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# A SIMPLE METHOD FOR ESTIMATING ROOT SPATIAL DISTRIBUTION AND ROOT BIOMASS OF SHRUBS BASED ON GROUND-PENETRATING RADAR

*Luyun Zhang, Xihong Cui*

State Key Laboratory of Remote Sensing Science, Faculty of Geographical Science, Institute of Remote Sensing Science and Engineering, Beijing Normal University

## ABSTRACT

The spatial distribution and biomass of roots are the key parameters to reflect plant growth and development. The object of this study is to develop a simple method to estimate the spatial distribution and biomass of roots based on GPR data. First, we measured 58 individual full-root systems of *Caragana microphylla* Lam. by ground-penetrating radar (GPR). Second, we examined the root distribution pattern in horizontal direction using the logistic model. Three critical root traits (i.e., parameters of the logistic model) including total root biomass, active root accretion zone and root growth rate are extracted from the fitted logistic model. Finally, the relationship between canopy area and root traits was tested, which can be further utilized to estimate the root biomass and characterize the root spatial distribution in a large region. GPR is a high-throughput phenotyping tool that allows for the detection of the root spatial distribution and quantitative characteristics.

***Index Terms*—**Root distribution pattern, Root biomass, Logistic model, Ground penetrating radar

## 1. INTRODUCTION

The root system, a fundamental component of plant productivity, serves as an important bridge between aboveground and belowground [1]. The distribution characteristics of the root system reflect the potential of using the soil material, delivering nutrients, and storing carbon, which determines the productivity of the aboveground part [2]. Root biomass distribution serves as an indicator of the plant's adaptation to water and nutrient availability. It also plays a crucial role in various ecological models, including those associated with the nutrient uptake model, carbon allocation, regional carbon sequestration, and net productivity model [3]. Therefore, it is crucial to present an efficient method to characterize root spatial distribution pattern and estimate root biomass.

Under the influence of global warming and human activities, the distribution area of shrub ecosystems and bare ground is increasing in arid and semiarid grassland with harsh climatic conditions and a fragile ecological environment [4]. The negative impacts of shrub encroachment on arid and semiarid grasslands are also gradually increasing, including vegetation change and landscape fragmentation [5]. There is still a lack of research on arid and semiarid shrubs on a large scale due to the difficulty of conducting systematic surveys of scrub ecosystems [6]. Accordingly, clarifying the spatial distribution pattern and estimating the biomass of the shrub root system helps understand the shrub encroachment process in the ecological system. This study aims to clarify the roots' spatial distribution model and establish a correlation between canopy area and root spatial distribution characteristics of *C. microphylla.*

## 2. MATERIALS AND METHODS

### 2.1. Field Experiment

The study site is located in the Xilin Gol League (43°54'59" N, 116°12'21" E, alt: 988.5 m), Inner Mongolia Autonomous Region, China. For this study, 58 relatively isolated individual *C. microphylla* shrubs with different crown sizes were selected as measurable objects, ensuring no other shrubs were growing within a 4 m distance from their stems. Each selected shrub was measured standing in the natural condition with metric measuring tapes, including the long and short axis of the crown.

According to the characteristics of the root architecture system and combined with previous experience in root detection, we employed the field-portable dual-frequency GPR system RIS MF Hi-MOD (Ingegneria Dei Sistemi Inc., Pisa, Italy), with an antenna center frequency of 900 MHz. Ten or more concentric survey lines with 0.2m intervals were established around the stem of the shrub to define the GPR survey area. The radius of each survey line varied from 0.4 to 3 m (Fig. 1).

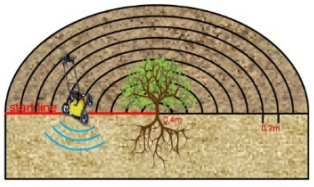

Fig. 1 Schematic diagram of the GPR survey line setting



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### 2.2. Data Processing

GPR data were processed using the RGPR package written in R, which includes first break correction, background removal, bandpass wave filtering, Automatic Gain Control (AGC), and travel time to depth [7, 8]. After radar image processing, the hyperbolic reflection signals of roots appeared on the radargrams. Following processing, the hyperbolic signals reflected by roots were automatically extracted using the enhanced YOLOv4 method [9]. The root counts were converted to dry root biomass using the model based on 900 MHz GPR data [10]. The original radar data and the relationship between radar signal and coarse root are also introduced in the previous study [10].

