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RESEARCH PAPER

Maintenance and natural regeneration of *Castanopsis sclerophylla* populations on islands of Qiandao Lake Region, China

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Abstract: Qiandao Lake was formed in 1959 when the Xin'anjiang Hydroelectric Plant was built. There are 1078 islands with areas larger than 2500 m^2 and many smaller islands. The population structure of *C. sclerophylla* was investigated to reveal whether it can sustain on islands so as to provide suggestions for ecological restoration. *C. sclerophylla* can be found on islands with a water level higher than 105.4 m, whereas the highest water level of Qiandao Lake was 108.2 m. Number of individuals on islands, with a range from 4 to more than 4000, was significantly related to the areas or altitudes of the islands. Population structure indicated that, at genet level, *C. sclerophylla* on large and most medium-size islands could be self-sustainable, whereas on small and some medium-size islands *C. sclerophylla* could not be self-sustainable and would decline. However, at the ramet level, almost all the *C. sclerophylla* populations, no matter on large, medium or small islands, seem to be self-sustainable. Further analysis indicated that re-sprouting contributed to more than 81.6% of the genets and 94.8% of the shoots formed after the creation of the Lake. The results above indicated that although small size of populations exist on some islands, these populations might be sustained via vegetative reproduction, especially re-sprouting, for a long period under the present situation without human disturbance and dramatic environmental changes. Conditions of most islands meet the standards necessary for the survival and growth of *C. sclerophylla*. Therefore, lack of seed or seedling is the main limitation for the ecological restoration of evergreen broad-leaved forests on islands of Qiandao Lake. However, that no individual was reproduced from sexual reproduction on some medium and small islands indicates that environmental condition might be another limiting factor for restoration.

Key Words: *Castanopsis sclerophylla*; islands; population structure; regeneration; ecological restoration; Qiandao Lake

Habitat fragmentation, the process where a large, continuous habitat is transformed into a number of small spatially isolated remnants, is one of the main types of ecosystem degradation[1]. Habitat fragmentation has been recognized as the most important single factor leading to biodiversity loss[2]. About one-third of the species listed under the Endangered Species Act of U.S.A. were caused by habitat fragmentation[3]. Extensive studies have been conducted on the ecological and population genetic consequences of the species surviving in fragmented habitats. However, variable even contradictive results have been obtained because such consequences are influenced by many factors, such as difference in characteristics of species and studied systems[4]. For example, most of previous studies were conducted in habitat island systems, where each fragment experienced distinct fragmentation history.

Qiandao Lake, a hydroelectric impoundment, was formed in 1959 when the Xin'anjiang Hydroelectric Plant was built. It is an ideal locality to study the ecological effects of fragmentation on terrestrial plant species. First, there are 1078 islands with an area larger than 2500 m^2 and many smaller islands at the water level of 108 m asl (above sea level), providing a number of islands with different characteristics (such as area, isolation, etc.) were chosen for specific studies. Second, each

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population has distinct boundaries surrounded by water which is unsuitable for terrestrial plants, avoiding the potential effects of scattered individuals as usually encountered in habitat island systems. Third, islands of Qiandao Lake region were formed at the same time, and fragmented populations experienced the effects of fragmentation at the same time.

Potential vegetation of Qiandao Lake region is evergreen broad-leaved forest dominated by *Castanopsis sclerophylla* and *Cyclobalanopsis glauca*[5]. At present, however, the vegetation on islands is mainly dominated by *Pinus massoniana*, a pioneer species. The main cause is that, just before the hydroelectric plant was built, forests below 108 m asl (above sea level) had been cleared off to avoid the potential negative effects of being submerged, and forests above 108 m were also destroyed owing to the absence of strict monitoring and control measures. Pure pine forest is prone to disease, such as *Dendrolimus punctatus* and pine wood nematodes, and prone to fire because of abundant turpentine, whereas evergreen broad-leaved forests are thought to play a more important role in the ecosystem than pine forest[6]. Therefore, there is a need to restore the potential vegetation, i.e., evergreen broad-leaved forest, in this area[7]. *C. sclerophylla* is the most common evergreen broad-leaved species in Qiandao Lake region, and was distributed on many islands, especially in the southeastern subregion (personal observations), but population size usually retained was very small for a couple of decades. The objectives of the present study are: (1) to investigate the population structure of *C. sclerophylla* on islands, (2) to reveal maintenance mechanisms of *C. sclerophylla* populations on islands with different areas, and (3) to provide some implications for ecological restoration on islands.

