heavily pigmented upper part of the operculum, pelvic axillary scale, and gill rakers reaching first or second raker below when appressed. Furthermore, its pharyngeal teeth hooked at tip and strongly serrated, mouth oblique and extends back to behind front margin of eye, lower jaw not or slightly protrudable, upper jaw slightly overlapping lower jaw, gut elongated and S-shape with an anterior loop, and male with tubercles on the pectoral fins and head. It inhabits streams or rivers with a spawning season from April to July. The maximum recorded age and total length are 4 years and 158 mm, respectively. Sex ratio is 1male: 2females, maturity usually attained at two and rarely one year, and absolute fecundity is up to 16,100 eggs. Food mainly includes zooplankton, insects, phytoplankton, filamentous algae, and benthic organisms. The distribution of this monolithic species is the Lake Urmia basin and endemic to the Godar-Chai and Mahabad-Chai rivers (Keivany et al., 2016).

Morphological characteristics such as meristic, morphometric data and the otoliths shape are widely used to identify species and fish populations (Ihssen et al., 1981; Cadrin, 2000). These characteristics are also used to delimit populations, revealing species diversity and classification of fishes (Hossain et al., 2009). Conservation of endemic species is of particular importance and have a priority in their management due to their limited distribution area (Alcma, 1984). *Petroleuciscus ulanus* is endemic to the Lake Urmia basin, and few studies on its biological features have been conducted (Keivany et al., 2016); therefore, it is crucial to study its various biological aspects, including morphological traits. Hence, this work aimed to provide basic morphological data on *P. ulanus* by comparing its morphometric and meristic traits in the two populations of the Godar-Chai and Mahabad-Chai rivers.

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Materials and methods

The sampling was carried out from the Mahabad-Chai (3652´N, 45°45´E, 66 specimens) and Godar-Chai (37° 00´ N, 49° 56´E, 34 specimens) rivers, the Lake Urmia basin, west of Iran during 2014 to 2015 (Table 1). Fishes were caught with an electrofishing device and a cast net. After anesthesia, they were fixed into 10% buffered formalin and transferred to the Lab where a total of 19 morphometric and 8 meristic traits (Table 2, Table 3) were measured and counted.

In the PAST software, in order to remove size data from measurements, the allometric method was used as follows: $M_{adj} = M (L_s / L_0)^b$, where M is the original measurement, M_{adj} – the size adjusted measurement, L_0 – the standard length of the fish, L_s – the overall mean of the standard length for all fish from all samples in each analysis, and b was estimated for each character from the observed data as the slope of the regression of log M on log L_0 using all fish in any group (Elliott et al., 1995). The results derived from the allometric method were confirmed by testing the significance of the correlation between transformed variables and standard length (Turan, 1999). Then, data were analyzed for normality distribution using the Kolmogorov-Smirnov test. Parametric and non-parametric morphometric and meristic characters were analyzed using T-test (Independent Samples T-test) and Mann-Whitney, respectively, in SPSS-19 software. After that, data with significant differences were analyzed using principal component analysis (PCA), discriminant function analysis (DFA), and T-test Hoteling using Hoteling's P-value in PAST V2.17b software (Hammer et al., 2001).

Results

Morphometric traits: Kolmogorov-Smirnov test showed snout length, minimum body depth, caudal peduncle length, pectoral-ventral distance, ventral-anal distance, and anal fin height; pre- and post-dorsal fin lengths were parametric ($P > 0.05$). The results of the T-test and Mann-Whitney tests showed significant differences in the head length, eye diameter, caudal peduncle length, dorsal fin base and height lengths, pectoral and ventral fin lengths, anal fin base and height lengths ($P < 0.05$) (Table 2). In the first two PCs, the pectoral fin length was the most effective characteristic to delimit the populations. In addition, DFA/Hotelling's T-test revealed a significant difference between the two populations ($P = 1.19E^{-06}$, $F = 6.10$, Hotelling's $t^2 = 59.87$) (Fig. 1). The PCA results plot is presented in Figure 2, showing the overlap between the populations.

Meristic traits: Meristic traits showed significant differences in three characters, including the branched dorsal fin rays, branched ventral fin rays and the number of the lateral line scales ($P < 0.05$) (Table 3). Unbranched and branched dorsal fin rays were 2-3 and 7-9, respectively. Unbranched and branched anal fin rays counted 3 and 8-11, respectively. In addition, the branched ventral fin rays were 7-8, and the count of the lateral line was 36-44. Outer and inner gill rakers were counted as 12-21 and 15-22, respectively, in both populations.

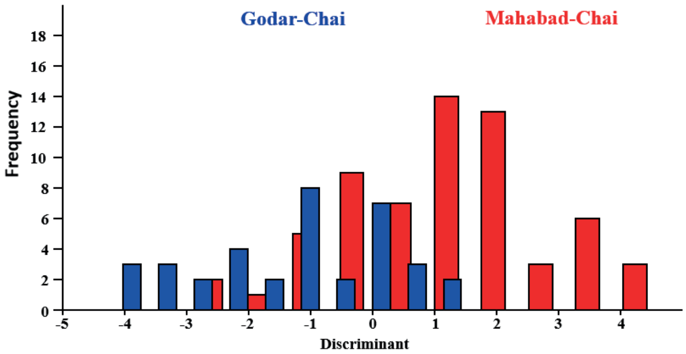

Fig.1. Discriminant function analysis (DFA) of morphometric traits of the *P. ulanus* populations.

Table 1. Different water quality parameters of sampling site of *P. ulanus* (Maleki et al., 1999; Khodaparast et al., 2002)

Parameters	Mahabad-Chai	Godar-Chai
pH	7.83	7.95
Temperature, °C	12.75	15.23
O_2, mg/dm^3	8.95	13.98
EC, µs/cm	0.4	0.49
Salinity, ppt	0.14	0.28
Water hardness, mg/dm^3	150.42	237.8
COD, mgO_2/dm^3	19.26	14.23
Depth, m	0.5-2.5	0.8-1
Width, m	5-15	8-15
Water current	Slow to moderate	Slow to moderate
Floor	Stone	Stone

Note: COD – chemical oxygen demand, mgO_2/dm^3.

Discussion

Morphological studies of fishes can illustrate the effect of environmental factors during their adaptation to their habitat (Zelditch, 2004). The results of the current study showed significant differences between the studied populations of *P. ulanus* in nine morphometric and three meristic characteristics. The major difference was ventral fin length, which can be used to identify these two populations. The observed differences are probably due to the hydrologic features of their habitats e.g., velocity and current patterns that facilities their swimming performance in their specific habitat (Bagarinao, 1981; Swain et al., 2005; Haas et al., 2010; Mahfuj et al., 2019; Styga et al., 2019). According to Kuliev (1997), it is expected to observe differences in meristic traits in fishes in different latitudes; however, due to the almost similar latitude of both populations, little differences in the meristic data were observed. In addition, the meristic characters of fish populations, including fin rays, gill rakers, scales (below, upper or on lateral line), and pharyngeal teeth, are controlled by genetic factors; however, lengths and their ratios in morphometric traits are affected by environmental factors (Brraich and Akhter, 2015; Mouludi-Saleh et al., 2018). Some works have been carried out about the morphometric and meristic traits of other members of the genus *Petroleuciscus* in Turkey (Turan et al., 2018) but no data is available regarding morphological features of *P. ulanus*, which we provided in the current study. In *P. ulanus*, the scales number on the lateral line is 36-44, whereas it is different from those of *P. ninae* (31-36), *P. smyrnaeus* (33-37), *P. kurui* (51-55), *P. borysthenicus* (36-41), and *P. squaliusculus* (40-47) (Turan et al., 2018). Keivany et al. (2016) reported that *P. ulanus* has 2-3 and 7-9 (vs. 2-3 and 7-9 in our study) branched and unbranched dorsal fin rays, 3 and 7-11 (vs. 3 and 8-11 in the current study) branched and unbranched anal fin rays, 7-8 branched (vs. 7-8) ventral fin rays, and 36-45 (vs. 36-44) lateral line scales, respectively, showing that previous reported meristic data are overlapped with the current work.

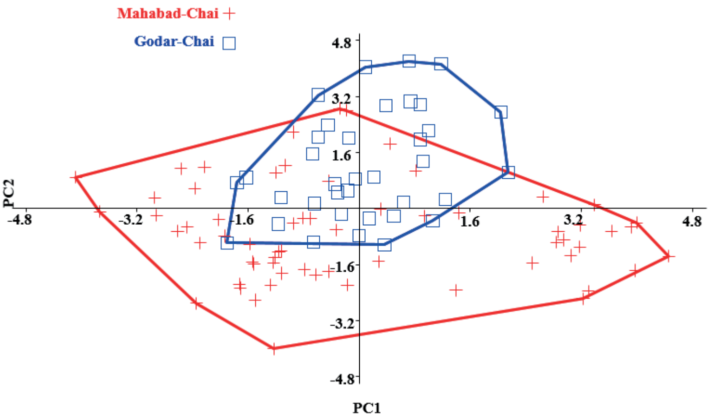

Fig.2. Principal component analysis (PCA) of morphometric traits of the *P. ulanus* populations

Table 2. T-test and Mann-Whitney tests and the mean (± standard deviation) of each morphological trait measured in *P. ulanus* from the Mahabad-Chai and Godar-Chai rivers.

