Population Structure and Dynamics of Natural Juniperus rigida in the Loess Hilly Region (Postprint)

Authors: Song Jiajia1, Li Gangtie 1, Guo Jingjie1, Gu Zhonghou2, 刘坤 2, Zhilong Li 3, Kang Xia 4

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Abstract

This study examined the natural Juniperus rigida population in the loess hilly region of Inner Mongolia, analyzing population structure and dynamics through static life tables, survival functions, dynamic quantitative analysis, and time series models. The results indicated that seedlings constituted the majority of individuals, followed by medium-sized trees, with adult trees being the least numerous. In conjunction with the population quantitative dynamic index Vpi > 0, the population was classified as increasing type. Survival curve validation via curve models demonstrated a tendency toward Deevey-II type, indicating stable age-specific mortality rates. When external disturbances were considered, the dynamic index approached 0, suggesting negligible population growth under disturbed conditions. Survival function analysis revealed a pattern of strong early-stage survival, mid-stage stability, and gradual decline in later stages. Projections for 2–8 age class intervals into the future showed a decrease in seedlings and increases in both medium-sized trees and adult trees. The seedling stage plays a decisive role in population regeneration and development; thus, scientific protection measures for seedlings are recommended to facilitate population renewal. 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 foundation for vegetation conservation and restoration in the loess hilly region.

Full Text

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

SONG Jiajia[1], LI Gangtie[1], GUO Jingjie[1], GU Zhonghou[2], LIU Kun[2], LI Zhilong[3], KANG Xia[4]

[1]Desert Science and Engineering College, Inner Mongolia Agricultural University, Hohhot 010018, Inner Mongolia, China
[2]Ordos Forestry and Grassland Development Center, Ordos 017000, Inner Mongolia, China
[3]Ordos Forestry and Grassland Survey and Inspection Center, Ordos 017000, Inner Mongolia, China
[4]Ejin Horo Banner Water Conservancy Technology Service Center, Ejin Horo Banner 017200, Inner Mongolia, China

Abstract

This study investigated the natural *Juniperus rigida* population in the loess hilly region of Inner Mongolia, analyzing its structure and dynamics through static life tables, survival functions, dynamic quantitative analysis, and time series modeling. The results revealed that seedlings constituted the majority of individuals, followed by medium-sized trees, with mature trees being the least abundant. Combined with the population dynamics index Vpi > 0, the population exhibited a growth-type pattern. Survival curve validation using model fitting indicated a Deevey-II type curve, suggesting stable mortality across age classes. When external disturbances were considered, the dynamic index approached 0, indicating negligible growth under interference conditions. Survival function analysis demonstrated strong early-stage survival, relative stability during mid-stage, and gradual decline in later stages. Over subsequent age classes, seedling numbers decreased while medium and mature trees increased. The seedling stage proved critical for population regeneration and development, warranting scientific protection measures to facilitate population renewal. This research on the intrinsic mechanisms of *Juniperus rigida* populations enriches vegetation restoration strategies in arid regions, provides references for population management, and offers theoretical foundations for vegetation conservation and restoration in loess hilly areas.

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

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 patterns of different individuals within a population, revealing quantitative dynamics and development trends while demonstrating the population's ecological status in its environment. Research based on diameter class structure and static life tables facilitates understanding the relationship between plant biological characteristics and habitat conditions, providing crucial theoretical guidance for plant resource conservation and utilization.

Juniperus rigida, belonging to the Cupressaceae family and *Juniperus* genus, is an evergreen shrub or small tree that thrives in relatively arid regions. As an important species in China's loess hilly areas adjacent to the Yellow River basin, it plays an extremely significant role in soil and water conservation, including soil retention, sand fixation, and water source conservation. Recent research has extensively focused on essential oil development and utilization, seedling cultivation techniques, and reproductive characteristics, with most scholars investigating cultivation technologies. While studies have examined phenotypic diversity and allelopathic effects, investigations of natural *Juniperus rigida* forest populations remain scarce. The loess hilly region of Inner Mongolia, located deep inland with scarce precipitation and ecologically sensitive and fragile conditions, faces severe threats to *Juniperus rigida* forest productivity due to mining development and logging activities, making population maintenance critical for ecosystem stability in the region.

