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# 坝下地区防护林不同树种生长特征

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**摘 要** 采用标准样地调查法对防护林林分结构指标进行调查,研究河北坝下地区丰宁县小坝子乡不同防护林树种榆树、杨树及油松的动态变化规律.结果表明: 该区域榆树、杨树和油松纯林的平均年龄均为10年,杨树纯林的平均胸径和树高分别是榆树纯林的2.3和3.8倍,是油松纯林的2.3和3.0倍.杨树纯林的平均胸径、树高、叶面积指数(LAI)、活枝下高等指标显著大于榆树纯林和油松纯林.与杨树混交林相比,杨树纯林的林分密度高10.8%,纯林平均胸径则低5.2%,平均树高低11.3%;与榆树混交林相比,榆树纯林的林分密度高6.6%,纯林平均胸径、树高分别低7.8%和14.2%;与油松混交林相比,油松纯林的林分密度大4.9%,纯林平均胸径和树高分别低29.3%和31.8%.各林分类型的平均胸径、树高与密度呈显著负相关;平均LAI与密度和活枝下高呈显著正相关,与胸径、树高呈显著负相关;平均活枝下高与密度呈显著正相关.针阔混交林的胸径和树高生长显著优于针叶纯林.该区域防护林综合生长潜力呈上升趋势,而横向生长潜力总体上呈下降趋势.

**关键词** 防护林; 生长特征; 榆树; 杨树; 油松

**Growth characteristics of different tree species in shelterbelts in the depression area of Hebei Province, China.** ZHANG Jie-ming, YU Xin-xiao*, JIA Guo-dong, LIU Zi-qiang, LU Wei-wei (*College of Soil and Water Conservation, Beijing Forestry University/Ministry of Education Key Laboratory of Soil and Water Conservation and Desertification Combating, Beijing* 100083, *China*).

**Abstract**: This research investigated shelterbelt structure indices using the standard sampling method, to study the dynamic changes of different tree species including *Ulmus pumila*, *Populus simonii* and *Pinus tabuliformis* in the depression area in Xiaobazi Township of Fengning County, Hebei Province, China. The results showed that the average age of *U. pumila*, *P. simonii* and *P. tabuliformis* pure forests was 10 years in this area. The average DBH and tree height of *P. simonii* pure forest were 2.3 times and 3.8 times as those of *U. pumila* pure forest, as well as, 2.3 times and 3.0 times as those of *P. tabuliformis* pure forest, respectively. The average DBH, tree height, LAI and height of first live branch of *P. simonii* pure forest were significantly larger than those of *U. pumila* pure forest and *P. tabuliformis* pure forest. Compared with *P. simonii* mixed forest, the stand density of *P. simonii* pure forest was 10.8% higher, average DBH of pure forest was 5.2% lower, and average tree height was 11.3% lower. Compared with *U. pumila* mixed forest, the stand density of *U. pumila* pure forest was 6.6% higher, average DBH and tree height of pure forest were 7.8% and 14.2% lower. Compared with *P. tabuliformis* mixed forest, the stand density of *P. tabuliformis* pure forest was 4.9% larger, but average DBH and tree height were 29.3% and 31.8% lower, respectively. The average DBH, tree height of different forest types showed significant negative correlation with the stand density. Average LAI showed significant positive correlation with density and height of first live branch, and significant negative correlation with the DBH, tree height. There was a significant

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positive relationship between the average height of first live branch and stand density. The increments of DBH and tree height of coniferous and broad-leaved mixed forest were significantly higher than those of coniferous pure forest. The comprehensive growth potential of the shelterbelts tended to increase, and the lateral growth potential on the whole exhibited a declining trend.

**Key words**: shelterbelt; growth characteristics; *Ulmus pumila*; *Populus simonii*; *Pinus tabuliformis*.

土壤风蚀是危害干旱、半干旱及部分半湿润地区的主要环境问题之一[1].由风蚀造成的农田、草场退化,不仅使土地生产力急剧下降,还严重影响当地及周边地区的生态环境.由于生态环境恶化,土地沙化严重,北方地区近年来春季的连续沙尘暴[2]影响了大半个中国.丰宁县是距离京津地区最近的沙化土地分布带之一,又是京津上游重要的水源地,生态位势极其重要[3].防护林的建设是增加该区域森林覆盖率、改善生态环境的有效措施.