### 2.3. Logistic Model and Root System Traits Extraction

The Logistic model was used to characterize the root spatial distribution pattern of shrubs based on the GPR data (Fig. 3). In this study, the logistic model is employed to delineate the spatial distribution pattern of shrub root biomass in the horizontal direction, expressed as Eq. 1:

$$y = \frac{A}{1+be^{-kx}} \quad (1)$$

where y is the cumulative root biomass corresponding to the x range. x is the radial distance to the center of the shrub stem. A, b, k are constants that need to be obtained by fitting.

We extracted three root traits based on the parameters of the fitted logistic model. Parameter A represents the total biomass of the shrub root system. The active root accretion zone, calculated using lnb/k, represents a region with the most active root growth, exhibiting the highest root biomass in the horizontal direction. The root growth rate equal to parameter k, reflects the ability of roots to explore new soil resources. The ecological meaning of parameters is shown in Fig. 2.

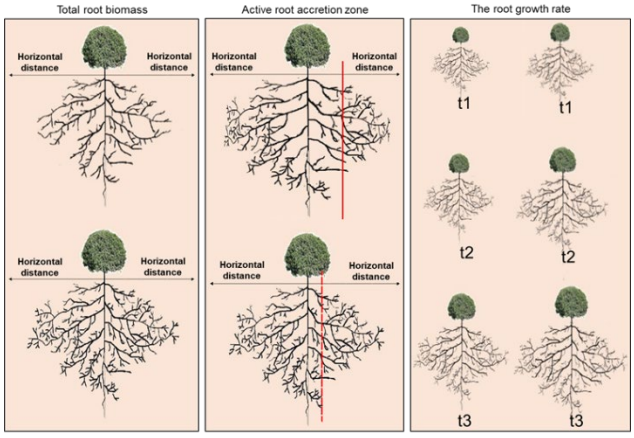


Fig. 2 Schematic diagram of the ecological meaning of logistic model parameters

### 2.4. Statistical analysis

We used the relationship between the canopy area and extracted root traits (i.e. parameters of the logistic model) to explore a method to effectively estimate the root traits and root spatial distribution, especially root biomass. In addition, the goodness-of-fit was compared based on the root mean squared error (RMSE), R-squared ($R^2$), Akaike information criterion (AIC), and Bayesian information criterion (BIC) performance metrics.

## 3. RESULTS

### 3.1. GPR measurement

A total of 58 shrubs were measured, with a canopy area ranging between 0.64 and 7.79 $m^2$ and a height between 0.5 and 1.79 m. The number of measuring lines varied from 10 to 14 based on the actual measurement and the size of the shrubs. GPR data could exhibit the distribution characteristics of shrub root systems. Taking two individual shrubs as examples, the first shrub has a crown width of 3.5 m, and the initial measurement radius for the GPR measurements is 1.2 m. The second shrub has a crown width of 2.3 m, and the initial measurement radius is 0.4 m. Although the distribution characteristics of the root system and the initial measurement distance varied among shrubs of different sizes, the distribution characteristics of roots can be effectively represented by the logistic model in the horizontal direction ($R^2$ =0.999 and 0.996, respectively) (Fig. 3).

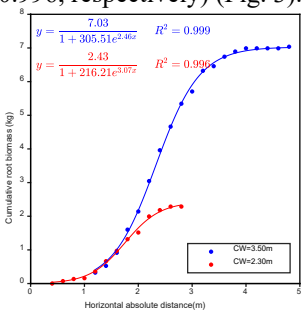


Fig 3 Cumulative root biomass varies with increasing horizontal absolute distance for two shrubs. Horizontal absolute distance is equal to radial distance from the stem.

### 3.2. Root distribution pattern

The models fitted to individual shrubs demonstrate great performance (mean $R^2$:0.99, mean RMSE:0.04, mean AIC: 37.79, mean BIC: 38.50). The curve illustrating cumulative root biomass distribution exhibits increased height and steepness with an expanding canopy area, indicating an increase in total root biomass. Logistic models have shown good performance in portraying the spatial distribution pattern of shrub root systems (Fig. 4). Thus, critical root system traits could be extracted from the fitted model.



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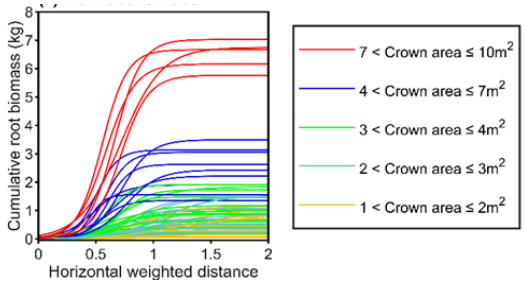


Fig. 4 Cumulative root biomass as a logistic function of horizontal distance for individual shrubs.