1.1 Study Area Overview

The study area is located in Xiyingzi, eastern Ordos City, southwestern Inner Mongolia (110°05 –111°27 E, 39°16 –40°20 N), characterized by typical loess hilly-gully geomorphology, surrounded by Yellow River bends on the west, north, and east. Elevations range from 1200–1400 m. The region experiences a continental climate deep inland, influenced by seasonal winds with southerly or easterly winds in summer and northwesterly winds from autumn to spring. The mean annual temperature is 8.7 °C with a diurnal temperature range of 14.1 °C. The area enjoys abundant solar energy resources with 1710 sunshine hours annually. Precipitation varies significantly, concentrated in specific periods, with an average annual precipitation of 400 mm. Soils are predominantly chestnut.

1.2 Sample Plot Establishment

At the end of the month, typical sample plots with natural *Juniperus rigida* distribution were selected through remote sensing imagery combined with field surveys. Representative sites within the plots were chosen, establishing three transects with equally spaced 20 m × 20 m quadrats distributed across upper, middle, and lower slope positions (totaling quadrats). The first transect was located at 110°41 E, 39°28 N, 1160–1220 m elevation; the second at 110°41 E, 39°28 N, 1140–1245 m; and the third at 110°41 E, 39°28 N, 1140–1230 m. Data collected for each *Juniperus rigida* individual included basal diameter, height, crown width, and health status, while 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 destructively sampled for age determination and have needle-like foliage, this study used diameter class structure based on basal diameter as a proxy for age structure. The diameter classes were defined as: $X < 2$ cm, 2 cm $\leq X <$ 5 cm, 5 cm $\leq X <$ 10 cm, 10 cm $\leq X <$ 15 cm, 15 cm $\leq X <$ 20 cm, 20 cm $\leq X <$ 25 cm, 25 cm $\leq X <$ 30 cm, and 30 cm $\leq X <$ 35 cm. The first three classes represented seedlings, subsequent classes represented medium trees, and the final class represented mature trees.

1.4 Static Life Table

Static life tables provide an effective method for studying population dynamics by investigating age structure at a specific time. Following Dong Lingbo and Wu Chengzhen's methodology, the static life table was compiled using space-for-time substitution. The table revealed that individual survival numbers increased from early to middle age classes, then decreased. Mortality numbers (dx) peaked at specific age classes before declining. Mortality rates (qx) remained around certain values, indicating viable and adaptable individuals. Life expectancy (ex) reached its maximum at particular age classes when physiological capacity was strongest, decreasing with age as the population approached physiological longevity. Disappearance rates (Kx) remained low with minimal fluctuation, while survival rates (Sx) stayed above certain thresholds. Overall, the population showed strong early-stage adaptability, mid-stage stability, and subsequent decline.

1.5 Population Dynamics Quantification

Following Chen Xiaode's methodology, dynamic quantitative analysis was employed to quantitatively describe *Juniperus rigida* population structure and reflect dynamic relationships between adjacent age classes. The formulas are:

$$Vn = (An - An+1) / (An + An+1) \times 100$$

$$Vpi = (1/k)\ \Sigma|Vn| \text{ from } n=1 \text{ to } k-1$$

$$V'pi = (1/k)\ \Sigma|Vn| \text{ from } n=1 \text{ to } k-1 - (1/k)\ |Vn|$$

$$P\ \text{极大} = \max(|Vn|)$$

Where: Vn represents dynamic changes in individual numbers across diameter classes; An represents individual numbers in each diameter class; Vpi represents population dynamics ignoring external interference; k represents total number of diameter classes; V'pi represents population dynamics considering future external interference; and P 极大 indicates maximum impact on population dynamics. Positive Vn, Vpi, and V'pi values indicate population growth, negative values indicate decline, and zero indicates stability.

1.6 Time Series Model

A first-order moving average method was used to predict population age structure. The calculation formula is:

Mt(1) = (1/n) ΣXk from k=t to t+n-1

Where: n represents the prediction time period; t represents diameter class; Xk represents individual numbers in class k; and Mt(1) represents predicted numbers after n diameter classes. This study predicted population dynamics over 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, the first age class accounted for % of total individuals, with the second age class (slightly larger seedlings) comprising %. Age classes 3–6 represented medium trees, with class 4 comprising the largest proportion at %. Age class 7 represented mature trees with the smallest proportion at %. The overall diameter class structure showed individual numbers initially increasing then decreasing with age, with abundant seedlings and medium trees, though some seedlings could transition to medium tree stage while mature trees remained scarce. The population structure exhibited a pyramid shape characteristic of growth-type populations.

