Postprint: Fractal Structure of Elymus nutans Root Systems under Different Density Conditions in Gahai Wetland

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Abstract

Root fractal structure influences root distribution patterns and represents the result of mutual adaptation between plant root systems and stressful habitats. Employing a combined method of whole-root excavation and Win-RHIZO root analyzer, and establishing three density gradients based on Elymus nutans population density—namely I (500-700 plants/m^2), II (300-500 plants/m^2), and III (100-300 plants/m^2)—this study examined the root fractal structure of Elymus nutans in Gahai Wetland under varying density conditions. The results indicated that with decreasing population density of Elymus nutans, the height, coverage, aboveground biomass, and root fractal dimension of the wetland community exhibited a gradual decreasing trend, while belowground biomass and fractal abundance progressively increased. The root fractal dimension and fractal abundance of Elymus nutans showed an extremely significant negative correlation ($P<0.01$) in both high-density (I) and low-density (III) plots, and a significant negative correlation ($P<0.05$) in medium-density (II) plots, demonstrating a trade-off relationship between root fractal dimension and fractal abundance. In high-density wetland communities, Elymus nutans tended toward an intensive root architecture construction mode, while in low-density wetland communities it adopted an extensive root growth pattern, reflecting the ecological adaptation mechanism of alpine wetland plant populations in response to multiple resource competition under density-dependent constraints.

Full Text

Preamble

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Fractal Root Systems of *Elymus nutans* under Different Density Conditions in Gahai Wetland

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Abstract

Root fractal architecture influences the spatial distribution patterns of root systems and represents an adaptive response of plant roots to stressful habitats. This study examined the relationship between root fractal dimension and root fractal abundance of *Elymus nutans* in response to population density in the Gahai Wetland of Gansu Province, China (102.08°-102.47° E, 33.97°-34.32° N). The study site, located at 3,430–4,300 m elevation, has an average annual temperature of 2.3°C. Sixty 1 m $\times$ 1 m quadrats were established along riverbanks in August 2016 to investigate *E. nutans* density across three density gradients: high (I: 500-700 plants/m^2), medium (II: 300-500 plants/m^2), and low (III: 100-300 plants/m^2). Community height, coverage, aboveground biomass, and root fractal dimension decreased significantly with declining density, whereas belowground biomass and fractal abundance increased. Root fractal dimension and fractal abundance showed a significant negative correlation across the alpine wetland ($P < 0.05$), with highly significant negative correlations observed in both high-density (I) and low-density (III) plots ($P < 0.01$). In high-density wetland communities, *E. nutans* adopted a compact root architecture strategy, while in low-density communities it exhibited a diffuse root growth pattern, demonstrating density-dependent ecological adaptation mechanisms for coping with multiple resource competition in alpine wetlands.

Keywords: density; root architecture; *Elymus nutans*; fractal dimension; fractal abundance; Gahai Wetland

Introduction

Root systems are critical vegetative organs for nutrient absorption and energy transport in plants. Their branching patterns and architectural characteristics determine how roots are distributed in soil, their resource acquisition strategies, and their capacity to support aboveground growth. Fractal abundance and fractal dimension are key parameters describing root fractal architecture. Fractal abundance reflects root distribution density, spatial expansion range, and resource competition capacity—higher fractal abundance indicates greater main root development, larger distribution ranges, and stronger support, transport, and spatial occupation capabilities. Fractal dimension characterizes root spatial distribution morphology, branching capacity, and developmental degree, directly influencing physiological functions and soil resource utilization efficiency. Plants with higher root fractal dimension typically possess complex branching structures, relatively well-developed lateral roots, higher biomass accumulation, and tend toward horizontal growth.

The close relationship between fractal abundance and fractal dimension comprehensively reflects a plant’ s nutrient absorption and transport capacity, resource utilization efficiency, and carbon consumption characteristics during root growth. Density represents a ubiquitous selective pressure in natural ecosystems that influences how plants acquire available resources and directly determines root colonization and proliferation. As population density increases, plants experience crowding effects from neighboring individuals through physical or geometric interference, causing varying degrees of shading and competition intensity. This prompts active adjustments in the function and status of exchange and compensation-related traits. Roots respond to shading and competition by adjusting biomass allocation between main and lateral roots, altering morphology and physiological reactions, and promoting optimal resource allocation among key traits such as fractal dimension and fractal abundance, thereby enhancing survival and competitive ability in heterogeneous environments.

Studying root fractal architecture patterns under different density conditions is crucial for understanding plant resource allocation mechanisms and ecological adaptation strategies in varying habitats. *Elymus nutans*, a perennial herb of the Poaceae family, is a dominant species in alpine wetlands. While previous research has systematically investigated plant root functional traits—including spatial heterogeneity, habitat adaptation, topological structure, fractal characteristics, slope aspect responses in trade-offs between root bifurcation number and branching angle, and root architecture differences—studies on *E. nutans* community structure, root morphology, biomass allocation, and density effects on growth have been extensive. However, research on root architecture construction patterns remains insufficient, particularly regarding how root fractal structures respond to heterogeneous resource allocation under different density conditions in alpine wetlands.