在林业生态工程建设领域,作为全世界规模最大的国家,如何更好地营造高效、健康的防护林体系,实现生态效益、社会效益和经济效益的统一,已成为我国防护林工程建设中急需解决的问题.目前,坝下地区防护林研究已经开展了大量工作[4-8],主要集中在涵养水源[4-5]、防风固沙[6-8]等功能方面,而关于该地域防护林自身生长特征的研究较少.林分结构是林分内各类特征因子之间所构成的关系,这类关系既存在差异性又具有相似性.林分结构作为森林生态系统的主要属性之一,决定了树木之间的竞争优势及其空间生态位,在很大程度上决定了林分的稳定性、发展的可能性和经营空间的大小[9-11].同时,林分结构作为林分功能的基础和表现,分析林分是研究新一代林分生长模型的重要基础,也是制定森林经营规划方案的前提.合理的林分结构是森林效益最优发挥的重要基础,有利于林分内合理的自然竞争,促进树木的生长[12].

本文以丰宁县小坝子乡不同防护林树种为研究对象,研究不同林分条件(林分类型、树种组成、林分密度、林分年龄等)下的生长特征和林分结构对树木胸径、树高及树冠结构等的影响,并建立了林分结构与林分生长因子关系模型,对该区域人工防护林的造林设计和科学经营管理具有重要意义.

## 1　研究地区与研究方法

### 1.1　研究区概况

研究区位于河北坝下地区丰宁县小坝子乡境内(41°22′8″—41°34′6″ N, 116°12′49″—116°29′30″ E),该地区属于大陆性季风型半干旱气候,年均温 7.3 ℃,年均无霜期 126 d.年降水量 450 mm,降雨主要集中在 6—8 月,占年总降雨量的 70%.该地区成土母质以花岗岩和片麻岩为主,以北梁为中心到小坝子村以及河谷滩地分布有风沙土.主要土壤类型为棕壤,土层较薄,养分含量普遍偏低.研究区植被主要由阔叶林、混交林、针叶林、灌草丛等植被组成.主要乔木树种有杨树(*Populus simonii*)、榆树(*Ulmus pumila*)、油松(*Pinus tabuliformis*)等,杨树在该区域防护林树种中约占 60%以上;主要灌木有榛子(*Corylus heterophylla*)、绣线菊(*Spiraea salicifolia*)等;草本植物以菊科的蒿类、禾本科杂草等为主.

### 1.2　研究方法

2016 年 7 月,在对试验地进行全面踏查的基础上,尽量避开人为干扰地段,按小坝子乡不同防护林树种、密度、林龄类型设置标准样地 145 块,样地大小为 20 m×20 m.对标准样地内的林木进行每木检尺,用 TRUPULSE200 测距仪测量树高和东、南、西、北 4 个方向的冠幅,冠幅取 4 个方向冠幅的平均值;用胸径尺测量胸径(树高低于 2 m 时,以精度为 0.001 cm 的游标卡尺贴地面测量地径);用 LAI-2000 测定叶面积指数(LAI),仪器探头距离地面 1.5 m,从 4 个方位逐次测试,每块样地测试 16 次,取平均值;用手持 GPS 经纬度测量仪测量每块样地的海拔和经纬度.样地概况见表 1.

### 1.3　数据处理

使用 R 软件进行数据统计分析,采用单因素方差分析法(one-way ANOVA)对样本数据进行分析($\alpha=0.05$).使用 Excel 2010 软件作图.

## 2　结果与分析

### 2.1　坝下地区不同树种防护林的生长状况

小坝子乡主要防护林树种中,榆树、杨树及油松纯林的平均年龄为 10 年,均属幼龄林.由表 2 可以看出,杨树纯林的平均胸径和树高分别是榆树纯林的 2.3和 3.8 倍,是油松纯林的 2.3 和 3.0 倍.该区域杨树纯林的平均树高、胸径、LAI及活枝下高均显著大于