Characters	Mahabad-Chai		Godar-Chai		
	Mean	±SD	Mean	±SD	*p*
Standard length, mm	64.93	0.00	64.93	0.00	-
Head length, mm	16.67	0.91	16 .32	0.58	**0.017**
Head height, mm	11.32	1.31	11.81	0.6	0.397
Snout length, mm	4.1	0.32	4.06	0.4	0.575
Eye diameter, mm	4.19	0.28	4.04	0.27	**0.016**
Inter-orbital width, mm	5.97	1.83	4.86	0.33	0.064
Maximum body depth, mm	17.04	0.82	16.74	1.19	0.151
Minimum body depth, mm	7.11	0.4	7.18	0.36	0.415
Caudal peduncle length, mm	13.19	2.13	14.05	0.92	**0.024**
Dorsal fin base length, mm	8.07	0.5	8.45	0.83	**0.019**
Dorsal fin height, mm	11.94	0.92	12.93	0.67	**0.00**
Pectoral fin length, mm	12.63	1.11	13.61	0.99	**0.00**
Ventral fin length, mm	9.56	0.8	10.04	0.71	**0.006**
Pecto-ventral distance, mm	15.7	0.95	15.87	0.97	0.39
Ventral-anal distance, mm	12.44	0.77	12.35	0.74	0.583
Anal fin height, mm	9.01	0.66	9.43	0.75	**0.006**
Anal fin base length, mm	8.16	0.6	8.72	1.09	**0.007**
Pre-dorsal distance, mm	35.77	1.11	35.49	0.87	0.20
Post-dorsal distance, mm	22.65	0.98	22.83	1.08	0.40

Table 3. Mann-Whitney test, the mean (± standard deviation) and Min-Max of each meristic character counted in *P. ulanus* from Mahabad-Chai and Godar-Chai populations.

Characters	Mahabad-Chai (mean+ SD)	Min-Max	Godar-Chai (mean+ SD)	Min-Max	*P*
Unbranched dorsal fin rays	2.98±0.125	2-3	3±0.00	-	0.453
Branched dorsal fin rays	8.12±0.33	7-9	7.77±0.42	7-8	**0.000**
Unbranched anal fin rays	3±0.00	-	3±0.00	-	1.000
Branched anal fin rays	9.06±0.61	8-10.5	9.02±0.67	8-11	0.409
Branched ventral fin rays	7.1±0.31	7-8	7.38±0.49	7-8	**0.001**
Lateral line scales	38.62±1.62	36-43	39.47±1.64	36-44	**0.018**
Outer gill rakers	14.32±1.65	12-21	14.11±1.23	12-17	0.885
Inner gill rakers	18.43±1.21	15-21	18.38±1.64	15-22	0.728

In recent years, *Alburnus hohenackeri* has been introduced to the habitats of *P. ulanus*; in their habitats, *P. ulanus* is distinguished by the number of the branched anal fins (7-11 in *P. ulanus* vs. 11-16 in *A. hohenackeri*) and the number of the gill rakers on the first gill arch (12-16 (mod = 14) in *P. ulanus* vs. 19-25 in *A. hohenackeri*) (Keivany et al., 2016).

Conclusions

As a general result, this study provides valid data on morphometric and meristic traits of endemic fish species to Iranian inland waters that can be useful to future studies.

Conflict of interests

The authors declare no conflict of interests.

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Original Article

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Spatial and seasonal variations in the physicochemical parameters of water quality of a tropical reservoir, Nigeria

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ABSTRACT. In this study, the physicochemical properties of a water supply reservoir in the Esa-Odo community, Obokun Local Government Area of Osun State, Nigeria, were determined. Thirteen selected sampling stations over the three reaches of Esa-Odo reservoir along its main axis were monitored between February 2017 to December 2018 with a view to determining the seasonal and spatial variations in the general physicochemical water quality parameters of the reservoir water. From each sampling station, surface water samples were collected bi-monthly for two annual cycles (rainy and dry seasons). The collected water samples were treated and analyzed for physicochemical water quality parameters using standard instrumental and non-instrumental methods. The data obtained were analyzed using appropriate descriptive and inferential statistics. The result of the analyses of the reservoir water showed an increasing clarity from the upstream to the downstream stations with regard to water temperature, depth, transparency, turbidity, and colour. The water was generally near neutral (pH: 7.01 ± 0.04 - 7.07 ± 0.50) but slightly more near neutral in the rainy season than during the dry season. The water in the reservoir can be classified as a dilute salt bicarbonate freshwater with mean conductivity at the three reaches ranging from 113.39 ± 1.67 μScm^{-1} to 115.24 ± 2.46 μScm^{-1}. Ca^{2+} and HCO_3^- were the dominant cation and anion, respectively, at all stations investigated irrespective of seasons of sampling. The mean values of most parameters determined were within permissible limits, making the river water suitable for most probable domestic and industrial uses and livestock support.

Keywords: reservoir, water quality, physico-chemical parameters, spatial variation, seasonal variations

1. Introduction

Water quality assessment is of immense importance to the management of fisheries, pollution control, irrigation and sewage reservoir and impoundment (Adakole et al., 2008). The Osun River is one of the two major rivers in the Ogun-Osun River Basin of Nigeria. Its headwaters and those of its primary tributaries (River Ayinba, R. Erinle, R. Oba, and R. Otin) rise from the central highlands in Southwestern Nigeria and drains most of the composite states (Oyo, Osun, Ekiti, and Ogun States) before emptying down its main course about 270 km into the Lekki Lagoon. (Ayodele and Adeniyi, 2006). The Osun River Basin, especially in the upper basin, is remarkable for its many impoundments and fish farming (Elliot, 1979). Most of the impoundments within the basin were created primarily for the provision of public water supply with fisheries development as a major ancillary benefit. To fully derive the benefits of impoundments and/or fish ponds and to ensure their good management and rational exploitation, adequate scientific information is required especially information on the physicochemical water quality.

Biological processes and some anthropogenic activities have been reported by Omoniyi et al. (2017) to influence river water and impoundments both in quantity and in quality, with physical and chemical quality parameters being mostly impacted by human activities. Bagenal and Braum (1978) reported that the physical and chemical properties of water bodies impact the species composition, abundance, productivity and physiological condition of aquatic organisms. Determination of physical and chemical properties of water in an aquatic ecosystem is, therefore, an important tool for the characterization of the system, assessing the recharge capacity and the sustainable use of its living resources (Carvalho et al., 2010).

Ayodele and Adeniyi (2006) reported Esa-Odo Reservoir to be one of six major impoundments on the

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Osun River, which showed a high degree of similarity both in zooplankton fauna composition and in water quality. Despite the age of Esa-Odo Reservoir, there is a dearth of in-depth information on its physicochemical water quality. This study, therefore, seeks to provide information on the spatial and seasonal variations in the physicochemical water quality of the reservoir.

2. Materials and methods

2.1. Study area

Esa-Odo Reservoir, an impoundment on the Osun River located in Esa-Odo community, Obokun Local Government Area, Osun State, is one of the typical reservoirs, which was created in 1973 (Fig. 1). The reservoir was impounded primarily for water supply, flood control and fisheries. The climate of the Esa-Odo town where the reservoir is located is a tropical continental climate of Koppen Af type humid tropical rainforest climate (Ifabiyi, 2005; Adediji and Ajibade, 2008). The rainy season over the basin is basically characterized by two maximum rainfalls with peaks in July and September/October separated by a short dry spell in August. The dry season is shorter according to Adediji and Ajibade (2008) and usually lasts for about five months (November to March).

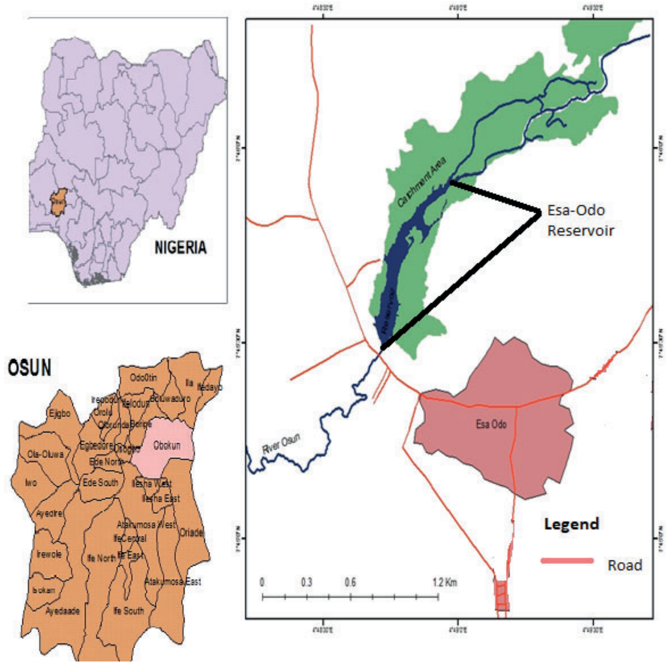

Fig.1. Map showing Nigeria, Osun state and the location of the study area in relation to the adjoining local government areas.

2.2. Sampling stations

The sampling area consists of thirteen sampling stations that were established across the entire water supply reservoir whereby the reservoir was divided along two habitat types, comprising three sections along its major axis (upstream, mid-basin and downstream) as well as along two zones (littoral and open water) across its width for the purpose of selecting sampling stations for the study. Information on the grid coordinates and elevation of each of the sampling stations obtained using Global Positioning System (GPS) is presented in Table 1. The sampled points on Esa-Odo Reservoir are shown in Figure 2.

2.3. Sample collection

Field surveys were conducted at every two-month intervals for a period of two annual cycles from February 2017 to December 2018, covering both the dry and rainy seasons. At each of the sampling stations, water samples were collected into clean, properly rinsed 5-litre capacity plastic bottle containers. The storage and treatment of samples were done according to APHA et al. (1995). Hand held portable (Jenway 4071) conductivity meter was used to measure water pH and electrical conductivity. Water transparency was measured using a Secchi disc. Collected samples were analyzed for colour, turbidity, sulphate and nitrate using

Table 1. The geographical location of water sampling stations in Esa-Odo study area.