[Figure 1: see original paper]

2.2 Population Static Life Table The static life table (Table 1) revealed that individual survival numbers increased from class 1 to 4, decreased from class 5 to 6, increased in class 7, then declined again, showing fluctuating survival patterns across age classes. Mortality numbers (dx) peaked in class 1 then decreased progressively. Mortality rates (qx) remained around %, indicating certain viability and adaptability across all classes. Life expectancy (ex) reached its maximum in class 1 when physiological capacity was strongest, decreasing with age as populations approached physiological limits. Disappearance rates (Kx) remained below with minimal overall fluctuation, while survival rates (Sx) stayed above %. In summary, the population demonstrated strong early-stage adaptability, mid-stage relative stability, and subsequent gradual decline.

2.3 Survival Curve Analysis The survival curve (Figure 2) visually describes population mortality patterns. Combined with the static life table, class 1 showed the lowest mortality while class 2 showed the highest. The Deevey-II survival curve type represents a diagonal line with relatively uniform mortality across age classes. Exponential and power function models were used for validation, yielding y = 7.2785e^(-0.155x) (R^2 = 0.9987) and y = 6.4631x^(-0.9069) (R^2 = 0.9069) respectively. The population better fit the exponential function model ($P < 0.001$), indicating the survival curve tended toward Deevey-II type with stable mortality across age classes.

[Figure 2: see original paper]

2.4 Survival Analysis Based on population succession patterns, Figure 3 shows a negative correlation between age class and survival rate, with survival rates decreasing as age class increased, while cumulative mortality showed the opposite trend. Survival rates dropped sharply and mortality rose dramatically between certain age classes, indicating competitive relationships and unstable survival conditions. The intersection point near specific age classes showed where survival and mortality rates balanced, marking the transition to population decline. Survival rates remained relatively stable in middle age classes before declining sharply after class 6, indicating entry into senescence. Figure 4 reveals that the death density curve peaked in class 1 then decreased, remaining low with minimal fluctuation, indicating suitable survival environments. The risk rate curve decreased in class 1, increased in class 2, showed a slight decrease in class 3, then increased monotonically, with overall function values not exceeding . In conclusion, the *Juniperus rigida* population possessed certain survival capabilities, with strongest adaptability in early stages, relative mid-stage stability, and subsequent entry into decline.

[Figure 3: see original paper]

[Figure 4: see original paper]

2.5 Dynamic Quantitative Analysis Population dynamic change indices (Table 2) showed negative growth values only for specific transitions, with positive growth for all others. Dynamic index magnitude indicates resistance to transition between adjacent age classes, with maximum resistance occurring between classes 1–2 at %, followed by transitions between classes 2–3 and 5–6. The population showed decline trends between classes 1–2 and 5–6, but growth trends in other classes, exhibiting an overall "decline-growth" pattern. Some age stages showed decline trends, but when external interference was ignored, the overall dynamic index (Vpi) was , indicating growth-type characteristics. When external interference was considered (V'pi), the dynamic index was , suggesting the population is sensitive to environmental impacts with negligible growth under disturbance. The maximum risk probability (P 极大) was %, confirming environmental sensitivity.

2.6 Time Series Prediction Based on individual numbers in each diameter class, time series prediction indicated that seedling numbers (classes 1–2) would decrease after 2, 4, and 6 age class periods, while medium and mature tree numbers would increase over time. Class 3 individuals showed significant increases after 2 and 4 periods. In summary, the *Juniperus rigida* population has abundant seedlings that will show a decreasing trend in the future but provide substantial regeneration stock, while medium and mature trees will increase, demonstrating overall population growth under favorable environmental conditions.

3 Discussion

3.1 Population Structure Characteristics Population age structure reflects quantitative dynamics and development trends. In the loess hilly region, % of natural *Juniperus rigida* individuals were seedlings, indicating adequate regeneration capacity. Medium trees accounted for % of total individuals, providing population stability, while mature trees were relatively scarce. The pyramid-shaped structure represents a growth-type population. Dynamic analysis revealed decline trends only between specific age classes, with growth trends in others. Although decline occurred between some classes, survival rates exceeded mortality rates, maintaining slow growth. The overall dynamic index Vpi > 0 confirms growth-type characteristics, consistent with static life table results. The concentration of individuals in the seedling stage creates certain obstacles for transition to medium tree stage, similar to findings for *Myricaria wardii* populations in Yarlung Zangbo River tributaries—a result of combined biological characteristics and environmental factors. *Juniperus rigida* produces large, heavy seeds in large quantities that primarily disperse near maternal plants, creating small-scale aggregated distributions. Seedlings require relatively fewer environmental resources, and aggregated distribution facilitates mutual protection. However, as seedlings transition to medium trees, density-dependent competition for light, nutrients, and water intensifies, causing individual numbers to decline. After this bottleneck, individual numbers in middle age classes decline slowly as the population adapts and stabilizes. Overall, the *Juniperus rigida* population shows growth-type characteristics, but environmental filtering and competition prevent massive seedling conversion to middle age classes, making the seedling stage crucial for population renewal and development.

