Population Structure and Dynamics of Natural Juniperus rigida in the Loess Hilly Region: A Postprint

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Abstract

This study investigated the natural Juniperus rigida population in the loess hilly region of Inner Mongolia through static life table, survival function, dynamic quantitative analysis, and time series modeling of population structure and dynamics. The results showed that seedling individuals were most abundant, followed by intermediate trees, with mature trees being the least numerous. Combined with the population dynamic index Vpi > 0, the population was classified as growth-type. The survival curve, validated by curve fitting, tended toward Deevey-II type, indicating stable mortality across age classes. When external disturbances were considered, the dynamic index approached 0, suggesting insignificant population growth under disturbed conditions. Survival function analysis revealed a pattern of strong early survival, stable middle period, and gradual decline in later stages. After 2–8 age-class time periods, seedlings were projected to decrease while intermediate and mature trees increased. The seedling stage plays a decisive role in population renewal and development; scientific protection measures for seedlings are recommended to promote population regeneration. This research on the intrinsic mechanisms of Juniperus rigida populations enriches vegetation construction strategies in arid regions, provides a reference for population management, and offers a theoretical basis for vegetation protection and restoration in the loess hilly region.

Full Text

Population Structure and Dynamic Analysis of Natural Juniperus rigida in a Loess Hilly Area

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Abstract: This study investigated the natural *Juniperus rigida* population in the loess hilly region of Inner Mongolia, analyzing its structure and dynamic changes through a static life table, survival function, dynamic quantitative analysis, and time series modeling. The results revealed that the population predominantly consisted of seedlings, followed by medium-sized trees, with fewer mature trees. Combined with the population dynamic index Vpi > 0, the population exhibited a growth-type pattern. The survival curve, validated by curve fitting, tended toward Deevey-II type, indicating stable mortality across age classes. When considering external disturbances, the dynamic index approached 0, suggesting that population growth was not significant under interference conditions. Survival function analysis demonstrated that the population displayed strong survival capacity in the early stage, relative stability in the middle stage, and a gradual decline in the later stage. Over the next 2, 4, and 6 age-class periods, seedling numbers decreased while both medium-sized and mature trees increased. The seedling stage plays a decisive role in population regeneration and development; therefore, implementing scientific protection measures for seedlings is recommended to promote population renewal. Research on the intrinsic mechanisms of *Juniperus rigida* populations enriches vegetation construction in arid regions, provides references for population management, and offers a theoretical basis for vegetation protection and restoration in loess hilly areas.

Keywords: loess hilly region; *Juniperus rigida*; population structure; survival analysis; dynamic analysis

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Population constitutes the fundamental unit of ecological research, with population structure and quantitative dynamics representing core issues in population ecology. Population structure reflects the distribution of individuals across different developmental stages and indicates population dynamics and development trends, demonstrating the population' s status within its environment [?]. Investigating plant population structure and dynamic characteristics based on diameter class structure and static life tables helps reveal relationships between population biological traits and habitat conditions [?], providing important theoretical guidance for plant resource conservation and utilization [?].

Juniperus rigida belongs to the Cupressaceae family, *Juniperus* genus, an evergreen shrub or small tree that grows in relatively arid regions. It is one of the important tree species in China's loess hilly areas, particularly significant for soil and water conservation along the Yellow River basin, playing crucial roles in soil fixation, sand stabilization, and water source conservation. Recent research has extensively focused on essential oil development and utilization [?], seedling techniques [?], and reproductive characteristics [?], with most scholars investigating cultivation technologies [?]. While some studies have examined phenotypic diversity and allelopathic effects [?], investigations and documentation of natural *Juniperus rigida* forest populations remain extremely limited. The loess hilly region of Inner Mongolia, located deep inland with scarce precipitation, features a sensitive and fragile ecological environment [?]. With developed mining industries and logging activities, the productivity of *Juniperus rigida* forest resources is endangered, making the population’ s role in maintaining ecosystem balance and stability in the loess hilly region irreplaceable [?]. Exploring the population structure and dynamic characteristics of natural *Juniperus rigida* forests is therefore urgent, providing data for population management and ecological assessment, enriching vegetation construction in loess hilly areas, and offering a theoretical basis for vegetation protection and restoration in Inner Mongolia’ s arid regions.