S/N	Reference code	Site description	Grid coordinate		Elevation (m)
1	Inflow	River water inflow to the reservoir	N07’45’986”	E004’49’275”	349 ± 2
2	1S	Surface sample of the first sampling station on the reservoir	N07’45’919”	E004’49’021”	349 ± 2
3	1B	Bottom sample of the first sampling station on the reservoir	N07’45’919”	E004’49’021”	349 ± 2
4	2S	Surface sample of the second sampling station on the reservoir	N07’45’670”	E004’48’730”	350 ± 2
5	2M	Mid-point sample of the second sampling station on the reservoir	N07’45’670”	E004’48’730”	350 ± 2
6	2B	Bottom sample of the second sampling station on the reservoir	N07’45’670”	E004’48’730”	350 ± 2
7	2L1	First littoral station of the second sampling station on the reservoir	N07’45’656”	E004’48’748”	351 ± 2
8	2L2	Second littoral station of the second sampling station on the reservoir	N07’45’663”	E004’48’710”	352 ± 2
9	3S	Surface sample of the third sampling station on the reservoir	N07’45’534”	E004’48’702”	353 ± 2
10	3M	Mid-point sample of the third sampling station on the reservoir	N07’45’534”	E004’48’702”	353 ± 2
11	3B	Bottom sample of the third sampling station on the reservoir	N07’45’534”	E004’48’702”	353 ± 2
12	3L1	First littoral station of the third sampling station on the reservoir	N07’45’511”	E004’48’739”	350 ± 2
13	3L2	Second littoral station of the third sampling station on the reservoir	N07’45’540”	E004’48’674”	351 ± 2

applicable standard colorimeter methods (Golterman et al., 1978; APHA et al., 1995). The concentrations of chloride ion, organic matter, alkalinity, acidity, calcium ion, and magnesium ion were determined using applicable standard volumetric analyses described by Golterman et al. (1978).

Samples for Dissolved Oxygen (DO) and five-day Biochemical Oxygen Demand (BOD_5) were collected into oxygen bottles and were fixed *in situ* with Winkler's reagents as described by Golterman et al. (1978). BOD_5 samples were collected in black reagent bottles and incubated in a dark cupboard at room temperature (28 ± 30°C) for five days, after which they were treated for dissolved oxygen determinations. The values of DO and BOD (after five days of incubation in the dark) were determined in the laboratory using the standard method described by Golterman et al. (1978). Sodium and potassium ions were determined using flame emission spectrophotometer (Flame Analyzer), FP640 model. The error of ionic balance in the analysis of the major ions was estimated based on the agreement between the sum of major anions (HCO_3^-, $SO4^{2-}$ and Cl^-) and the sum of the major cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+), expressed in % milliequivalent per liter. The data obtained were subjected to appropriate descriptive statistics, ANOVA and cluster analysis.

3. Results and discussion

3.1. Spatial and seasonal variations in reservoir water physical characteristics

None of the means of physicochemical parameters of water quality analyzed in the three zones of the reservoir (up, mid and down streams) showed statistically significant variation ($p > 0.05$). However, the water temperature mean value was the highest in the mid-stream portion of the reservoir followed by the mean temperature of water in the downstream section (Table 2). The lowest water temperature recorded in the upstream region could be attributed to the presence of trees with dovetailing branches at the portion of the reservoir, which probably obstructed direct penetration of incident solar radiation, causing the water in the zone to be cooler than in the other part of the reservoir.

The mean water depth was highest in the upstream section followed by the downstream section; the mean depth in the mid-stream portion of the reservoir was the smallest. The variation in the mean depth at various sections of the reservoir could be topographical in nature attributable to various events at the bottom of the reservoir. Also, turbidity mean value was found to increase from the upstream to mid-stream region of the reservoir with the lowest value recorded in the downstream portion of the reservoir. The higher turbidity value recorded in the mid-stream zone of the reservoir was probably attributable to the high retention of small particles of authochthonous and allochthonous materials as a result of less mixing of water. This portion of the reservoir was also noticed to be the region with the highest fishing activities during the period of study.

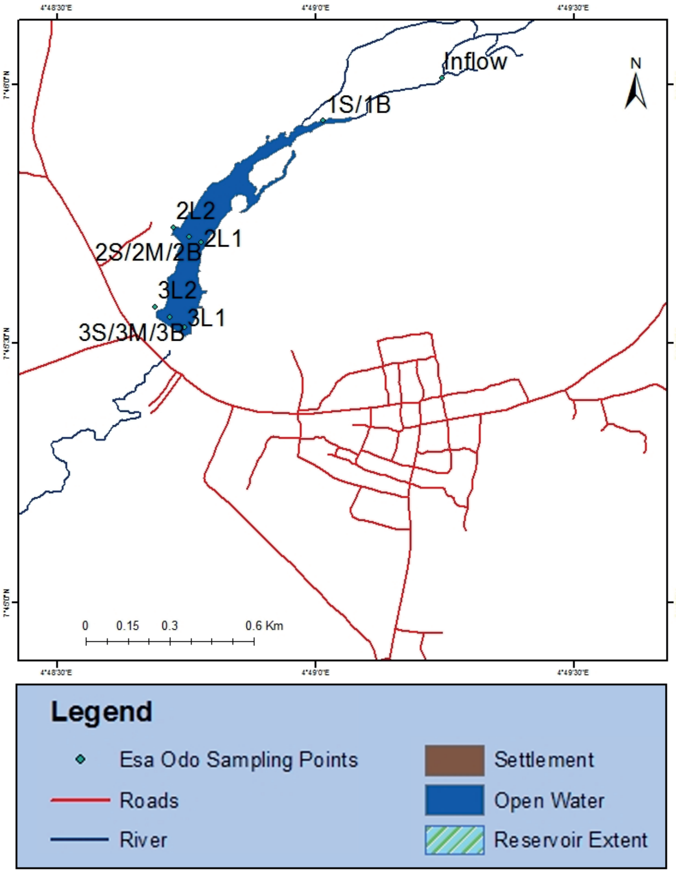

Fig.2. Map showing all the sampling points on Esa-Odo Reservoir during the period of study.

Mean apparent colour values were observed to increase from downstream to the upstream region of the lake, while the mean true colour value was the highest in the mid-stream section of the reservoir followed by the downstream section. Seasonal variations in the levels of the investigated physical parameters of the water quality of Esa Odo Reservoir are shown in Table 3. On the other hand, water temperature mean value was significantly higher ($P < 0.05$) in the rainy season than in the dry season, as presented in Table 3, and this may have resulted due to the fact that because of the distance and logistics, most of the sampling period of this study was done in the afternoon when the sun must have set, which may have probably slightly increased the water temperature. Also, the cumulative effect of higher occurrence of rainy season values (26.32 ± 0.19 mgL^{-1}) than the dry season values (25.50 ± 0.24 mgL^{-1}) may have contributed to the slightly higher mean value of water temperature in the rainy season. Other physical parameters; transparency, depth, turbidity, true colour ($P > 0.05$), and apparent colour ($P < 0.05$), have higher mean values in the rainy season than in the dry season (Table 3). Similar observations on the turbidity and colour of some other tropical water bodies were made by Omoniyi et al. (2017), Adebisi (1981), Ikomi et al. (2003) and Idowu et al. (2013) which was attributed to the influx of inorganic and organic materials from over land run-off during the rainy season than that of the dry season. However, contrast to their observations was the fact that the mean water clarity (transparency) was slightly higher in the rainy season than in the dry season, this could be as a result of the Statistical influence of

Table 2. Spatial variation in the investigated physicochemical parameters of water quality of Esa-Odo Reservoir during the period of study.