Based on field investigations, this study addresses three key questions: (1) the relationship between root fractal abundance and fractal dimension of *E. nutans* under different density conditions in alpine wetlands; (2) the underlying causes of density-dependent changes in these parameters; and (3) the theoretical basis for understanding ecological adaptation of alpine wetland plant populations.

1. Study Area and Site Description

The study area is located in Gahai Wetland, Luqu County, Gannan Tibetan Autonomous Prefecture, Gansu Province (102.08°-102.47° E, 33.97°-34.32° N). Situated on the northeastern edge of the Qinghai-Tibet Plateau in a transitional zone to the Longnan Mountains and Loess Plateau, this region represents a typical alpine wetland with a cold, humid climate. The elevation ranges from 3,430 to 4,300 m, with an average annual temperature of 2.3°C and annual precipitation of 781.8 mm. Soils are primarily subalpine meadow soil, dark meadow soil, and peat soil. Dominant plant species include *Kobresia tibetica*, *Ligularia virgaurea*, *Blysmus sinocompressus*, *Polygonum viviparum*, and *Aster tataricus*.

2. Community Survey and Plant Sampling

In August 2016, we selected a relatively uniform elevation area where *E. nutans* density decreased gradually from riverbanks to surrounding gentle slopes. A 200 m horizontal transect was established perpendicular to the riverbank, along which sixty 1 m × 1 m quadrats were set at equal distances in a zigzag pattern. The transect was divided into three density gradients: high (I: 500-700 plants/m^2), medium (II: 300-500 plants/m^2), and low (III: 100-300 plants/m^2), with six replicates per gradient.

For each quadrat, we measured plant density, height, coverage, and aboveground biomass. Soil compaction was measured using an SC-900 Soil Compaction Meter with five replicates per quadrat. Root samples were collected using an XDB-12 Root Sampler. Observations via trenching revealed that *E. nutans* root systems had a maximum spread of 30 cm and were primarily distributed in the 0-10 cm soil layer.

To obtain complete root systems, we excavated soil cores (30 cm × 30 cm × 50 cm) from six 30 cm × 30 cm subplots within each density gradient. Roots were sieved (mesh size = 0.25 mm) and cleaned in a nearby river, then transferred to the laboratory. In the lab, root samples were scanned using Win-RHIZO (Pro 5.0, Regent Instruments, Canada) to measure root fractal dimension and abundance. Biomass was measured after oven-drying at 105°C for 12 hours, while soil moisture content was determined by oven-drying at 84°C for 24 hours.

For fractal analysis, we used the box-counting method: root distribution images were overlaid with grids of varying side length (r), and the number of squares intersecting roots (Nr) was counted. The relationship Nr r^(-FD) was established, where FD (fractal dimension) equals the negative slope of the log(Nr) vs. log(r) regression line, and K represents fractal abundance. Main and lateral roots were separated using Pregitzer' s ordinal classification system.

3. Results

3.1 Community Characteristics and Soil Physical Properties under Different Densities

Community characteristics and soil physical properties varied significantly among density treatments (Table 1). As density decreased from high (I) to low (III), plant height, coverage, and aboveground biomass decreased by 42.19%, 32.29%, and 58.30%, respectively ($P < 0.05$). Conversely, soil compaction increased by 27.59% while soil moisture content decreased by 27.74% ($P < 0.05$), showing opposite trends.

Community characteristics and soil physical properties under different densities (mean±SE)

Density	Plant height (cm)	Coverage (%)	Aboveground biomass (g/m²)	Soil moisture content (%)	Soil compaction (MPa)
I (500-700 plants/m²)	76.54±0.65a	96±2.45a	467.98±8.41a	26.21±0.61a	1.16±0.03c
II (300-500 plants/m²)	65.76±0.88b	82±3.43b	279.84±3.92b	22.90±0.70b	1.23±0.03b
III (100-300 plants/m²)	44.25±0.53c	65±1.06c	195.15±1.51c	18.94±0.54c	1.48±0.04a

Note: Different lowercase letters within columns indicate significant differences among densities ($P < 0.05$).

3.2 Biological Characteristics of *E. nutans* under Different Densities

All biological characteristics of *E. nutans* differed significantly among density treatments (Table 2). As population density decreased from high to low, plant height and coverage decreased gradually, while root-shoot ratio and main-to-lateral root ratio showed opposite trends, increasing significantly. From high-density (I) to low-density (III) plots, height and coverage decreased by 42.32% and 66.30%, respectively, whereas root-shoot ratio and main-to-lateral root ratio increased by 19.85%, 25.45%, and 26.45%, respectively ($P < 0.05$).