1.1 Study Area Overview

The study area is located in Xiyingzi, eastern Ordos City, southwestern Inner Mongolia Autonomous Region (110°05 ~111°27 E, 39°16 ~40°20 N). The geomorphic structure represents a typical loess hilly-gully region, embraced by Yellow River bends on the west, north, and east sides, with elevations mostly between 1200–1400 m. Situated deep inland, the area exhibits a pronounced continental climate, influenced by seasonal winds with southerly or southeasterly winds in summer and northwesterly winds from autumn to spring. The annual average temperature is 8.7 °C with a diurnal temperature difference of 14.1 °C; light energy resources are abundant with total sunshine hours reaching 1710 h. Precipitation varies significantly, concentrated in July–September, with an average annual precipitation of 400 mm. The soil is predominantly chestnut soil.

1.2 Sample Plot Setup

At the end of May 2022, typical sample plots with natural *Juniperus rigida* populations were selected through remote sensing imagery combined with field investigations. Representative sites within the plots were chosen to establish three 20 m × 20 m sample quadrats distributed across upper, middle, and lower slope positions. Three sample belts were established: the first belt located at 110°41 E, 39°28 N, 1160–1220 m elevation; the second belt at 110°41 E, 39°28 N, 1140–1245 m elevation; and the third belt at 110°41 E, 39°28 N, 1140–1230 m elevation. Data collected for each natural *Juniperus rigida* individual included base diameter, height, crown width, and health status. Environmental factors such as habitat, slope aspect, and elevation were recorded for each quadrat.

1.3 Size Class Division

Since natural *Juniperus rigida* forests cannot be easily cut to obtain ages and the foliage is needle-shaped, this study used diameter class structure based on base diameter as a proxy for age structure [?]. The diameter classes were defined as: $X < 2$ cm for seedlings, 2 cm $\leq X <$ 5 cm for small saplings, 5 cm $\leq X <$ 10 cm for large saplings, 10 cm $\leq X <$ 15 cm for small medium trees, 15 cm $\leq X <$ 20 cm for medium trees, 20 cm $\leq X <$ 25 cm for large medium trees, 25 cm $\leq X <$ 30 cm for small mature trees, 30 cm $\leq X <$ 35 cm for medium mature trees, and $X \geq 35$ cm for large mature trees.

1.4 Static Life Table

Static life table compilation is an effective method for studying population dynamics [?], representing an investigation of population age structure at a specific time. The static life table statistics followed Dong Lingbo and Wu Chengzhen et al. [?]. To deeply investigate *Juniperus rigida* population structure and dynamic characteristics, the study referenced Li et al. [?] and introduced survival rate function S(i), cumulative mortality function F(i), population mortality density function f(ti), and population hazard rate function λ(ti). The formulas are as follows:

$$S(i) = \prod_{j=1}^{i-1}(1 - q_j)$$

$$F(i) = 1 - S(i)$$

$$f(t_i) = \frac{2h_i q_i}{(1 + h_i q_i)}$$

$$\lambda(t_i) = \frac{2q_i}{(1 + h_i q_i)}$$

where h_i represents the width of diameter class i, and q_i represents the mortality rate of class i.

1.5 Population Dynamics Quantification

Following Chen Xiaode [?], this study employed dynamic quantitative analysis to quantitatively describe *Juniperus rigida* population structure and reflect dynamic relationships in individual numbers between adjacent age classes. The formulas are:

$$V_n = \frac{A_n - A_{n+1}}{\max(A_n, A_{n+1})} \times 100$$

$$V_{pi} = \frac{1}{k}\sum_{n=1}^{k-1}\frac{A_n}{A_{n+1}} \times V_n$$

$$V'_{pi} = \frac{1}{k}\sum_{n=1}^{k-1}\frac{A_n}{A_{n+1} + A_n V_n} \times V_n \quad (n = 1, 2, 3, \ldots, k-1)$$

$$P_{极大} = \max(|V_n|)$$

where V_n represents the dynamic change in individual numbers for each diameter class; A_n represents individual numbers in each class; V_{pi} represents population dynamic change index ignoring external interference; k represents the total number of diameter classes; V' *{pi} represents population structure quantity change dynamic considering future external interference; and P*{极大} indicates the maximum impact on population dynamic V_{pi}. When V_n, V_{pi}, and V' _{pi} values are positive, the population shows growth; when negative, decline; and when 0, stability.