Parameter	Up stream (n = 36)			Mid-stream (n = 58)			Down stream (n = 60)			ANOVA	
	Min	Max	Mean ± S.E	Min	Max	Mean ± S.E	Min	Max	Mean ± S.E	F	P
Water temperature (^{o}C)	23.00	29.00	25.83 ± 0.25	20.00	33.00	26.19 ± 0.26	22.80	33.40	26.04 ± 0.26	0.397	0.673
Depth (m)	0.00	4.70	2.08 ± 0.28	0.00	4.55	1.97 ± 0.16	0.00	4.70	2.06 ± 0.14	0.096	0.909
Transparency (m)	0.00	2.10	0.88 ± 0.11	0.00	1.65	0.73 ± 0.08	0.00	2.00	0.76 ± 0.08	0.691	0.502
Turbidity (NTU)	3.63	113.72	62.34 ± 4.54	0.37	136.92	63.76 ± 3.87	3.63	144.11	59.58 ± 3.60	0.329	0.720
Apparent colour (Pt.Co)	66.00	95.00	78.58 ± 1.28	66.60	97.50	81.19 ± 1.07	66.60	97.50	82.17 ± 1.04	2.301	0.104
True colour (Pt.Co)	43.97	95.00	72.93 ± 1.48	43.97	95.00	74 45 ± 1.06	43.97	94.00	73.83 ± 1.17	0.347	0.708
Total Dissolved Solids (mgL^{-1})	65.40	331.00	90.18 ± 7.61	63.50	153.00	81.75 ± 2.06	61.70	174.00	81.54 ± 2.29	1.437	0.241
pH	6.45	7.60	7.07 ± 0.50	6.40	7.55	7.07 ± 0.04	6.20	7.60	7.01 ± 0.04	0.821	0.442
Conductivity (μScm^{-1})	80.00	133.80	115.24± 2.46	82.00	135.70	113.39± 1.67	90.00	132.80	114.56±1.45	0.261	0.771
Alkalinity (mgCaCO$_3$L^{-1})	14.00	76.00	48.72 ± 2.53	16.00	83.00	51.19 ± 1.80	0.00	103.00	53.35 ± 2.53	1.086	0.340
Total Hardness (mgCaCO$_3$L^{-1})	17.16	73.56	43.70 ± 2.09	15.12	89.88	47.00 ± 2.47	17.16	88.74	46.24 ± 1.87	0.812	0.446
Acidity (mgCaCO$_3$L^{-1})	8.00	32.00	16.55 ± 0.93	6.00	32.00	18.86 ± 0.71	0.00	38.00	19.37 ± 0.49	2.597	0.078
Bicarbonate (mgL^{-1})	5.81	142.45	56.21 ± 5.90	3.05	142.45	58.05 ± 4.34	3.05	130.21	57.68 ± 3.94	0.038	0.963
Dissolved Oxygen (mgL^{-1})	1.60	14.00	7.28 ± 0.34	0.00	9.35	6.34 ± 0.29	1.80	11.60	6.89 ± 0.24	2.542	0.082
Biological Oxygen Demand (mgL^{-1})	0.40	11.20	4.15 ± 0.35	0.80	6.80	3.51 ± 0.23	0.40	13.60	3.89 ± 0.26	1.317	0.271
Calcium (mgL^{-1})	4.84	20.19	11.83 ± 0.62	2.54	26.00	12.72 ± 0.78	2.54	22.00	12.67 ± 0.50	0.467	0.627
Magnesium (mgL^{-1})	0.79	7.43	3.54 ± 0.28	0.09	8.31	3.95 ± 0.26	0.27	13.54	3.55 ± 0.28	0.728	0.484
Sodium (mgL^{-1})	5.43	7.92	6.71 ± 0.12	2.23	8.21	6.53 ± 0.13	3.53	9.28	6.57 ± 0.13	0.403	0.669
Potassium (mgL^{-1})	3.70	7.88	5.76 ± 0.19	3.07	11.15	5.62 ± 0.17	2.12	7.82	5.57 ± 0.15	0.268	0.765
Sulphate (mgL^{-1})	0.56	22.11	5.11 ± 0.81	0.07	23.85	5.92 ± 0.83	0.28	24.20	5.16 ± 0.74	0.330	0.719
Chloride (mgL^{-1})	3.25	13.81	7.34 ± 0.49	2.54	15.90	7.67 ± 0.46	2.89	13.15	7.02 ± 0.34	0.668	0.514

Table 3. Seasonal variation in the investigated physicochemical parameters of water quality of Esa-Odo Reservoir during the period of study.

Parameter	Dry season (n = 51)			Rainy season (n = 103)			ANOVA	
	Min	Max	Mean ± SE	Min	Max	Mean ± SE	F	P
Water temperature (^{o}C)	20.00	29.00	25.50 ± 0.24	23.00	33.40	26.32 ± 0.19	6.610	0.011*
Transparency (m)	0.00	1.30	0.69 ± 0.59	0.00	2.10	0.81 ± 0.07	1.426	0.234
Depth (m)	0.00	3.50	1.38 ± 0.14	0.00	4.70	1.88 ± 0.16	1.051	0.307
Turbidity (NTU)	6.90	82.36	56.40 ± 2.83	0.37	144.11	64.48 ± 3.07	2.828	0.095
Apparent colour (Pt.Co)	43.97	82.20	80.01 ± 0.77	55.40	95.00	81.43 ± 0.89	9.591	0.002*
True colour (Pt.Co)	70.90	99.00	70.89 ± 1.36	60.30	97.50	75.32 ± 0.75	1.059	0.305
pH	6.40	7.50	6.99 ± 0.05	6.20	7.60	7.04 ± 0.03	2.219	0.138
Conductivity (µScm^{-1})	80.00	131.50	111.98 ± 1.74	82.00	135.70	115.42 ± 1.24	2.561	0.112
Alkalinity (mgCaCO$_3$L^{-1})	24.00	103.00	57.94 ± 2.31	0.00	76.00	48.24 ± 1.30	15.611	0.000*
Total Hardness (mgCaCO$_3$L^{-1})	34.00	89.88	57.92 ± 1.85	15.12	88.74	40.56 ± 1.36	55.384	0.000*
Acidity (mgCaCO$_3$L^{-1})	10.00	36.00	19.90 ± 0.83	0.00	38.00	17.84 ± 0.60	3.972	0.048
Bicarbonate (mgL^{-1})	28.80	123.60	69.44 ± 2.76	3.05	142.45	51.55 ± 3.53	11.062	0.001*
Dissolved Oxygen (mgL^{-1})	2.00	14.00	7.01 ± 0.28	0.00	10.80	6.65 ± 0.20	1.069	0.303
Biological Oxygen Demand (mgL^{-1})	1.20	11.20	4.16 ± 0.27	0.40	13.60	3.64 ± 0.19	2.448	0.120
Calcium (mgL^{-1})	7.91	26.00	15.62 ± 0.62	2.54	21.23	10.95 ± 0.40	42.977	0.000*
Magnesium (mgL^{-1})	1.67	8.27	4.67 ± 0.20	0.09	13.54	3.22 ± 0.20	20.230	0.000*
Sodium (mgL^{-1})	3.53	7.33	6.06 ± 0.10	2.23	9.28	6.85 ± 0.09	28.685	0.000*
Potassium (mgL^{-1})	2.12	7.23	5.50 ± 0.17	3.58	11.15	5.70 ± 0.12	0.992	0.321
Sulphate (mgL^{-1})	0.07	12.46	2.94 ± 0.40	0.39	24.20	6.68 ± 0.63	15.849	0.000*
Chloride (mgL^{-1})	2.89	13.81	7.53 ± 0.42	2.54	15.90	7.24 ± 0.30	0.302	0.583
Nitrate (mgL^{-1})	1.32	6.63	4.42 ± 0.24	0.04	8.18	4.57 ± 0.19	0.212	0.646

Note. * - $P < 0.05$

the sample sizes obtained in both seasons (dry season: n = 51; rainy season: n = 103). In addition to that, many studies have reported that wind-driven sediment resuspension, which is a generally phenomenon in shallow reservoirs, usually have negative impacts on water clarity (transparency); a condition more prevalent in the reservoir during the dry season (i.e., shallower) than rainy season. Also, it could be probably due to the availability of favorable temperature conditions from increased solar inputs during the dry season period which could favour the growth of phytoplankton in the reservoir and eventually lowers the water clarity (transparency) in the dry season (Somasundaram et al., 2021).

3.2. Spatial and seasonal variations of chemical characteristics of the water in reservoir

The mean hydrogen ion potential (pH) values at the stations showed that the reservoir was generally slightly alkaline with mean pH values in the three portions of the reservoir, ranging between 7.01 and 7.07 over the two annual cycles studied. (Table 2). The overall range (6.2 – 7.6) falls within the WHO permissible limits of 6.5 to 8.5 (WHO, 2017) for drinking water and also for most aquatic life (6.5 to 8.5) (USEPA, 1994). During daylight, algae and underwater plants remove carbon dioxide from the water as part of the sunlight-driven process of photosynthesis. The relative rates of respiration and photosynthesis within the pond determine whether there is a net addition or removal of carbon dioxide, and, therefore, whether pH falls or rises (Craig and Louis, 2008). Acidification of water recorded during the dry season could be attributed to increased metabolism, elevated microbial degradation of organic debris and concentrated dissolved solids in warmer water during this period (Rajasegar, 2003; Tukura et al., 2012; Omoniyi et al., 2017).

Conductivity is a measure of the ability of water to conduct electric current, and it is sensitive to variations in the concentration of dissolved solids, mostly mineral salts. The degree of dissociation of these solids into ions, the valency of each ion, ion mobility, and water temperature all have an influence on conductivity (Omoniyi et al., 2017). The conductivity mean value of water in Esa-Odo Reservoir during this study was the highest in the upstream region followed by the downstream and lowest in the midstream portion of the reservoir. The result also showed that the conductivity mean value of water in the reservoir was higher during the rainy season than in the dry season ($P > 0.05$). The conductivity result of this study slightly differs from what was recorded by (Omoniyi et al., 2017) for natural points of the Osun River where conductivity decreases down the three reaches of the river in the dry season. However, palm oil processing effluents very close to the upstream portion of the reservoir by the riparian farmers during the rainy season and anthropogenic activities around the downstream portion of the reservoir probably contributed to the elevated conductivity values recorded during the period of study. However, the range of conductivity values recorded (80 – 135 μScm^{-1}) for the entire reservoir didn't exceed the USEPA (1994) permitted limit (20 to 2000 μScm^{-1}) for freshwaters.

The range of the mean values of total hardness (43.70 ± 2.09 to 47.00 ± 2.47 $mgCaCO_3L^{-1}$) recorded in the three portions of Esa-Odo Reservoir showed that the water was generally soft with the hardness increasing down the course of the reservoir, having the highest value at the mid-stream portion (Table 2). The water mean total hardness during the dry season was significantly higher ($P < 0.0001$) than during the rainy season (Table 3). Both seasonal and spatial variations in the values of other salinity parameters (acidity and alkalinity) followed the same trend as they increased down the course of flow of the reservoir in the dry season (Table 3) with a mean range of alkalinity value in the three portions of the reservoir from 48.72 ± 2.53 to 53.35 ± 2.53 mgL^{-1}, and this corresponds to the work carried out by Omoniyi et al. (2017).

