

Modeling Forest Age and NPP and Developing Site Index Tables for the Manas River Basin, Xinjiang

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Abstract

The dynamic changes in Net Primary Productivity (NPP) with forest age are key to assessing forest carbon sink capacity. This study aims to construct an age-NPP relationship model for the main tree species in the Manas River Basin of Xinjiang and compile a site index table to reveal the evolution of forest productivity and its site dependence in the region. The findings will provide scientific basis for precise carbon sink assessments and sustainable forest management in the area. Based on the forest resource survey data of Category I and Category II, five dominant tree species—*Spruce*, *Poplar*, *Elaeagnus angustifolia*, *Populus euphratica*, and *Mixed wood*—were fitted with five functional models (SEM, SDP, L, M, and Γ) to establish the forest age-NPP relationship and select the optimal model. At the same time, growth processes of dominant trees' height were fitted using guiding curve methods such as the Schumacher formula, Richards formula, Korf formula, Gompertz formula, and Weibull formula to determine the baseline age and index distance, and a site index table was compiled. Finally, a point-check method was used for accuracy verification. The results showed that: (1) SEM and Γ functions were the best models for simulating the forest age-NPP relationship. The NPP of dominant tree species follows a "initial growth-middle-aged peak-senescence decline" dynamic pattern, but the peak age varies significantly, reflecting the regional characteristic that drought stress delays the forest development process. (2) Site index tables for each tree species were compiled, and the point-check rate was $\geq 94\%$ for all species. The site index levels revealed a significant gradient of site quality within the basin. The site index (SI) for *Spruce* ranged from 16 to 24 m, indicating sensitivity to environmental gradients; the SI for *Poplar* ranged from 15 to 19 m, indicating stronger adaptability. The site index was significantly positively correlated with the NPP peak, suggesting that site quality is a key factor controlling the forest carbon sink potential. Based on this, carbon sink capacity assessments can be made under different site conditions within the basin. The forest age-NPP model and site index table developed in this study can accurately depict the temporal and spatial variation of forest productivity in the Manas River Basin. The results not only deepen the theoretical understanding of forest carbon cycling in arid areas but also provide direct quantitative tools and decision-making support for developing differentiated forest management strategies, such as harvesting plans based on site quality, ecological restoration, and enhancing regional forest carbon sink functions.

Introduction

Net Primary Productivity (NPP) refers to the total amount of organic matter accumulated by green vegetation per unit area and per unit time through photosynthesis, after deducting the losses from autotrophic respiration (Zhao, Zhang et al. 2021), reflecting the productive capacity of vegetation and the quality of the ecosystem (Yuan 2017). Compared to environmental factors, disturbances (such as forest age, fire, insects, and harvesting) exert more significant impacts on NPP (Kurz WA 2009). Differences in forest age structure and species composition can further enhance the spatial heterogeneity of NPP. Additionally, factors such as hydraulic limitations, changes in nutrient availability, and increased respiratory costs also contribute to variations in NPP (Ryan, Binkley et al. 1997). Shifts in carbon

allocation patterns and the depletion of soil nutrients are potential mechanisms driving the decline in NPP as forest stands age (Gower, McMurtrie et al. 1996). NPP exhibits certain fluctuations with stand age: it increases rapidly in young forests, reaches its maximum at the mature stage, and then gradually declines in old-growth forests (Zha, Barr et al. 2013). Research has demonstrated significant differences in the productivity-age relationship patterns across various biomes (e.g., boreal, temperate, and tropical forests), thereby elevating the research perspective from individual stands to regional and global scales (Pregitzer and Euskirchen 2004). Due to differences in forest composition and growing environments, the models describing the relationship between forest age and NPP vary significantly across regions, which complicates the analysis of environmental factors' effects on the growth of different forest types. Consequently, comparing different models becomes crucial when constructing age-NPP relationships for diverse forests.

While the influence of stand age on NPP and its underlying mechanisms have been extensively studied, the pronounced variations across different biomes and even individual forest stands pose a significant challenge to developing universal age-NPP models. This spatial heterogeneity is largely attributable to differences in forest site conditions, whereby site quality directly regulates the actual growth process and productive potential of trees (Liu). Therefore, to deeply understand and accurately predict the relationship between stand age and NPP, an indispensable prerequisite is the objective and quantitative assessment of forest site quality (Skovsgaard and Vanclay 2008). Among various methods, the Site Index approach, recognized internationally as the most universal and reliable direct evaluation method, provides a crucial technical bridge. By modeling the relationship between dominant height and stand age, it enables the quantification of site productive potential and effectively integrates individual tree growth with the study of ecosystem functions. (Li 2019, Luo 2025)

Site quality refers to the inherent productive potential of a given location for a specific forest or other vegetation type. The evaluation of site quality is essential for enabling efficient forest land utilization, scientific silviculture, and the development of management decision-support systems (Guo 2012, Wang 2016). Based on a synthesis of domestic and international research, methods for evaluating site quality can be categorized into three approaches: direct evaluation, indirect evaluation, and comprehensive evaluation (Yang 2004). Currently, the Site Index method (a direct evaluation approach) is a widely adopted and effective technique for assessing forest site quality. By fitting age-dominant height equations and developing site index tables and curves, this method enables the evaluation of tree growth status and productive potential (KIMBERLEY 26 June 1998, Wu 2015, Wang, Zhong et al. 2020, Zhang 2021). Commonly used methods for developing site index tables include the standard deviation adjustment method, the coefficient of variation adjustment method, the relative dominant height method, and the difference equation method (Zeng, Tang et al. 2010, Kitikidou, Milios et al. 2015, Luo 2019). Among them, the standard deviation adjustment method and the relative advantage high method are more widely applied. Meng Xianyu (Meng Xianyu. 1988) employed a methodology that integrated the conceptual approach with adjustment techniques to elucidate how distribution functions can be utilized to describe and predict stand structure. Following the development of dominant height growth models using the difference equation approach, a common methodology involves selecting superior height

growth models to compile site index tables through either the guide curve method or the difference equation method(Wang 2004). Simultaneously, utilizing forest resource inventory data, height-diameter curves for major tree species were developed, site index tables were compiled, and estimation models for site index were fitted using topographic and soil factors(Huang 2014). The compiled site index tables can be utilized for evaluating forest site quality. Numerous domestic scholars have already employed site index models and these tables to assess the site quality of various forest stand types(Li 2016, Yang 2018, Gong 2019, Li 2019, Chen 2023). Furthermore, methodologies for predicting tree growth have progressively matured, transitioning from qualitative to quantitative approaches. In particular, commonly used techniques such as linear regression equation fitting and the development of site index tables have been demonstrated to be effective for estimating stand growth.

The Manas River Basin in the Xinjiang Uygur Autonomous Region is the most representative inland river basin on the southern margin of the Junggar Basin. The spatial pattern of its ecosystem profoundly influences both the economic and ecological security of Northern Xinjiang(Xia 2020, Jiao, Wang et al. 2022). Simultaneously, this basin serves as a natural laboratory for studying arid land ecology and global change ecology. The vegetation within the basin, particularly the dominant tree species such as *Spruce*, *Populus euphratica*, and *Elaeagnus angustifolia*, constitutes the core lifeblood of this oasis. These forests play an irreplaceable and critical role in ecological barrier protection, water conservation, biodiversity maintenance, and climate and environmental improvement(Ding 2017). They are a decisive factor in maintaining the ecological balance of the watershed and represent a lifeline for safeguarding the socio-economic development and ecological security of the Northern Xinjiang region. Therefore, the conservation and development of these dominant tree species resources represent a fundamental strategy for achieving sustainable development in the Manas River Basin and throughout Xinjiang as a whole(Wang 2014). Based on the aforementioned context and utilizing forest resource inventory data, this study analyzes the height growth processes of dominant tree species in Xinjiang's Manas River Basin. Building on plot surveys and dominant tree growth analysis, it constructs age-NPP models for these species and compares the performance of five candidate models to identify the optimal growth model describing the relationship between forest age and NPP. Furthermore, the guide curve method is applied to compile site index tables. This work establishes a foundation for the subsequent quantitative evaluation of forest site quality using these tables and provides a reference for future forest resource management and planning in the region.

1. Study Area

The Manas River Basin is situated on the northern foothills of the Tianshan Mountains and the southern margin of the Junggar Basin (43°27'N–45°21'N, 85°01'E–86°32'E), representing one of the vital inland river basins in Xinjiang. As a core area of the economic belt on the north slope of Tianshan Mountains, the basin also serves as a critical ecological barrier for the Silk Road Economic Belt. It holds significant strategic importance for maintaining ecological security in Xinjiang and even the broader Central Asian arid region(Li 2025). The basin features an alternating distribution of mountains and basins, extending from south to north as the Tianshan Mountains, the Junggar Basin, and the Tarbagatai Mountains, with

an average elevation of approximately 1000 m(Nan 2025-08-28). The primary land cover types consist of cultivated land, forest land, grassland, and desert gobi, forming a typical mountain-oasis-desert ecosystem characterized by distinct vertical ecological zonation(Wang 2025). *Spruce* is the most important constructive species in this basin, forming the main body of water conservation forests and playing an irreplaceable role in precipitation interception and soil-water preservation. It is primarily distributed in the mid-mountain to subalpine zones of the Tianshan Mountains, at elevations between 1,500 and 2,800 m(Wang 2020). *Poplar* plays a key role in mountain ecological restoration and riparian corridor function. It is primarily distributed at elevations between 1,400 and 2,000 meters, located at the margins of spruce forests or on cutover and burned areas. There, it intermingles with or forms mosaics within spruce forests, occurring in patches or strips(Ye 2012). *Populus euphratica* serves as the ecological backbone of desert riparian zones and is distributed in the desert regions of the lower reaches of the basin. *Elaeagnus angustifolia* acts as a guardian of artificial oases, being exclusively distributed within and on the edges of plain-based artificial oases in the middle and lower reaches of the basin. Together, these tree species collectively form a continuous green ecological corridor stretching from the mountains to the deserts within the Manas River Basin(Zhang 2020). In terms of forest types, evergreen coniferous forests constitute the dominant component of the ecosystem. As the most extensively distributed and largest forest type within the basin, they significantly enrich the ecosystem's diversity and dynamic processes(Ling 2007, Zhou 2010).

