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Inter-annual litterfall variation in *Abies georgei* var. *smithii* forests of Southeastern Tibet

Inter-annuelle Streufallvariation in *Abies georgei* var. *smithii* Wäldern im Südosten Tibets

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Keywords: *Sejila Mountain, Forrest's fir, Abies chengii, Forest gap, Litter annual production, Plant organs, Seasonal dynamics, Subalpine forest, nutrients, carbon*

Schlüsselbegriffe: *Sejila Mountain, Forrest's Tanne, Abies chengii, Bestandeslücken, Baumkomponenten, Saisonalität, Subalpine Wälder, Nährstoffe, Kohlenstoff*

Abstract

Since litterfall is an important process in high-altitude forest ecosystems, we measured over three years the litterfall amount and composition in five habitats (i.e., closed canopy forest, forest gaps of three sizes, and logged forest) in an *Abies georgei* var. *smithii* forest in Sejila Mountain, southeastern Tibet. The annual litterfall ranged between 2.08 Mg ha^{-1} year^{-1} and 2.35 Mg ha^{-1} year^{-1} with an average of 2.21 Mg ha^{-1} year^{-1}, is thus relatively stable and lower than litterfall in other dark coniferous forest types in the same region. Approximately 86.3 % of litterfall is composed of needles and twigs, with needles being the dominant component. Seasonal litterfall exhibited a single peak (about 20 % of the total litterfall) from October to November every year. The period August-September produced with about 4 % the least litterfall. The an-

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nual litterfall dynamic was mainly determined by the biological characteristics of *A. georgei* var. *smithii*. Significant differences in litterfall were evident in the five different habitats with the highest amount of litterfall occuring in the small forest gap. Tree regeneration and shrub distribution apparently lead to changes in litterfall distribution in closed forest, compared to logged forest and different gap sizes.

Zusammenfassung

Da Streufall ein wichtiger Prozess in Bergwäldern ist, haben wir über einen Zeitraum von drei Jahren die Streufallmenge und deren Zusammensetzung an fünf Standorten (geschlossener Bestand, drei unterschiedlich große Bestandeslücken und ein geschlägerter Bestand) in einem *Abies georgei* var. *smithii* Wald in den Seijila Bergen von Südost Tibet gemessen. Der jährliche Streufall variierte von 2.08 Mg ha^{-1} $year^{-1}$ bis 2.35 Mg ha^{-1} $year^{-1}$ mit einem Mittelwert von 2.21 Mg ha^{-1} $year^{-1}$; somit ist der Streufall von *A. georgei* var. *smithii* relativ stabil und geringer als der Streufall in anderen dunklen Nadelwäldern in dieser Region. 86.3 % der Streufallmenge sind Nadeln und Zweige, wobei Nadeln der Hauptbestandteil sind. Die saisonale Verteilung zeigt einen Streufallpeak (etwa 20 % der jährlichen Streufallmenge) für jedes Jahr zwischen Oktober und November. Zwischen August und September wurde mit 4 % die geringste Streufallmenge gemessen. Die jährliche Streufalldynamik wurde beeinflusst durch die Besonderheiten von *A. georgei* var. *smithii*. Wir konnten signifikante Unterschiede in der Streufallmenge zwischen den fünf untersuchten Standorten feststellen, wobei der höchste Streufall in der kleinsten Bestandeslücke gemessen wurde. Verjüngung und Sträucher bewirken scheinbar Veränderungen in der Streufallverteilung zwischen geschlossenen, lückigen und geschlägerten Beständen.

1. Introduction

Litterfall, in addition to fine root turnover, is the major source of matter and energy for decomposing organisms in terrestrial ecosystems. Plant litterfall is correlated with primary production and plays a crucial role in stabilizing the ecosystem functions (e.g., Wang 1989; Maguire 1994; Witkamp 1963; Berg *et al.*, 2001). As soil microbial decomposition of litterfall releases CO_2 to the atmosphere, studies of litterfall and its decomposition receive increasing attention in the context of global changes. Forest litterfall is expected to increase with global warming, particularly in temperate and cold regions, where temperature increase is expected to be larger than in tropical and subtropical regions (Delucia *et al.* 1999). Understanding the dynamic processes of accumulation and decomposition of litter is crucial to understand the structure and function of forest ecosystems temperate and cold zones (Peng *et al.* 2002).

Abies georgei var. *smithii* (synonyms *Abies forrestii Creib* var. *smithii* (Trav. Lab. Forest. Toulouse 1 (2, 1): 177, 1929); *Abies delavayi* var. *smithii* (Monogr. 143. t. 8B. 1971), FOC I, 1999) forests are the most widespread and well-preserved primary forests in southeastern Tibet. These forests represent the zonal vegetation and climax community in subalpine zones of southeastern Tibet and play an essential role in maintaining biodiversity of the high-altitude valleys of the Brahmaputra river basin. Previous studies of litterfall in subalpine coniferous forests have been carried out mostly in closed canopy forests, as researchers hold the view that the canopy forest is the most representative habitat (Ye, 2016; Wu, 2014; NFGA, 2012). However, using closed canopy stands as reference may lead to substantial biases, as it ignores the impact of heterogeneous stand structure, including natural gaps and logging, on litterfall distribution. *Abies georgei* var. *smithii* forests frequently exhibit gaps and open patches as the result of tree death due to natural causes and/or human intervention. These gaps are also important for natural forest regeneration. The regeneration and changes in tree density in gaps may change the amount, composition and distribution of litterfall in gaps compared to closed canopies.

In this study, we investigated five different habitat types of *A. georgei* var. *smithii* forests, to better understand the litterfall production and nutrient circulation of this important forest ecosystem. The purpose is to provide a scientific basis for long-term ecological research on carbon cycling and energy conversion in subalpine dark coniferous forest ecosystems in southeastern Tibet.

2. Material and Methods

2.1 Overview of the research area

The sampling sites are located on the eastern slopes of Sejila Mountain at an elevation of about 3800 m.a.s.l. (29° 48′ N, 94° 49′ E, Fig. 1). These sampling sites are part of long-term fixed standard plots of the National Forest Ecosystem Observation & Research Station of Nyingchi Tibet (http://lzf.cern.ac.cn). The dominant tree species in this region is *Abies georgei* var. *smithii*. Meteorological observations at Nyingchi Ecological Research Station show annual temperature of 3.5 °C. The mean temperature in the warmest month (July) is 11.2 °C and in the coldest month (January) it is -4.1 °C. The annual precipitation sum is 1095 mm. Summer precipitation from June to September accounts for 75 % – 82 % of the annual total. The annual average evaporation is 544 mm, and the annual average relative humidity is 83 %. The annual number of sunshine hours is 1150 h with an average annual percentage of sunshine of 26 % (Xu *et al.* 2010; Luo *et al.* 2014).

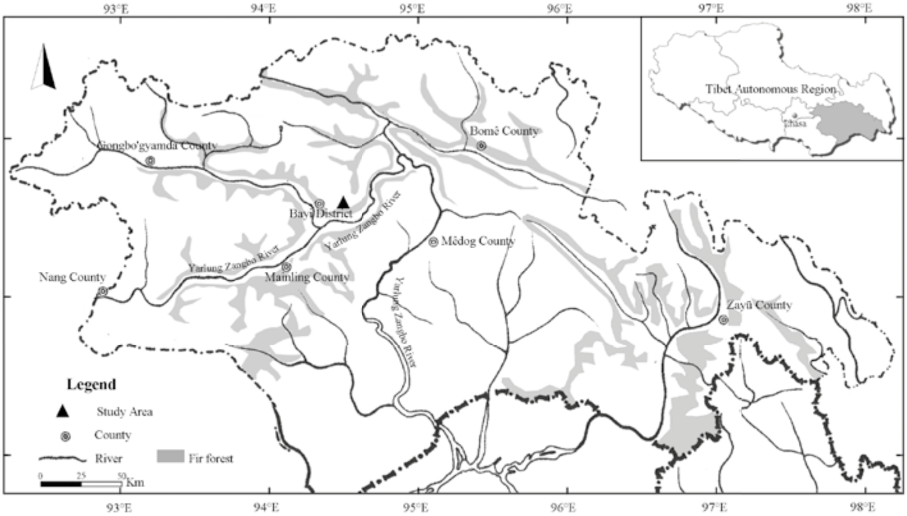

Figure 1: Location of study area in southeast Tibet.