### 3.3. Root Biomass estimation

Critical root traits for 58 individual shrubs were directly extracted from the fitted logistic model presented in Fig. 4. These traits include the total root biomass, active root accretion zone, and root growth rate. These critical root traits are related to the parameters in the logistic model. The mean total root biomass and root growth rate were 1.45 kg and 3.64, respectively. The average crown radius is 0.99 m, indicating that the zone with the maximum root biomass is consistently located outside the crown (1.41 m > 0.99 m, 1.49 > 1).

The correlation between the canopy area and root traits in the horizontal direction is shown in Fig. 5. The results showed that with the increase in canopy area, the total biomass increased gradually, and the active accretion zone became more distant, with $R^2$ being 0.8 and 0.44 respectively. On the other hand, there is a negative correlation between the canopy area and the root growth rate, $R^2$ up to 0.14.

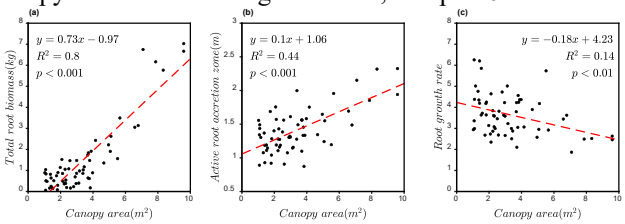


Fig. 5 Association between canopy area and (a) total root biomass (kg); (b) active root accretion zone (m); (c) root growth rate.

## 4. DISCUSSION

### 4.1. Effectiveness of Logistic Models in Characterizing Root Spatial Distribution Patterns

The logistic model is widely used in the study of individual and population size, quantity, and density of animals and plants. It has been employed to characterize the global patterns of root depth distribution across various vegetation types [11]. The belowground biomass of C. microphylla exhibited a similar pattern, increasing initially and then decreasing with depth [12]. While the logistic model has not been directly utilized to characterize the horizontal distribution of roots, several studies have reported a comparable trend in root abundance. A previous study observed that the root system acreage ($cm^2$) of caragana-grass compound systems increased and then decreased with the horizontal distance (m) from caragana bushes [13]. In this study, the use of the logistic model not only can accurately fit the changes of cumulative root biomass in the horizontal direction but also has certain ecological significance.

### 4.2. Advantages of Studies

In the process of analyzing the spatial distribution of the root system and the estimation of root biomass, the proposed method has the following advantages: (1) The logistic model reflects that the root system of *C. microphylla* is limited by species and environmental conditions, and its root system can not grow and expand indefinitely in space. (2) Previous studies often correlate the aboveground and underground characteristics of plants by directly measuring variables and analyzing the root-shoot ratio and biomass allocation strategies of plants. In this study, three root traits extracted indirectly from radar data were used to analyze the aboveground and underground correlation characteristics of shrubs from horizontal directions. (3) GPR increases the research scope and improves the sampling efficiency. Related articles have been mainly used for data sampling through field mining experiments, which can only be applied to individual or small-scale research. As a new geophysical detection technology, GPR can efficiently complete the investigation of plant roots in small and medium-sized areas. (4) The research methodologies and processes can be extended. Owing to the convenience of GPR, this method can be applied to diverse areas and other species, contingent upon meeting the experimental conditions.

### 4.3. Limitations of Studies

The limitations of this study come from the analysis method and the detection method. First, although the sample is well representative of individual shrubs, it is not applicable to analyze the root distribution of clustered shrubs. In the process of collecting data, only the individual shrub with a maximum canopy area of 7.79$m^2$ was selected. For clustered shrubs composed of multiple individual shrubs, due to the difficulty of sampling, they were not considered as experimental subjects. Therefore, the results of this study may not effectively reflect the characteristics of the root system of clustered shrubs. What's more, this method may not be suitable for the analysis of competition and cooperation among shrubs. If the distance between shrubs is close, and there is competition and cooperation between roots, additional testing may be required to validate this conclusion. Finally, there is a lack of equivalence between the above-ground and underground information. The canopy area representing the aboveground information is 1D data, however, the location of root points representing the underground information is 3D data. If the aboveground data



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uses the point cloud data obtained by Lidar, more interesting conclusions may be obtained.