**表 1 样地基本概况**

**Table 1 Condition of experimental plots**

| 林分结构类型 Stand structure type | 主要树种组成 Main tree species composition | 样地数 Number of plots | 株数 Number of plants | 海拔分布 Altitude distribution (m) | 林龄分布 Age distribution (a) |
|---|---|---|---|---|---|
| 杨树纯林 *Populus simonii* pure forest | 杨树 *Populus simonii* | 33 | 1368 | 829~933 | 5~22 |
| 榆树纯林 *Ulmus pumila* pure forest | 榆树 *Ulmus pumila* | 29 | 1102 | 747~759 | 6~20 |
| 油松纯林 *Pinus tabuliformis* pure forest | 油松 *Pinus tabuliformis* | 30 | 1171 | 869~875 | 4~19 |
| 针阔混交林 Coniferous and broad-leaved mixed forest | 油松×杨树 *Pinus tabuliformis* × *Populus simonii* | 28 | 1023 | 763~890 | 4~18 |
| 阔叶混交林 Broad-leaved mixed forest | 杨树×榆树 *Populus simonii* × *Ulmus pumila* | 25 | 1042 | 762~867 | 5~20 |

**表 2 小坝子乡不同树种防护林的生长状况**

**Table 2 Growth status of different tree species shelterbelts in Xiaobazi Township**

| 主要树种 Main species | 平均海拔 Average altitude (m) | 平均年龄 Average age (a) | 平均胸径 Average DBH (cm) | 平均树高 Average tree height (m) | 平均叶面积指数 Average LAI | 平均冠幅 Average crown width (m) | 平均活枝下高 Average live branch height (m) |
|---|---|---|---|---|---|---|---|
| 杨树 *Populus simonii* | 890 | 10 | 13.52±0.15a | 10.31±0.09a | 2.37±0.10a | 2.58±0.35a | 2.47±0.09a |
| 榆树 *Ulmus pumila* | 758 | 10 | 5.81±0.15b | 2.71±0.08b | 1.03±0.13b | 1.77±0.16b | 0.62±0.06b |
| 油松 *Pinus tabuliformis* | 874 | 10 | 5.79±0.17b | 3.39±0.06b | 0.78±0.09b | 2.16±0.24a | 0.44±0.08b |

同列不同小写字母表示差异显著($P<0.05$) Different small letters in the same column meant significant difference at 0.05 level. 下同 The same below.

榆树纯林和油松纯林.

**2.2** 坝下地区不同密度防护林中不同树种的生长特征

从表 3 可以看出,小坝子乡防护林的林分密度为 891.7~1036.5 株 · $hm^{-2}$,且随着林分平均密度的增加,不同林分类型的平均胸径、树高都有不同程度的下降.与杨树混交林相比,杨树纯林的林分密度高 10.8%,平均胸径低 5.1%,平均树高低 11.3%;与榆树混交林相比,榆树纯林的林分密度高 6.6%,平均胸径、树高分别低 7.8%和 14.2%.杨树纯林、榆树纯林与杨树×榆树、榆树×杨树混交林相比,均为混交林的生长指标优于纯林.与油松混交林相比,油松纯林的林分密度高 4.9%,平均胸径、树高分别低29.3%和31.8%;油松混交林生长指标显著优于油松纯林.

各类林分的平均胸径、树高与林分密度呈显著负相关,并且针阔混交林的胸径和树高生长显著优于针叶纯林.各类林分的平均 LAI 与林分密度和活枝下高呈显著正相关,与胸径、树高呈显著负相关,而与冠幅的相关性不显著;杨树、榆树及油松林分纯林和混交林平均活枝下高与平均密度均呈显著正相关.

**2.3** 坝下地区不同林龄杨树防护林的生长特征

将 33 个杨树纯林样地,按林龄不同分为 13 组(5、6、7、8、9、10、11、12、15、17、18、19、22 年生),该区域杨树纯林平均密度为1013.5~1050.5株 · $hm^{-2}$,林