Abbildung 1: Lage des Untersuchungsgebietes im Südosten Tibets.

Abies georgei var. *smithii* is a shade-tolerant tree species under cool and cold climates. The low demand for light is especially pronounced in the seedling stage. This species often forms pure forests in valleys, shaded or semi-shaded slopes in subalpine and alpine regions. *Abies georgei* var. *smithii* is also known to form coniferous mixed forests with spruce, larch, hemlock, pine and broad-leaved species. The *A. georgei* var. *smithii* coniferous forest in sub-alpine region of the southeast Tibet is commonly found at altitudes between 3100 and 4380 m and represent about 30 % forest area in this region. The average age of the assessed trees was about 200 years, their average height 31.9 m, and average diameter at breast height (DBH) 49.7 cm. Natural regenerating trees (with height of 1.5 – 20 m) under closed canopy have density of 196 ha^{-1} and an average DBH is 5.6 cm. The density of naturally regenerated saplings (tree height 0.2 – 1.5 m) is 369 ha^{-1} and their average root collar diameter (DRC) is 2.5 cm. In comparison, in forest gaps, the density of naturally regenerated saplings (with height of 0.2 – 1.5 m) is higher with 470 ha^{-1} and an average DRC is 3.1 cm and the density of naturally regenerated trees (with height of 1.5 – 20 m) is 246 ha^{-1} with an average DBH of 6.8 cm.

In our study region, 5.2 ha forest has been logged about 25 years ago in 1990. 8 trees per hectare with tree height between 25 – 30 m were left as mother trees. Saplings with density of 62 ha^{-1} (average DRC 1.4 cm) and trees with height of 1.5 – 20 m of 43 ha^{-1} (average DBH of 6.2 cm) were found in this logged area.

Shrub layer was composed of three species of honeysuckle (*Lonicera* spp.) and three species of rhododendron (*Rhododendron hirtipes*, *R. uvarifolium*, and *R. oreotrephes*) and *Rosa omeiensis*, *Sorbus rehderiana*, *Artemisia desertorum*, *Berberis franchetiana Schneid* var., and *Rubus biflorus*. All shrub species were found in gaps, while only five appeared in the closed canopy forest.

The herb layer plants mainly consisted of *Impatiens nyimana*, *Cacalia pentaloba*, *Aster albescens*, *Iris bulleyana*, *Primula florimdae*, *Polyonatum cirrhifolium*, *Streptopus simplex*, *Hemiphragma heterophyllum*, *Polygonum polystachyum*, *Ainsliaea latifolia*, and *Epilobium sikkimense*. The vine layer plant is *Smilax menispermoidea*.

This forest is characterized by poorly developed acid brown soils with mild humification process.

2.2 Sampling sites

A series of litterfall traps were placed in five different habitat types: closed canopy forest, small gap, middle gap, large gap, and logged forest. 30 × 30 m square sampling plots were set under closed canopy and logged forest. In contrast, elliptical sampling plots with consistent size were used in the three gaps. The area of small gaps was smaller than 100 m^2, middle gaps were sized 100 – 300 m^2 and large gaps were bigger than 300 m^2. In total, 15 plots were established with three replications in each of the five habitat types (Table 1).

Table 1: Description of sampling plot setup.

Tabelle 1: Beschreibung der Probeflächen.

Habitat	Description	Sample plot shape	Number of sample plots	Number of litter traps	Area (m^2)
Closed canopy forest	Natural primary forest, canopy density 0.6-0.8	Rectangle	3	27	900
Small gap	Formed by natural tree death	Approximately Ellipse	3	27	75-90
Middle gap	Formed by natural tree death	Ellipse	3	27	157-210
Large gap	Formed by natural tree death	Ellipse	3	27	320-370
Logged forest	Logged ~25 years ago, now regenerating naturally	Rectangle	3	27	900

We divided rectangular plots into 36 grids, and placed nine litter traps equidistantly between each grid point (Fig. 2B). For elliptical plots, nine litter traps were placed along short and long axis (Fig. 2A). 54 traps were set in six sampling plots of closed canopy forests and logged forests and 81 traps were set in nine plots of the three gap types. The litter traps were made of a 40-mesh nylon nets and 100 cm × 10 cm × 2 cm wooden slats and thus each trap collected litter for an area of 1.0 m^2. Traps were placed at a height of 20 cm above ground.

From May 2013 to May 2016, litter was collected regularly every month. Since it was difficult to collect litter in winter during snow cover from late December to March, litter accumulated during this period was collected in March and we thus made 10 collections per year.

The collected litter was sorted into components: needles, branch, bark, flowers, cone (including seminiferous scales, bract scales and cone axis), epiphytic (including usnea, moss and lichen) and clastics (too small to identify further). After oven-drying to constant weight at 80 °C, all components were weighted on an electronic scale accurate to 0.01 gram. The average annual litterfall of each habitat type was calculated by upscaling the collected litterfall amount to Mg ha^{-1} $year^{-1}$. We used the monthly average litterfall (December-March pooled) to explore seasonal variations.

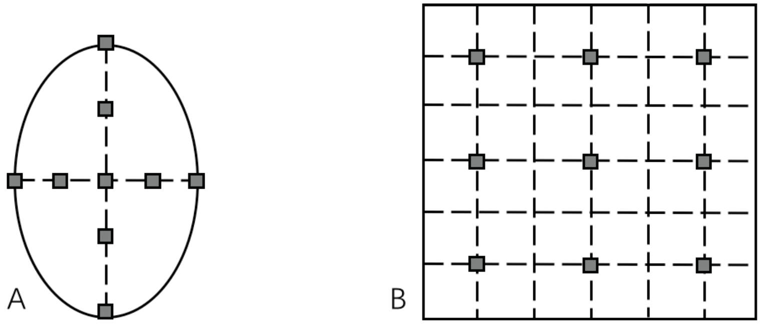

Figure 2: Placement of litterfall traps in elliptic plots (A) and rectangular plots (B).

Abbildung 2: Positionierung der Streufall-Sammler in elliptischen (A) und rechteckigen Flächen (B).

2.3 Statistics

One-way ANOVA was used to study the significance of data differences in litterfall among different habitats. LSD (Least-Significant Difference) was used to make multiple comparisons between litterfall in the five different habitat types.

3. Results

3.1 Annual litterfall by year and habitat

The annual litterfall of *Abies georgei* var. *smithii* was 2.08 to 2.35 Mg ha^{-1} $year^{-1}$ over three years, the average litterfall was 2.21 Mg ha^{-1} $year^{-1}$, and the coefficient of variation was 6 %. There was no significant difference in annual litterfall between different years ($p > 0.05$). The five habitats can be ordered based on the annual litterfall as: small gap (3.31 Mg ha^{-1} $year^{-1}$) > closed canopy forest (2.73 Mg ha^{-1} $year^{-1}$) > middle gap (1.92 Mg ha^{-1} $year^{-1}$) > large gap (1.82 Mg ha^{-1} $year^{-1}$) > logged forest (1.27 Mg ha^{-1} $year^{-1}$, Table 2).

The litterfall in the gap habitats were significantly different compared to other habitats. Only between the middle gap and large gap there was no significant difference. The analysis of the regeneration of shrubs and saplings (Table 3) indicated, that litterfall was negatively correlated with sapling and shrub coverage in the five habitats with a correlation coefficient of -0.94.

Table 2: Litterfall by year and habitats (mean ± standard deviation) in Abies georgei var. smithii forests (Mg ha^{-1} year^{-1}). Different lowercase letters for the same parameter in the same column indicate significant differences among different years and habitats at $p < 0.05$. Period is from May to April of the following year.

Tabelle 2: Streufall pro Jahr und Habitat (Mittelwert ± Standardabweichung) für *Abies georgei* var. *smithii* Wälder (Mg ha^{-1} year^{-1}). Unterschiedliche Buchstaben zeigen signifikante Unterschiede an mit $p < 0.05$. Messperiode ist von Mai bis April des darauffolgenden Jahres.