2. Data Sources and Research Methods

2.1 Survey Data

2.1.1 Forest Inventory Data

The data foundation of this study primarily stems from two authoritative forest resource inventories: the Continuous Forest Inventory (CFI) of Xinjiang (also known as the "First Category" inventory) and the Forest Management Planning Inventory (FMPI, or "Second Category" inventory). The CFI data, collected at 5-year intervals, are characterized by nationally standardized protocols, extensive coverage, and high precision, making them a cornerstone data source for forest carbon sink assessment in China(Zan 2016). This study selected plot data for the major dominant tree species in the Manas River Basin, including stand age, tree height, diameter at breast height (DBH), and distribution area. The numbers of valid plots for *Spruce*, *Poplar*, *Elaeagnus angustifolia*, *Populus euphratica*, and *Mixed wood* were 1,726, 313, 21, 27, and 86, respectively. Thirty percent of the plots were randomly selected for model validation.

To enhance the estimation accuracy of NPP, this study further integrated data from the "Second Category" inventory (Forest Management Planning Inventory). This dataset provides detailed information on carbon pool components, including various tree organs (stem, branch, leaf, and bark), deadwood, litter, and fine roots(Wang 2013). By matching corresponding plots from the two datasets, a reliable NPP estimation framework was established, ensuring the development of accurate age-NPP models. Additionally, the vector boundary data of the study area were obtained from the Resource and

Environment Science and Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/>). Prior to data analysis, all spatial datasets underwent uniform processing, including extent clipping, coordinate system unification, and projection transformation, to guarantee consistency in the spatial analysis baseline.

2.1.2 Accurate Estimation of NPP in the Manas River Basin

This study utilized data from the Second Category inventory plots within the basin, including forest litter, fine root biomass, and the diameter at breast height (DBH) of deadwood. Using previously developed species-specific volume tables for the basin, the DBH of both deadwood and living trees was converted into stock volume. A continuous function conversion method was then applied to transform the stem volume into biomass. Finally, the accurate forest biomass for each plot was obtained by summing the biomass of the tree stems with the biomass of forest litter and fine roots, the latter being derived from field measurements supplemented by remote sensing estimations. The NPP for each plot was subsequently estimated by combining the forest survey time with the calculated biomass data from corresponding periods (Zan 2016, Zhou, Zan et al. 2025). Building upon this foundation, growth models relating age to NPP were developed. The optimal model was selected through validation to establish quantitative age-NPP relationships for the dominant tree species in the basin. This approach enabled the analysis of growth curve characteristics for the major dominant species and clarified the influence of forest age on NPP in the Manas River Basin.

2.2 Research Methods

2.2.1 Construction and Verification of the Linling-NPP Model

For the five dominant tree species (*Spruce*, *Poplar*, *Populus euphratica*, *Elaeagnus angustifolia*, and *Mixed wood*) in the Xinjiang Manas River Basin, five models—SEM, SDP, L, M, and Γ functions—were constructed respectively (Table 1). The SEM function, serving as a core mechanistic-empirical model, was designed to accurately capture the complete dynamic of NPP characterized by "growth–peak–gradual decline" with stand age. The Γ function, as a robust ecological statistical model, was employed to verify the universality of unimodal growth curves. The SDP function, a basic polynomial, provided a simple benchmark for fitting unimodal trends. The L and M functions, representing saturated growth models, were jointly used to test the competing scientific hypothesis that "NPP tends to saturate rather than decline with increasing stand age." Key parameters for each model were fitted and optimized. The R^2 and RMSE of different models were calculated and compared to identify the optimal age-NPP model for each dominant tree species in the basin.

Table 1
Model Names and Expressions

Model Name	Model Formula
SEM Model	$y = a \cdot (1 + (((b \cdot (x/c)^d) - 1) / (\exp(x/c))))$
SDP Model	$y = a \cdot x^2 + b \cdot x + c$
L Model	$y = a[\log(i + 1)]^b$
M Model	$y = a \cdot x / (b + x)$
Γ Model	$y = a \cdot x^{b \cdot e^{(c \cdot x)}}$

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{n-p}} \# (2)$$

2.2.2 Calculation and Validation of Site Index Tables

The compilation of site index tables represents a core technique in forest site quality evaluation. It involves establishing typical sample plots within the study area to obtain data on the height and age of dominant trees. The core step is the fitting of a guide curve, which entails selecting the optimal model from a series of candidate theoretical growth equations, such as the Richards and Schumacher models. This selection is based on criteria including the correlation index, residual sum of squares, and adherence to biological principles. The resulting curve represents the regional benchmark for height growth under average site conditions. The determination of the base age is crucial for table compilation. This age is typically chosen when stand height growth stabilizes and can adequately reflect site differences, often identified by analyzing the trend of the height coefficient of variation over time (Rennolls, Clutter et al. 1983). The site index class interval is rationally defined based on the actual distribution range of dominant tree height at the base age and specific management requirements. Building on this foundation, mathematical methods—such as the standard deviation adjustment method, the relative height method, or the difference equation method—are employed to expand the single guide curve into a family of site index curves that share an identical growth pattern but represent distinct site quality classes (Duan 2009). Finally, rigorous accuracy validation was conducted to ensure the reliability of the compiled tables, resulting in practical site index tables ready for management application.

2.2.2.1 Fitting of the Guide Curve

A guide curve refers to the central tendency of dominant tree height change with stand age within a forest stand. The dominant tree height growth model is derived by fitting the age-height relationship of these trees. The selection of the guide curve directly determines the quality of the resulting site index

table(Liu 2021, Zhao 2025). This study employed commonly used statistical metrics for model selection, prioritizing equations with biological significance as candidate height growth models. Specifically, the Gompertz, Richards, Weibull, Korf, and Schumacher models were selected for guide curve fitting, as detailed in the table below:

Table 2
Function Model Names and Forms

Regression Equation Names	Regression Equation Expressions
Compertz Model	$H = a\exp[-b\exp(-ct)]$
Richards Model	$H = a[1-\exp(-bt)]^c$
Weibull Model	$H = a[1-\exp(-bt)^c]$
Korf Model	$H = a\exp(-b/t^c)$
Schumacher Model	$H = a\exp(-b/t)$

2.2.2.2 Determination of Base Age and Site Index Class Interval (D)

The base age is defined as the stage at which height growth stabilizes while remaining sensitive to site quality variations. The site index class interval refers to the ratio of the range of dominant height at the base age to the number of index classes (Shan 2017, Li 2019). The base age (A_0) for the study area was determined by analyzing the standard deviation (S_i) and coefficient of variation (CV) of tree height, combined with the dynamics of biomass and height relative to stand age. The site index class interval was then defined based on the range of dominant heights at this base age. The specific formulas are provided below:

$$S_i = \sqrt{\frac{\sum H_{ij}^2 - \frac{\sum H_{ij}}{n_i}}{n_i - 1}} \quad \# (3)$$

$$CV = \frac{S_i}{\bar{x}} * 100\% \quad \# (4)$$

Here, x_i represents the standard deviation of tree height within the i -th age class, H_{ij} denotes the htight of the j -th dominant tree in the i -th age class, and n_i is the number of dominant trees in the i -th age class. CV stands for the coefficient of variation, and $\bar{x}$ significant the mean value of the sample plots.

2.2.2.3 Compilation of Site Index Tables

Site quality refers to the productive potential of a given forest or other vegetation type on a specific area of land. The evaluation of site quality is essential for the efficient utilization of forest land, scientific

silviculture, and the development of management decision-support systems(Guo 2012, Wang 2016). The Relative Dominant Height Method, the Adjustment Method, and the Standard Deviation Adjustment Method are commonly used techniques for the compilation of Site Index Tables. This paper uses the height guide curve as the basis for developing the Site Index Tables and employs the Relative Dominant Height Method to compile these tables for five dominant tree species in the Manas River Basin of Xinjiang. The calculation formula is as follow: $H_a = k * H_d \# (5)$

In the formula: H_a denotes the height value for each age class and site index class; k represents the ratio of the height value at each age class on the guide curve to the height value at the base age; H_d is the theoretical height value at each age class.

2.2.2.4 Verification of Site Index

This study employed the fall-point test method to validate the computed Site Index Tables. Specifically, 70% of the sample points were randomly selected from the resulting family of site index curves for the test. The results showed that the fall-point rate for all tree species was $\geq 94\%$, which meets the standard criteria, confirming their applicability for subsequent research(Duan 2009, Du 2019). The calculation formula for the fitting precision index (I) is as follows:

$$I = [1 - \frac{N_{out}}{N_{total}}] * 100\% \# (6)$$

where, N_{out} denotes the number of invalid sample points falling outside the family of site index; N_{total} represents the total number of sample points involved in the test.