1 Materials and methods

1.1 Study locality

The study sites are located in southeastern Qiandao Lake region and south to Chun'an County (N29°30′00"– N29°35′ 00", E119°00′00"–E119°07′30"). In previous surveys, it was found that *C. sclerophylla* is the most common evergreen broad-leaved species in this subregion. In this study, a total of 31 islands and 2 peninsulas were investigated, and *C. sclerophylla* was found in 67.57% of forested islands. Except for Laoshan Island, all other forested islands were dominated by *Pinus massoniana*. On Laoshan Island, besides the pine forest, there are some tea and orange gardens, and at Chushuiwu, there is a secondary evergreen broad-leaved forest dominated by *C. sclerophylla* with an importance value of over 60%[8].

1.2 Methods

Three plots (40×30, 40×40 and 40×50 m^2) were set with the total area of 5600 m^2 on Laoshan Island (LS), 3 plots (25×25, 25×35 and 30×80 m^2) with the total area of 3900 m^2 on Aci Island (AC), 1 plot (40×45 m^2) on Guanmiao Island (GM), 1 plot (20×35 m^2) on Heyang Island (HY), 2 plots (30×15, 50×40 m^2) on Huangshan Island (HS) with the total area of 2450 m^2, 1 plot (20×20 m^2) on Taiping B Island (TB) and Taiping D Island (TD), 3 plots (60×50, 80×35 m^2 and 40×25 m^2) with the total area of 6800 m^2 on Shilinzhen peninsula (SL), and 2 plots (45×40, 90×25 m^2) with the total area of 4050 m^2 on Xianshan peninsula (XS). On other islands, every individual of *C. sclerophylla* was surveyed and the diameter of breast height (*DBH*) was measured.

1.3 Data analysis

The islands were digitized based on a 1∶10000 topographic map of Qiandao Lake. Area, perimeter, and shape index of each island were estimated using programs of Arcview GIS 3.2 and FRAGSTATS.

Population structure was studied according to the size class of individuals. Size class was classified using following criteria: class I with individual height < 0.33 m; class II with height > 0.33 m but *DBH* < 2.5 cm; then each increment of 5 cm in *DBH* corresponds to an increment in size class[9]. Because *C. sclerophylla* is capable of sprouting, which plays an important role in maintenance, two approaches, genet- and ramet-based, were used to evaluate population structure. The type of population structure was identified according to the peak curve of the respective size class[10].

2 Results

2.1 Distribution of *C. sclerophylla*

The smallest island where *C. sclerophylla* was found is DB, with an area of 0.63hm^2 (Table 1), but 36.84% of islands larger than DB showed no surviving of *C. sclerophylla* species. Although the highest water level of Qiandao Lake was 108.2 m, *C. sclerophylla* was found on island SH with the altitude of 105.4 m. For islands where *C. sclerophylla* occurred, a number of individuals, with a range from 4 to more than 4000, were significantly related to the areas or to altitudes of the islands (p<0.01). The larger the island, the greater the occurrence of *C. sclerophylla* (Fig. 1).

2.2 Population size structure

2.2.1 Genet-based structure

Unimodal type means the type that has one distinct peak in size class, such as populations in the large island LS or peninsula SL. These populations have large size and most individuals belong to size class III and IV, indicating a stable status. Populations with such a structure are located mainly in evergreen broad-leaved forests or mixed forests with coniferous and broad-leaved species, which were dominated by *C. sclerophylla*, indicating that communities were at the climax stage or approaching the climax stage.

Inverse-J type describes a population with a large number of seedlings and saplings, and a small number of medium and large trees. Such a population has a large seedling pool and has a potential for further development. The population on peninsula XS, located in a mixed forest, belongs to this type.