The Dissolved Oxygen (DO) concentration along Esa-Odo Reservoir zones was the highest in the upstream portion followed by the downstream portion and the lowest at the mid-stream portion (Table 2). Water movement at the upstream and downstream locations on the reservoir, which was noticed to be higher, as well as a higher density of trees plantation cover, might have contributed to the higher DO mean concentration recorded at these sections of the reservoir. Dry season mean value of DO higher than rainy season mean value (Table 3) could be attributed to the longer days of intense sunlight during this period, which most probably accelerated photosynthetic activities of phytoplanktonic organisms that release more dissolved oxygen as a by-product (Krishnamurthy, 1990). A similar observation was reported by Tukura et al. (2012) in the Mada River located in a semi-arid region in Nassarawa State, Nigeria, where, due to biological decomposition, deoxygenation rate was expectedly higher than oxygenation from the atmosphere during the rainy season. The range of DO observed in the three portions of the reservoir (≈ 0.0 to ≈ 14.0 mgL^{-1}) during the period of study, however, was reported by Stickney (2000) to be good for the production and survival of a large spectrum of aquatic biota.

The mean value of BOD_5 of water recorded in the reservoir during the period of study (Table 2) decreased from the upstream portion to the downstream portion with the least value recorded at the midstream portion of the reservoir. The direction of water flow that increases along its course was towards the point of discharge upstream. The higher amount of organic matter deposited in the upstream portion of the reservoir would probably increase the amount of microbial decomposition and most probably increase the biological oxygen demand from the upstream to the downstream portion. The dry season mean values of BOD_5 higher than rainy season mean values across the entire reservoir (Table 3) could be attributed to the increased water temperature during the dry season, which increases biological activities such as decomposition and microbial and algal respiration (Omoniyi et al., 2017; WMO, 1980).

On average, the cationic hierarchy (i.e., $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$) was the same for all the zones investigated during the period of study, suggesting a similar/common geology and/or similar weathering influence within the river basin. Calcium and magnesium ions (in that order) were the dominant cations in the reservoir water, having higher concentrations than other cations. The high Ca^{2+} content was probably responsible for the slightly alkaline nature of the water in the reservoir since calcium and magnesium combine with carbonate and bicarbonate ions in water to raise the alkalinity (Omoniyi et al., 2017). In the same vein, the uniform anionic hierarchy ($HCO_3^- > Cl^- > SO_4^{2-}$) shows that the water is of the bicarbonate type with the concentrations of bicarbonate ion being the highest at all stations investigated on the reservoir.

3.3. Relationships between the sampling stations in relation to the physico-chemical characteristics of water quality

Figure 3 and Figure 4 show the relationships between the investigated stations and the respective determined physicochemical parameters of water quality during the dry and rainy seasons respectively. The clustering pattern of the stations both in the dry and rainy seasons were the same with the two distinct cluster groups identified, showing the interconnection that existed among the stations established on the reservoir. The mass of the reservoir water at a station, which virtually flows into the next station in the same reach/region, probably accounted for the deal of uniformity in the physicochemical conditions of the stations recorded in both dry and rainy seasons.

4. Conclusions

The study has shown that Esa-Odo Reservoir was generally moderately alkaline, soft, fairly clean, and dilute bicarbonate freshwater suitable for most probable domestic and industrial uses. The river water, if properly harnessed, could serve a good proportion of the population of communities as the reservoir that was originally designed to serve with a municipal water supply and aquatic livestock. However, there is a need for continuous monitoring and assessment as the riparian area of the reservoir becomes progressively utilized for agricultural and other anthropogenic activities.

Conflict of interests

The authors declare no conflict of interests.

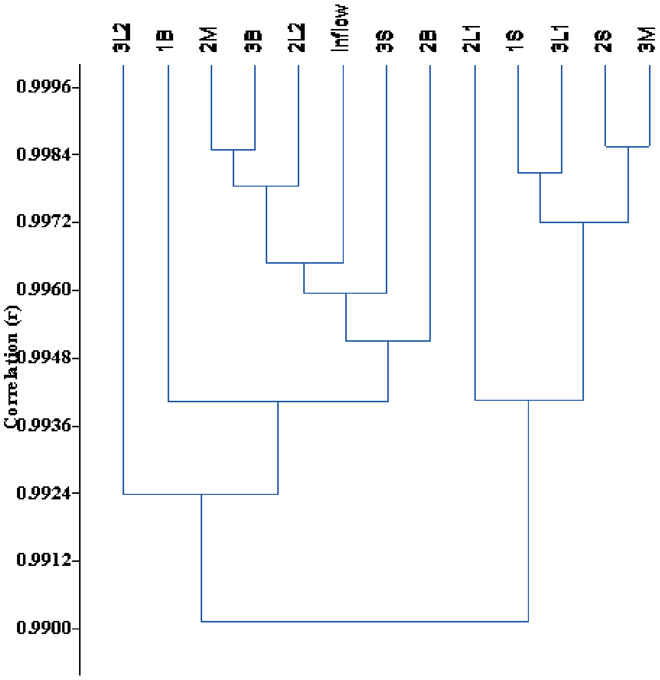

Fig.3. Relationship among the sampled locations based on the assayed water quality parameters in the dry season during the period of study.

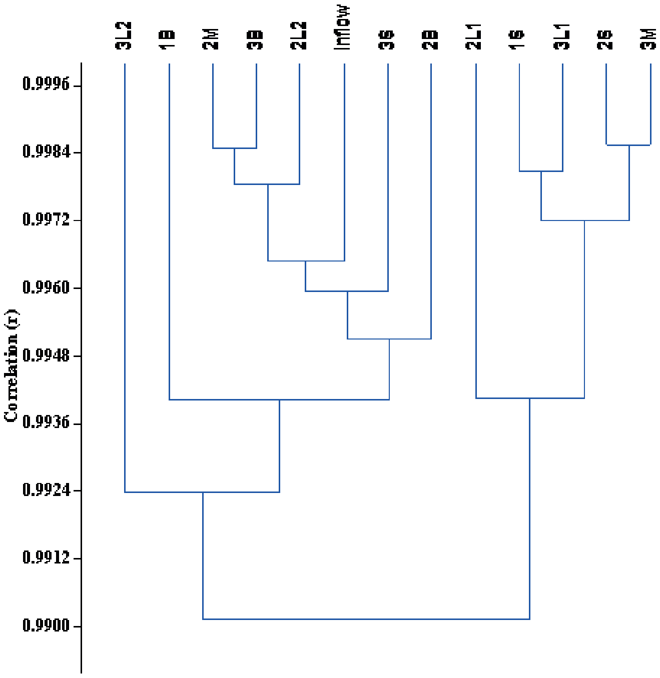

Fig.4. Relationship among the sampled locations based on the assayed water quality parameters in the rainy season during the period of study.

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Influence of breeding strategy on genetic diversity of individuals

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ABSTRACT. Using a computer simulation model, we tried to investigate how the transition from sexual reproduction to asexual reproduction will affect the population of diploid organisms with a neutral character of molecular evolution. At the same time, special attention was paid to the specificity of microsatellite markers. In this paper, we develop fast and inexpensive methods for assessing the changes in populations that occur with a change in reproductive strategy.

Keywords: microsatellite markers, object-oriented modeling, asexual reproduction, parthenogenesis

1. Introduction

The most widespread method of asexual reproduction in animals is parthenogenesis that is also found among highly organized organisms (Slatkin, 1987). Even in stable natural populations of multicellular organisms, the phenomenon of the formation of offspring due to asexual reproduction is rather common when there is no recombination and unification of the genetic material of different organisms. This process is the most widespread among plants and primitive animals (annelids, coelenterates, etc.). Often, the appearance of a new generation in such populations occurs according to a mixed type, some individuals are formed as a result of sexual reproduction, and some - during asexual reproduction. There are situations when populations, depending on environmental conditions, can switch from sexual reproduction to asexual reproduction and vice versa (Delmotte et al., 2002; Combosch and Vollmer, 2013). In such cases, violations of the patterns of genetic diversity should be expected.

In populations having a sexual process with neutral molecular evolution, fixation of new alleles due to gene drift is established by the Hardy-Weinberg principle.

The Hardy-Weinberg principle is the position of population genetics, which states that in a population of an infinitely large size where natural selection does not work there are no mutation process, exchange of individuals with other populations and gene drift. All crosses are random, for which the frequencies of genotypes or a gene (if there are two alleles of this gene in the population) will be kept constant from generation to generation and will correspond to equation (Wigginton et al., 2005).

The formation of genetic diversity in populations with sexual reproduction occurs due to the recombination and independent segregation of genetic material in several generations. This leads to the formation of new combinations of alleles. Some of the new alleles that have arisen as a result of spontaneous mutations are fixed or eliminated from the population due to gene drift and/or natural selection. In vegetatively propagating populations, the process of recombination and segregation of alleles is absent. For this reason, during vegetative reproduction, the genotype is completely transferred from one individual to another. In this case, genetic diversity is formed only due to the mutational process (Page and Holmes, 2009; Wang and Bradburd, 2014) and competition/drift of clones. The mutation appears independently in different alleys.

In populations with a sexual process with neutral molecular evolution, fixation of new alleles occurs due to gene drift, and the equilibrium of frequencies by the allele is maintained following the Hardy-Weinberg principle.

Violation of this ratio, as a rule, indicates the impact on the population of any processes that dramatically change genetic diversity. Such processes can be as follows: natural selection, fixing new alleys, expansion or decline in numbers (“bottleneck”), and migration. The bottleneck effect is common in many invertebrates because their number is greatly reduced when the temperature regime changes (autumn-winter

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period). The sharp drop in numbers leads to significant difficulties in the analysis of various genetic markers. In highly organized animals, this effect can lead to the low viability of the species. Individuals also have to resort to inbreeding, and this, in turn, leads to inbred depressions within the species.

In our study, using a computer simulation model, we attempted to investigate how the transition from sexual reproduction to vegetative reproduction will affect the population of diploid organisms with a neutral character of molecular evolution. At the same time, special attention was paid to the specificity of microsatellite markers. This specificity is a consequence of the multi-allele nature of microsatellite repeats and the high rate of their mutation.