**表 3 小坝子乡不同密度防护林生长状况**

**Table 3 Growth status of different density shelterbelts in Xiaobazi Township**

| 林分类型 Forest type | 树种组成 Tree species composition | 平均胸径 Average DBH (cm) | 平均树高 Average tree height (m) | 平均叶面积指数 Average LAI | 平均冠幅 Average crown width (m) | 平均活枝下高 Average live branch height (m) | 平均密度 Average density (plants · $hm^{-2}$) |
|---|---|---|---|---|---|---|---|
| 纯林 Pure forest | 杨树 *Populus simonii* | 13.52±0.15a | 10.31±0.09b | 2.37±0.10a | 2.58±0.35a | 2.47±0.09a | 1036.5±22.1a |
| 混交林 Mixed forest | 杨树×榆树 *Populus simonii* × *Ulmus pumila* | 14.26±0.21a | 11.62±0.15a | 2.07±0.06a | 2.94±0.26a | 2.29±0.08a | 935.2±36.3b |
| 纯林 Pure forest | 榆树 *Ulmus pumila* | 5.81±0.15c | 2.71±0.08d | 1.03±0.13b | 1.77±0.16b | 0.62±0.06b | 950.2±23.4b |
| 混交林 Mixed forest | 榆树×杨树 *Ulmus pumila* × *Populus simonii* | 6.30±0.09c | 3.16±0.13d | 0.89±0.12b | 2.15±0.08b | 0.27±0.08c | 891.7±17.3c |
| 纯林 Pure forest | 油松 *Pinus tabuliformis* | 5.79±0.17c | 3.39±0.06d | 0.78±0.09b | 2.16±0.24b | 0.44±0.08b | 975.4±23.0b |
| 混交林 Mixed forest | 油松×杨树 *Pinus tabuliformis* × *Populus simonii* | 8.19±0.22b | 4.97±0.10c | 0.68±0.05b | 2.55±0.14b | 0.29±0.11c | 930.3±27.2b |

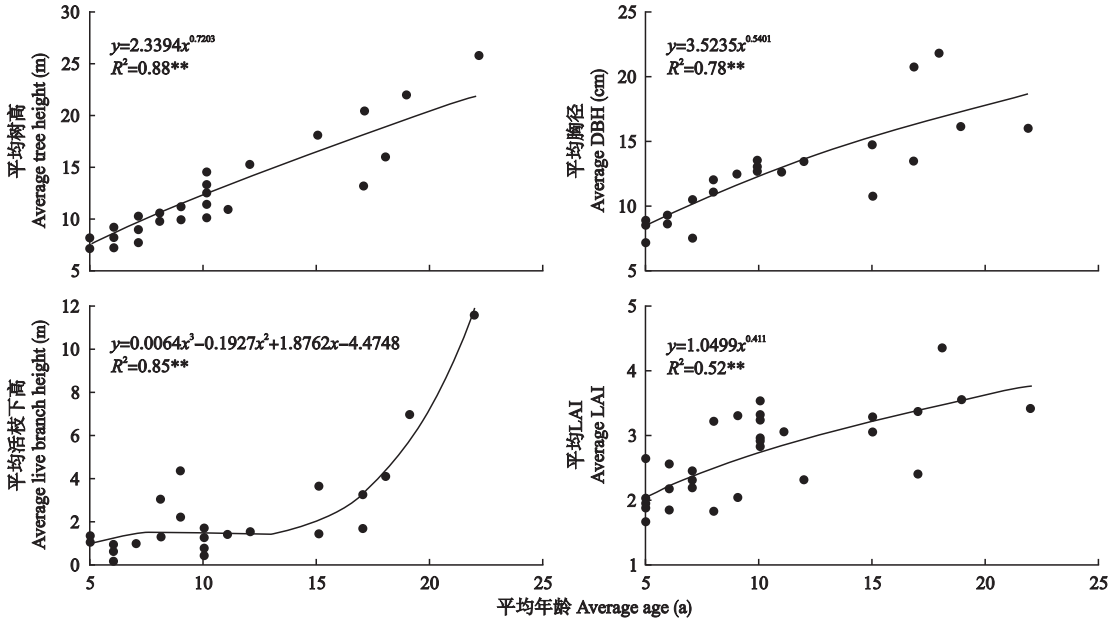


**图 1**　不同林龄杨树防护林的生长特征

**Fig.1**　Growth characteristics of *Populus simonii* shelterbelts with different ages.

* $P<0.05$；* * $P<0.01$.

**表 4　生长因子间的相关系数**

**Table 4　Correlation coefficients between growth factors**

| | 树高 Tree height | 胸径 DBH | 活枝下高 Live branch height | 冠幅 Crown width |
|---|---|---|---|---|
| 胸径 DBH | 0.685** | | | |
| 活枝下高 Live branch height | 0.864** | 0.519** | | |
| 冠幅 Crown width | 0.287 | 0.673** | 0.311 | |
| 叶面积指数 LAI | 0.652** | 0.892** | 0.553* | 0.753** |

* $P<0.05$；* * $P<0.01$.

龄分布在 5~22 年,均属幼龄林.杨树林龄与树高、胸径、活枝下高、LAI 呈显著正相关,而林龄与冠幅的相关性不显著(图 1).