Table 1 Baseline data of islands surveyed in the present study

Island (Abbre)	Area (hm^2)	Perimeter (km)	Shape index	Highest altitude (m)	No. individuals	Community type
Laoshan island (LS)	874.9115	33.45	3.19	408.5	4000	EBLF* and MF**
Aci island (AC)	50.5839	3.75	1.49	225.8	400	MF
Huangshan island (Hs)	39.8005	3.78	1.69	266	500	MF
Guanmiao island (GM)	15.6034	2.47	1.76	146.0	31	MF
Heyang island (HY)	13.0042	1.58	1.23	143.0	200	MF
Taiping C island (TC)	7.0633	2.40	2.55	145.5	30	Coniferous forest
Longpao island (LP)	6.9202	1.45	1.55	127.0	4	MF
Taiping B island (TB)	5.7190	1.86	2.19	139.0	50	Coniferous forest
Taiping N island (TN)	4.5879	2.06	2.71	125.5	0	Orange plantation
Taiping I island (TI)	4.1242	1.66	2.30	122.5	0	Coniferous forest
Taiping D island (TD)	3.8965	1.38	1.97	132.0	40	Coniferous forest
Wuming island (WM)	3.1774	0.73	1.15	121.5	17	Coniferous forest
Cuizhu island (CZ)	3.1121	0.76	1.21	130.5	0	Coniferous forest
Taiping M island(TM)	2.4377	1.53	2.76	118.3	0	Coniferous forest
Shihu island (SH)	1.5016	0.53	1.21	105.4	5	Bamboo forest
Dongnan island (DN)	1.1187	0.51	1.36	111.5	32	Coniferous forest
Shihu3 island (S3)	0.7240	0.34	1.13	105.8	0	Bush
Taiping L island (TL)	0.7002	0.37	1.24	116.5	0	Coniferous forest
Shihu2 island (S2)	0.6348	0.40	1.42	105.0	0	Bush
Dongbei island (DB)	0.6305	0.39	1.40	110.0	14	Coniferous forest
Shihu4 island (S4)	0.6132	0.31	1.12	106.0	0	Bush
Taiping E island (TE)	0.4432	0.38	1.60	111.4	0	Coniferous forest
Cuizhu3 island (C3)	0.4048	0.25	1.10	110.8	0	Bush
Taiping J island (TJ)	0.3546	0.27	1.26	111.7	0	Coniferous forest
Taiping F island (TF)	0.2652	0.2	1.14	109.5	0	Coniferous forest
Cuizhu4 island (C4)	0.2342	0.23	1.33	105.0	0	Bush
Taiping P island (TP)	0.1762	0.20	1.37	103.0	0	Bush
Taiping K island (TK)	0.1447	0.16	1.18	105.0	0	Bush
Cuizhu2 island (C2)	0.1187	0.15	1.23	101.0	0	Grassland
Taiping H island (TH)	0.0663	0.12	1.25	101.6	0	Grassland
Taiping G island (TG)	0.0519	0.09	1.11	102.8	0	Grassland

* EBLF means evergreen broad-leaved forest; ** MF means mixed forest with coniferous and broad-leaved species