Period	Small gap	Middle gap	Large gap	Closed canopy forest	Logged forest	Annual average
2013–2014	3.58	2.17	1.97	2.66	1.36	2.35 ± 0.83a
2014–2015	3.13	1.72	1.69	2.75	1.14	2.08 ± 0.82a
2015–2016	3.21	1.86	1.80	2.79	1.31	2.19 ± 0.78a
Average	3.31 ± 0.24A	1.92 ± 0.23B	1.82 ± 0.14B	2.73 ± 0.07C	1.27 ± 0.12D	2.21 ± 0.81

Table 3: Comparison of litterfall and coverage by shrubs and saplings in different habitats.

Tabelle 3: Vergleich von Streufall und Deckungsgrad von Sträuchern und Verjüngung in den untersuchten Habitaten.

Habitat	Average litterfall (Mg ha^{-1} year^{-1})	Coverage shrubs and saplings (%)	Coverage (%)	
			Shrubs	Saplings
Closed canopy forest	2.73	18	8	10
Small gap	3.31	14	9	5
Middle gap	1.92	33	20	13
Large gap	1.82	47	27	20
Logged forest	1.27	69	49	20

3.2 Annual variation of litterfall components

The litterfall components in decreasing order were needles (1.35 Mg ha^{-1} year^{-1}) > branches (0.55 Mg ha^{-1} year^{-1}) > cones (0.11 Mg ha^{-1} year-*1*) > epiphytes (0.07 Mg ha^{-1} year^{-1}) > clastics (0.05 Mg ha^{-1} year^{-1}) > bark (0.04 Mg ha^{-1} year^{-1}) > flowers (0.03 Mg ha^{-1} year^{-1}) (Fig. 3). Among the seven components, needles accounted for 61.3 % of the total litterfall, followed by branches (25.0 %). All other components accounted for 13.7 % of the total litterfall produced. Thus, needles and branches were the most important components of litterfall in the studied *A. georgei* var. *smithii* forests. Needle and branch litterfall differed significantly between each year ($p < 0.01$), while there were no significant difference in the litterfall of other components in different years ($p > 0.05$).

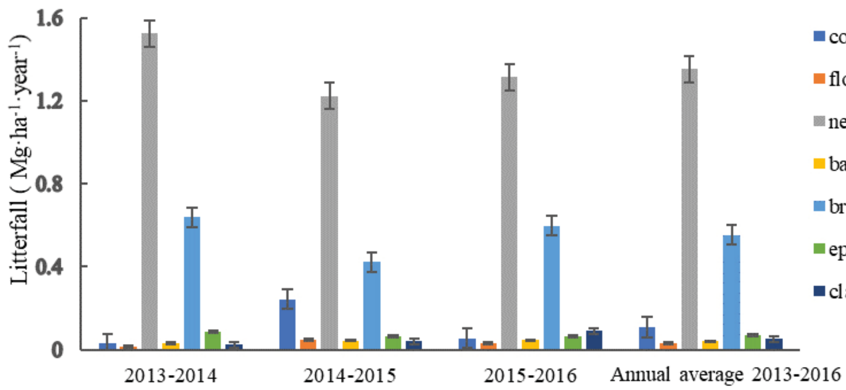

Figure 3: Annual litterfall components of the Abies georgei var. smithii forests, using average values from the five studied habitats.

Abbildung 3: Streufallkomponenten pro Jahr in Wäldern mit *Abies georgei* var. *smithii* (Mittelwert der fünf untersuchten Habitate).

3.3 Monthly dynamics of litterfall by components

Because of the large differences in litterfall by components, we did a more detailed analysis of their seasonal litterfall dynamics. Monthly variation of litterfall by component of litterfall in the *A. georgei* var. *smithii* forest are shown in Fig. 4.

The peak litterfall period is from October to November with 0.43 Mg ha^{-1} of litterfall was produced. Litterfall fluctuates after November decreasing to 0.09 Mg ha^{-1} from August to September, when the next litterfall peak starts. This pattern appears to be typical for the dynamic litterfall in *A. georgei* var. *smithii* forests.

Among the components, needle litterfall was produced at a higher rate than other components, with a maximum of 0.35 Mg ha^{-1} and a minimum of 0.03 Mg ha^{-1}. Dynamic changes in needle litterfall were similar to those in total amount, which indicated that needles were not only the most important contributor to litterfall in absolute terms, but also determined the litterfall dynamic.

Branch litterfall was different from needle litterfall with less annual variation. Two small peaks (0.09 and 0.08 Mg ha^{-1}) were evident in March – April and July – August.

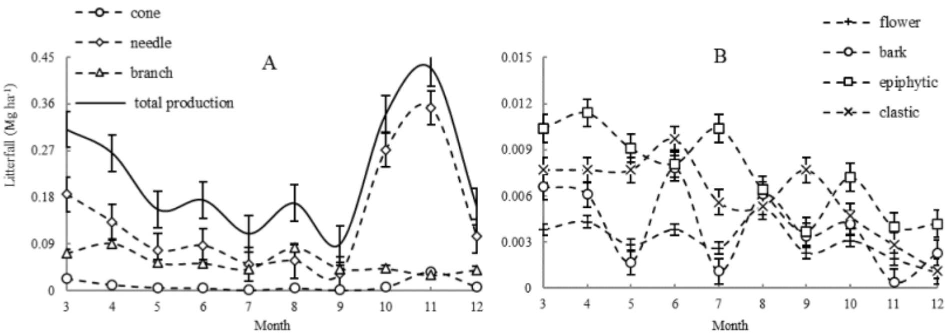

Figure 4: Monthly litterfall of cones, needles, branch, and the monthly total litterfall (A) and litterfall of flowers, barks, epiphytes and clastics (B).

Abbildung 4: Monatswerte des Streufalls von Zapfen, Nadeln, Ästen und vom Gesamtstreufall (A) und Streufall von Blüten, Rinden, Flechten und Fragmenten (B).

4. Discussion

4.1 Comparison of litterfall between this study and other coniferous forests in China, Europe and worldwide

Our 3-year study showed that annual litterfall of *Abies georgei* var. *smithii* forests in southeastern Tibet is much lower than that of temperate coniferous forests and boreal coniferous forests in China (Zhang, *et al.*, 2014). The annual litterfall is similar to that of *Pinus sylvestris* in northern Europe (Portillo-Estrada, *et al.*, 2013), but lower than that of *A. borisii-regis* in northern Greece (Kavvadias, *et al.*, 2001) and *Pseudotsuga menziesii* in Western Europe (Portillo-Estrada, *et al.*, 2013). It is also lower than the litterfall of coniferous European forests (Neumann, *et al.*, 2018). The annual litterfall of *A. georgei* var. *smithii* forests is lower than *Picea likiangensis* var. *linzhiensis* forests (Wang et al., 1998), which is located in the same geographical area. Our results are also lower compared to *P. schrenkiana* forests in Tianshan region (Liu *et al.*, 2014), spruce–fir forests in the Lesser Khingan Mountains of Heilongjiang (Hou *et al.*, 2013), *A. fabri* forests in Mount Gongga (Luo *et al.*, 2003) and *A. fabri* forests in Shennongjia Mountain (Chun *et al.*, 2009; Cui *et al.*, 2017). Similar amount of litterfall was observed in the eastern part of Qinghai-Tibet plateau (Fu, *et al.*, 2017). We summarized the available data on litterfall of conifer forests in Table 4.

The average litterfall of different components is relatively stable, which appears to be a key characteristics of old-growth *A. georgei* var. *smithii* forests. High altitude areas are sensitive to global climate changes. Some researchers predict that forest biomass will increase with the increasing temperature in high-altitude areas, and that litterfall might increase correspondingly (Delucia *et al.*, 1999; Peng *et al.*, 2002). Our study indicates that there has been no significant litterfall change between years no increasing trend, indicating currently no obvious change of litterfall amount over our observation period. *A. georgei* var. *smithii* forests can be categorized as old growth forest forests with low litterfall production. This result is consistent with a European study on *Picea abies* and *Picea sitchensis* (Hansen, *et al.*, 2009).