**2.4**　坝下地区杨树生长状况的综合评价

**2.4.1** 综合指标的建立　选取树高、胸径、活枝下高、冠幅、LAI 等 5 个变量反映植物地上部分的纵向、横向生长以及生长潜力,且这 5 个变量之间的相关性较好(表 4),其中,除了冠幅与树高和活枝下高之间相关性不显著之外,其他各指标之间均达到了显著性水平,因此可以采用因子分析法将树高、胸径、活枝下高、冠幅、LAI 构建成代表防护林生长状况的综合指标.

采用主成分分析法,得到各主分量的特征值和方差累积贡献率(表 5),由于前 2 个主分量综合了整个信息量的 90.3%,所以只取前 2 个主分量作为防护林的综合生长状况指标.第 1 主成分对应的符号都相同,其值在 0.5 左右,且均为负值,5 个指标的值越大,第 1 主成分的值越小,防护林生长越好.因此,第 1 主成分反映了防护林的综合生长潜力.第 2 主成分是横向生长指标与纵向生长指标的差,第 2 主成分值越大表明该防护林横向生长越有优势.因此,第 2 主成分为防护林的横向生长潜力.根据计算的特征向量,得

**表 5　总方差分解表**

**Table 5　Total variance decomposition table**

| 主分量 Principal component | 初始特征值 Initial eigenvalue | | | 旋转后各因子的特征值 Eigenvalue of each factor after rotation | | |
|---|---|---|---|---|---|---|
| | 特征根 Eigenvalue | 方差百分比 Percent variance (%) | 累积贡献率 Cumulative contribution rate (%) | 特征根 Eigenvalue | 方差百分比 Percent variance (%) | 累积贡献率 Cumulative contribution rate (%) |
| 1 | 1.872 | 70.1 | 70.1 | 1.579 | 68.6 | 68.6 |
| 2 | 1.004 | 20.2 | 90.3 | 1.004 | 21.7 | 90.3 |
| 3 | 0.562 | 6.3 | 96.6 | | | |
| 4 | 0.314 | 2.0 | 98.6 | | | |
| 5 | 0.267 | 1.4 | 100 | | | |

出主成分与标准化变量的关系,使 2 个主成分表达为原 5 个指标的加权组合:

防护林综合生长潜力($Y_1$):

$$Y_1 = -0.448X_1 - 0.487X_2 - 0.412X_3 - 0.382X_4 - 0.496X_5$$

防护林横向生长潜力($Y_2$):

$$Y_2 = -0.496X_1 + 0.194X_2 - 0.544X_3 + 0.6X_4 + 0.246X_5$$

式中:$X_1$为树高;$X_2$为胸径;$X_3$为活枝下高;$X_4$为冠幅;$X_5$为 LAI.

**2.4.2** 生长状况的综合评价 由图 2 可以看出,编号 5-22 是根据坝下地区杨树防护林年龄(5~22 年)增长趋势进行排序的,表示坝下地区杨树防护林随林龄的生长状况.随着林龄的增加,第 1 主成分值呈下降趋势,说明随着林龄增加,防护林综合生长潜力逐步提高;而第 2 主成分值总体上与林龄呈负相关,说明随林龄增长,防护林横向生长潜力呈下降趋势.可见,随着林龄增加,防护林横向生长速率小于纵向生长速率.

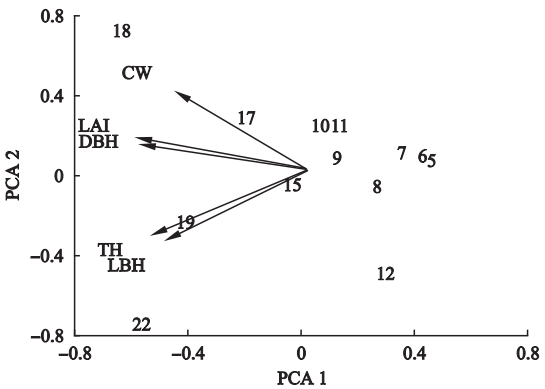


**图 2** 坝下地区杨树防护林生长状况的主成分分析

**Fig.2** Principal component analysis on growth status of *Populus simonii* shelterbelts in the dam area.

CW: 冠幅 Crown width; LAI: 叶面积指数 Leaf area index; DBH: 胸径 Diameter at breast height; TH: 树高 Tree height; LBH: 活枝下高 Live branch height.