Biological characteristics of *E. nutans* under different densities (mean±SE)

Density	Plant height (cm)	Coverage (%)	Root biomass (g/m²)	Root-shoot ratio	Main-to-lateral root ratio
I (500-700 plants/m²)	74.20±1.86a	92.00±2.04a	55.56±1.50c	0.22±0.04c	1.55±0.08c
II (300-500 plants/m²)	53.00±1.52b	77.00±0.80b	59.76±1.70b	0.36±0.02b	1.71±0.01b
III (100-300 plants/m²)	42.80±1.28c	31.00±0.18c	66.59±2.31a	0.78±0.07a	1.96±0.06a

Note: Different lowercase letters within columns indicate significant differences among densities ($P < 0.05$).

3.3 Root Fractal Characteristics under Different Densities

One-way ANOVA revealed significant differences in both root fractal dimension and fractal abundance among density treatments ($P < 0.05$). As density decreased, root fractal dimension decreased gradually (16.88% reduction from high- to low-density plots), while root fractal abundance showed the opposite trend, increasing by 31.61% from high- to low-density plots. This indicates that *E. nutans* root architecture shifted from compact to diffuse as density decreased.

[Figure 1: see original paper] Changes in fractal dimension and fractal abundance of *E. nutans* roots under different densities (mean±SE). Different lowercase letters indicate significant differences ($P < 0.05$).

3.4 Relationship between Root Fractal Dimension and Fractal Abundance

Correlation analysis showed a highly significant negative correlation between root fractal dimension and fractal abundance in both high-density (I) and low-density (III) plots ($P < 0.01$), and a significant negative correlation in medium-density (II) plots ($P < 0.05$). Standardized major axis slopes of the regression equations differed significantly among density gradients ($P < 0.05$). The slope was steepest in high-density plots, indicating that fractal dimension decreased faster than fractal abundance increased. In contrast, low-density plots showed a shallower slope, suggesting greater soil exploration capacity per unit decrease in fractal dimension.

[Figure 2: see original paper] Relationship between fractal dimension and fractal abundance of *E. nutans* roots under different densities (mean±SE).

4. Discussion

During growth and development, plants allocate resources among different functional traits to form phenotypic characteristics adapted to heterogeneous habitats, thereby enhancing risk avoidance capacity. Root systems adjust their distribution range and resource acquisition strategies through fractal architecture, enabling self-compensation and renewal. This study found that as *E. nutans* population density decreased, root fractal dimension decreased while fractal abundance increased, revealing a trade-off relationship between these traits across the density gradient. This trade-off reflects how alpine wetland plants adjust above- and below-ground modules and biomass allocation patterns between main and lateral roots in response to habitat stress.

Differences in root architecture construction arise from the coordinated relationship between photosynthate investment and underground resource acquisition capacity. In high-density wetland communities, adequate soil moisture and low compaction favor root development. *E. nutans* communities exhibited maximum height and aboveground biomass, with intense internal shading. To avoid competition from larger neighbors and acquire more light resources, plants allocated more biomass to aboveground growth while limiting underground investment, constructing a compact root system with high fractal dimension but low fractal abundance. This strategy suppressed main root growth, reduced spatial distribution range, and decreased resource investment in support and transport systems, thereby alleviating inter-root competition while optimizing the balance between water/nutrient absorption and carbohydrate consumption.

In low-density plots, reduced community height, coverage, and biomass minimized shading, requiring less stem-leaf investment to meet photosynthetic demands. However, lower soil moisture and higher compaction constrained root growth. *E. nutans* responded by limiting aboveground biomass allocation and increasing investment in main roots, constructing an extensive root system with high fractal abundance and low fractal dimension. This foraging strategy expanded spatial occupation, enhanced support and transport functions, and enabled more efficient water utilization. By reducing branching intensity and increasing fractal abundance, plants avoided root overlap within populations, reduced competition among fine roots, and improved habitat suitability.

Medium-density plots represented a transitional state where community height, biomass, and soil properties were intermediate. To adapt, *E. nutans* balanced support, transport, and absorption functions, resulting in fractal dimension and abundance values between those of high- and low-density plots. This intermediate strategy aligns with findings from studies on other species and demonstrates how plants shape architecture and adjust adaptively in heterogeneous environments.

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5. Conclusion

In Gahai Wetland, *E. nutans* exhibits contrasting investment patterns in root fractal dimension versus fractal abundance under different density conditions. In high-density plots, the species increases fractal dimension while decreasing fractal abundance, constructing a compact root system that reflects a life-history strategy of habitat co-adaptation and stress avoidance. In low-density plots, *E. nutans* adopts the opposite strategy—increasing fractal abundance while decreasing fractal dimension—to expand root spatial extension and reduce internal root crowding. These divergent root architecture strategies validate the mechanism by which plants adjust plastic traits in response to environmental variation. Future research should examine additional factors such as topography and grazing disturbance to further elucidate these patterns.

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