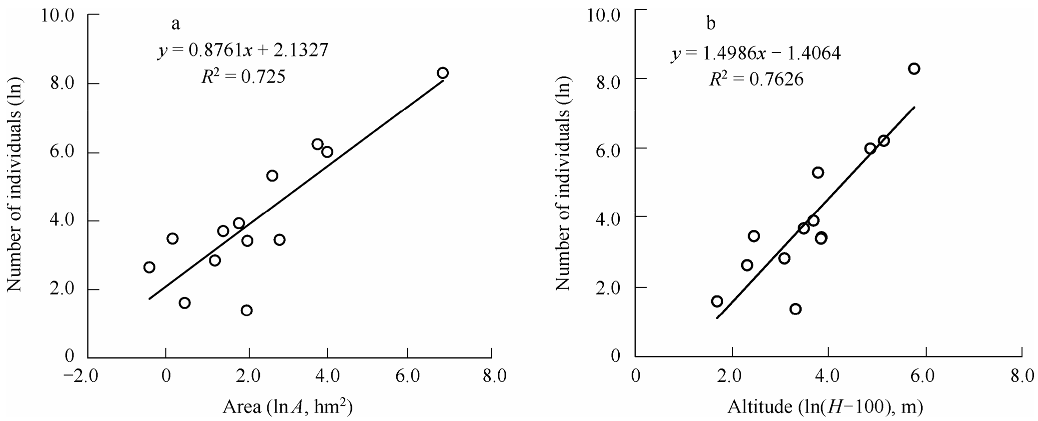

Fig. 1 Relationship between number of *C. sclerophylla* individuals and area (A) or altitude (B) of islands

Multimodal type (instable type) has 2 or more indistinct peaks in size class, such as populations on islands GM and HY, especially on HY with a wavy curve. These populations were mainly found in mixed forest with coniferous and broad-leaved species or pine forest. Populations of this type might have suffered from disturbance. If disturbance decreases, population of such structure type might develop and be transformed to unimodal or inverse-J type. Otherwise, the population will decline and be transformed into the discrete type.

Discrete type was found on smaller islands or seriously disturbed medium islands. Population size of this type is small and several *DBH* classes were found to be absent. For example, all individuals on SH island belong to size class IV or V, and other size classes were absent. This type has no or few seedlings and saplings, shows a declining trend and easily approaches local extinction.

2.2.2 Ramet-level structure

Ramet-based population structure was shown in Table 2. Populations with unimodal type at genet level usually also had the same size structure based on ramet. However, the peak was moved to smaller size classes. Populations with multimodal type based on genets were transformed into the unimodal when based on ramets, whose peak was in classes II and III, or inverse-J type. Owing to abundant sprouts, most shoots belonged to classes II or III.

2.2.3 Contributions of clonal and sexual reproduction

The relationship between *DBH* and age revealed by tree rings indicated that an individual with the *DBH* of 32.5 cm is 45 years old, corresponding to the time taken for the formation of the lake. Individuals with *DBH* smaller than 32.5cm were newly formed after fragmentation. Therefore, the contributions of asexual and sexual reproduction were estimated to the newly formed individuals (Table 2).

Contribution of sexual reproduction of genet-based population of *C. sclerophylla* ranged from 0 to 36.36%. No sexually reproduced individual was found in all these 3 populations. Mean sexual contribution of all population was 18.40%. Contribution of sexual reproduction of populations on small islands (10.13%) was significantly lower than that of large- (23.62%) and medium- (27.89%) island populations ($p<0.05$), and marginally lower than that of peninsula populations ($p=0.074$).

When using ramet-based data, mean contribution of sexual reproduction declined to 5.16%. Sexual contributions of populations on medium (7.50%) and large (8.33%) islands were significantly higher than those on small islands (2.24%, $p=0.0129$), and those of peninsula populations were still marginally higher than those of small island populations ($p=0.0555$).

3 Discussion

Island ecosystems have offered great opportunities for ecological studies, and some important theories and hypotheses have been proposed based on such systems[11,12]. Island system is also ideal for studying ecological consequences of habitat fragmentation. In the system currently under study, populations of *C. sclerophylla* were fragmented at the same time, providing special chance to check the maintenance mechanisms on islands with different areas.

Whether *C. sclerophylla* can survive on an island depends on the altitude as well as frequency and persistent time of high water level in Qiandao Lake region. Water level of Qiandao Lake is usually lower than 100 m, and the highest water level is 108.2 m. Owing to disturbance caused by seasonally higher water level, there is no forest on islands with the altitude lower than 105 m and no *C. sclerophylla* occurred. *C. sclerophylla* was found on island SH with altitude of 105.4 m, indicating that *C. sclerophylla* can endure temporary water flooding. *C. sclerophylla* is dispersed by gravity, and rodents serve as the secondary disperser. Therefore, water surrounding the

Table 2 Population structure and contributions of clonal and sexual reproductions