## 5. CONCLUSION

This study illustrates the inherent stability of root spatial distribution patterns of *C. microphylla*. In the horizontal direction, the root spatial distribution adheres to the logistic model. Critical root system traits, such as total root biomass, active root accretion zone, and root growth rate, can be extracted from the fitted logistic model. These traits effectively describe the root characteristics. In addition, the root traits (i.e., parameters of the logistic model) can also be estimated by the canopy area, which can be quickly calculated from the unmanned aerial vehicle image. The combination of remote sensing data and the relationship between the canopy area and root traits can be employed to map root biomass in large regions in the future. GPR expands the research perspectives on plant root system architecture and aboveground-belowground interactions. The method proposed in this study not only contributes to understanding the root distribution pattern of *C. microphylla* in Inner Mongolia but also provides a simple and efficient method for mapping root biomass in large areas.

## 6. REFERENCE


[1] R. A. Gill and R. B. Jackson, "Global patterns of root turnover for terrestrial ecosystems," *New Phytol.,* vol. 147, no. 1, pp. 13-31, Jul 2000, doi: 10.1046/j.1469-8137.2000.00681.x.

[2] J. P. Lynch and K. M. Brown, "New roots for agriculture: exploiting the root phenome," *Philos Trans R Soc Lond B Biol Sci,* vol. 367, no. 1595, pp. 1598-604, Jun 5 2012, doi: 10.1098/rstb.2011.0243.

[3] H. Schenk and R. Jackson, "The global biogeography of roots," *Ecological Monographs,* vol. 72, pp. 311-328, 08/01 2002, doi: 10.2307/3100092.

[4] J. P. Huang, H. P. Yu, X. D. Guan, G. Y. Wang, and R. X. Guo, "Accelerated dryland expansion under climate change," *Nat Clim Change,* vol. 6, no. 2, pp. 166-171, Feb 2016, doi: 10.1038/Nclimate2837.

[5] R. Scholtz, J. A. Polo, E. P. Tanner, and S. D. Fuhlendorf, "Grassland fragmentation and its influence on woody plant cover in the southern Great Plains, USA," (in English), *Landscape Ecol,* vol. 33, no. 10, pp. 1785-1797, Oct 2018, doi: 10.1007/s10980-018-0702-4.

[6] Y. Wang *et al.*, "Biomass allocation patterns of Loropetalum chinense," *Chinese Journal of Plant Ecology,* vol. 41, no. 1, pp. 80-86, 2017.

[7] L. Guo, H. Lin, B. H. Fan, X. H. Cui, and J. Chen, "Forward simulation of root's ground penetrating radar signal: simulator development and validation," *Plant Soil,* vol. 372, no. 1-2, pp. 487-505, Nov 2013, doi: 10.1007/s11104-013-1751-8.

[8] E. Huber and G. Hans, "RGPR—An open-source package to process and visualize GPR data," in *2018 17th International Conference on Ground Penetrating Radar (GPR)*, 2018: IEEE, pp. 1-4.

[9] S. Li, X. Cui, L. Guo, L. Zhang, X. Chen, and X. Cao, "Enhanced automatic root recognition and localization in GPR images through a yolov4-based deep learning approach," *IEEE Trans Geosci Remote Sens,* vol. 60, p. 14, 2022, doi: 10.1109/tgrs.2022.3181202.

[10] L. Zhang *et al.*, "A simple method for estimating the coarse lateral root biomass of shrubs using ground-penetrating radar: Validation by Caragana microphylla Lam. in Inner Mongolia," *Science of The Total Environment,* vol. 919, p. 170897, 2024, doi: 10.1016/j.scitotenv.2024.170897.

[11] H. J. Schenk and R. B. Jackson, "Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems," *J Ecol,* vol. 90, no. 3, pp. 480-494, Jun 2002, doi: 10.1046/j.1365-2745.2002.00682.x.

[12] F. Hu, Y. Yan, D. Yu, X. Lu, L. Liu, and Z. Liu, "Above- and below-ground biomass carbon allocation pattern in temperate desert steppe of Inner Mongolia, China," *Journal of Ecology and Rural Environment,* vol. 36, no. 02, pp. 220-226, 2020, doi: 10.19741/j.issn.1673-4831.2019.0542.

[13] Y. De, H. An, Q. Guo, D. Ye, and L. Guo, "Study on the characteristics of roots distributions area in the caragana-grass compound system," *Environmental Engineering & Management Journal (EEMJ),* vol. 10, no. 6, 2011.




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