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POPULATION DYNAMICS OF THE ENDANGERED PLANT *PAEONIA QIUI* (PAEONIACEAE)

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Abstract

Paeonia qiui belonging to the family Paeoniaceae, is a perennial deciduous shrub, having ornamental and medicinal value. Recently the distribution of wild *P. qiui* has gradually reduced in China due to anthropogenic activites and the influence of various natural factors making its protection a great concern. A population of *Paeonia qiui* in the eastern Qinling Mountains was surveyed and created a static life table, survival curve, fecundity schedule and Leslie matrix model for analysis of numeric population dynamics. The *P. qiui* population experienced environmental screening and competitive self-thinning at ages ≤ 6 years and ages 9 to 15 years, respectively. The age of '11 years' is the physiological lifespan of *P. qiui* and the age of ~27 years is the lifespan limit. The survival curve was classified as a Deevey-I type, with a low net population growth rate of $R_0 = 0.8005$, an intrinsic rate of increase of $r = -0.0205$, and a finite rate of increase of $\lambda = 0.9797$, indicating a declining population. Leslie matrix model simulation results indicated that the *P. qiui* population will decrease by about 78.8% within the next 30 years and that the current population mainly relied on asexual shoot regeneration for maintenance. The possible causes of endangerment of the *P. qiui* population are biological characteristics, population size, habitat conditions, and human disturbance. We recommend the establishment of protected areas in the original habitat of *P. qiui* to gradually restore population size, and individual plants valuable for research or other uses can be saved off-site.

Key words: Static life table; Leslie model; Survival curve; Fecundity schedule.

Introduction

Population dynamics are result of the influence of environmental factors and reflect reproductive adaptability (Kojima *et al*., 1998). Study of population dynamics is the core of population ecology (Chapman & Reiss, 2001; Jiang, 1992). The age structure, life table and survival curve of a plant population reflect the growth status of the population, population dynamics and changes in development, largely showing the conflicting relationship between plants and the environment (Manuel & Molles, 2002; Zhang, 1998). A Leslie matrix model can simulate and predict the number and age structure changes of all age groups in a population (Yue *et al*., 2002; Hu & Wang, 1998), with important application (Li *et al*., 2012; Yang *et al*., 2007) in the protection and management of endangered species. Although research on plant population dynamics is well developed (Zhang *et al*., 2004; Li *et al*., 2002; Zu *et al*., 1999; Zhang & Zu, 1999), the population structure and dynamics for *Paeonia qiui* have not yet been reported and the mechanism of endangerment is not known.

Paeonia qiui belonging to the family Paeoniaceae, is a perennial deciduous shrub with an underground stem, capable of both sexual and asexual reproduction. A primitive type in the MOUTAN subgroup (Zhou & Yao, 2002), *P. qiui* has important ornamental and medicinal value (Fig. 1). In recent years, due to human destruction and the influence of various natural factors, the distribution of wild *P. qiui* has gradually reduced together with a drastic reduction in individuals and population extinctions. Therefore, *P. qiui* protection has become an important consideration in the Wild Peony Conservation program of China. The present study created a static life table and prepared a survival curve and fecundity schedule to investigate population change characteristics of *P. qiui*. A Leslie matrix model is established to predict the change in population dynamics, and time sequences are used to predict numeric population dynamics. Thus, numeric change characteristics of a *P. qiui* population is quantitatively analyzed to provide a theoretical basis for better protection and effective use of the resource of wild *P. qiui*.

Materials and Methods

Survey area: *P. qiui* is mainly distributed in the eastern Qinling Mountains and grown mainly under trees and on mountain slopes (Fig. 1). This region is characterized by warm and humid climates of the northern subtropical zone with an annual average temperature of 15.4°C, annual average sunshine hours of 1790.4 h, an annual average rainfall of 851.2 mm, and 252 frost-free days (Weather China, http://en.weather.com.cn). *Paeonia qiui* is mainly distributed between 32.97° – 33.22° N latitude and 109.32° – 109.8° E longitude, growing in mountain shrub or under deciduous forest at an altitude from 1200 – 1600m. The main type of soil was yellow brown soil, with a pH 6.5 – 6.7, 1.5 – 1.84% organic matter, 0.11 – 0.124% total nitrogen, 0.149 – 0.193% total phosphorus, and 1.75 – 2.57% total potassium. Associated trees are mainly *Quercus variabilis*, *Quercus acutissima*, *Toxicodendron vernicifluum*, and *Carya cathayensis* while associated shrubs include *Lonicera tatarinowii*, *Kerria japonica*, and *Rosa multiflora*. Associated low shrubs are *Dendranthema indicum*, *Juncus effusus*, and *Carex lanceolata* Boott.