3. Analysis of Results

3.1 Development of Age-NPP Models for Each Dominant Tree Species

Based on the computed NPP and the 2011 forest inventory data from the Manas River Basin in Xinjiang, SEM, SDP, L, M, and Γ function models were developed for *Spruce*, *Poplar*, *Elaeagnus angustifolia*, *Populus euphratica*, and *Mixed wood*. This was done to investigate the characteristics of forest NPP dynamics with age in the Manas River Basin. The calculated model parameters and precision evaluation metrics are presented in Table 3. A quantitative comparison of the five function models applied to the five dominant tree species in Xinjiang's Manas River Basin was conducted, with the results presented in Fig. 2. Significant differences in model performance were observed. The SEM and Γ function models demonstrated superior and the most stable predictive performance. Specifically, in terms of goodness-of-fit, the SEM and Γ functions achieved the highest R^2 values for most species, reaching 0.90 for *Populus euphratica*. Regarding error control, these two models also exhibited exceptional performance, corresponding to the globally lowest error metrics, with the minimum error for *Populus euphratica* being 0.34. In contrast, the SDP function model showed moderate accuracy, while the L and M function models

exhibited relatively poor fitting effectiveness, generally characterized by lower R^2 values and larger errors. In conclusion, the SEM and Γ function models possess higher reliability and application value for the ecological modeling involved in this study.

Table 3
Parameter Magnitude and Accuracy Assessment of Dominant Tree Species Models

Tree Species Names	Model Name	a	b	c	d	R ²	RMSE
Spruce	SEM	5.27	2.05	78.42	0.27	0.41	0.34
	SDP	-5.77	-0.01	8.20	/	0.41	0.34
	L	2.20	2.40	/	/	1.95×10^{-28}	0.44
	M	6.11	-11.69	/	/	0.32	0.36
	Γ	6.48	0.07	0.0001		0.41	0.34
Poplar	SEM	1.87	0.65	41.50	24.48	0.51	5.38
	SDP	-0.007	0.16	30.1	/	0.50	5.50
	L	3.66	2.56	/	/	1.26×10^{-30}	7.66
	M	23.36	-3.14	/	/	0.15	7.06
	Γ	10.36	0.62	0.02	/	0.51	5.38
Elaeagnus angustifolia	SEM	16.36	-3.72	1.07	11.37	0.47	2.15
	SDP	0.03	-0.42	8.67	/	0.46	2.17
	L	5.50	1.42	/	/	2.76×10^{-32}	2.94
	M	-211.19	-301.78	/	/	0.45	2.18
	Γ	8.16	-0.40	-0.08	/	0.45	2.17
Populus euphratica	SEM	0.13	0.06	12549968.31	-0.52	0.90	0.35
	SDP	0.003	-3.00	12.85	/	0.88	0.38
	L	0.11	-0.86	/	/	0.00	1.09
	M	4.85	-6.97	/	/	0.85	0.43
	Γ	37.72	-0.52	-0.006	/	0.90	0.35
Mixed wood	SEM	7.63	2.34	8.62	1.52	0.61	1.57
	SDP	-0.0008	-0.09	15.01	/	0.59	1.6
	L	2.92	2.32	/	/	6.89×10^{-30}	2.51

Tree Species Names	Model Name	a	b	c	d	R ²	RMSE
	M	9.22	-4.65	/	/	0.37	2
	Γ	8.79	0.29	0.003	/	0.61	1.59

3.2 Computation Process of Site Index Tables

3.2.1 Selection and Fitting of the Guide Curve

The correct determination of the mathematical model for the guide curve is crucial for the quality of the Site Index Table. To ensure that the guide curve accurately reflects the height-growth characteristics of dominant tree species across different site conditions, an appropriate regression equation model must first be selected, one that comprehensively covers and describes different theoretical patterns of tree growth. Subsequently, multiple equation models should be analyzed and compared based on extensive data on the average age and average height of standard dominant trees. The final model selection should take into account both the biological principles of tree height growth and the goodness-of-fit of the equation (Ma 1986). This study constructed age-height models for five dominant tree species, primarily employing five common regression equation models: Gompertz, Richards, Weibull, Korf, and Schumacher. Details are provided in Tables 4 through 8:

Table 4
Results of Spruce Growth Guide Curve Fitting Equations

Regression Model Names	Regression Equation Expressions	a	b	c	R ²	RMSE
Compertz	$H = a \exp[-b \exp(-ct)]$	20.0463	2.4779	0.0188	0.7508	2.3032
Richards	$H = a[1 - \exp(-bt)]^c$	22.0198	0.0116	1.2547	0.7531	2.2928
Weibull	$H = a[1 - \exp(-bt)^c]$	24.8728	0.0296	0.2666	0.7519	2.3004
Korf	$H = a \exp(-b/t^c)$	40.7242	15.7289	0.5798	0.7536	2.2903
Schumacher	$H = a \exp(-b/t)$	25.4438	59.2336	/	0.7481	2.3201

Table 5
Results of Poplar Growth Guide Curve Fitting Equations

Regression Model Names	Regression Equation Expressions	a	b	c	R ²	RMSE
Compertz	$H = a \exp[-b \exp(-ct)]$	15.67	13.32	0.247	0.8133	1.8286
Richards	$H = a[1 - \exp(-bt)]^c$	16.3	0.1707	5	0.788	1.946
Weibull	$H = a[1 - \exp(-bt)^c]$	15.45	0.0007	2.792	0.8029	1.8591
Korf	$H = a \exp(-b/t^c)$	18.1	100	1.9527	0.7731	2.0156
Schumacher	$H = a \exp(-b/t)$	24.82	12.9353	/	0.7109	2.2751

Table 6
Results of Elaeagnus angustifolia Growth Guide Curve Fitting Equations

Regression Model Names	Regression Equation Expressions	a	b	c	R ²	RMSE
Compertz	$H = a \exp[-b \exp(-ct)]$	1246.45	6.23	0.0104	0.5508	1.2494
Richards	$H = a[1 - \exp(-bt)]^c$	224.54	0.0016	0.9644	0.5405	1.2636
Weibull	$H = a[1 - \exp(-bt^c)]$	287.06	0.0016	0.9636	0.5506	1.2563
Korf	$H = a \exp(-b/t^c)$	1475.15	8.857	0.1772	0.5378	1.2673
Schumacher	$H = a \exp(-b/t)$	17.98	15.8767	/	0.5223	1.2884

Table 7
Results of Populus euphratica Growth Guide Curve Fitting Equations

Regression Model Names	Regression Equation Expressions	a	b	c	R ²	RMSE
Compertz	$H = a \exp[-b \exp(-ct)]$	10.11	2.56	0.1081	0.7263	0.8543
Richards	$H = a[1 - \exp(-bt)]^c$	10.54	0.0794	1.4946	0.7303	0.8481
Weibull	$H = a[1 - \exp(-bt^c)]$	10.91	0.0419	1.1046	0.7286	0.8507
Korf	$H = a \exp(-b/t^c)$	12	20.744	1.2696	0.7401	0.8324
Schumacher	$H = a \exp(-b/t)$	13.35	11.561	/	0.7389	0.8343

Table 8
Results of Mixed wood Growth Guide Curve Fitting Equations

Regression Model Names	Regression Equation Expressions	a	b	c	R ²	RMSE
Gompertz	$H = a \exp[-b \exp(-ct)]$	11.14	1.66	0.0827	0.7484	0.9146
Richards	$H = a[1 - \exp(-bt)]^c$	11.42	0.0606	0.9699	0.7506	0.9105
Weibull	$H = a[1 - \exp(-bt^c)]$	11.49	0.0675	0.9664	0.7507	0.9103
Korf	$H = a \exp(-b/t^c)$	13.63	7.8871	0.9093	0.7533	0.9055
Schumacher	$H = a \exp(-b/t)$	13.12	9.5061	/	0.753	0.9061

Five common theoretical growth equations were used to fit the guide curves. For the dominant tree species *Picea asperata*, the R² values of the equations, ranked in descending order, were: Korf > Richards > Weibull > Gompertz > Schumacher. The RMSE values, ranked in ascending order, were: Korf < Richards < Weibull < Gompertz < Schumacher. The results demonstrated that the Korf model achieved the highest R² and the lowest RMSE. Consequently, the Korf equation was selected as the final guide curve for *Spruce*: $H = 40.7241 \exp(-15.7289/t^{0.5798})$; Similarly, the Gompertz model was selected as the optimal guide curve for *Poplar*: $H = 15.67 \exp[-13.32 \exp(-0.2470t)]$; The Gompertz model was determined to be the optimal growth guide curve for *Elaeagnus angustifolia*: $H = 1246.45 \exp[-6.23 \exp(-0.0104t)]$; The Korf function model was established as the optimal guide curve for *Populus euphratica*: $H = 12.00 \exp(-20.7435/t^{1.2696})$; The Korf model was determined to be the optimal guide curve for *Mixed wood*: $H = 13.63 \exp(-7.8871/t^{0.9093})$.