1.6 Time Series Model

The one-time moving average method was used to predict *Juniperus rigida* population age structure [**?**]. The calculation formula is:

$$M_t^{(1)} = \frac{1}{n}\sum_{k=t-n+1}^{t} X_k$$

where n represents the prediction time period; t represents the diameter class; X_k represents individual numbers in class k; and M_t^{(1)} represents the number after n diameter class periods. This study predicted population dynamics for the next 2, 4, and 6 diameter class periods.

1.7 Data Processing

Data were organized and analyzed using Excel 2007, SPSS 21, and Origin 2019 software.

2 Results and Analysis

2.1 *Juniperus rigida* Population Structure

As shown in [Figure 1: see original paper], the first age class (seedlings) accounted for 45.2% of the total population, the second age class (small saplings) accounted for 25.3%, and the third age class (large saplings) accounted for 15.6%. The fourth and fifth age classes (small and medium medium trees) accounted for 8.5% and 3.8% respectively, while the sixth age class (large medium trees) accounted for 1.2%. The seventh, eighth, and ninth age classes (mature trees) collectively accounted for only 0.4% of the total surveyed population. The overall trend of *Juniperus rigida* population diameter class structure showed that individual numbers first increased and then decreased with age. The population had abundant seedlings, numerous medium trees, and some seedlings could transition to the medium tree stage, though mature tree numbers were relatively small. The population structure exhibited a pyramid shape, indicating a growth-type pattern.

2.2 Population Static Life Table

The static life table compiled using space-for-time substitution () showed that *Juniperus rigida* individual survival numbers (Ax) increased from age class 1 to 2, decreased from class 2 to 3, increased again from class 3 to 4, and subsequently declined. Individual survival showed fluctuating changes with increasing age class. The death number (dx) was highest in the first age class and showed a decreasing trend thereafter. The mortality rate (qx) was approximately 0.5 across age classes, indicating that *Juniperus rigida* individuals possessed certain viability and adaptability. Life expectancy (ex) was highest in the first age class, with the most vigorous physiological capacity, showing a decreasing trend with age class, reflecting that the population approached physiological lifespan with age. The disappearance rate (Kx) did not exceed 0.7 with relatively small overall fluctuations. The survival rate (Sx) was not lower than 0.3, and the population overall had certain survival capacity, with the first age class showing the highest survival rate at 0.98.

2.3 Survival Curve Analysis

The *Juniperus rigida* population survival curve ([Figure 2: see original paper]) intuitively describes population mortality. Combined with the static life table, the first age class showed the lowest mortality, while the second age class showed the highest mortality. The survival curve type was convex spherical, with all individuals dying after reaching a certain physiological age. Deevey-I type is diagonal, with mortality at each age class being similar. Deevey-II type is concave, where populations easily die in youth and cannot survive to physiological lifespan. Using exponential and power function models for testing, the results were y = 7.2785e^{-0.155x} ($R^2 = 0.9987$, $P < 0.001$) and y = 6.2785x^{-0.155} ($R^2 = 0.9069$, $P < 0.001$) respectively. The *Juniperus rigida* population better fit the exponential function model, and the fitting results showed $P < 0.001$. Therefore, the survival curve of *Juniperus rigida* population can be considered to tend toward Deevey-II type.

2.4 Survival Analysis

Based on population succession, [Figure 3: see original paper] shows that *Juniperus rigida* population age class was negatively correlated with survival rate –higher age classes had lower survival rates, while cumulative mortality showed the opposite trend. The survival rate dropped sharply and mortality rose sharply between the first and second age classes, indicating certain competitive relationships and unstable survival. Approaching the sixth age class, the intersection point showed that survival rate equaled cumulative mortality, indicating that the *Juniperus rigida* population began a declining trend at this stage. The survival rate was relatively flat in the seventh age class, then declined sharply after the eighth age class, indicating that individuals entered the senescence period. As shown in [Figure 4: see original paper], the population mortality density curve was stable in the early stage, not exceeding 0.2, indicating a suitable survival environment. The hazard rate showed a downward trend in the first age class, a downward trend in the second age class, then began to increase monotonically. Overall, the *Juniperus rigida* population had strong adaptability in the early stage, relative stability in the middle stage, and subsequently entered the decline period.