Table 4: Comparison of litterfall observations of fir and other coniferous forests in China, Europe and worldwide (Mg ha^{-1} year^{-1}).

Tabelle 4: Vergleich der Ergebnise dieser Studie mit der Literatur zu Tannen- und anderen Nadelwäldern in China, Europa und weltweit (Mg ha^{-1} year^{-1}).

Region	Forest Types	Litterfall	Source
China	*Abies georgei* var. *smithii*	2.21	This study
	Picea likiangensis var. *linzhiensis*	3.84	Wang et al., 1998
	Spruce–fir forest in eastern Qinghai-Tibet Plateau	2.38	Fu et al., 2017
	Picea schrenkiana in Tianshan	2.62	Liu et al., 2014
	Spruce–fir forest in Xiao Hinggan Mountains	3.44	Hou et al., 2013
	Abies fabri in Mount Gongga	2.81	Luo et al., 2003
	Abies fragesii in Shennongjia Mountain	5.7~6.22	Cui et al., 2017
Europe	*Pinus sylvestris* in northern Europe	2.86	Portillo-Estrada et al., 2013
	Abies borisii-regis in northern Greece	2.51	Kavvadias et al., 2001
	Pseudotsuga menziesii in Western Europe	4.34	Portillo-Estrada et al., 2013
	Coniferous forests in Europe	3.22~4.65	Neumann et al., 2018
World	Temperate coniferous forests	4.7~6.0	Zhang et al., 2014

4.2 Annual litterfall of different components

Among the seven studied litterfall components, needles and branch are in absolute terms the most important components. Despite annual variations of epiphyte fall, litterfall of other components remained stable between different years. This indicates that annual litterfall of *A. georgei* var. *smithii* forests is relatively stable, which was also observed in other studies on fir forests in China.

4.3 Seasonal dynamics of litterfall

There is controversy about seasonal dynamics in litterfall of spruce and fir forests. Some scientists reported that monthly dynamic trend of spruce and fir forest litterfall is not significant (Zhang et al·, 2014), while others support that there are significant fluctuations of the monthly litterfall of spruce and fir forest (Bray, et al·, 1964). Litterfall in A· georgei var. smithii is driven by the biological characteristics of this tree species. The regularity of litterfall seasonality suggest a strong link to seasonal meteorological conditions. Among the components of litterfall, needle litterfall was produced at a significantly higher rate than other components, with a maximum value of 0.35 Mg ha^{-1} and a minimum value of 0.03 Mg ha^{-1}. Dynamic in needle fall are similar to those of total litterfall, which indicates that needle are not only the most important contributor to litterfall, but also drives the seasonal dynamics. Branch litterfall had less seasonal variation compared to needle litterfall. Two small peaks of branch litterfall (0.09 and 0.08 Mg ha^{-1}) were evident in March – April and July – August. Other components were produced all year round with no obvious regularity and at low rates.

4.4 Differences in litterfall between different habitats

Forest gaps are heterogeneous features formed by disturbances and are common in forest ecosystems (Dusan, *et al.*, 2007). Gaps in subalpine dark coniferous forests modify habitat conditions, species composition, biodiversity, structure, function, regeneration and succession dynamics of forest communities (Luo, *et al.*, 2014; Oakley, *et al.*, 2006; Xue, *et al.*, 2013). We found that the subalpine dark coniferous forest represented by *A. georgei* var. *smithii* can be categorized as old growth forest. There are significant differences in litterfall between old-growth forests and gaps. The amount of litterfall in the small gap habitat is higher than in closed canopy forest and also higher than in middle gaps, large gaps and logged forest, which indicates that litterfall distribution pattern is affected by gap size. This result is different from the conclusion that litterfall of closed canopy forest is greater than gap in *Abies faxoniana* Rehd. primary forest in western Sichuan, China. The statistical analysis shows that the gap size is correlated to tree regeneration and shrub coverage in the studied habitats. There are fewer saplings and shrubs in small gaps and closed canopy forest habitat, while there are more shrubs and saplings in middle to large gaps and the regeneration density is higher (Luo *et al.*, 2002). Sheltering effect of the canopy of shrubs and saplings cause the distribution of litterfall to become more uneven, which appears to be an important reason for the difference in the litterfall in different habitats. This is supported by clear inverse relationships between litterfall of different habitats and understory tree regeneration and shrub density.

4.5 Synthesis

This study reveals that dynamics of litterfall production in *A. georgei* var. *smithii* forests exhibits a single peak (about 20 % of the total litterfall) from October to November every year. The period from August to September produces the least (only 4 %) amount of litterfall. Significant differences were evident in litterfall of some components, with needles dominating both annual and seasonal litterfall. The tree species regeneration and shrub distribution appears to be important for changes in litterfall distributions across different habitats.

Subalpine dark coniferous forests are the most important component of Tibetan forest resources. As the climax community and typical representative of alpine mountainous vegetation, it plays a crucial role in the study of several ecological concepts, in terms structural characteristics, forest functions, understand8ing the effects of forest management in response to climate change, restoration and conservation of degraded forests. Previous studies about litterfall in Southeast Tibet alpine dark coniferous forests have mainly focused on the accumulation, nutrients and decomposition of spruce litterfall. There is a lack of research on litterfall production and dynamic process. This paper expands our understanding of the litterfall production, seasonal and annual dynamics for *A. georgei* var. *smithii* forests and its spatial heterogeneity, closing an important knowledge gap fills in high-altitude forest ecosystems in Tibet.

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Response of tree growth, crown, and branch development to planting density in four *Populus tomentosa* clones

Auswirkung der Pflanzdichte auf Wachstum, Kronen- und Zweigentwicklung von vier *Populus tomentosa* Klonen

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Keywords: *Populus tomentosa; initial spacing; crown attributes; branch development; triploid, diploid, genetic improvement, plant breeding*

Schlüsselbegriffe: *Populus tomentosa, Anfangsabstand; Kronenattribute; Zweigentwicklung; triploid, diploid, genetische Verbesserung, Pflanzenzüchtung*

Abstract

The tree growth, crown and branch development of four *Populus tomentosa* clones (one diploid clone: 1316; three triploid clones: S86, B331 and B301) were examined in an 11-year-old trial plantation with seven planting density (PD) treatments ranging from 417 to 2500 stems per hectare (stems·ha^{-1}) in northern China. Significant differences (P < 0.01) in the diameter at breast height (DBH), individual volume (V), stand volume (SV), slenderness index (SI), crown diameter (CD), ratio of CD to DBH (k/d) and live branch length (BL) were found among the PD treatments. The mean DBH, V, and CD were markedly higher under the two lowest PD treatments (417, 500 stems·ha^{-1})

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than the two highest PD treatments (1667, 2500 stems·ha^{-1}), while SV and k/d were much higher in the two highest PD treatments. BL decreased significantly with increasing PD. Crown length (CL), the crown ratio (CR), and the numbers of all (NAB), live (NLB) and dead branches (NDB) varied in a narrow range. All growth, crown and branch development traits apart from k/d differed markedly among the four clones, demonstrating that most of these traits were under genetic control. Among the four tested clones, the three triploid clones performed better than the diploid clone for most of the traits, implying an obvious advantage of polyploidization, with B301 being the best performing triploid clone. A significant interaction was observed between the PD treatment and clone for V, SV and NAB. The findings of this study will support determining the optimal stand density and will provide scientific guidelines for the intensive management and genetic improvement of *P. tomentosa* plantations.