3.2.2 Determination of the Base Age (A₀)

The base age (A₀) refers to the age at which tree growth stabilizes and can sensitively reflect site-related differences (Yang 2018). The base age (A₀), indicative of stabilized height growth, is characterized by S_i and CV approaching 1, which reflects greater relative stability in height growth. This study integrated the growth dynamics of both tree height and biomass with age to more accurately determine the species-specific A₀. The specific computational results and growth trends for the five dominant tree species are presented in Fig. 3: The height growth curve of *Spruce* showed a significant slowdown after approximately 100–120 years, with the curve approaching an asymptote. The standard deviation generally increased until 150 years, indicating a widening absolute height difference among individual trees within the stand as age increased—a typical process of natural forest competition. Around 150 years, the standard deviation peaked and began to stabilize or decline slowly, suggesting that the phase of intense competition and differentiation had largely concluded. Between 0–50 years, the CV was notably high, which can be attributed to the high environmental sensitivity and growth volatility of young trees. During this stage, observed variations were primarily driven by random factors rather than reflecting true site potential. Subsequently, the CV gradually decreased, stabilizing around 150 years at a low level. Therefore, the A₀ for *Spruce* was determined to be 150 years. The biomass and height of

Poplar exhibited a period of rapid growth between 5 and 15 years, after which the growth rate began to decelerate from 15 to 25 years, stabilizing after 25 years. The S_i for poplar height increased rapidly, peaking around 25 years before stabilizing or declining. This indicates that the phase of intense competition and differentiation among trees was largely complete by approximately 25 years. During the initial growth stage, the CV was relatively high, attributable to random factors such as genetic variation and micro-environmental differences among individuals, which led to uneven growth. Subsequently, the CV decreased rapidly, stabilizing around 25 years at a relatively low level. Based on this analysis, the A_0 for *Poplar* was determined to be 25 years. For *Elaeagnus angustifolia*, tree height increased rapidly during the initial 0–5 years, enabling adaptation to the harsh environment. Height growth essentially ceased by 10–15 years. The S_i for *Elaeagnus angustifolia* stands peaked very quickly and began to decline or stabilize before 20 years, indicating that the phase of intense competition and differentiation among individuals concluded early. The CV was extremely high during the first 2–3 years, then decreased to its minimum before 20 years. Biologically, *Elaeagnus angustifolia* is characterized by a relatively short lifespan, rapid growth rate, and early maturation. Its peak height growth and stabilization phases occur very early, and an age of 20 years is sufficient to capture its main growth stages and peak productivity. Therefore, the A_0 for *Elaeagnus angustifolia* was determined to be 20 years. Based on the analysis of biomass and height dynamics with age for *Populus euphratica*, height growth began to decelerate after 20 years and essentially stagnated after 30 years. Biomass increased rapidly during 11–20 years, followed by a period of high volatility between 21 and 30 years. Integrating both height and biomass trends, the first stabilization period occurred after the height growth inflection point at 25 years, coinciding with the stabilization of biomass. Consequently, the base age (A_0) for *Populus euphratica* was determined to be 25 years. For *Mixed wood*, the growth rate in height showed a marked deceleration around 30–40 years, after which it levelled off. Similarly, biomass accumulation increased with age but also slowed noticeably around 30–40 years, although it continued to increase gradually. From a growth dynamics perspective, approximately 35 years represents a transitional period during which both height and biomass shifted from rapid to slow growth phases. Analysis of the CV showed relatively high values between 20–35 years, followed by a decline and subsequent stabilization or slight decrease after about 35 years. Before 35 years, the high CV was attributed to factors such as inter-tree competition and natural thinning, which resulted in considerable individual variation. After 35 years, the stand structure stabilized, as reflected by the decreased and stabilized CV, indicating that the stand reached a relatively stable structural state around this age.

3.2.3 Determination of the Site Index Class Interval (D)

The index class interval is defined as the ratio of the height range of dominant trees at the base age to the number of index classes (Bravo-Oviedo, Río et al. 2004, Liu 2017). The determination of the index class interval should, in principle, balance precision with practical applicability for field-level implementation. Based on domestic and international experience, it is generally recommended that the number of classes should not exceed ten. In this study, at the base age of 150 years, the average height of dominant *Spruce* trees ranged from 16.3 to 23.4 m, with a range amplitude of 7.1 m. Consequently, an index class interval of 1 m was adopted, resulting in the establishment of nine site index classes: 16, 17,

18, 19, 20, 21, 22, 23, and 24 m. For *Poplar*, the average height of dominant trees at the base age of 25 years ranged from 15.5 to 18.3 m, yielding a range amplitude of 2.8 m. Accordingly, an index class interval of 1 m was established, defining five site index classes: 15, 16, 17, 18, and 19 m. For *Mixed wood* at the base age of 35 years, the average height of dominant trees ranged from 8.0 to 10.4 m, resulting in a range amplitude of 1.6 m. An index class interval of 1 m was initially determined, which would define only three site index classes: 8, 9, and 10 m. However, an excessively small number of site index classes can compromise the precision of the resulting site index curves. Therefore, to ensure methodological rigor and meet research requirements, the range of site index classes was extended to include values from 5 to 12 m. For *Elaeagnus angustifolia* at the base age of 20 years, the average height of dominant trees ranged from 6.5 to 7.5 m, giving a range amplitude of 1 m. Consequently, an index class interval of 1 m was adopted, defining three site index classes: 6, 7, and 8 m. For *Populus euphratica*, the base age is 25 years. At this age, the average height range of dominant trees is 7.0-10.3 m. An index class interval of 1 m was thus determined, resulting in four site index classes: 7, 8, 9, and 10 m.

3.2.4 Compilation of Site Index Tables

This study utilized the height guide curve as the foundation for compiling Site Index Tables. Using the Relative Dominant Height Method, specific Site Index Tables for the five dominant tree species were developed, as presented in Tables 9–13: As evidenced by the Site Index Tables, *Poplar* exhibits typical early rapid-growth characteristics, demonstrating exceptionally fast growth prior to the base age of 25 years, with a mean annual increment significantly surpassing that of other tree species. *Populus euphratica* exhibits an "early-maturing - stagnant" pattern, with its height growth largely completed before the base age and remaining largely stable thereafter. *Spruce* and *mixed wood* exhibit a sustained and stable growth pattern characterized by a long growth cycle, maintaining considerable growth increment even beyond the base age. *Elaeagnus angustifolia* demonstrates slow yet persistent growth, with both its absolute and annual growth increments being the lowest among the studied species, reflecting its characteristic as a stress-tolerant tree species.

Table 9
Spruce Site Index Table(A0 = 140yr)

Stand age/A	Site Index								
	SI = 16	SI = 17	SI = 18	SI = 19	SI = 20	SI = 21	SI = 22	SI = 23	SI = 24
15	1.49	1.58	1.67	1.77	1.86	1.95	2.04	2.14	2.23
25	3.44	3.66	3.87	4.09	4.3	4.52	4.73	4.95	5.16
35	5.3	5.63	5.96	6.29	6.62	6.95	7.28	7.61	7.94
45	6.95	7.38	7.81	8.25	8.68	9.12	9.55	9.99	10.42
55	8.4	8.93	9.45	9.98	10.5	11.03	11.55	12.08	12.6
65	9.68	10.29	10.89	11.5	12.11	12.71	13.32	13.92	14.53
75	10.82	11.5	12.18	12.85	13.53	14.21	14.88	15.56	16.24
85	11.85	12.59	13.33	14.07	14.81	15.55	16.29	17.03	17.77
95	12.76	13.56	14.36	15.16	15.96	16.75	17.55	18.35	19.15
105	13.6	14.45	15.3	16.15	17	17.85	18.7	19.55	20.4
115	14.36	15.26	16.15	17.05	17.95	18.85	19.74	20.64	21.54
125	15.06	16	16.94	17.88	18.82	19.76	20.7	21.64	22.58
135	15.7	16.68	17.66	18.64	19.62	20.6	21.58	22.56	23.55
140	16	17	18	19	20	21	22	23	24
145	16.29	17.31	18.33	19.35	20.36	21.38	22.4	23.42	24.44
155	16.84	17.9	18.95	20	21.05	22.11	23.16	24.21	25.26
165	17.36	18.44	19.53	20.61	21.7	22.78	23.87	24.95	26.04
175	17.84	18.95	20.07	21.18	22.3	23.41	24.53	25.64	26.76
185	18.29	19.43	20.58	21.72	22.86	24	25.15	26.29	27.43

Table 10
Poplar Site Index Table(A0 = 25yr)

Stand age/A	Site Index				
	15	16	17	18	19
5	2.1	2.3	2.4	2.6	2.7
10	6.3	6.7	7.2	7.6	8
15	10.2	10.9	11.6	12.3	13
20	13	13.9	14.8	15.6	16.5
25	15	16	17	18	19
30	16.3	17.4	18.5	19.6	20.7

Table 11
Elaeagnus angustifolia Site Index Table
(A0 = 20yr)

Stand age/A	Site Index		
	6	7	8
10	3.52	4.11	4.7
15	4.87	5.69	6.5
20	6	7	8
25	6.92	8.07	9.23

Table 12
Populus euphratica Site Index Table(A0 = 25yr)

Stand age/A	Site Index			
	7	8	9	10
5	2.1	2.4	2.7	3.0
10	4.3	4.9	5.5	6.1
15	5.8	6.6	7.4	8.2
20	6.7	7.7	8.6	9.6
25	7.0	8.0	9.0	10.0
30	7.2	8.2	9.2	10.3
35	7.3	8.4	9.4	10.5
40	7.4	8.5	9.5	10.6
45	7.5	8.6	9.6	10.7
50	7.5	8.6	9.7	10.8

Table 13
Mixed wood Site Index Table(A0 = 35yr)

Stand age/A	Site Index							
	5	6	7	8	9	10	11	12
10	2.24	2.69	3.14	3.59	4.04	4.48	4.93	5.38
15	3.3	3.96	4.62	5.28	5.94	6.6	7.26	7.92
20	4.06	4.87	5.68	6.49	7.3	8.12	8.93	9.74
25	4.63	5.55	6.48	7.4	8.33	9.25	10.18	11.1
30	5.07	6.08	7.1	8.11	9.13	10.14	11.16	12.17
35	5.45	6.54	7.63	8.72	9.81	10.9	11.99	13.08
40	5.78	6.93	8.09	9.24	10.4	11.55	12.71	13.86
45	6.07	7.28	8.5	9.71	10.93	12.14	13.36	14.57
50	6.33	7.6	8.87	10.13	11.4	12.67	13.94	15.2
55	6.57	7.88	9.2	10.51	11.83	13.14	14.46	15.77

Based on the compiled Site Index Tables and their optimal fitting curves, the families of site index curves for each dominant species were generated by plotting tree height values against age classes, with age classes as the abscissa and tree height under each site index class as the ordinate. The results are visually presented in Fig. 4: The tree species exhibited distinct growth patterns: *Poplar* displayed typical early rapid-growth characteristics; *Populus euphratica* followed an early-maturation with subsequent stagnation pattern; both *Spruce* and *Mixed wood* demonstrated sustained and stable growth rhythms, though *Spruce* exhibited a longer growth cycle; while *Elaeagnus angustifolia* manifested a slow yet persistent stress-tolerant growth strategy. All tree species exhibited significant cumulative effects in site index differentiation with increasing age, with particularly pronounced divergence observed in long-growth-cycle species such as *Spruce* and *Mixed wood*. These quantified growth rhythms provide a scientific basis for species selection and silvicultural strategy development across varying site conditions.