3.2 Population Dynamic Trends Plant population dynamics reflect interactions between individual survival capacity and environmental conditions. Static life tables showed that after environmental and competitive filtering, population numbers decreased but extinction rates remained low. Life expectancy decreased with age class, peaking in class 1 when environmental resources were abundant, competition was minimal, and seedlings showed strong adaptability and growth, ensuring population regeneration capacity. Survival curve validation indicated a Deevey-II type with relatively uniform mortality across age classes, consistent with studies on *Betula albo-sinensis* populations and natural forests in the Greater Khingan Mountains. Survival function analysis revealed strong early-stage survival capacity, mid-stage stability, and gradual later-stage decline, aligning with population structure research. Studies show that survival rates exceeded cumulative mortality between certain age classes, with adequate regeneration stock to compensate for environment-induced mortality. The intersection point where survival equaled cumulative mortality marked dynamic equilibrium, after which the population entered decline phase—primarily due to space and resource allocation limitations. In limited space, increasing nutritional requirements could not be fully met by the habitat, leading to decline. Death density remained stable with suitable environments, while risk rates increased in later stages, indicating obstacles in mature tree stages related to physiological longevity and high mortality risk in old age, similar to *Myrica nana* populations in central Yunnan. The population possesses certain survival capabilities, with strong early adaptability, mid-stage stability, and subsequent physiological decline. Dynamic quantitative analysis showed that growth was not obvious under external interference, indicating sensitivity to random disturbances. Individual numbers will increase under favorable environmental conditions, showing overall growth within a certain timeframe. The population shows no sharp decline trend in the short term, but protection measures are recommended to prevent future decline risk.

3.3 Time Series Prediction Time series predictions indicated that class 1 individuals would decrease after 2, 4, and 6 age class periods, while class 2 individuals would also decline over time. Seedling stage individual numbers decreased, while medium and mature trees showed increasing trends and would dominate the future population, similar to predictions for natural *Pinus koraiensis* seedling populations in eastern Liaoning and extremely small populations of *Sinojackia microcarpa*. Field observations revealed that mature *Juniperus rigida* have large crowns, creating complex distance-dependent relationships with seedlings that may restrict seedling growth under closed canopies through maternal effects. However, death of a few old individuals could facilitate seedling development and promote population renewal, creating a dynamic cycle. Under favorable environmental conditions, the total population will increase in the future. As a primary afforestation species in arid regions, *Juniperus rigida* plays important roles in windbreak and sand fixation, water conservation, and climate regulation in the loess hilly region with its severe water erosion and harsh climate. Combined with local mining development and overgrazing, the population faces significant pressures. While not facing catastrophic decline in the short term, it remains at risk without protection. We recommend intensifying scientific protection of seedlings, establishing nature reserves, implementing soil and water conservation biological projects, and enhancing ecological restoration efforts in loess hilly areas.

4 Conclusion

The *Juniperus rigida* population exhibits a pyramid-shaped structure where the seedling stage determines population renewal and development, showing overall growth-type quantitative characteristics. The survival curve follows Deevey-II type with stable mortality rates. Age class shows negative correlation with survival rate—higher age classes have lower survival rates, while cumulative mortality shows the opposite trend. The population demonstrates strong early-stage adaptability, mid-stage stability, and gradual later-stage decline. Dynamic quantitative analysis reveals that growth is not obvious under external interference, showing sensitivity to environmental disturbances. Individual numbers show increasing trends, and under favorable environmental conditions, the population will exhibit quantitative growth within a certain timeframe. The population shows no sharp decline trend in the short term, but scientific seedling protection is recommended to support ecological restoration.

References

[References are preserved as originally formatted in the Chinese text, with author names, years, titles, and publication details maintained in their original form to ensure accurate citation.]

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