Zusammenfassung

Wachstum, Kronen- und Zweigentwicklung von vier *Populus tomentosa*Klonen (ein diploider Klon: 1316; drei triploide Klone: S86, B331 und B301) wurden in einer 11 Jahre alten Versuchsplantage unter sieben verschiedenen Pflanzdichten (PD) von 417 bis 2500 Stämmen pro Hektar (stems·ha^{-1}) in Nordchina untersucht. Durchmesser in Brusthöhe (DBH), Einzelbaumvolumen (V), Bestandesvolumen (SV), Schlankheitsindex (SI), Kronendurchmesser (CD), Verhältnis von CD zu DBH (k/d) und Länge lebender Äste (BL) zeigten signifikante Unterschiede ($P < 0.01$) zwischen den verschiedenen PD. DBH, V und CD waren bei den beiden niedrigsten PD (417, 500 stems·ha^{-1}) deutlich höher als bei den beiden höchsten PD (1667, 2500 stems·ha^{-1}), wobei SV und k/d bei den beiden höchsten PD viel höher waren. Die Kronenlänge (CL), das Kronenverhältnis (CR) und die Anzahl aller Äste (NAB), die Anzahl der lebenden Äste (NLB) und die Anzahl der toten Äste (NDB), variierten hingegen wenig. Alle Merkmale des Baumwachstums, der Kronen- und Zweigentwicklung, ausgenommen k/d, zeigten bei den vier Klonen signifikante Unterschiede. Dies zeigt, dass die meisten dieser Merkmale genetisch beeinflusst sind. Von den vier untersuchten Klonen zeigten die drei triploiden Klone in den meisten getesteten Merkmalen eine bessere Leistung als der diploide Klon, was auf einen offensichtlichen Vorteil der Polyploidisierung schließen lässt. B301 war der beste triploide Klon. Es wurde eine signifikante Interaktion zwischen PD und den Klontypen V, SV und NAB beobachtet. Diese Ergebnisse erlauben eine wissenschaftlich fundierte Bestimmung angemessener Pflanzdichten und Entwicklung von Richtlinien für die intensive Bewirtschaftung von *P. tomentosa*-Plantagen.

1. Introduction

Populus tomentosa is a native tree species in northern China (Du et al. 2014). It is naturally distributed along the middle and lower reaches of the Yellow River (30°N–40°N, 105°E–125°E) in northern China (Figure 1) and covers an area of approximately one million km² (Zhang et al. 2005; Du et al. 2012). Its wood is widely used for construction, furniture and plywood production due to its straight texture, fine structure, light weight, and easy processing properties (Zhu and Zhang 1997). *Populus tomentosa* wood is also suitable for paper and fiber production due to its long fibers as well as high holocellulose content and low lignin content (Jin et al. 2005; Zhang et al. 2010). In the last two decades, programs aimed at germplasm selection and hybrid breeding in *P. tomentosa* have greatly advanced (Zhu et al. 1998; Lu et al. 2013), and considerable gains in terms of volume or biomass have been achieved through genetic improvement. However, the mean productivity of *P. tomentosa* plantations in China is still far lower than that of poplar plantations around the world (Xi et al. 2016). Studies on cultivation techniques are important to increase the productivity and to improve wood quality of poplar plantations (Larocque 1999). For *P. tomentosa*, only irrigation and fertilization have been applied so far (Xi et al. 2014; He et al. 2020), and studies on other cultivation techniques, such as planting density have not received considerable attention.

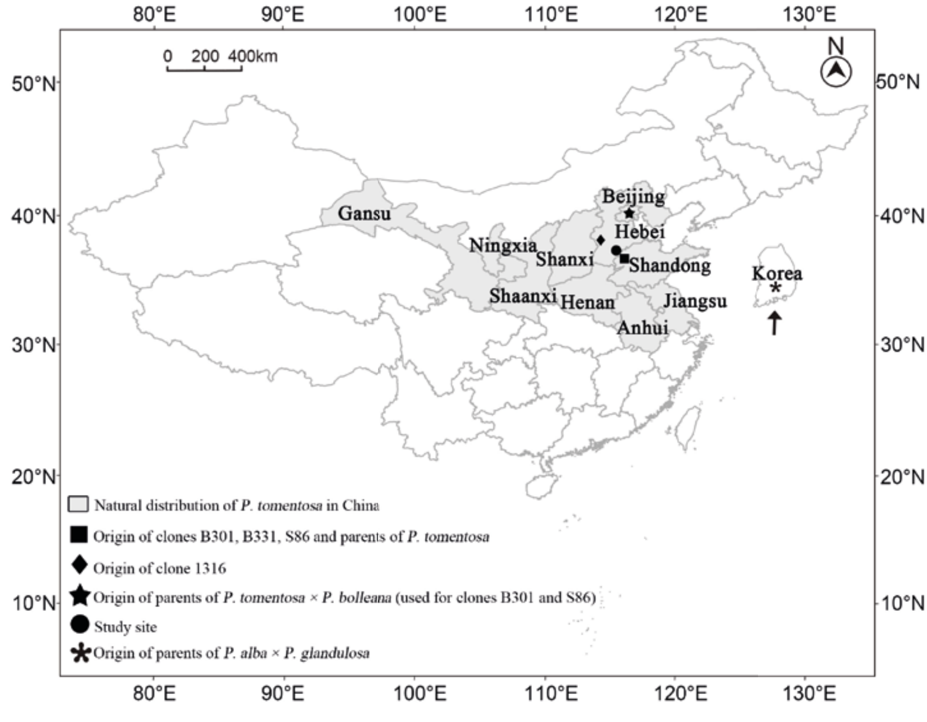

Figure 1: Natural distribution area of Populus tomentosa in China and origins of clones used in this study.

Abbildung 1: Natürliches Verbreitungsgebiet von Populus tomentosa in China und Ursprung der Klone, die in dieser Studie verwendet wurden.

Planting density (PD) determines inter-tree competition intensity, and influences tree growth and potential timber quality (e.g. branch characteristics, knot properties and stem shape) (Medhurst et al. 2001; Gort et al. 2010). PD is the key technical parameter linked to high-yield plantations with high-quality wood production (Roth et al. 2007; Ikonen et al. 2009). The significant effects of PD on growth-related traits have been widely confirmed in a number of tree species such as *P. deltoides* and *P. euramericana* (Fang et al. 1999), *Populus deltoides* × *P. nigra* (Toillon et al. 2013), *Acer velutinum* (Naji et al. 2015), and *Betula pendula* (Niemistö 1995; Lintunen and Kaitaniemi 2010). These effects are closely related to the response of crown and branch development to PD (Hummel 2000; Pinkard and Neilsen 2003; Wang et al. 2017; 2018), since branches are the main component of the crown and supports for leaves and are responsible for nutrition and water transport among leaves as well as between leaves and stems (Ceulemans et al. 1990). The number and distribution of branches also determine the spatial distribution of leaves and, thus, crown shape and size, which affect the photosynthetic efficiency of trees (Lowell et al. 2014). Additionally, branch development directly reflects the knot properties of the stem, which determine the wood quality (Cameron and Watson 1999; Ares 2002; Mäkinen and Hein 2006; Barbour et al. 2012). As a whole, reasonable PDs play critical roles not only in making full use of forest resources and increasing stand volume and stand stability, but also in improving stem shape and reducing knot-related defects in wood.

There is abundant literature available addressing the influence of planting density on tree growth, crown and branch development, while the genetic regime has rarely been simultaneously taken into consideration, and almost none of the research in this field has involved *P. tomentosa*. Therefore, in the present study, growth performance and crown and branch traits were investigated in four clones of *P. tomentosa*, including one diploid clone and three triploid clones, under different PD treatments. The objectives were to evaluate the effects of the PD and clone on the tree growth, and crown and branch development of *P. tomentosa*. The findings will be contributed to the determination of reasonable planting densities, and provide evidence for the intensive plantation management of *P. tomentosa* and other poplar species.

2. Materials and Methods

2.1 Experimental site

The study site was located at the tree breeding base in Wei County, Hebei Province (37°2′ N, 114°18′ E), China (Figure 1). The region has a warm temperate continental semiarid monsoon climate with four distinct seasons. The mean annual temperature is 13.4°C. The mean precipitation is 584 mm and is normally concentrated from June to September. The frost-free period last on average 198 days, and the annual average sunshine duration is 2575 hours. The study site is flat with an altitude of 30-50 m.a.s.l, and the soil is a sandy loam.

2.2 Plant materials

Three triploid clones (2n = 3X = 57) and one diploid clone (2n = 2X = 38) of *P. tomentosa* were involved in the present study. The triploid clones were B301 ((*P. tomentosa* × *P. bolleana*) × *P. tomentosa*), B331 ((*P. alba* × *P. glandulosa*) × *P. tomentosa*) and S86 ((*P. tomentosa* × *P. bolleana*) × (*P. alba* × *P. glandulosa*)). The parents of *P. tomentosa* were selected in Shandong by Zhu in 1985. The parents of *P. tomentosa* × *P. bolleana* were selected in Beijing by Xu in 1958, and those of *P. alba* × *P. glandulosa* were introduced from Korea in 1984 (Wu et al. 2013). The diploid clone 1316 developed from a plus tree of P. *tomentosa* in Hebei Province, China (Figure 1). These clones are now widely used in commercial plantations.