3.3 Validation of Site Index Tables

Upon completion of their compilation, Site Index Tables must undergo validation to ensure their precision and applicability before being implemented in operational forestry. Commonly employed validation methods include the Chi-square test and the fall-point test (Ma 2024). Based on the second-class forest inventory data from the study area, a systematic sampling method was applied to the five classified dominant tree species. 70% of all sample plots for each species were randomly selected as validation samples for field verification. According to the fitted site index curves, sample points were categorized into two types: those falling within the confidence interval were classified as valid points (conforming to model predictions), while those outside the interval were deemed invalid points (deviating from model predictions). The accuracy of the site index curves for each species was validated by calculating the fall-point rate.

As shown in the validation results of Fig. 5, the fall-point tests for all five tree species met the required standards. Using 70% of the total sample points randomly selected for validation, the fall-point rate for *Spruce* reached 95.8%. Similarly, when 70% of the modeling sample points were randomly selected for testing, only two points fell outside the compiled site index curves, resulting in a fall-point rate of 94.3%. For *Poplar*, despite its fast-growing nature and complex site conditions, the compiled site index tables passed the validation and can provide scientific guidance for forest management in the Manas River Basin. In the case of *Mixed wood*, only two sample points fell outside the curves, yielding a fall-point rate of 95.8%, which complies with specifications. *Elaeagnus angustifolia* also met the site index validation standards with its fall-point rate. *Populus euphratica* achieved a 97.2% fall-point rate, confirming its suitability for subsequent research applications.

4. Discussion

4.1 Comparative Analysis of Age-NPP Model Accuracy

Based on the calculated R^2 and RMSE values of the age-NPP models for each tree species, the performance of SEM, Γ , and SDP functions across different species was compared using Taylor diagrams. In Fig. 6, a model's performance is considered better the closer its corresponding point is to the reference point labeled "Observation" (typically situated at a specific location on the x-axis)(Ma 2024). Among the evaluated models for each tree species, the SEM model demonstrated optimal performance in simulating the age-NPP relationship of *Populus euphratica*, achieving the highest R^2 of 0.90, while also exhibiting stable performance and strong generalization capability across other species. The SDP function closely approached SEM's performance with a maximum R^2 of 0.88 in *Populus euphratica*, though slightly lower, and maintained relatively stable performance across the other four species. In contrast, the L function showed extreme instability in age-NPP modeling for all five species, producing either abnormally high R^2 values or zero values. The M function performed well only for *Populus euphratica* ($R^2=0.85$) but demonstrated poor performance for the remaining species. The Γ function exhibited highly consistent performance with the SEM model, reaching an identical peak R^2 of 0.90 and maintaining stable and excellent performance in modeling age-NPP relationships across all other tree species.

In summary, regarding the dominant tree species, the SEM and Γ functions achieved the optimal R^2 of 0.90, followed by the SDP function ($R^2 = 0.88$). The M function performed at a relatively acceptable level ($R^2 = 0.85$), while the L function completely failed ($R^2 = 0$). In conclusion, the SEM function is identified as the globally optimal model and is recommended for subsequent simulations of other tree species.

4.2 Regional Characteristics of Age-NPP Relationships

This study systematically simulated the age-NPP relationship of major tree species in the Xinjiang Manas River Basin by constructing five function models. The results indicate that NPP generally follows a trend of "initial growth - midlife peak - senescence decline" with increasing age. This pattern exhibits significant variation among tree species (Li 2016, Wang 2019), fully reflecting the uniqueness and complexity of forest ecosystems in arid regions.

Among all species, *Populus euphratica* exhibits the most characteristic age-NPP curve. Its NPP increases rapidly during the juvenile stage, peaks around 25 years, and subsequently stabilizes before gradually declining. This trend aligns well with the growth stagnation pattern observed after 25 years in its site index table, indicating synchronized carbon accumulation and morphological development. After reaching physiological maturity, photosynthetic capacity declines while respiratory consumption increases, leading to the observed NPP reduction. In contrast, *Spruce* demonstrates a notably delayed peak in its age-NPP curve. The NPP continues to increase until 50 years and stabilizes around 150 years without significant decline. This pattern reflects *Spruce's* characteristics as a slow-growing, long-lived species with an extended carbon accumulation period and high ecosystem stability. These findings are consistent with the designated base age of 150 years in its site index table, confirming that *Spruce* can sustain relatively high productivity in the more favorable moisture conditions of the northern slopes of the Tianshan Mountains (Calvert, Dyer et al. 2017, Luo 2020.08). In contrast, In comparison, *Poplar*, *Elaeagnus angustifolia*, and *Mixed wood* reach their NPP peaks around 30–50 years, but differ

significantly in their post-peak decline patterns. As a fast-growing species, *Poplar* experiences an earlier and more pronounced NPP decline. In contrast, *Elaeagnus angustifolia* and *Mixed wood* demonstrate greater resilience, with only gradual NPP reductions after peaking. These differences reflect distinct ecological strategies: *Poplar* prioritizes resource allocation to rapid growth, while *Elaeagnus angustifolia* and *Mixed wood* enhance ecosystem resistance through species complementarity and efficient resource utilization (Forrester 2014). The "initial increase followed by decrease" pattern of NPP with forest age revealed in this study aligns with findings from numerous global studies (Ryan, Binkley et al. 1997, Pregitzer and Euskirchen 2004, Tang, Luyssaert et al. 2014). However, forests in the Manas River Basin—particularly *Spruce*—exhibit a later NPP peak age compared to their counterparts in humid regions, highlighting a regional characteristic shaped by drought stress that delays forest development (Zhang 2015, Li, Li et al. 2019, Souza, Villar et al. 2022, Chen, Wang et al. 2023). This finding provides critical insights for accurately assessing carbon sink potential and maturity in arid zone forests.

4.3 Mechanistic Interpretation and Implications of Site Index Tables

Site Index reflects the average height of dominant trees in a stand at the base age, and its value directly indicates the quality of the site conditions (Klinka. 1996, Skovsgaard and Vanclay 2008). This study employed the guide curve method to model the age-height relationship, thereby deriving site index classes for each tree species. The distribution of site index ranges across species is shown in Fig. 7. *Spruce* exhibited a relatively wide site index range of 16–24 m, indicating its high sensitivity to environmental gradients such as elevation, soil moisture, and temperature. Particularly in arid and semi-arid regions, moisture availability becomes the primary limiting factor for its growth. In contrast, the site index classes of *Poplar* are more concentrated, ranging from 15 to 19 m. This reflects its strong adaptability and fast-growing characteristics, but also implies that its growth potential is relatively uniform across the Manas River Basin. As a typical species in arid regions, *Populus euphratica* exhibits a relatively low site index range of 7–10 m. This aligns with its biological traits of drought tolerance, salt tolerance, and slow growth, while also revealing the generally low productivity level of its stands in this region. *Elaeagnus angustifolia* and *Mixed wood* exhibit concentrated site index classes of 6–8 m and 5–12 m, respectively, demonstrating the significant constraints imposed by arid zone site conditions on tree growth.

Site Index Tables represent not only theoretical achievements but also provide quantitative tools and a scientific basis for forest management and stewardship. They play a significant role in supporting forest management decision-making, harvest and regeneration planning, as well as ecological restoration and sustainable management. Specifically, Site Index enables the rapid assessment of a forest stand's productive potential and guides practical decisions such as species selection, planting density, and silvicultural treatments (Stanturf, Palik et al. 2014). For instance, forest stands with higher site indices, such as *Spruce*, can be prioritized for timber production, while those with lower site indices, like oleaster, are better suited for ecological restoration and soil-water conservation purposes. The base age (A_0) of 25 years for *Populus euphratica* can serve as a reference for determining harvest schedules, preventing

premature harvesting before the growth peak to maximize both timber yield and carbon sequestration. In low site index areas (e.g., $SI < 8$ m), priority should be given to ecological function restoration rather than economic utilization. For instance, introducing drought-tolerant shrubs or herbaceous plants into *Elaeagnus angustifolia* stands can enhance ecosystem stability. Site Index Tables not only elucidate the site-dependent growth dynamics of forests in the Manas River Basin, but also establish a scientific foundation for precision silviculture, optimized resource allocation, and enhanced carbon sequestration. Future research should integrate remote sensing with long-term in-situ monitoring data to dynamically refine these tables, thereby improving their applicability across diverse climatic scenarios (Hofmeister, Hošek et al. 2019).