Fig. 1. *Paeonia qiui*. A: Population; B: Seedlings; C: A flowering individual; D: Flower; E, F: leaves; G, H: Follicles; I: Tomentose carpels; J: Seeds; K: Root suckers.

Table 1. Three geographical distribution of *Paeonia qiui*.

No.	Distribution	Longitude and latitude	Elevation	Habitat
1.	Xunyang Co., Shaanxi Prov.	109.32-109.39/33.52-33.53	1386-1456	Hillsides, open forests
2.	Xunyang Co., Shaanxi Prov.	109.41-109.50/32.99-33.05	1274-1305	Hillsides, dense forests, thickets
3.	Shangnan Co., Shaanxi Prov.	110.63-110.71/33.40-33.46	1141-1260	Hillsides, dense forests

Field survey: Based on preliminary field investigation from 2014 to 2018, fifteen plots with 10 m × 10 m were chosen in the eastern Qinling Mountains, with plots spaced greater than 200 m apart, a total of 45 plots in three distribution area (Table 1). *P. qiui* potted plants were individually measured for height, basal diameter and crown size. The specimen was collected during the field investigation in 2015 and conserved in the WUK. Herb coverage, abundance and height distribution, investigated for layered frequency, were also surveyed. Simultaneously, environmental factors such as elevation, aspect, slope, soil moisture, and human disturbance were examined. Plant ages were determined based on the number of bud scales marks and rings in branches (Yang *et al*., 2007), and the seed number and replacement condition were also explored. Thirty adult plants were randomly selected for investigation of offspring production. Based on the scope of seed dispersal and crown coverage of mother trees, the annual number of seedlings in 2 m^2 area surrounding the mother tree was determined (slope was measured as a flat area). The number of seeding plants and plant seed plumpness were counted. Adult plant seeding rate (%) was the number of plants with seeds/ total number of adult plants × 100. Seed plumpness rate (%) was the number of full seeds / total seeds × 100.

Preparation of static life table: Woody plants have a longer life span and for population studies '5 years' is usually used as an age class. However, *P. qiui* grows as bushes and has a relatively shorter lifespan. Based on biological characteristics and survey results, this study used '3 years' as an age class and a "space push time" method (Harper, 1997; Harcombe, 1987) to draw the static life table. X is the age class; l_x is the number of survivors at age X (1000); dx is the number of deaths from age X to X + 1; qx is individual mortality at age X class, where $q_x = d_x/l_x$; L_x is the number of individuals alive from age X to X + 1, $L_x = (l_x + l_x + 1)/2$; T_x is the total number of individuals at age X class and beyond, where $T_x = L_x + L_{x+1} + L_{x+2} +$; E_x is expected life of individuals entering age X, where $e_x = T_x/l_x$; a_x is the number of alive individuals at age X (The number of individuals, hm^{-2}); K_x is killing power, where $K_x = \ln l_x - \ln l_{x+1}$.

Plotting the survival curve: To describe age-specific mortality, the survival of a particular age group was plotted versus age (Yang *et al*., 2007). The logarithm of survival (i.e., logarithm of l_x) was plotted as the vertical axis and age as the horizontal axis.

Preparation of population fecundity schedule: The population fecundity schedule contained the following values. X is the age class; l_x is the survival rate of age X class; m_x is the average number of offspring produced of plants at age X class; N_{t+1}, N_t are surviving number of the population at time t + 1 and t. Population net reproductive rate (R_0), intrinsic rate of increase (r_m), finite rate of increase (λ), and mean generation time (T) were calculated as follows (Huang et al. 2013). $R_0 = \Sigma l_x\, m_x$, $\lambda = N_{t+1}/N_t$ or $\lambda = e^r$, $T = \Sigma x\, l_x\, m_x/\Sigma l_x\, m_x$, $r_m = \ln R_0/T$.

Construction of leslie matrix model and simulation analysis: This model used the population age structure in the life table, the survival rate of all age levels, and fertility as elements of the matrix, and calculated the theoretical number and the total number of all ages at any time. Detailed methods can be found in Zheng *et al*., (1997), Zu *et al*., (1999), and Yue *et al*., (2002). An amount of 3 years was the age class for simulation calculations.

Results

Static life table analysis: The survey results of 45 plots were used for the life table of the *P. qiui* population (Table 2). The age structure distribution of the *P. qiui* population was also created (Fig. 2).