2.3 Experimental design

The spacing trial was established in April 2007 using a split-plot, randomized complete block (RCB) design with three replicates. Seven planting density (PD) treatments (2500, 1667, 1111, 833, 625, 500 and 417 stems per hectare) were randomly allocated to the main plots and the four clones (sub-factors) were then randomly arranged to each PD treatment. In total, 84 sub-plots in 21 main plots were included in the trial (Figure 2). Each replicate was surrounded with at least two rows as a buffer area with the same clone as the nearest subplot.

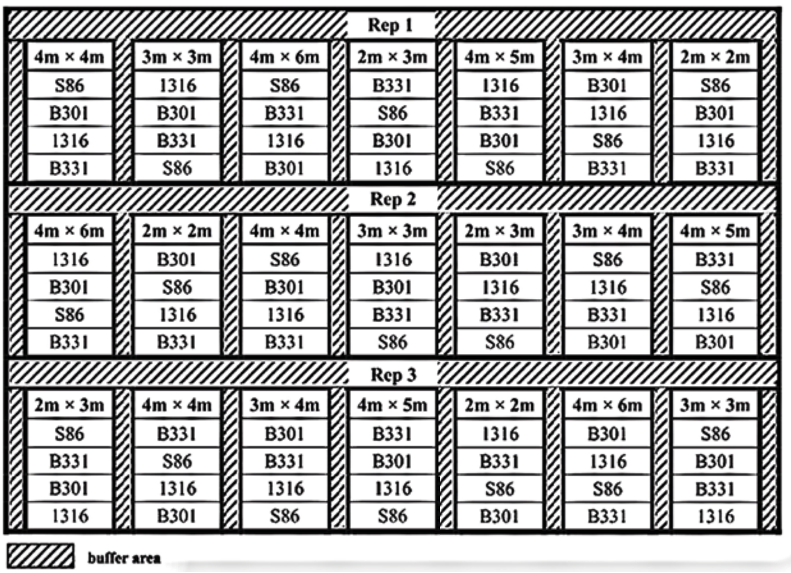

Figure 2: Plot layout for spacing trial.

Abbildung 2: Plotlayout für den Abstandsversuch.

2.4 Data collection

Tree height and diameter at breast height (DBH) were measured annually at the end of the growing season from 2007 until 2012 and reported earlier (Wang et al. 2012). In the present study, DBH, tree height, the height to crown base (HCB), DBH and crown diameter (CD) were measured for all trees in each plot in July 2018. Tree height, HCB and CD were measured with a Vertex IV-360 instrument (accuracy 0.01 m), and DBH was measured with diameter tape (accuracy 0.1 cm). CD was measured as the horizontal projection of the crown in four directions. A summary of all abbreviations of the measured tree attributes is given in Table 1. A mean tree was then sampled in the centre of each sub-plot with in total 84 sampled trees. The sampled trees were then felled carefully, avoiding branch loss or damage as much as possible. Their height, height to live crown base (HCB) and crown length (CL) were measured again with tape (0.1 m); live branch length (BL) and live branch diameter (BD) were measured with an electronic digital caliper (0.01 mm); and the live branch angle (BA) was measured with an electronic protractor (1°). Only the first-order branches, which were connected directly to the stem, have been considered. BD was measured as the diameter of the branch base for each live branch. This means that the largest live branch diameter (LBD) was the diameter of the largest live branch for a tree. The numbers of all (NAB), dead (NDB), and live branches (NLB) in the crown were recorded for each sampled tree. The individual stem volume (V, from tree top to ground level) was calculated on the basis of the function developed by Chen (1989) for *P. tomentosa* at northern China regions (Equation 1). Stand volume (SV) was the product of V multiplied by the number of stocking per hectare (N) (Equation 2). The slenderness index (SI) was the ratio of height to DBH (Equation 3). The ratio of CD and DBH (k/d) and the crown ratio (CR) were calculated using Equations 4 and 5 below, respectively.

$$V = 0.5134\ H^{0.826958}\ DBH^{1.995375} \quad (1)$$

$$SV = V \cdot N \quad (2)$$

$$SI = Height/DBH \quad (3)$$

$$k/d = CD/DBH \quad (4)$$

$$CR = CL/Height \quad (5)$$

Table 1: Explanation of symbols and abbreviations.

Tabelle 1: Erläuterung der Symbole und Abkürzungen.

Abbreviation	Attributes represent	Precision
H	Tree height	0.1 m
DBH	Stem diameter at breast height	0.1 cm
HCB	Height to crown base	0.1 m
SI	Slenderness index	/
V	Individual stem volume	0.001 m^3
SV	Stand volume	0.001 m^3ha^{-1}
CD	Crown diameter	0.1 m
CL	Crown length	0.1 m
CR	Crown ratio	/
k/d	The ratio of crown diameter and stem diameter at breast height	/
BD	Live branch diameter	0.01 mm
BL	Live branch length	0.1 m
BA	Live branch angle	1°
NAB	Number of all branches	/
NDB	Number of dead branches	/
NLB	Number of live branches	/
LBD	The largest live branch diameter	0.01 mm

2.5 Statistical analysis of the data

The growth (i.e., H, DBH, V, SV, HCB, SI) and crown (i.e., CD, CL, CR, k/d) traits as well as survival rate were analyzed using analysis of variance (ANOVA) for a split-plot design and Tukey's multiple range tests. Prior to the analyses, the data of survival rate was arcsine transformed. The differences in the branch number (i.e., NAB, NLB, NDB) and morphology traits (i.e., BL, BD, BA) were analyzed using linear mixed models (6) and (7) below, with PD and clone as fixed effects and the block or the block and tree as random effects, respectively.

$$y_{dcb} = \mu + \beta_d + \beta_c + \mu_b + \varepsilon \qquad (6)$$

$$y_{dcbt} = \mu + \beta_d + \beta_c + \mu_b + \mu_{bt} + \varepsilon \qquad (7)$$

where y_{dcb} and y_{dcbt}, the observed value; μ , the overall mean; β_d, effect of PD; β_c, effect of clone; μ_b, random effect for block; μ_{bt}, random effect for tree; and ε, the residual error. All statistical analyses were conducted with R statistical software (R 3.5.2).

3. Results

The results indicated that diameter at breast height (DBH), individual volume (V), stand volume (SV), the slenderness index (SI), crown diameter (CD), the ratio of CD to DBH (k/d), and live branch length (BL) differed significantly ($P < 0.01$) among the planting density (PD) treatments. Almost all traits differed markedly among the four clones except for k/d and the survival rate; and only V, SV and the number of all branches (NAB) showed a significant interaction between the PD treatment and clone (Table 2).

Table 2: Effects of planting density, clone and their interaction (planting density × clone) on tree growth, crown and branch properties Populus tomentosa

Tabelle 2: Auswirkungen der Pflanzdichte, des Klontyps und deren Interaktion (Pflanzdichte × Klon) auf Baumwachstum, Kronen- und Zweigeigenschaften bei Populus tomentosa.