## 3 讨 论

本研究中,坝下地区防护林树种中杨树、榆树及油松都属于幼龄林,但杨树的平均胸径、树高、LAI 及活枝下高等生长指标均明显优于榆树纯林和油松纯林.这表明杨树是该区域防护林中的优势乔木树种,杨树更适合于在该区域生长.但由于树木生长周期较长,对其中龄林到成熟林阶段的适宜性问题,还有待于长期研究[13-14].

本研究表明,混交林的生长指标均优于纯林,其中针阔混交林的胸径和树高生长显著优于针叶纯林,这可能是由于种间竞争,针阔混交林更易形成明显的复层林冠结构,充分利用空间资源,从而对针阔树种各自的生长均起到促进作用,这与沈爱华等[15]、陈得水[16]的研究结果一致.因此,建议在保持人工林生长优势的同时发展多层次林分结构;在坝下防护林整体结构的基础上,提倡由人工纯林向针阔混交林发展.

有研究表明,林分密度的增加会导致林分所需营养空间的减小,进而导致林内竞争加剧,直接影响林木营养物质的吸收,从而导致胸径和树高的降低[17-19].本研究中,不同密度林分的平均胸径、树高均存在明显差异,其与林分密度均呈显著负相关,这与李钢铁等[20]、赵赫然等[21]、田新辉等[22]的研究结果一致.建议相关林业管理单位可以通过适当调整林分密度来改善林分的营养空间,使林内竞争趋缓,从而提高林分的生长量.

LAI 是叶覆盖量的无量纲度量,受植物大小、年龄和其他因子的影响[23].本研究表明, LAI 与林分密度和活枝下高呈显著正相关,这说明高密度林分的 LAI 较大;LAI 与林分平均胸径、树高呈显著负相关,说明高大林木的林分,其 LAI 较小.这与姚丹丹等[24]的研究结果相似,而与 Bequet 等[25]的研究结果有差异,这可能是由该树种自身的生理生态特性引起的,使得林分因子对 LAI 空间分布的影响变异较大.雷相东等[26]提出,林分密度对冠幅影响显著,本研究中,林分冠幅随密度的增加呈减小趋势,这是因为林分密度增大、郁闭增加,导致自然整枝使得林分冠幅呈减小趋势,这与谌红辉等[27]的研究结果一致.但谌红辉等[27]还发现,林分生长后期,各密度的冠幅差异开始变小,这还有待长期的跟踪研究.各林分纯林和混交林平均活枝下高与平均密度均呈正相关,高密度下具有较高的活枝下高,这是由于高密度下林分郁闭、树木个体间的竞争以及自然整枝都早于低密度,针阔叶间的差别可能也与树种本身的特性有关,这与刘青华等[18]的研究结果一致.

有研究表明,林龄较大的林分树高、胸径等显著大于林龄较小的林分[28-29].本研究表明,杨树纯林平均树高、胸径、LAI 随林龄呈显著正相关,而 5~10 年生的杨树活枝下高随林龄变化规律不明显,但在 10 年之后,杨树活枝下高随林龄增加呈显著正相关,这可能是由树木自身生理生态特性决定的;除活枝下高外,平均树高、胸径、LAI 随林龄上升而增大的趋势减缓,这是因为养分、水分等需求超过阈值后竞争激烈,导致树木生长变慢.经主成分分析,选择林分树高、胸径、活枝下高、冠幅、LAI 这 5 个生长指标反映防护林

综合生长潜力和防护林的横向生长潜力;随林龄增加,该区域防护林综合生长潜力呈上升趋势,而横向生长潜力整体上呈下降趋势.在实际生产中,建议林业主管部门可以加强管理,适度间伐,改善土壤水分不足的状况,从而促进防护林的横向生长潜力.