Population	Contribution of clonal reproduction		Contribution of sexual reproduction		Population size structure	
	Genet-based	Ramet-based	Genet-based	Ramet-based	Genet-based	Ramet-based
Shilinzhen peninsula	0.7113	0.8967	0.2887	0.1033	Unimodal	Unimodal
Xianshan peninsula	0.8163	0.9534	0.1837	0.0466	Inverse-J	Inverse-J
LS	0.6364	0.8497	0.3636	0.1503	Unimodal	Unimodal
AC	0.7414	0.9355	0.2586	0.0645	Unimodal	Unimodal
HS	0.7813	0.9478	0.2188	0.0522	Multimodal	Unimodal
GM	0.8065	0.9552	0.1935	0.0448	Multimodal	Inverse-J
HY	0.6400	0.8953	0.3600	0.1047	Multimodal	Inverse-J
LP	0.7500	0.9333	0.2500	0.0667	Unimodal	Unimodal
TB	0.8000	0.9663	0.2000	0.0337	Unimodal	Unimodal
TD	1.0000	1.0000	0.0000	0.0000	Unimodal	Inverse-J
WM	1.0000	1.0000	0.0000	0.0000	Discrete	Unimodal
SH	1.0000	1.0000	0.0000	0.0000	Discrete	Unimodal
DN	0.8125	0.9568	0.1875	0.0432	Multimodal	Unimodal
DB	0.9286	0.9870	0.0714	0.0130	Unimodal	Inverse-J
Mean	0.8160	0.9484	0.1840	0.0516		

islands is an insurmountable obstacle for seed dispersal, indicating that the *C. sclerophylla* individuals on islands were remnant of previously large populations.

Number of individuals on islands with *C. sclerophylla* was significantly related to island area and the latter was significantly related to island altitude. Therefore, number of individuals was also significantly related to altitude. The results were easy to understand because the bigger the area, the more the suitable habitats for *C. sclerophylla*. This relationship is in accordance with other researches[14], and similar to the species-area relationship in biogeography, which emphasizes on equilibrium between immigration and extinction.

4 Maintenance of populations on islands

Unimodal or inverse-J types of population structure indicated that *C. sclerophylla* on peninsula, large and most medium islands are self-sustainable. Populations on small islands might decline, as indicated by the multimodal or discrete structure type at genet level. However, it is notable that all populations are stable or are of developing type with respect to ramets.

Trade-offs between vegetation growth and seeding are key issues in the evolution of life history strategies of plant species. Vegetation growth, such as re-sprouting, is concerned with the maintenance of current generation, whereas seeding is concerned with the production for future generation[15]. There is a growing appreciation regarding the role of sprouting, including root sprouting and stem sprouting[15], as a form of rapidly regaining biomass after disturbance[15]. Sprouts grow much faster than seedlings and can quickly reoccupy the gaps after the removal of aboveground biomass[17]. Sprouting ability can have major impacts on plant populations: reducing the turnover of populations, minimizing the effects of disturbance, and decreasing the dependence on seeds for population maintenance[17]. Many plant species have the ability of re-sprouting, but vary among taxa. For example, about 11% of gymnospermous species can sprout whereas in Rosaceae, 80% species can re-sprout. In Fagaceae, about 78% of species can re-sprout[18], which is higher than the average.

Disturbance is the most important factor that influences the trade-off between clonal and sexual reproduction. When disturbance is severe, populations are usually maintained by re-sprouting; otherwise, by seeding. A lot of studies have reported increased re-sprouting under disturbance, such as fire[19,20], cutting and other naturally or man-made damages[21]. In a valley with serious flooding disturbance in Huangshan of Anhui Province, *Cyclobalanopsis glauca* produced seeds of low quality, and re-sprouting is very evident, whereas in less disturbed sites, seed is larger and heavier, indicating that sexual regeneration is the main means of regeneration[22]. In Qiandao Lake region, *C. sclerophylla* was maintained mainly via re-sprouting, and contribution of re-sprouting to the newly formed individuals was higher than 80%, which is likely because of the extensive cutting before building the hydroelectric plant. In fact, many individuals were sprouted from stumps. Maintenance of populations on some small islands was fully based on re-sprouting, indicating that there are some serious disturbances on these islands.