2. Materials and methods

Two population scenarios were considered and compared:

1. the formation of genetic diversity and the frequency of occurrence of homozygous and heterozygous organisms in a population with sexual reproduction;
2. the formation of allelic diversity and frequencies of occurrence of homozygous and heterozygous organisms in a population with asexual reproduction.

Comparing the results of the two model experiments, it is possible to understand how inconsistent are the frequencies of alleles, homo and heterozygous individuals in two contrasting population scenarios.

In this paper, we present models suitable for describing speciation processes in ancient lakes. To obtainthe data that mimic the results of real studies, all the described individual models include a neutral mutating microsatellite sequence (vector *n*1 … *nm*, $n \in \{10,11,12\}$ (if the allele has three states)) that can be transmitted to descendants in the form of a copy with an asexual method of reproduction or be presented in the form of two copies that independently segregate in several generations.

The question arises of how to correctly process and extract the necessary information about genetic diversity if we work with a sample characterizing the distribution of alleles in a population with a mixed type of reproduction. To do this, it is reasonable to move from analyzing the frequencies of occurrence of alleles to analyzing genotypes. The genotype in this case will be any combination of alleles that characterize the individual. During reproduction, in this case, if the mutation has not occured, then the offspring inherits the genotype entirely from the parent; with mutation, a new genotype will appear in the offspring.

The main characteristics of genetic diversity in a population, in this case, will be the number of genotypes and the frequency of their occurrence in the population. The transition from loci to genotypes can be performed for both diploid and polyploid organisms. Thus, the population is considered rather a population of diploids or polyploids than a population of virtual haploid organisms. For the samples transformed in this way, the entire set of methods is applicable, which is used for the analysis of haploid populations or markers of mitochondrial DNA or Y chromosome transmitted through the maternal or paternal lines. For such virtual haploids, it is possible to calculate the indicator of the expected heterozygosity (*He*) according to the formula (1). Then, in this formula, n is the number of genotypes, and ai is the frequency of occurrence of the i - genotype number in the sample.

$$He = 1 - \sum_{i=1}^{n} a_i^2 \qquad (1)$$

It is no longer possible to interpret *He* as the expected heterozygosity; in this case, there will be a probability that two randomly taken individuals from the population will have different genotypes. The more *He* is shown for the vegetative population, the more diverse it is. It cannot be interpreted as an indicator of the genetic diversity of a population.

The observed heterozygosity (*Ho*) was estimated directly as the proportion of heterozygous individuals in the sample. Statistical comparison of the *He* and *Ho* samples calculated in the framework of experiments with different reproductive strategies (comparison of mean values) was carried out using the nonparametric $\chi2$ test.

The disadvantage of this criterion is that it does not take into account the effective population size. The effective population size (*Ne*) is the number of parents responsible for the genetic makeup of the next generation. The effective population size (*Ne*) that reflects only the number of breeding individuals and can be inferred from genetic data through the theta parameter can be used to estimate the effective population size based on data on population genetic polymorphism.

$$\theta = 4Ne\mu \qquad (2)$$

where μ is the mutation rate expressed as changes in the length of the microsatellite locus per generation.

One of the ways to study the processes of formation of genetic diversity is mathematical and computer modeling.

We described the general pattern of violation of the Hardy-Weinberg principle using the methods of object-oriented simulation modeling. Such a model is a program that creates a set of virtual “organisms” with several properties. The parameters that will affect the simulation result are selected for the study. The program gives us data similar to real ones.

The model algorithm was implemented in the Python programming language.

The genotype of the organism was a diallelic locus (diploid organism). Each of the two loci could be in its state. Their length varied in the following ranges:

1. 10 to 12 (3 alleles)
2. 10 to 14 (5 alleles)
3. 10 to 18 (9 alleles)

At the starting moment of the calculation (zero generation), the state of organisms was set randomly. The states were selected from a range of possible values. Organisms could be both homozygous and heterozygous.

Scenarios with different values of the probability of sexual reproduction (h) were also implemented: 0.01, 0.25, 0.5, 0.75, and 0.99. At the minimum value, the population is reproduced exclusively asexually. At 0.25, sexual reproduction is optional. Sexual reproduction is inherent in populations with h = 0.99.

Mutations occurred with a given probability, m (0.005, 0.0005 and 0.00005). Upon mutation in the offspring, the old position of the locus was changed to a new one chosen at random from a set of possible positions. This value works only for microsatellite sequences because they mutate much more often than the rest of the genome. Mutations occur mainly due to the sliding of DNA polymerase along the homopolymer sequence by several nucleotides, which is multiple of the repeat length.

The population size during the entire simulation was limited to a fixed value, N (10 tons). Since the Hardy-Weinberg principle assumes neutral molecular evolution, it was necessary to set the N value, with which the results would not be distorted and, at the same time, did not greatly increase the running time of the software pipeline. The value of this parameter was selected experimentally.

The number of reproductive cycles is equal to the T value (50 000).

At the initial moment, the program creates 10 t individuals with random states of alleles. An organism can have both a homozygous state of an allele and a heterozygous one. Next, the program selects organisms that will begin the reproduction process in this generation. Depending on the indicator of parameter h, the individual chooses the breeding method and sex (only if the breeding method is sexual). Depending on parameter m, the state of the locus in the offspring may change to another value selected from the range of possible ones. Individuals that have reached the maximum possible age are eliminated from the population. The number of offsprings that appeared in a given generation can exceed the established value of 10 tons, so their number is reduced randomly to the value of parameter N. This mechanism reduces the probability of fixing new variations of allelic states in the population. After that, the program enters a cycle and repeats the algorithm for 50 t. cycles (Fig. 1).

Every t = 100 generations, and information on the genotypes of n = 1000 individuals was saved. The information was saved in the form of a text table. According to the tables of the stored intermediate results for the populations, the indicators of the expected heterozygosity (*He*) were calculated. The observed heterozygosity (*Ho*) was estimated directly as the proportion of heterozygous individuals in the sample. The population parameter θ and the average *He* / *Ho* values were also estimated.

The script for calculating the *Ho* / *He* parameters and the population parameter, θ, were written in the R programming language. Data visualization was carried out using the ggplot2 and violplot data packages.

The number of individuals who have passed to the next reproductive cycle amounts to 10,000.

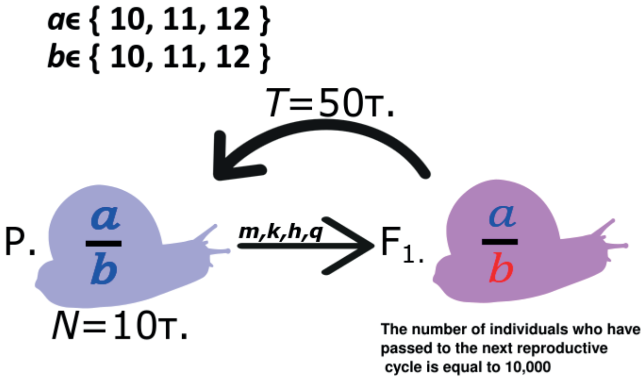
3. Results and discussion

The simplest case was a population of strictly constant size, in which polymorphism of a microsatellite marker was simulated, being limited to only three alleys. The physical size of the population accounted for 10,000 organisms, and the duration of the computer experiment was 50,000 generations. The life cycle of an organism was one step of the simulation, respectively; each of the organisms could participate in one reproductive cycle.

Within the framework of this study, models were analyzed, in which the fate of only one bite was monitored; therefore, the estimated population parameters belonged to the one-locus group. The same applies to all other cases considered in this study.

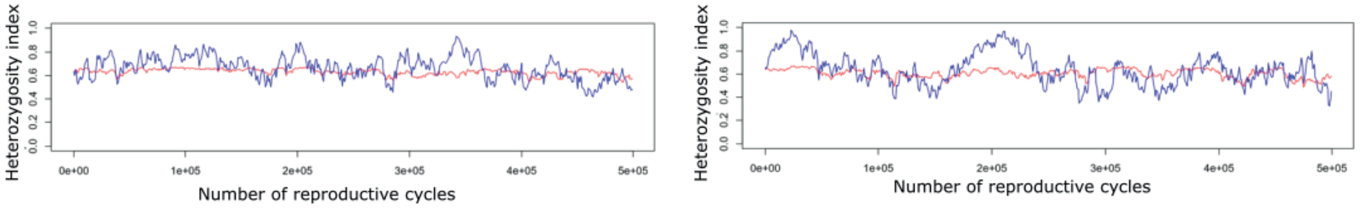
Figure 2 shows the result of one of the experiments, in which the polymorphic locus had three possible states. Such cases are not typical of microsatellites. They usually have more allelic states. The red color indicates expected heterozygosity, and the blue color indicates observed heterozygosity. The observed heterozygosity varies from ~0.5 to 0.9, following the scenario with asexual reproduction. In the second case (sexual reproduction prevails in the population), the range of values is greater, from 0.4 to 1. The analysis revealed no significant differences between the samples. The same situation is observed when measuring the θ-parameter.