**参考文献**


[1] Sun Y-C (孙悦超), Ma S-S (麻硕士), Chen Z (陈智), *et al*. Test and analysis of wind erosion on the surface soil in arid and semiarid area of north piedmont of Yinshan Mountain. *Transactions of the Chinese Society of Agricultural Engineering* (农业工程学报), 2007, **23** (12): 1-5 (in Chinese)

[2] Qu Z-C (屈志成), Ai W-X (艾万祥), Qu J-P (屈金鹏), *et al*. Once the sand channel green corridor today: Investigation and thinking on the effect of sand prevention and control in Xiaobazi watershed of Fengning County. *Water Resources Development Research* (水利发展研究), 2009, **9**(5): 53-56 (in Chinese)

[3] Guo H-Z (郭宏忠), Zhao T-N (赵廷宁), Li X-G (李孝广), *et al*. Study on soil water erosion and wind erosion prediction models and grading of soil erosion in Mt. Xiaoban: A case study of Xiaobazi Township of Fengning Manzu Autonomous County. *Research of Soil and Water Conservation* (水土保持研究), 2004, **11**(3): 66-69 (in Chinese)

[4] Tian C (田　超), Yang X-B (杨新兵), Li J (李军), *et al*. Study on hydrological effects of litter layer and soil layer on the hillside of mountainous area in northern Hebei Province. *Journal of Soil and Water Conservation* (水土保持学报), 2011, **25**(2): 97-103 (in Chinese)

[5] Qi T (齐　特), Li Y-T (李玉婷), He H-B (何会宾), *et al*. Water conservation capacity of water forest land in Fengning County of northern Hebei. *Science of Soil and Water Conservation* (中国水土保持科学), 2016, **14** (3): 60-67 (in Chinese)

[6] Guo Y-H (郭雨华), Zhao T-N (赵廷宁), Ding G-D (丁国栋), *et al*. Effects of shrub cover on wind erosion of wind-sand soil. *Research of Soil and Water Conservation* (水土保持研究), 2006, **13**(5): 245-247 (in Chinese)

[7] Ma Z-W (马增旺), Fan S-H (范少辉), Guan F-Y (官凤英), *et al*. Study on sediment transport rate of *Populus simonii* artificial sand-fixing forest in sporadic sandy land of northern. *Journal of Agricultural University of Hebei* (河北农业大学学报), 2013, **36**(5): 65-70 (in Chinese)

[8] Guo Y-H (郭雨华), Zhao T-N (赵廷宁), Sun B-P (孙保平), *et al*. Field investigation on the effects of shrubbery on surface wind conditions and aerodynamic parameters: A case study of Xiaobazi Township in Fengning Manchu Autonomous County. *Forest Inventory and Planning* (林业调查规划), 2006, **31**(4): 72-76 (in Chinese)

[9] Zeng S-Q (曾思齐), Li J (李　俊), Li D-L (李东丽), *et al*. Study on the structure of *Choerospondias axillaria* secondary forest in southern collective forest region. *Journal of Central South University of Forestry & Technology* (中南林业科技大学学报), 2012, **32**(4): 1-6 (in Chinese)

[10] Li C-P (李春平), Guan W-B (关文彬), Fan Z-P (范志平), *et al*. Advances in the study of the ecological structure of farmland shelterbelts. *Chinese Journal of Applied Ecology* (应用生态学报), 2003, **14**(11): 2037-2043 (in Chinese)

[11] Dai L-M (代力民), Chen G (陈　高), Deng H-B (邓红兵), *et al*. Evaluation of structural composition and health distance of broad-leaved *Pinus koraiensis* in disturbed Changbai Mountain. *Chinese Journal of Applied Ecology* (应用生态学报), 2004, **15**(10): 1750-1754 (in Chinese)

[12] Bai J (白　静), Tian Y-L (田有亮), Han Z-R-G-T (韩照日格图), *et al*. Study on the relationship between aboveground biomass, leaf area index and stand density in *Pinus tabuliformis* plantations. *Journal of Arid Land Resources and Environment* (干旱区资源与环境), 2008, **22**(3): 183-187 (in Chinese)

[13] Li HM, He XY, Wang KL. Effects of climate factors on the height increment of *Populus simonii* protection forest in the riverbank field. *Journal of Forestry Research*, 2004, **15**: 177-180

[14] Yu B (玉　宝), Wu J-S-G-L (乌吉斯古楞), Wang B-T (王百田), *et al*. Analysis on growth characteristics of canopy of *Larix gmelinii* natural forest. *Scientia Silvae Sinicae* (林业科学), 2010, **46**(5): 41-48 (in Chinese)

[15] Shen A-H (沈爱华), Jiang B (江　波), Yuan W-G (袁位高), *et al*. Community types and their growth benefits of mixed layers in beach. *Acta Ecologica Sinica* (生态学报), 2006, **26**(10): 3479-3484 (in Chinese)