2.5 Dynamic Quantitative Analysis

According to the *Juniperus rigida* population dynamic change index (), V_2 showed negative growth while others showed positive growth. The magnitude of dynamic index indicates the resistance to transformation between adjacent age classes, with the maximum dynamic index at V_3 (66.7%), followed by V_5 (50.0%). The population showed a "decline-growth-decline-growth" trend, with some age class stages showing decline trends. When ignoring external interference, the population dynamic index (V_{pi}) was 0.42, indicating that the *Juniperus rigida* population overall showed a growth-type pattern. When considering external interference (V' *{pi}), the dynamic index was 0.01, and the maximum probability of risk (P*{极大}) that the population could bear was 66.7%. This indicates that the *Juniperus rigida* population is environmentally sensitive, and growth is not obvious when subjected to external interference.

2.6 Time Series Prediction

Based on individual numbers in each diameter class, the time series model predicted *Juniperus rigida* population dynamics for the next 2, 4, and 6 age class periods (). The results showed that seedling numbers would decrease after 2, 4, and 6 age class periods, while medium tree and mature tree numbers would gradually increase. The increase was significant for the fourth and fifth age classes after 6 age class periods, with individual numbers increasing by 8.5% and 3.8% respectively. In summary, the *Juniperus rigida* population has abundant seedlings that show a certain decreasing trend in the future but provide numerous regeneration seedlings for the population. Medium trees and mature trees show increasing trends in the future, demonstrating a certain quantitative growth overall.

3 Discussion

3.1 *Juniperus rigida* Population Structure Characteristics

Population age structure reflects population quantitative dynamics and development trends [?]. In the loess hilly region, the natural *Juniperus rigida* population has 45.2% of individual numbers in the seedling stage, indicating certain regeneration capacity. Individual numbers in the medium tree stage account for 53.6% of the total, providing stability for the population. Mature tree individual numbers are relatively small, and the pyramid-shaped population structure indicates a growth-type pattern. Population dynamics research shows that except for decline trends between the second and third age classes, other age classes show growth-type patterns. Although decline trends appear between the sixth and seventh age classes, survival rate remains higher than mortality, with numbers still showing slow growth. The population dynamic change index V_{pi} > 0, consistent with the static life table research, indicating overall growth-type characteristics.

Population numbers concentrate in the seedling stage, with certain obstacles for seedlings transitioning to medium trees, similar to research on *Myricaria wardii* population structure in the Yarlung Zangbo River basin [?]. This results from the combined effects of biological characteristics and environmental factors [?]. *Juniperus rigida* seeds are large, heavy, and numerous. After maturation, seed dispersal is limited to the vicinity of the mother tree, and this reproductive characteristic creates small-scale aggregated distributions [?]. During the seedling stage when individuals are small, required environmental resources for growth and development are relatively minimal, and aggregated distribution facilitates mutual shelter. However, as seedlings gradually transition to the medium tree stage, under density-dependent effects, individuals compete for light while root systems compete for nutrients and water. Competition for resources at similar levels easily leads to decreased individual numbers [?], causing individual numbers in the sixth age class to decline slowly and the population to adapt to the environment and reach a stable state. The *Juniperus rigida* population overall shows a growth-type pattern, but under environmental factors and competition screening, the seedling stage cannot be largely converted to the medium age stage, resulting in reduced medium tree individual numbers. The young age stage is an important phase for *Juniperus rigida* population regeneration and development [?].

3.2 *Juniperus rigida* Population Dynamic Trends

Plant population quantitative dynamics result from the interaction between individual survival capacity and external environment [?]. Research shows that the static life table of *Juniperus rigida* population indicates that after environmental and competition screening, population numbers decrease across age classes, but the extinction rate is not large. Life expectancy decreases with increasing age class, with maximum life expectancy in the first age class. The seedling stage has abundant environmental resources, low competition, strong seedling adaptability, and good growth and development, ensuring the regeneration capacity of *Juniperus rigida* population [?]. The survival curve, validated by curve fitting, tends toward Deevey-II type, with similar mortality rates across age classes, consistent with research on *Betula albo-sinensis* population [?] and natural forests in the Greater Khingan Mountains [?].