Site productivity (i.e., moisture and/or fertility) also contributes to the trade-offs between re-sprouting and seeding[15,23,24]. For example, *Nothofagus cunninghamii* regenerates via seed in moist and fertile sites, but mostly re-sprout in drier and less fertile sites[15]. In South Africa, *Sideroxylon inerme* and *Pterocelastrus tricuspidatus* are multi-stemmed trees and few seedlings are found at low rainfall sites, whereas at higher rainfall sites both species are single-stemmed and seedling regeneration is evident[15,25]. In Qiandao Lake region, for *C. sclerophylla* the situation may be the same. For example, small islands had barren soil and low ability of retaining water and fertility, while large islands had deep soil and high ability of retaining water and fertility. Thus, re-sprouting on small islands was more evident. However, Walters and his colleagues found that water and nutrient availabilities do not affect lignotuber growth and the sprouting ability of three eucalyptus species of southeastern Queensland[26].

The ability of sprouting is also related with stumps. For example, Randall and his colleagues reported that stump size affects number of sprouts in *Taxodium distichum* var. *nutans*. Percentage of stumps with sprouts after 2 years was 68% for trees of 10–14 cm *DBH* and 28% for trees of 20–24 cm *DBH*. Their results indicated that sprouting may be an important, but inadequate, form of regeneration[27]. Sprouting is unusual in wetland plants, but it is common in juveniles, and not in adults, of *Dryobalanops rappa* (Dipterocarpaceae). Mature trees developed buttresses and were rarely decumbent, whereas juvenile trees were frequently decumbent and their decumbent shoots sprout vegetatively. This stage-dependent sprouting is important for regeneration in wetland forests with soft soil[28].

In subtropical areas of eastern China, re-sprouting is a common mechanism of maintenance and natural regeneration in dominant species in evergreen broad-leaved forests[29]. After biomass loss, they can quickly re-sprout from remnant stumps. Strong ability of sprouting makes these trees survive serious anthropogenic disturbance, such as cutting, burning, *etc*. This strong sprouting in dominant species has also been observed in other evergreen broad-leaved forests. In some cases, the whole community is formed by sprouts, indicating frequent anthropogenic disturbance. Sprouting is also common in other forests in China, such as firewood forests[30,31], *Cyclobalanopsis oxyodon* forest[31], and middle mountain moist evergreen broad-leaved forest[33].

Although individual number of *Castanopsis sclerophylla* populations at genet level was limited and most population sizes were smaller than the number of 50/500 rule in conservation genetics, strong sprouting might sustain populations for some time. A similar situation was observed in the endangered species *Heptacodium miconioides*[34]. However, sprouting cannot increase genetic variation, which reflects potential ability to adapt to changing environments. Therefore, once environment changes, re-sprouting-maintained populations might approach local extinction. Furthermore, although many sprouts can be found on a single stump, high mortality is expected in sprouts owing to strong competition. At last, one or two sprouts on a stump can develop into mature plants.

5 Implications for ecological restoration

Existence of *C. sclerophylla* on islands as low as 105.4 m and as small as 0.63 hm^2 (Table 1) indicated that conditions of most islands meet the survival and growth of *C. sclerophylla*. No *C. sclerophylla* was found on some islands, which is likely due to dispersal limitations. Water surrounding islands are a barrier for natural seed dispersal of *C. sclerophylla* and other species of Fagaceae, which are dominant species of evergreen broad-leaved forests in China. Therefore, for such islands, especially large and medium islands, introduction of seed or seedlings is critical for ecological restoration. This has been evidenced by the introduction experiments of seedlings to some islands (unpublished data).

However, on some islands, there are *C. sclerophylla* trees, but the population sizes have been retained to be very small for a couple of decades, indicating that there are some factors influencing the sexual regeneration. By automonitoring humidity and temperature in the air and soils for a year, drought in the summer was observed to be the main cause affecting survival of seedlings (unpublished data). In addition, extensive seed consumption by rodents also limits sexual regeneration. The above two issues are most serious on small islands. Therefore, introduction of seedlings is better than introduction of seed. Furthermore, to successfully restore potential vegetation on small and some medium islands, besides introduction of seedlings, some engineering measures are necessary to retain water.

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