4.4 Assessment and Development of Regional Carbon Potential

Based on the constructed age-NPP models and Site Index Tables, a quantitative assessment of the forest carbon sink potential in the Xinjiang Manas River Basin was conducted, providing a scientific basis for sustainable forest management and ecological construction in the region. This study reveals significant interspecific and site-specific variations in the carbon sink capacity of forests within the Manas River Basin. The carbon sequestration capabilities of *Elaeagnus angustifolia* and *Mixed wood* fall between those of the aforementioned species. Specifically, under favorable site conditions, *mixed wood* exhibits relatively high carbon sink potential and stability, attributable to species complementarity (Loreau, Naeem et al. 2001, Chen 2005). In contrast, owing to its drought and barrenness tolerance, *Elaeagnus angustifolia* maintains a certain carbon sequestration function even in poorer sites, albeit with a lower absolute carbon sink capacity. A preliminary estimation based on the NPP simulated by the optimal models (SEM and Γ functions) indicates a considerable total carbon sink potential for forest vegetation in the Manas River Basin. To maximize forest carbon sink functionality and promote regional sustainable development, the findings of this study suggest demarcating forest areas with high site indices (e.g., *Spruce and Poplar* stands) as priority carbon sink zones for targeted conservation and precision management. Conversely *Elaeagnus angustifolia* stands with low site indices should be designated as core areas for ecological restoration and protection. Measures such as closed forest management can be implemented to facilitate natural vegetation recovery, prevent carbon pool depletion, and progressively improve site conditions—following a strategic sequence of first "securing existing carbon stocks" and then "enhancing carbon sequestration".

4.5 Limitations and Future Prospects

This study systematically developed five age-NPP relationship models for major tree species in the Xinjiang Manas River Basin and compiled high-precision Site Index Tables. However, constrained by the limited temporal scope, the research primarily relied on the 2011 forest inventory data, lacking support from long-term continuous monitoring records. Although the constructed SEM and Γ function models demonstrated excellent performance with the available dataset, their predictive capability under extreme site conditions or for ages beyond the sample range requires further validation—particularly for NPP trends in stands older than 150 years. Building upon these limitations, future work should integrate

remote sensing data, meteorological station records, and long-term ecological monitoring to establish a multi-temporal-scale NPP dynamic monitoring system. This will enhance the spatiotemporal extrapolation capacity of the models and improve the simulation of their response to climate change. Additionally, dynamic revision of Site Index Tables under future climate scenarios should be considered to assess the evolution of site quality, thereby providing forward-looking guidance for adaptive forest management.

5. Summary

Focusing on the Manas River Basin in Xinjiang, this study systematically developed age-NPP models for the main dominant tree species based on data from both continuous forest inventory and forest management inventory. Utilizing the optimal guide curve method, Site Index Tables were compiled. The primary conclusions are as follows:

(1) Through fitting and comparing five candidate models (SEM, SDP, L, M, and Γ), the SEM and Γ functions, both achieving a maximum R^2 of 0.90, were identified as the optimal models for simulating the age-NPP relationship of forests in the Manas River Basin. These models effectively capture the characteristic "initial increase followed by decrease" dynamic of NPP with stand age, providing a reliable tool for the precise assessment of forest productivity within the watershed.

(2) Using the guide curve method, Site Index Tables for the five dominant tree species in Xinjiang's Manas River Basin were compiled, and their A_0 was determined. Validation confirmed that all tables achieved a fall-point test accuracy exceeding 94%, meeting the requirements for both scientific research and practical application. This work establishes a quantitative and standardized framework for evaluating site quality.

(3) This study clarifies significant differences in the peak NPP age and carbon sequestration capacity among tree species in the Manas River Basin. Deciduous broadleaved forests, such as *Populus euphratica* and *Poplar*, are characterized by high early-stage carbon sequestration efficiency. In contrast, evergreen coniferous forests like *Spruce* possess long-term, stable carbon sink functionality. This pattern is closely coupled with site conditions: forests with higher site indices exhibit greater carbon sink potential.

In summary, this study integrates age-NPP relationships with site quality assessment, which not only deepens the theoretical understanding of carbon cycle dynamics in arid region forests but also yields models and Site Index Tables of significant practical value. These outputs provide direct scientific evidence and technical support for future resource management, carbon sink enhancement, and ecological sustainable development in the Manas River Basin and similar arid regions. Future research should focus on integrating multi-source remote sensing data with long-term in-situ monitoring to refine model parameters and incorporate disturbance factors such as climate change and human activities, thereby enhancing the predictive power and applicability of the models.

Declarations

Conflicts of Interest:

The authors declare no conflicts of interest.

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Author Contribution

Conceptualisation, Z. Z. and M. Z.; methodology, J. Z.; software, J. Z.; validation, Y. Z. and R. Y.; formal analysis, M. Z.; investigation, M. Z.; resources, J. Z. and C. G.; data curation, R. Y. and C. G.; writing—original draft preparation, Z. Z. and J. K.; writing—review and editing, M. Z. and Z. Z.; visualisation, J. L., L. Z., and J. Z.; supervision, M. Z.; project administration, M. Z. and J. L.; funding acquisition, M. Z. and J. L. All authors have read and agreed to the published version of the manuscript.

Data Availability

The codes and data used are available upon request from the corresponding authors.