As shown in Table 2, the highest age of the *P. qiui* population was 24 years. Before age 6, mortality was negative, indicating a serious shortage of seedlings. The population was strongly screened by the environment. To maintain a sustainable amount in the population, at least a corresponding number of seedlings is required to be added. Otherwise the population will decline. After age 9, mortality rates began to rise again, indicating that when the population entered the median age, the individuals had increasing nutritional and space requirements. Because of the competition for the light, water, nutrients and space, population self-thinning was enhanced, resulting in a second wave of deaths, which may be related to shoot regeneration of *P. qiui*.

Population age structure analysis is an important method to reveal population status and regeneration strategy (Zhang *et al*., 2005). Fig. 2 shows that the *P. qiui* proportion had high proportion of individuals at a median age but lacked young and aging individuals. The population structure was unstable and depended on individuals of median age to maintain the population. The survey found that the seeding rate of *P. qiui* in adult plants was only about 10%, indicating that *P. qiui* in this region had difficulty propagating by seeds. The current population mainly depends on shoot regeneration for maintenance.

Analysis of population survival curve and death curve: Based on the life table of *P. qiui*, the survival curve was drawn using the logarithm of survival number (i.e., the logarithm of l_x) as the vertical axis and median age as the horizontal axis (Fig. 3A). The mortality curve was plotted using individual mortality value (i.e., q_x) as the vertical axis and median age as the horizontal axis (Fig. 3B).

Table 2. Static life table of *Paeonia qiui* population.

Age class (X)	Standard number of survivors (l_x)	Standard number of deaths (d_x)	Mortality (q_x)	Individuals alive (L_x)	Total individuals (T_x)	Expected life (e_x)	Observed number of individuals alive (a_x)	Killing power (K_x)
1	269	-269	-1.000	403.5	3249.5	12.080	21	-0.693
3	538	-103	-0.191	589.5	2846.0	5.290	42	-0.175
6	641	-359	-0.560	820.5	2256.5	3.520	50	-0.445
9	1000	385	0.385	807.5	1436.0	1.436	78	0.486
12	615	384	0.624	423.0	628.5	1.022	48	0.979
15	231	180	0.779	141.0	205.5	0.890	18	1.511
18	51	25	0.490	38.5	64.5	1.265	4	0.674
21	26	13	0.500	19.5	26.0	1.000	2	0.693
24	13	13	1.000	6.5	6.5	0.500	1	-

Note: X, age class; l_x, the number of survivors at age X, assuming the number of individuals at the beginning is 1000; d_x, the number of deaths from age X to X +1; q_x, the proportion of death during the interval age (X, X +1); L_x, the number of individual alive during unit time (X, X +1); T_x, total number of individuals from age X; e_x, expectation of life at age X; a_x, the number of alive individuals at age X; K_x, killing power

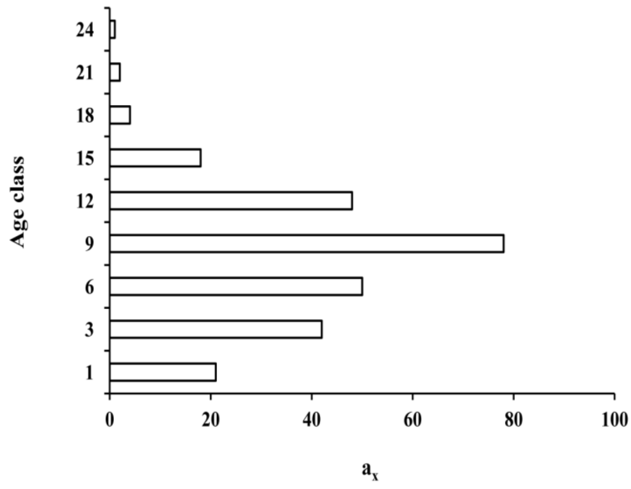

Fig. 2. Age structure of *Paeonia qiui* population.