[16] Chen D-S (陈得水). Effects of different mixed models on growth characteristics of young *Cunninghamia lanceolata* plantations. *Protection Forest Science and Technology* (防护林科技), 2014(7): 6-8 (in Chinese)

[17] Li X-H (李晓宏), Gao J-R (高甲荣), Zhang J-R (张金瑞), *et al*. Store density and growth factors of *Pinus tabuliformis* plantations in Miyun Reservoir. *Journal of Zhejiang Forestry College* (浙江林学院学报), 2010, **27** (6): 821-825 (in Chinese)

[18] Liu Q-H (刘青华), Zhou Z-C (周志春), Zhang K-M (张开明), *et al*. Effects of afforestation density on growth and wood basic density of different *Pinus massoniana* provenances. *Scientia Silvae Sinicae* (林业科学), 2010, **46**(9): 58-64 (in Chinese)

[19] Song H (宋　浩). Density and Clonal Allocation of *Poplar* Growth and Undergrowth of Plant Diversity. Master Thesis. Nanjing: Nanjing Forestry University, 2013 (in Chinese)

[20] Li G-T (李钢铁), Wang Y-S (王永胜), Yu X-X (余新晓), *et al*. Spatial patterns of *Ulmus pumila* populations in different densities in Hunshandake Sandland.

*Journal of Arid Land Resources and Environment* (干旱区资源与环境), 2011, **25**(3): 141-145 (in Chinese)

[21] Zhao H-R (赵赫然), Wang H (王 辉), Duan Y-N (段雅楠). Analysis of growth characteristics of different tree species in the Huajialing shelterbelt. *Journal of Arid Land Resources and Environment* (干旱区资源与环境), 2015, **29**(1): 48-52 (in Chinese)

[22] Tian X-H (田新辉), Sun R-X (孙荣喜), Li J (李军), *et al*. Effect of stand density on growth of *Populus*×*euramericana neva* plantations. *Scientia Silvae Sinicae* (林业科学), 2011, **47**(3): 184-188 (in Chinese)

[23] Wang X-Q (王希群), Ma L-Y (马履一), Jia Z-K (贾忠奎), *et al*. Advances in the research and application of leaf area index. *Chinese Journal of Ecology* (生态学杂志), 2005, **24**(5): 537-541 (in Chinese)

[24] Yao D-D (姚丹丹), Lei X-D (雷相东), Yu L (余黎), *et al*. Spatial heterogeneity of leaf area index of coniferous and broad-leaved mixed forest. *Acta Ecologica Sinica* (生态学报), 2015, **35**(1): 71-79 (in Chinese)

[25] Bequet R, Campioli M, Kint V, *et al*. Spatial variability of leaf area index in homogeneous forests relates to local variation in tree characteristics. *Forest Science*, 2012, **58**: 633-640

[26] Lei X-D (雷相东), Zhang Z-L (张则路), Chen X-G (陈晓光). Study on crown canopy forecast model of several species of *Larix olgensis*. *Journal of Beijing Forestry University* (北京林业大学学报), 2006, **28**(6): 75-79 (in Chinese)

[27] Chen H-H (谌红辉), Ding G-J (丁贵杰), Wen H-H (温恒辉), *et al*. Effects of plantation density on stand growth and benefit of *Pinus massoniana* forest. *Forest Research* (林业科学研究), 2011, **24**(4): 470-475 (in Chinese)

[28] Shi X (施 翔), Tang C-P (唐翠平), Wu K (吴轲), *et al*. Study on growth regularity of tree species *Populus simonii* in shelter-forest of Junggar Basin. *Journal of Arid Land Resources and Environment* (干旱区资源与环境), 2013, **27**(7): 155-160 (in Chinese)

[29] Chu X-L (楚秀丽), Wang Y (王 艺), Jin G-Q (金国庆), *et al*. Changes in growth, wood properties and stand differentiation of *Schima superba* plantation in different habitats, planting densities and forest ages. *Scientia Silvae Sinicae* (林业科学), 2014, **50**(6): 152-159 (in Chinese)

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Zhang J-M, Yu X-X, Jia G-D, *et al*. Growth characteristics of different tree species in shelterbelts in the depression area of Hebei Province, China. *Chinese Journal of Applied Ecology*, 2017, **28**(10): 3174-3180 (in Chinese)