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Figures

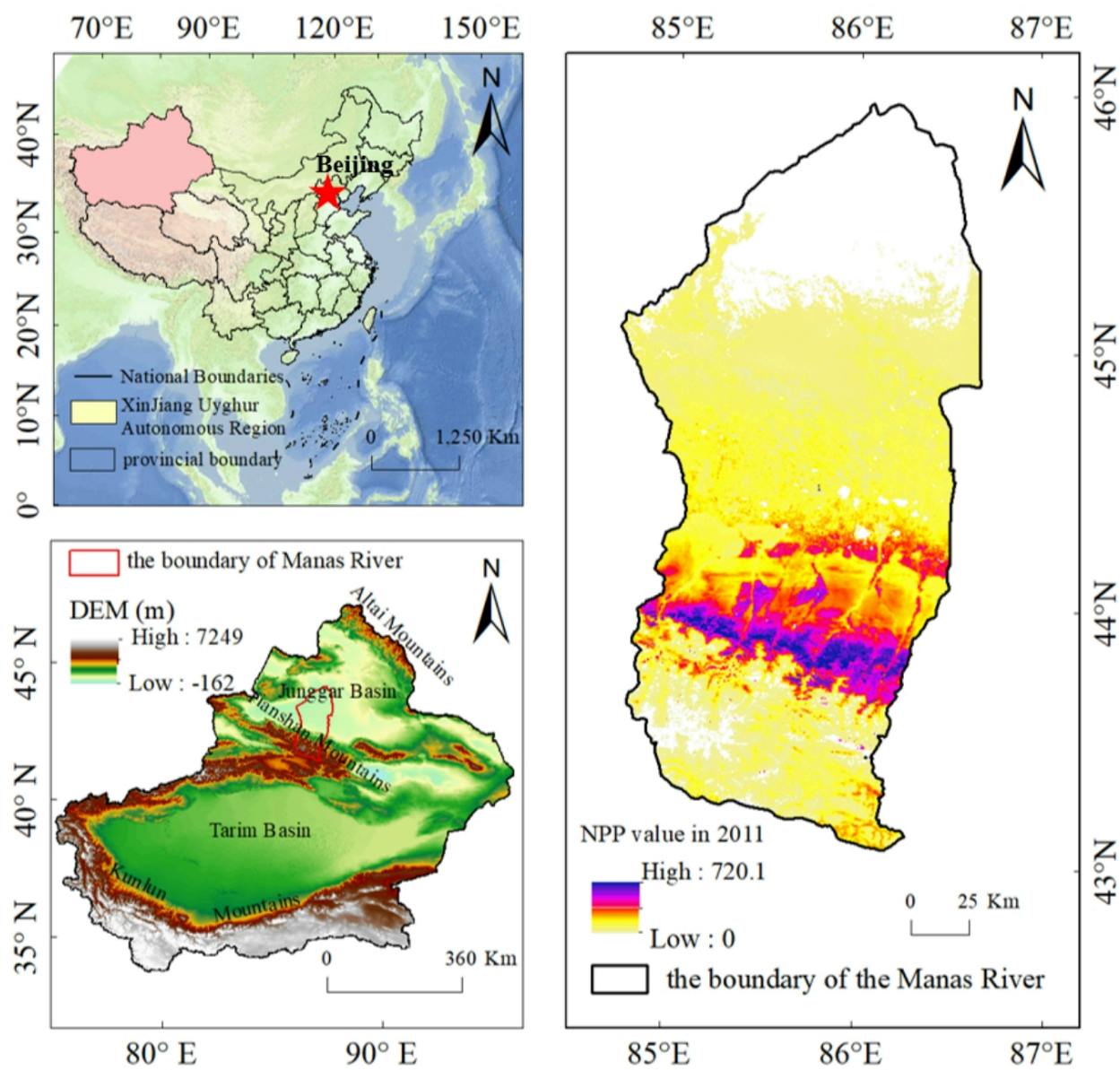


Figure 1

Map of Basic Overview of the Manas River Basin

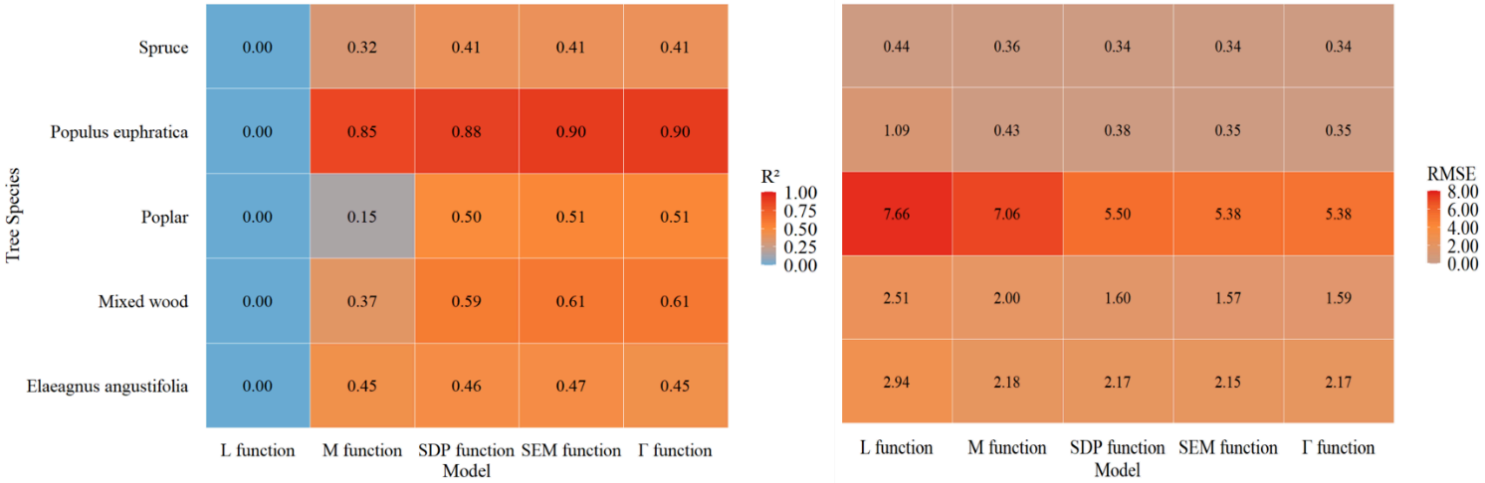


Figure 2

Heatmap Comparison of Evaluation Metrics for Dominant Tree Species Models

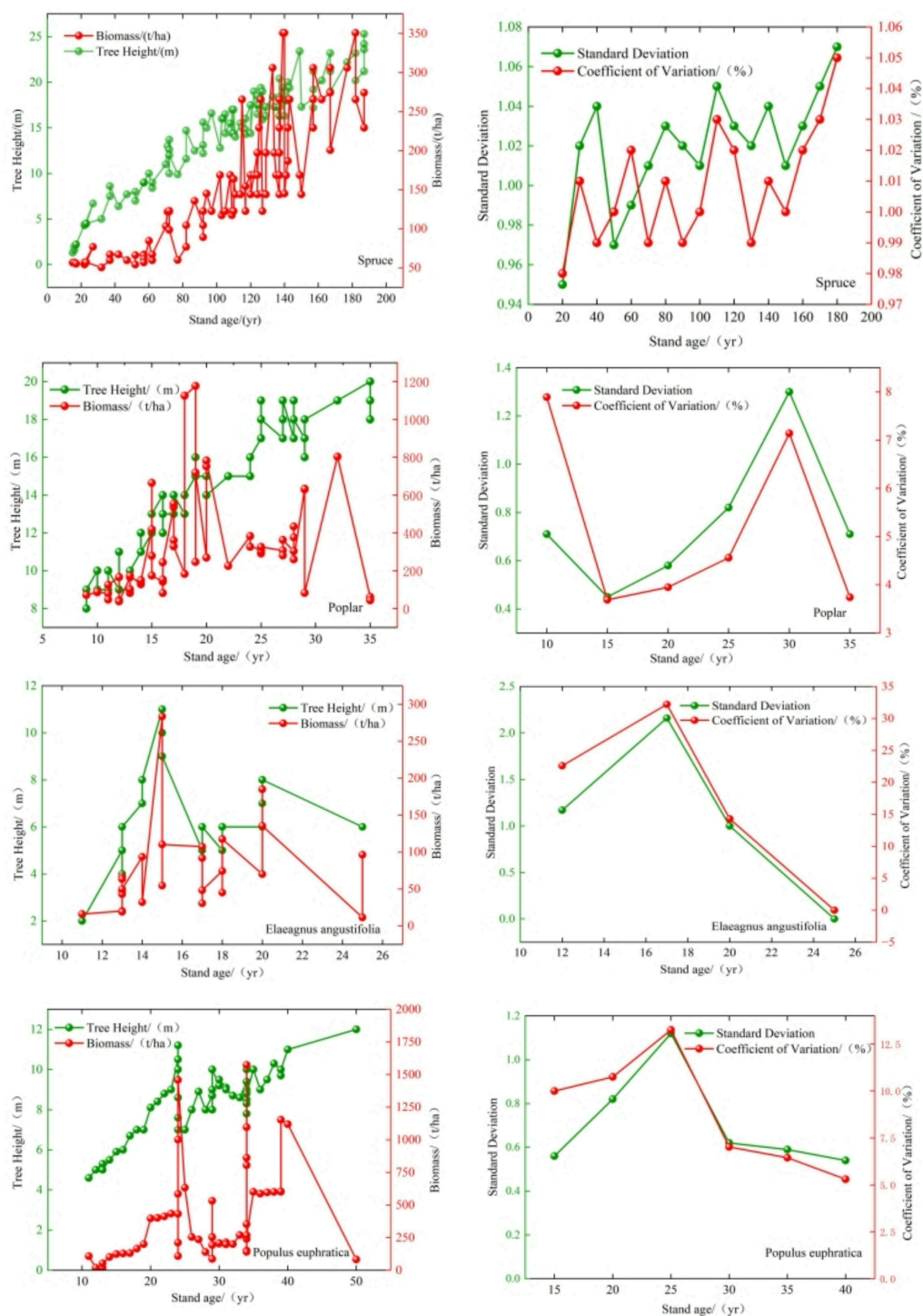


Figure 3

Variations in Biomass, Tree Height, Standard Deviation, and Coefficient of Variation across Tree Species

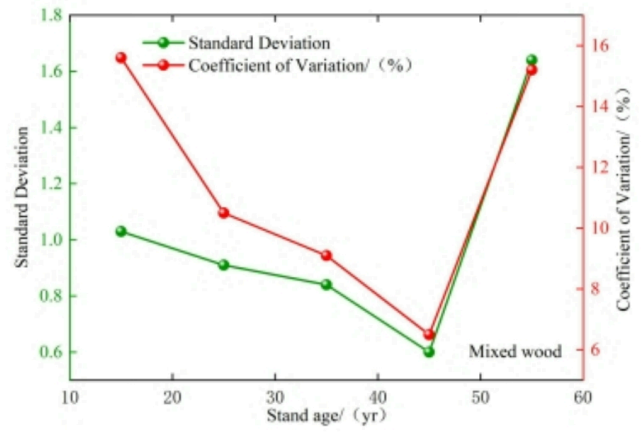
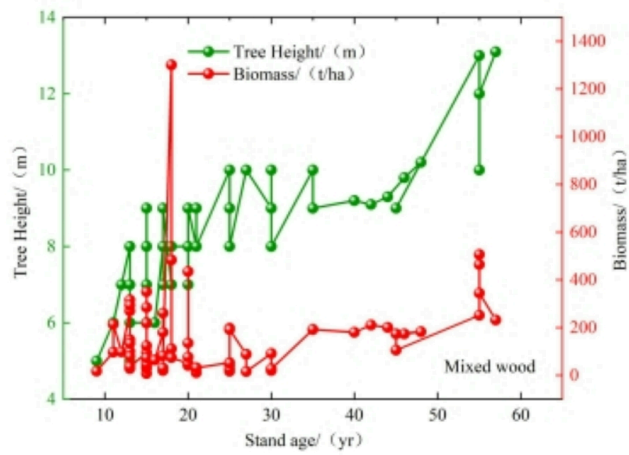