The results of the scenario, in which the polymorphic locus had nine allelic states are shown in Figure 3. This scenario is more typical of microsatellites because they usually have a large number of allelic conditions. In the case of sexual reproduction, the values of the observed heterozygosity are distributed over a wider range. No significant differences are also found in the Ho / He parameters, but when measuring the θ-parameter, the blue line in two cases goes beyond the graph. This indicates very high values of the observed heterozygosity. In the scenario with asexual



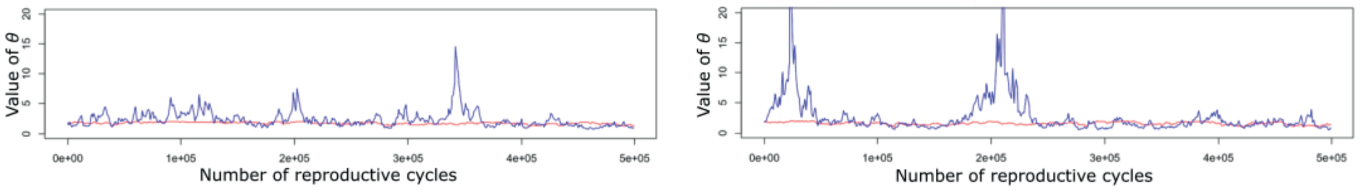
The number of individuals who have passed to the next reproductive cycle is equal to 10,000

Fig.1. Reproduction of the evolutionary scenario with three allelic states.



Ho/He with a probability of sexual reproduction 0.01

Ho/He with a probability of sexual reproduction 0.99



θ-parameter with a probability of sexual reproduction 0.01

θ-parameter with a probability of sexual reproduction 0.99

Fig.2. Results of analysis of *Ho / He* and θ-parameters for three allelic states (m = 0.0005). The upper figure is the dynamics of the distribution of observed and expected heterozygosity in the population with asexual and sexual reproduction. The lower figure is the density of distribution of the θ value of the observed and expected heterozygosity in the population with asexual and sexual reproduction.

reproduction, there is a strong excess of the observed heterozygosity over the expected. Also, when measuring the θ-parameter, more peaks are going beyond the graph than in the case of a predominance of sexual reproduction. Therefore, the lower the likelihood of sexual reproduction, the higher the level of observed heterozygosity. Comparing the results for the three and nine states, the spread in the expected heterozygosity is higher for the nine states. This is due to a large number of variations in heterozygous states.

An analysis was also carried out with different values of the probability of mutations. With a high value of probability of mutation (m = 0.005), no significant differences were found between sexual and asexual reproduction. There is also no difference between scenarios with three and nine states of alleles.

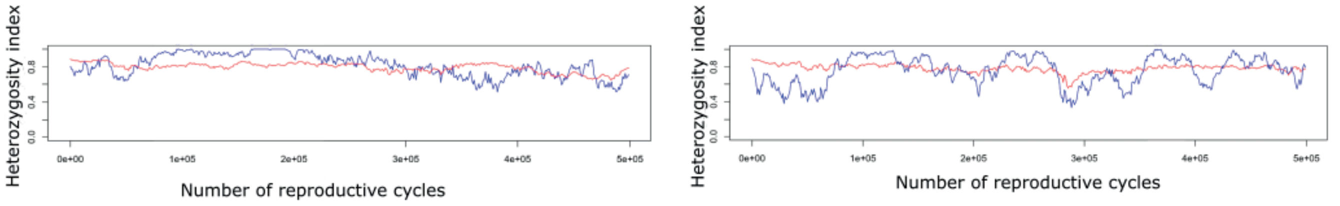
At a low value of the mutation probability (m = 0.00005), in the scenario with sexual reproduction, the observed heterozygosity is 1, for θHo = 499 (maximum possible value) from 4000 to 50,000 generations (Fig. 4.).

This is because all individuals in the population have become heterozygotes, but due to the low m value, new variations of states do not have time to appear. All organisms are heterozygous for the first and third allelic states from 4000 until the very end of the program.

In the case of asexual reproduction, the values of the observed heterozygosity are distributed over a wider range. There are also several peaks in the θ-parameter. Throughout the simulation, genetic diversity was maintained in the population and asexual reproduction, contributing to this.

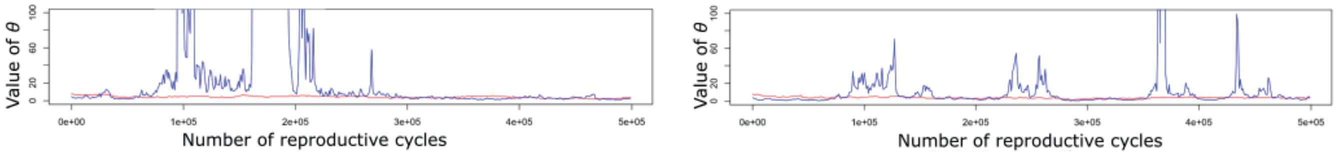
These results appeared due to the exposed parameters of the model. Since organisms reproduced sexually are eliminated from the population after the reproduction act, a low value of parameter m does not play any role in the occurrence of genetic diversity. With asexual reproduction, the individual survives. If it acquires new variations in allelic states, they can become fixed in the population. In summary, we can conclude that asexual reproduction helps preserve genetic diversity in the population.

Animals that can reproduce themselves in two ways generally resort to asexual reproduction when the population is in constant and favorable conditions.



Ho/He with a probability of sexual reproduction 0.01

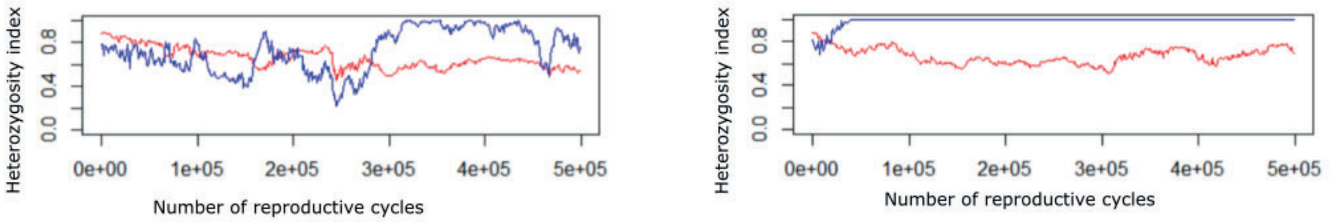
Ho/He with a probability of sexual reproduction 0.99



θ-parameter with a probability of sexual reproduction 0.01

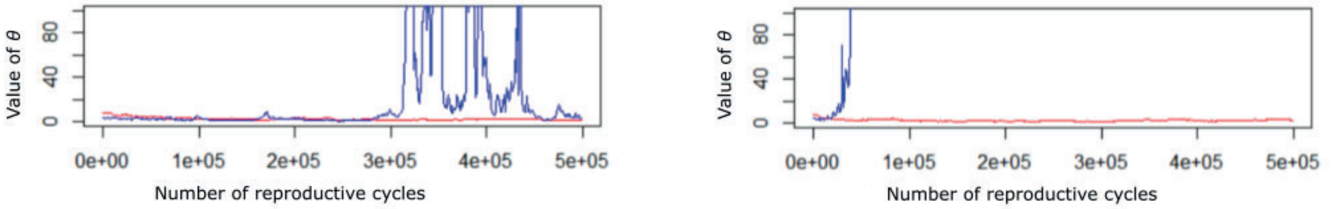
θ-parameter with a probability of sexual reproduction 0.99

Fig.3. Results of analysis of *Ho / He* and θ-parameters for nine allelic states (m = 0.0005). The upper figure is the dynamics of the distribution of observed and expected heterozygosity in the population with asexual and sexual reproduction. The lower figure is the density of distribution of the θ value of the observed and expected heterozygosity in the population with asexual and sexual reproduction.



Ho/He with a probability of sexual reproduction 0.01

Ho/He with a probability of sexual reproduction 0.99



θ-parameter with a probability of sexual reproduction 0.01

θ-parameter with a probability of sexual reproduction 0.99

Fig.4. Results of analysis of *Ho / He* and θ-parameters for nine allelic states (m = 0.00005). The upper figure is the dynamics of the distribution of observed and expected heterozygosity in the population with asexual and sexual reproduction. The lower figure is the density of distribution of the θ value of the observed and expected heterozygosity in the population with asexual and sexual reproduction.

Switching to another mode of reproduction occurs under unfavorable or stressful situations as well as with rapid changes in environmental parameters that are important for the survival of the species. For example, a representative of hybridization of the same species in river ecosystems is reproduced only by parthenogenesis, while in coastal waters of the seas they switch to sexual reproduction. In other words, the latter strategy prevails in nature when the need for increased genetic diversity arises.

There were no significant differences in the values of both observed and expected heterozygosity, even taking into account the effective population size, m = 0.005, between populations where one or the other reproductive strategy predominates. Consequently, at a low mutation rate, regardless of the method of reproduction, under stressful conditions, various combinations and variations of genotypes should be fixed at the same rate.

During asexual reproduction, populations are usually dormant. The population does not need to adapt to new environmental conditions; therefore, there is no need for increased genetic diversity. When loci have a fast and slow rate of mutation, genetic diversity will be preserved during asexual reproduction.

An analysis was also carried out using “violin” diagrams. Comparing scenarios with low and high mutation levels, it can be concluded that the values of the parameter of the observed heterozygosity are distributed over a wider range in the scenario with three allelic states, with a value of m = 0.00005. Also, the median values of expected and observed heterozygosity are higher in the case of a high m value (Fig. 5, Fig. 6.).

In the scenario with nine allelic states, the main differences are observed in the θ-parameter. There are discrepancies in the median values between sexual and asexual reproduction with m = 0.00005. The parameter values are distributed over a wider range in the case of asexual reproduction. The expected heterozygosity is higher with m = 0.005. In the scenario with a high probability of mutation during asexual reproduction, there are discrepancies in the median values for the expected and observed heterozygosity. In the case of sexual reproduction, no significant differences are found.

The mean values were also calculated for three, five and nine states of the locus (m = 0.005) (Table 1). Differences between observed and expected heterozygosity are traced only for the θ-parameter and in the case of nine allelic states. The lower the value of the probability of sexual reproduction, the greater the value of the observed heterozygosity, taking into account the effective population size. Differences are also observed for five allelic states. There are also

Table 1. Mean values for three, five and nine states of alleles (*m* = 0.0005).