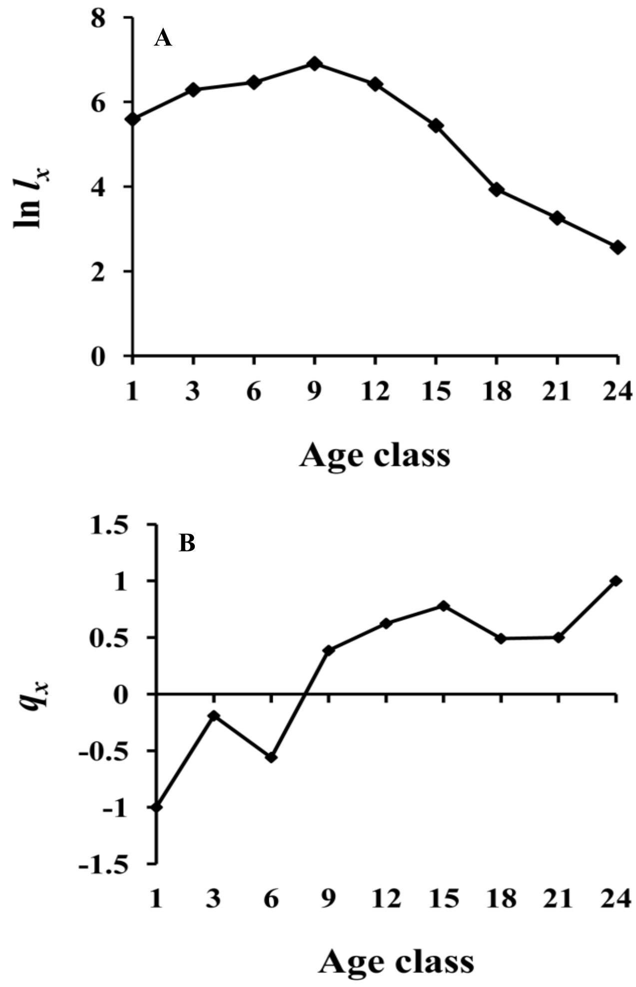

Fig. 3. Survival (A) and Mortality curves (B) of *Paeonia qiui* population.

As shown in Fig. 3A, the survival curve of *P. qiui* population displayed a Deevey-I type curve (Pan *et al*., 2011; Li, 2000). The survival curve suggests that one-year-old seedlings had a low survival rate and a high mortality rate occurred in the late physiological life of the plants. Fig. 3B shows an unstable population structure of *P. qiui*, different mortality rates at all ages, and high mortality rate of young individuals (1–6 age class). In addition, there was a serious shortage of young seedlings (a negative value), indicating a declining population. The mortality rate of the age 9 to 15 class rapidly increased and the population had difficulty maintaining stability. The mortality rate of the age 15 to 21 class leveled off and the population was relatively stable. After the age 21 class, *P. qiui* entered the aging stage and mortality increased. An amount of 27 years was the lifespan limit of *P. qiui*.

Analysis of population fecundity schedule and important parameters: A fecundity schedule is mainly used to interpret the growth model of a population. Table 3 shows that the net growth rate of *P. qiui* was 0.8005, indicating that each generation proliferated 0.8005 times. The intrinsic growth rate was −0.0205, indicating that the instantaneous birth rate was less than the instantaneous death rate. The finite growth rate was 0.9797, indicating that the *P. qiui* population geometrically decreased at a rate of 0.9797 times. The mean generation time was 10.84a, indicating the average reproductive age; thus 11 years was the physiological lifespan of *P. qiui*. The parameter $R_0<1$, $r_m<0$, $\lambda<1$ all show that the size of the *P. qiui* population will fall and fail to self-renew. It is a declining population.

Leslie matrix model and simulation analysis: Survey results showed that the seeding rate of adult *P. qiui* was only 10% and seed plumpness rate was 65%. Natural germination rate was 50%. Based on to the calculation methods of Xiao *et al*., (2004) and Ma *et al*., (2007), the effective seed yield rate of *P. qiui* was only 3.25%. The above data were used to build and analyze the Leslie matrix model. The results are shown in Tables 4 and 5.

The Leslie matrix model simulation results show that the *P. qiui* population is a declining population, consistent with the analysis of the fecundity schedule. The Leslie matrix model reflects different aspects of *P. qiui* population growth and population changes. The number of *P. qiui* declines from the current 264 thicket/hm^2 down to 56 thicket / hm^2 through 30 years. The population declines by 78.8% and the plant number at each age class shows a downward trend.

Table 3. Fecundity schedule of *Paeonia qiui* population.

Age class (X)	Survival rate (l_x)	Number of average generations (m_x)	$l_x * m_x$	$x * l_x * m_x$	
1	0.269	0.000	0.000	0.000	
3	0.538	0.000	0.000	0.000	
6	0.641	0.168	0.108	0.646	Net reproductive rate R_0 = 0.8005
9	1.000	0.281	0.281	2.529	Intrinsic rate of increase r_m = −0.0205
12	0.615	0.435	0.268	3.210	Finite rate of increase λ = 0.9797
15	0.231	0.501	0.116	1.736	Generation span T = 10.84 (a)
18	0.051	0.348	0.018	0.319	
21	0.026	0.313	0.008	0.171	
24	0.013	0.205	0.003	0.064	

Note: X, age class; l_x, the survival rate at the age X; m_x, the number of average generations at age X

Table 4. Leslie matrix model of *Paeonia qiui* population.