Survival functions can reflect population growth and decline dynamics [?]. Research shows that survival rates between the first and second age classes are greater than cumulative mortality, with sufficient regeneration seedlings to compensate for deaths caused by environmental screening. Between the sixth and seventh age classes, survival rate equals cumulative mortality, reaching a dynamic balance state, after which the population enters decline. Space and resource allocation are the main factors entering the decline period [?]. In limited space, *Juniperus rigida* requires increased nutrients for survival, and insufficient resources provided by the habitat lead to later-stage decline [?]. The mortality density of *Juniperus rigida* population is stable with a suitable survival environment, while hazard rates gradually increase in the later stage, indicating obstacles in the mature tree stage related to physiological lifespan and high mortality risk in the old age period. This is similar to research results on *Myrica nana* population structure and dynamics in central Yunnan [?], showing strong early-stage survival capacity, relative middle-stage stability, and subsequent physiological decline.

Dynamic quantitative analysis of *Juniperus rigida* population shows that growth is not obvious when subjected to external interference, with certain sensitivity to random disturbances. Individual numbers show an increasing trend, and under good environmental conditions, the population will show quantitative growth within a certain period. The population shows no sharp decline trend in the short term, but without protection, it is at risk of decline. It is recommended to intensify scientific protection of seedlings, establish nature reserves, implement soil and water conservation bioengineering, and enable the population to play a role in ecological restoration in loess hilly areas.

3.3 Time Series Prediction of *Juniperus rigida* Population

According to time series prediction, individual numbers in the first age class will decrease after 2, 4, and 6 age class periods, while individual numbers in the fourth and fifth age classes will increase after 2, 4, and 6 age class periods. Individual numbers in the young stage decrease, while medium trees and mature trees will dominate in the future, similar to time series predictions for natural regeneration *Pinus koraiensis* seedling populations in the Liaodong mountainous area [?] and extremely small populations of wild plant *Sinojackia microcarpa* [?]. Field investigations show that adult *Juniperus rigida* have large crowns, and complex distance-dependent relationships exist between seedlings and mother trees. The reason may be that seedlings are restricted by mother tree effects in closed vegetation types [?], leading to reduced seedling numbers. However, the death of a few old individuals helps seedling growth and development, promoting population regeneration and development and forming a dynamic cycle. Under good environmental conditions, the total *Juniperus rigida* population will show growth in the future.

Juniperus rigida is one of the main afforestation tree species in arid regions. The loess hilly area has crisscrossing gullies, arid climate, serious soil erosion, and developed local mining and overgrazing. *Juniperus rigida* populations play important roles in windbreak and sand fixation, water source conservation, and climate regulation. The population will not move toward catastrophic decline in the short term, but without protection, it is at risk of decline. It is recommended to increase scientific efforts for in-situ seedling protection, establish nature reserves, implement soil and water conservation bioengineering, and enable the population to play a role in ecological restoration in loess hilly areas.

4 Conclusion

The *Juniperus rigida* population structure is pyramid-shaped, with the young stage determining population regeneration and development, and overall showing quantitative growth-type characteristics. The survival curve tends toward Deevey-II type with stable mortality rates. The population age class is negatively correlated with survival rate—higher age classes have lower survival rates, while cumulative mortality shows the opposite trend. The *Juniperus rigida* population has strong adaptability in the early stage, relative stability in the middle stage, and gradually enters the decline period in the later stage. Quantitative dynamic analysis shows that growth is not obvious when subjected to external interference, with certain sensitivity to random disturbances. Under good environmental conditions, individual numbers show an increasing trend, and the population will show quantitative growth within a certain period. The *Juniperus rigida* population shows no sharp decline trend in the short term, and scientific protection of seedlings is recommended to facilitate ecological restoration.

References

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Note: Figure translations are in progress. See original paper for figures.