***m* = 0.0005**												
	he			***ho***			***thhe***			***thho***		
h	**3**	**5**	**9**	**3**	**5**	**9**	**3**	**5**	**9**	**3**	**5**	**9**
0.01	0.629	0.717	0.792	0.665	0.764	0.818	1.714	2.592	4.107	2.353	5.669	72.08
0.25	0.603	0.719	0.779	0.616	0.735	0.914	1.547	2.682	3.759	2.019	5.491	78.47
0.5	0.599	0.737	0.773	0.584	0.843	0.893	1.530	2.896	3.623	1.756	8.145	48.91
0.75	0.607	0.691	0.772	0.634	0.787	0.806	1.575	2.425	3.658	2.473	11.75	112.49
0.99	0.6060558	0.713	0.783	0.636	0.806	0.754	1.561	2.553	3.805	2.690	15.03	113.142

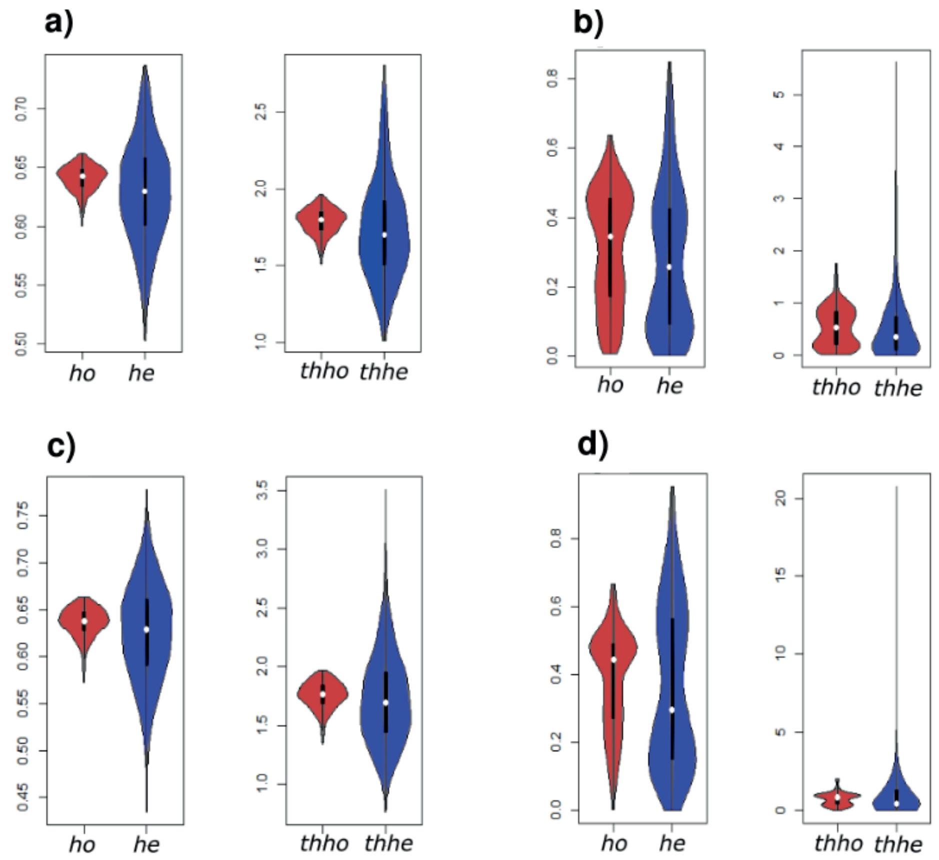


Fig.5. Results of analysis of parameters *Ho / He* and θ for three allelic states. a) and b) show the results of the program with the probability of sexual reproduction equal to 0.01. In cases c) and d) h = 0.99. In diagrams a) and c) m = 0.005, b) and d) m = 0.00005.

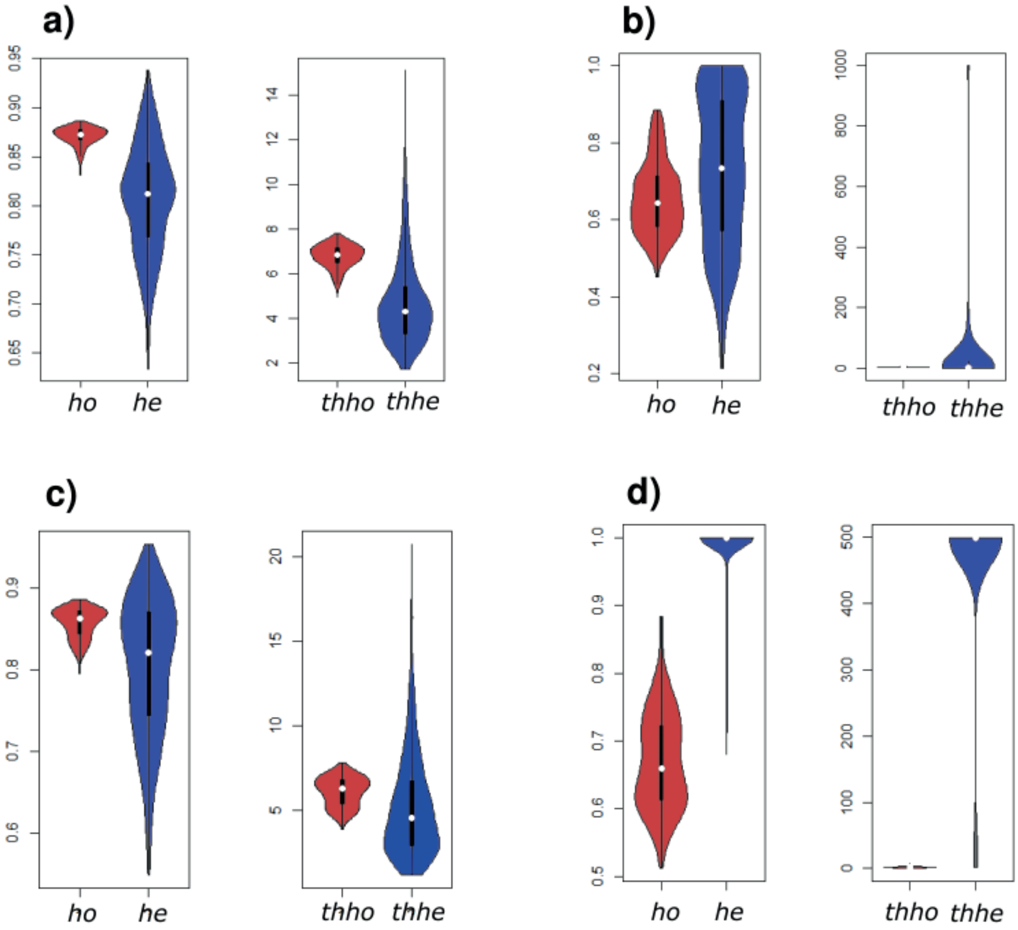


Fig.6. Results of analysis of *Ho / He* and θ-parameters for nine allelic states. a) and b) show the results of the program with the probability of sexual reproduction equal to 0.01. In cases c) and d) h = 0.99. In diagrams a) and c) m = 0.005, b) and d) m = 0.00005.

Table 2. Mean values at different mutation levels for three and nine states of alleles ($m = 0.005$, $m = 0.0005$ and $m = 0.00005$).

$m = 0.005$								
	he		***ho***		***thhe***		***thho***	
h	**3**	**9**	**3**	**9**	**3**	**9**	**3**	**9**
0.01	0.6410578	0.871074	0.62942	0.807004	1.788459	6.792643	1.735566	4.661963
0.99	0.6366654	0.8575254	0.626058	0.804354	1.757177	6.127904	1.726423	5.246142
$m = 0.0005$								
	he		***ho***		***thhe***		***thho***	
h	**3**	**9**	**3**	**9**	**3**	**9**	**3**	**9**
0.01	0.6297884	0.7926326	0.66569	0.818118	1.714792	4.107697	2.353728	72.08677
0.99	0.6060558	0.7834572	0.636492	0.754904	1.56149	3.805604	2.69068	113.14267
$m = 0.00005$								
	he		***ho***		***thhe***		***thho***	
h	**3**	**9**	**3**	**9**	**3**	**9**	**3**	**9**
0.01	0.3123436	0.6565852	0.277626	0.727656	0.5403204	2.23307	0.5678965	40.21082
0.99	0.385361	0.6693028	0.362432	0.988946	0.7178024	2.20507	1.033858	460.5871

minor differences in the five states of bite. This is due to the higher rate of equilibration according to the Hardy-Weinberg principle. The fewer allelic states at a locus, the faster equilibrium is established. The θHo value is higher in the case of asexual reproduction. The more the locus has allelic states, the greater the indicators of expected and observed heterozygosity.

An analysis was also carried out for various values of the mutation probability (Table 2). With a high value, no significant differences were found. With a high m value, differences are observed in the θ-parameter.

The higher the probability of mutagenesis, the greater the values of the expected and observed heterozygosity.

4. Conclusions

Taking into account all of the aforesaid, we can conclude that the analysis should take into account the effective population size, the lower the value of the mutation probability and the greater the difference between the observed and expected heterozygosity. The differences are more obvious in asexual reproduction.

The average values of the θ-parameter in apomixis populations are much higher than the average values in sexually reproducing populations. The more states at a locus, the stronger the difference between the scatter of expected and observed values. Asexual reproduction helps preserve genetic diversity in a population. This study has demonstrated that the use of *Ho / He* parameters to assess the differences between breeding methods is not relevant. Research is being conducted on other population parameters, including multi-locus ones.

Confict of interests

Authors declare no conflict of interests.

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