Attribute	Planting density		Clone		Planting density × Clone	
	F-values	*P*-values	*F*-values	*P*-values	*F*-values	*P*-values
Height	0.880	0.538	6.293	0.001	1.253	0.267
DBH	6.743	0.003	18.318	< 0.001	0.873	0.611
Survival rate	0.882	0.514	0.262	0.853	0.209	0.996
HCB	0.660	0.683	8.626	< 0.001	0.678	0.812
SI	6.883	0.002	7.148	0.001	0.831	0.655
V	10.446	< 0.001	59.269	< 0.001	2.935	0.002
SV	55.318	< 0.001	54.663	< 0.001	5.448	< 0.001
CL	0.917	0.515	10.948	< 0.001	1.493	0.141
CD	11.728	< 0.001	5.832	0.002	0.914	0.568
CR	0.717	0.644	10.219	< 0.001	0.965	0.514
k/d	3.507	0.031	1.751	0.171	1.745	0.069
BD	1.883	0.100	8.938	< 0.001	0.554	0.916
BL	2.612	0.029	7.180	0.012	0.483	0.953
BA	1.144	0.349	4.817	0.005	1.775	0.053
NAB	0.242	0.954	5.347	0.003	2.031	0.030
NDB	0.206	0.968	8.794	< 0.001	1.320	0.225
NLB	0.801	0.588	14.698	< 0.001	1.365	0.200
LBD	1.047	0.443	10.697	< 0.001	1.022	0.457

3.1 Tree growth performance

Mean DBH and V of 11-year-old *P. tomentosa* decreased, while SI and SV increased with increasing PD (Table 3). DBH of the 2500 stems·ha^{-1} treatment was significantly lower than all other PDs, while DBH of the 1667 stems·ha^{-1} treatment was still significantly lower than DBH of the two lowest PD (500 and 417 stems·ha^{-1}). DBH reached a peak in the 500 stems·ha^{-1} treatment, but it did not differ significantly from those of the 833 and 417 stems·ha^{-1} treatments. V showed similar differences to DBH among the PD treatments, while SV and SI were the highest in the 2500 stems·ha^{-1} treatment, and was significantly higher than those under the four lower PD treatments. H, HCB and survival rate ranged from 20.0 to 21.8 m, from 6.4 to 8.0 m and from 85 % to 92 %, respectively, in the four *P. tomentosa* clones at the age of 11 years, and significant differences were absent among the PD treatments ($P \geq 0.05$) (Table 3).

Growth performance differed greatly among the clones. H, DBH, V, SV and HCB of diploid clone 1316 were generally much lower, while the SI of this clone was significantly higher than those of triploid clones S86, B331 and B301. Among the three triploid clones, B301 performed the best in terms of H, DBH, V and SV, followed by S86 (Table 3).

Since V and SV were significantly affected by the interaction of PD and clone, the differences among clones in each PD treatment were further analyzed. The V of all four clones declined, and SV increased significantly as PD increased. For any given PD treatment, the V and SV of diploid clone 1316 were markedly lower than those of triploid clones B331, B301 and S86, and a significant difference was always found between diploid clone 1316 and triploid clone B301. For the other two triploid clones, the V and SV of S86 were much higher than those of B331 under all PD treatments except 1667 stems·ha^{-1}. The highest V (0.455 m^3) was observed under the 500 stems·ha^{-1} treatment in triploid clone S86, and was 4.35 times greater than that of diploid clone 1316 under the 2500 stems·ha^{-1} treatment. The highest SV (520.621 m^3·ha^{-1}) was found under the 2500 stems·ha^{-1} treatment in triploid clone B301, which was 4.4 times greater than that of diploid clone 1316 under the 417 stems·ha^{-1} (Table 4).

Table 3: Growth performance of 11-year-old Populus tomentosa plantations in response to planting density. Numbers in the parentheses are standard error of mean value. Means within the same row marked with the same lowercase letters are not significantly different (P ≥ 0.05).

Tabelle 3: Wachstumsleistung von 11-jährigen Populus tomentosa Plantagen in Abhängigkeit von der Pflanzdichte. Die Zahlen in Klammern sind Standardfehler des Mittelwerts. Mittelwerte innerhalb derselben Zeile, die mit denselben Kleinbuchstaben markiert sind, unterscheiden sich nicht signifikant (P ≥ 0.05).

Source		Attribute						
		Height (m)	DBH (cm)	Survival rate (%)	HCB (m)	SI	V (m^3)	SV ($m^3 \cdot ha^{-1}$)
Planting density	2500	20.0(0.7)a	16.1(0.9)d	85.42(0.93)a	7.4(0.8)a	125.88(3.58)a	0.163(0.016)c	365.864(35.786)a
	1667	21.1(0.6)a	18.9(0.9)c	89.93(1.20)a	8.0(0.9)a	113.07(3.30)b	0.251(0.025)cd	367.523(37.435)a
	1111	21.0(0.3)a	19.1(1.0)bc	90.83(1.49)a	6.7(0.8)a	113.67(5.78)ab	0.234(0.025)d	233.896(24.573)b
	833	21.7(0.5)a	20.9(1.4)abc	90.42(1.56)a	8.0(0.7)a	109.18(7.52)b	0.272(0.027)bcd	204.124(20.059)bc
	625	21.5(1.0)a	20.3(0.9)bc	88.89(1.93)a	7.0(0.9)a	106.71(4.10)b	0.289(0.028)abc	162.540(15.564)cd
	500	21.5(0.9)a	23.0(1.1)a	90.28(2.26)a	7.7(1.0)a	94.58(4.12)c	0.333(0.029)a	149.733(12.994)d
	417	21.8(0.4)a	21.9(0.7)ab	91.67(3.20)a	6.4(0.5)a	100.83(3.87)bc	0.32(0.021)ab	120.121(7.910)d
Clone	1316	20.0(0.5)b	16.85(0.68)c	90.02(1.08)a	5.7(0.3)b	121.34(4.16)a	0.185(0.015)c	149.039(12.924)d
	S86	22.0(0.4)a	21.65(0.68)a	88.92(2.07)a	6.1(0.5)b	103.51(3.37)b	0.311(0.022)a	255.218(19.911)b
	B331	20.6(0.5)b	19.19(0.90)b	88.95(1.03)a	8.9(0.5)a	110.23(3.86)b	0.227(0.013)b	211.347(28.777)c
	B301	22.3(0.5)a	22.40(0.69)a	90.63(1.51)a	8.4(0.7)a	101.44(3.57)b	0.341(0.015)a	305.837(32.71)a

Table 4: Comparison of individual volume (V) and stand volume (SV) for four clones of Populus tomentosa under different planting density treatments. We show means and standard errors in brackets; lowercase letters represent significant difference between planting densities for the same clone, and capital letters represent the difference between clones under the same planting density treatment. Absent significant difference between paired treatments or clones are indicated by the same letters (P ≥ 0.05).

Tabelle 4: Vergleich des Einzelvolumen (V) und des Ständervolumen (SV) für vier Klone von Populus tomentosa unter verschiedenen Pflanzdichten. Daten werden als Mittelwerte angezeigt (Standardfehler in Klammer); Kleinbuchstaben zeigen signifikante Unterschiede zwischen Pflanzdichten für denselben Klon und Großbuchstaben stellen den Unterschied zwischen Klonen unter derselben Pflanzdichtebehandlung dar. Es liegt kein signifikanter Unterschied zwischen gepaarten Behandlungen oder Klonen bei denselben Buchstaben vor (P ≥ 0.05).

Attribute	Clones	Planting density (stems·ha^{-1})						
		2500	1667	1111	833	625	500	417
V (m^3)	1316	0.085(0.019)bB	0.146(0.019)abC	0.165(0.031)abB	0.199(0.048)abB	0.207(0.03)abB	0.244(0.029)aC	0.246(0.015)aC
	S86	0.187(0.012)dA	0.216(0.013)dBC	0.252(0.026)cdAB	0.313(0.036)bcdAB	0.362(0.033)abcAB	0.455(0.043)aA	0.395(0.02)abA
	B331	0.163(0.011)bA	0.294(0.023)aAB	0.176(0.004) abB	0.208(0.019)abAB	0.217(0.052)abAB	0.256(0.01)abBC	0.276(0.028)abBC
	B301	0.217(0.012)bA	0.347(0.032)abA	0.344(0.037) abA	0.369(0.04)aA	0.37(0.019)aA	0.375(0.019)aAB	0.363(0.029)aAB
SV ($m^3 \cdot ha^{-1}$)	1316	190.208(42.48)aB	219.503(28.333)aC	165.072(31.058)aB	149.473(35.912)aB	116.654(16.707)aB	110.01(12.924)aC	92.351(5.688)aC
	S86	420.027(26.372)aA	323.615(20.094)abBC	251.511(26.436)bcAB	234.573(27.065)bcAB	203.67(18.377)cAB	204.827(19.27)cA	148.306(7.665)cA
	B331	365.89(24.924)aA	441.244(34.42)aAB	175.507(4.346)bB	155.929(13.899)bAB	121.981(29.252)bAB	115.293(4.63)bBC	103.587(10.656)bBC
	B301	487.329(27.954)aA	520.621(47.914)aA	343.493(36.992)bA	276.521(29.967)bcA	207.854(10.437)bcdA	168.801(8.544)cdAB	136.239(11.064)dAB