	0	0	0.127	0.156	0.191	0.183	0.107	0.059	0
	1.384	0	0	0	0	0	0	0	0
	0	1.052	0	0	0	0	0	0	0
	0	0	0.754	0	0	0	0	0	0
	0	0	0	0.555	0	0	0	0	0
Matrix =	0	0	0	0	0.439	0	0	0	0
	0	0	0	0	0	0.365	0	0	0
	0	0	0	0	0	0	0.308	0	0
	0	0	0	0	0	0	0	0.189	0
	0	0	0	0	0	0	0	0	0

Table 5. Numerical dynamics of *Paeonia qiui* population in future 30 years.

Age class	N_0	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	N_9	N_{10}
1	21	32	24	17	16	14	12	11	9	8	7
3	42	29	44	34	24	21	20	17	15	12	11
6	50	44	31	46	36	25	23	21	18	15	13
9	78	38	33	23	35	27	19	17	16	14	12
12	48	43	21	18	13	19	15	11	9	9	8
15	18	21	19	9	8	6	8	7	5	4	4
18	4	7	8	7	3	3	2	3	2	2	2
21	2	1	2	2	2	1	1	1	1	1	1
24	1	0	0	0	0	0	0	0	0	0	0
Total	264	215	182	158	137	117	101	87	75	65	56

Note: N_0, current survival number; N_1−N_{10}, the survival number of prediction in future 3−30 years

Discussion

The static life table, survival curve, fecundity schedule and Leslie matrix model analysis of a *P. qiui* population provided similar results of a high death of early individuals, a lack of young seedlings, difficulty in natural regeneration, and classification as a declining population. Before 6 years and between 9–15 years, the *P. qiui* population respectively experienced strong environmental screening and competitive self-thinning. An age of 11 years is the physiological lifespan of *P. qiui*. The individuals enter a physiological aging period at 21 years. The lifespan limit for *P. qiui* is ~27 years. The maintenance of the population depends on the individuals at median ages. The current population mainly relies on shoot regeneration for maintenance.

As a unique wild rare plant in China, the endangered status of *P. qiui* is already known. The main reasons for this endangerment are as follows. First, the size of the population is small. Plant population size directly affects the survival potential of a population (Liang *et al*., 2018). Small populations have difficulties in pollination and self-pollination leads to lower seed set rate and lower viability (Jing *et al*., 1995). A small population and low competitive ability are features of endangered populations. Second, sexual reproduction is poor. Throughout the life cycle, *P. qiui* mainly depends on rhizomes and suckers for reproduction, which then replaced and expanded the bush. New plants were mostly concentrated around maternal plants, forming a characteristic asexual clonal clustered distribution. Field observations found that the natural reproductive capacity of *P. qiui* was not strong. High ovule abortion rate, low fruit set rate, and poor seed germination were important factors reducing sexual reproduction. After long-term adaptive evolution, *P. qiui* adopted an obligate vegetative reproduction mode, mainly using root-budding asexual reproduction. In modern habitats, there is a huge obstacle to natural regeneration, which has critically endangered *P. qiui*. Third, man-made destruction is an issue. Artificial dredging has resulted in the reduction of population volume and density. Human activities cause serious damage to the ecological environment, which is another important factor in the endangerment of *P. qiui*. Fourth, habitat conditions are constrained. *Paeonia qiui* usually grow under the high canopy of the forest, with a low light transmission rate and insufficient light. Combined with barren soil and slow growth, they have difficulty with population regeneration and population density declined.

Paeonia qiui is a unique germplasm resource of China, with significant scientific, cultural, ornamental and medicinal value. Under natural conditions, seeding rate, seed germination rate, and seed-seedling conversion rate is generally low. Accompanied by the recent frequent anthropogenic excavation, it is very urgent to work to enhance the protection of *P. qiui*. Based on the population dynamics analysis of *P. qiui*, we recommend the establishment of protected areas in the original habitat of *P. qiui* to gradually restore population size. At the same time, important individuals of *P. qiui* can be screened in the protected areas, and individual plants valuable for research or other uses can be saved off-site. In addition, further research should focus on breeding characteristics and population adaptability of *P. qiui* to improve the environmental competitiveness of *P. qiui*.

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