Figure 4

Site Index Curves for Dominant Tree Species

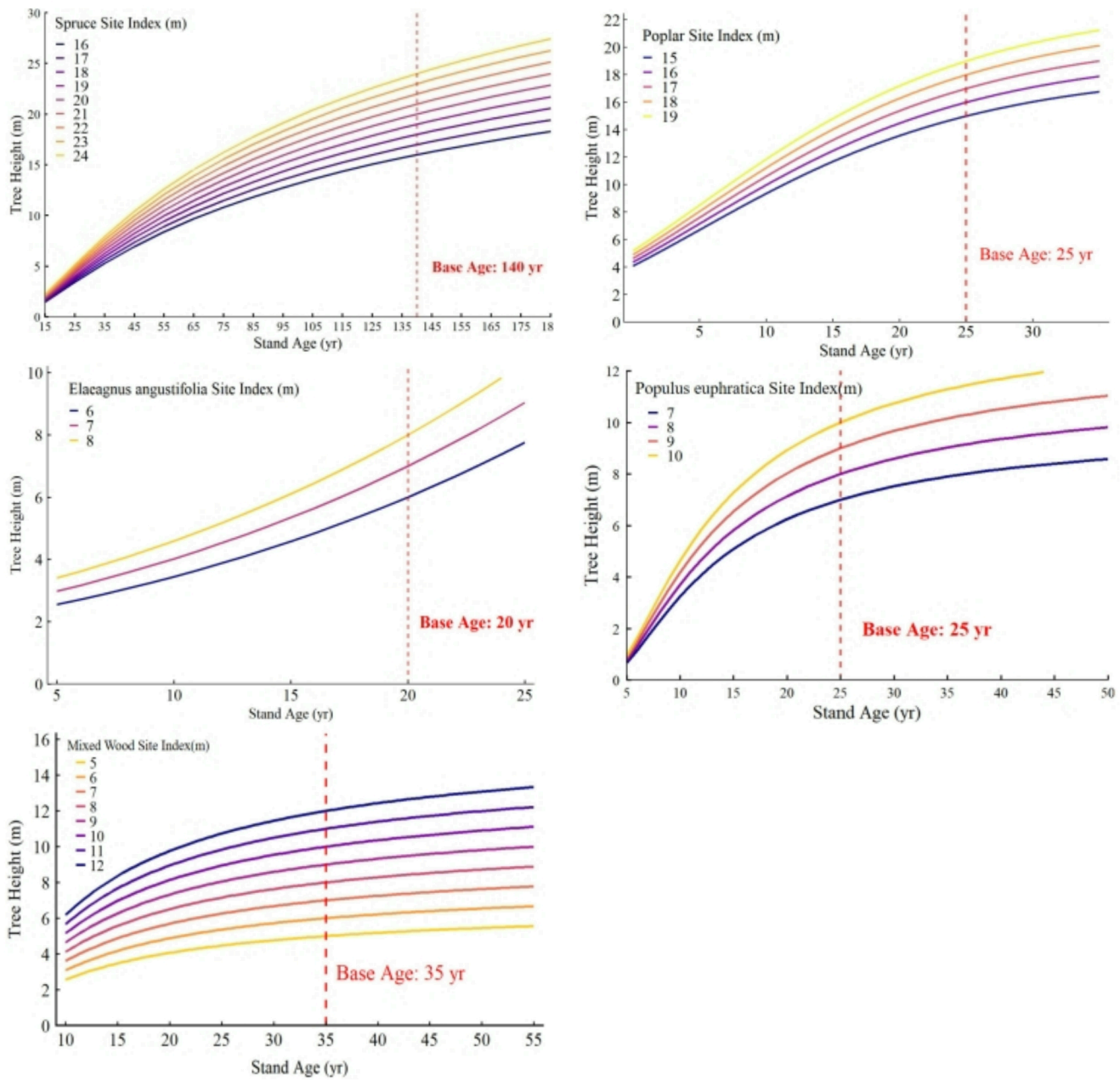


Figure 5

Field Validation of Site Index Tables for Dominant Tree Species

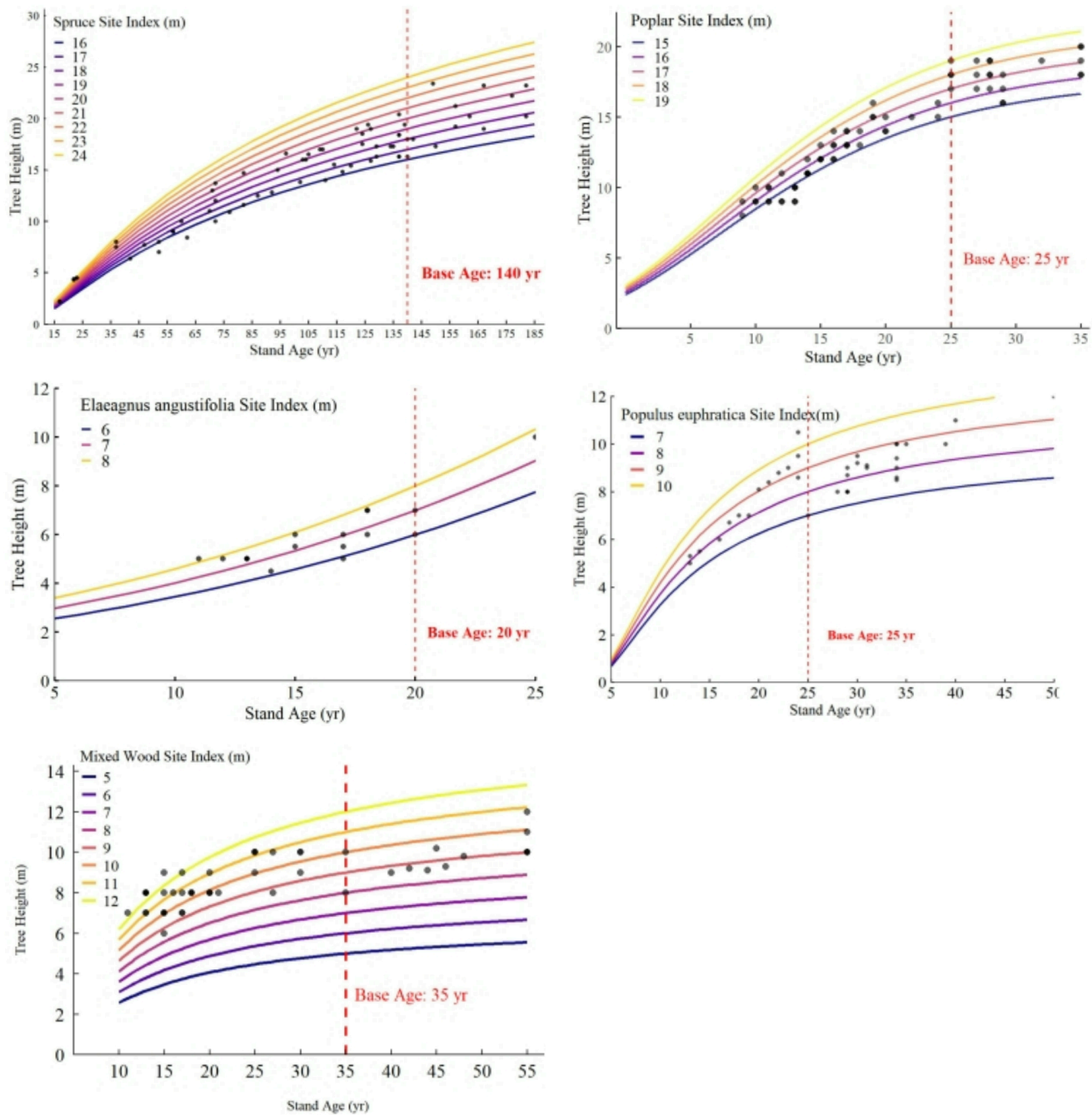


Figure 6

Taylor Diagram for Dominant Tree Species Models

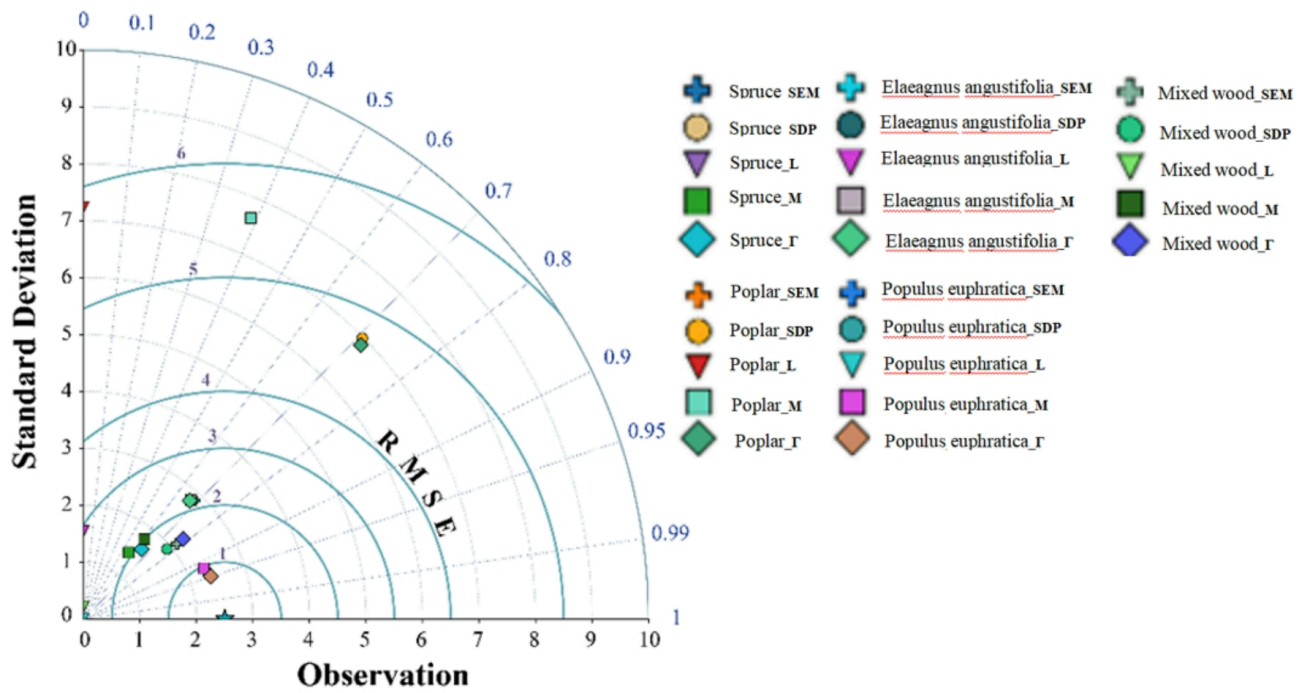


Figure 7

Distribution of Site Index Ranges