3.2 Crown attributes

The crown length (CL), crown diameter (CD), crown ratio (CR) and k/d were presented in Table 5 for the 11-year-old *P. tomentosa* clones under different PD treatments. CL increased slightly from 12.5 m in the 2500 stems·ha^{-1} treatment to 15.4 m in the 417 stems·ha^{-1} treatment. CR showed slight fluctuation around 0.66. CD increased markedly with decreasing PD and differed significantly between the high-PD (2500, 1667 stems·ha^{-1}) and low-PD (625, 500, 417 stems·ha^{-1}) treatments. The CD of the lowest PD treatment was approximately 68.1 % higher than that of the highest PD treatment. There was an obvious increasing trend of k/d with decreasing PD, and significant differences were observed between the lowest (417 stems·ha^{-1}) and the two highest (1667 and 2500 stems·ha^{-1}) PD treatments.

Regarding the variation in crown traits among the four *P. tomentosa* clones (Table 5), diploid clone 1316 showed no significant difference in CL from triploid clone B301, while their CLs were significantly higher than that of triploid B331, but lower than that of triploid clone S86. The CRs of clones 1316 and S86 were markedly higher than those of clones B331 and B301. The CDs of the three triploid clones were significantly higher than that of diploid clone 1316. Significant difference was absent in k/d among the four clones.

Table 5: The crown attributes of 11-year-old Populus tomentosa plantations under seven planting density treatments. For details please see Table 3.

Tabelle 5: Die Kroneneigenschaften bei 11-jährigen Populus tomentosa-Plantagen mit sieben Pflanzdichtebehandlungen. Für Details verweisen wir auf Tabelle 3.

Source		Attribute			
		CL (m)	CD (m)	CR	k/d
Planting density	2500	12.5(1.0)a	4.7(0.3)d	0.63(0.04)a	29.73(1.84)bc
	1667	13.2(0.7)a	5.1(0.3)d	0.63(0.04)a	27.24(1.64)c
	1111	14.4(0.8)a	5.8(0.3)cd	0.68(0.04)a	31.11(1.50)abc
	833	13.8(0.7)a	6.3(0.4)bc	0.63(0.03)a	30.53(1.12)abc
	625	14.5(1.1)a	7.1(0.4)ab	0.67(0.04)a	35.15(1.45)ab
	500	13.8(1.2)a	7.7(0.4)a	0.64(0.05)a	33.92(1.87)ab
	417	15.4(0.6)a	7.9(0.3)a	0.71(0.02)a	36.17(1.79)a
Clone	1316	14.3(0.7)b	5.6(0.3)b	0.71(0.02)a	33.15(1.35)a
	S86	15.9(0.4)a	6.6(0.3)a	0.73(0.02)a	30.63(1.08)a
	B331	11.6(0.7)c	6.3(0.4)a	0.56(0.03)b	33.25(1.62)a
	B301	14.0(0.6)b	7.0(0.4)a	0.63(0.03)b	30.89(1.29)a

3.3 Branch Attributes

Among the seven tested traits related to branch development, only the live branch length (BL) differed significantly among the seven PD treatments, and a considerable difference was observed between the highest (2500 stems·ha^{-1}) and lowest (417 stems·ha^{-1}) PD treatments in the 11-year-old trees (Table 6). However, increasing trends with decreasing PD were observed for the mean live branch diameter and the largest live branch diameter although significant difference was absent in them among PD treatments.

Table 6 also showed that branch development differed significantly among the four *P. tomentosa* clones. The BL, live branch diameter (BD), and the largest live branch diameter (LBD) of the triploid clones were larger than those of diploid clone 1316, with B301 showing the highest values among all four clones. For the live branch angle (BA), significant difference was absent between the triploid clones and diploid clone, but a significant difference was seen between triploid clones B331 and S86.

The numbers of all branches (NAB) and dead branches (NDB) in the crown were approximately 30 and 10, respectively, regardless of the PD treatment (Table 6). However, significant differences in NAB, number of live branches (NLB), and NDB were found among the four clones. The NAB of clone B301 was markedly lower than those of clones S86, B331, and 1316. The NDBs of clones B331 and B301 were significantly higher than that of clone 1316. The NLBs of clones 1316 and S86 were significantly higher than those of clones B331 and B301.

The NABs of the different clones responded differently to the PD treatments. Significant differences among planting densities were only observed for diploid clone 1316 and triploid clone B301. NAB under the lower PD treatments (417, 500 and 625 stems·ha^{-1}) was considerably higher than that under the higher PD treatments (2500 and 1667 stems·ha^{-1}) for clone 1316, while for clone B301, the 1111 stems·ha^{-1} treatment showed the highest NAB, which was significantly higher than that under the lowest PD treatment (417 stems·ha^{-1}). Regarding the NAB differences among clones, only the highest PD treatment and the two lowest PD treatments showed notable differences. Under the 2500 stems·ha^{-1} treatment, the NAB of clones S86 and B331 was considerably greater than that of clone 1316, while the NAB of clone 1316 was significantly higher than that of clone B301 under the 500 and 417 stems·ha-1 treatments (Table 7).

Table 6: The branch attributes of 11-year-old Populus tomentosa plantations under seven planting density treatments. For details please see table 3.

Tabelle 6: Die Zweigmerkmale bei 11-jährigen Populus tomentosa-Plantagen mit sieben Pflanzdichtebehandlungen. Für Details verweisen wir auf Tabelle 3.

Source		Attribute						
		BL (m)	BD (mm)	BA (°)	LBD(mm)	NAB	NDB	NLB
Planting density	2500	3.1(0.10)b	32.25(0.93)a	48.65(1.16)a	53.99(4.82)a	29(2)a	11(1)a	18(1)a
	1667	3.2(0.09)ab	32.19(0.99)a	48.31(0.97)a	65.13(6.58)a	30(2)a	10(1)a	20(2)a
	1111	3.4(0.11)ab	33.91(1.2)a	49.81(1.06)a	80.78(8.42)a	31(2)a	11(2)a	20(2)a
	833	3.4(0.11)ab	35.48(1.25)a	51.95(0.93)a	73.08(10.09)a	32(3)a	10(2)a	22(2)a
	625	3.7(0.10)ab	37.02(1.3)a	50.07(0.93)a	82.17(12.64)a	31(2)a	11(1)a	21(3)a
	500	3.7(0.13)ab	38.55(1.45)a	50.54(1.11)a	82.67(9.65)a	31(2)a	11(1)a	19(2)a
	417	3.8(0.12)a	38.76(1.2)a	47.19(0.87)a	78.62(5.93)a	30(2)a	9(1)a	21(2)a
Clone	1316	3.1(0.06)b	30.49(0.59)b	50.34(0.71)ab	56.06(3.05)c	32(2)a	7(1)c	24(1)a
	S86	3.6(0.07)ab	35.81(0.68)ab	51.81(0.69)a	71.02(4.31)bc	33(1)a	10(1)bc	23(1)a
	B331	3.3(0.09)ab	35.01(1.06)ab	47.19(0.79)b	72.53(7.05)b	31(1)a	13(1)a	18(1)b
	B301	4.2(0.13)a	43.68(1.46)a	47.48(0.85)ab	95.49(8.25)a	27(1)b	11(1)ab	15(1)b

Table 7: Comparison on number of all branches for four clones of Populus tomentosa under different planting density treatments. For details please see Table 4.

Tabelle 7: Vergleich der Anzahl aller Zweige für vier Klone von Populus tomentosa mit verschiedenen Pflanzdichtebehandlungen. Für Details verweisen wir auf Tabelle 4.

Clones	Planting density (stems·ha^{-1})						
	2500	1667	1111	833	625	500	417
1316	23(2) bB	25(2)bA	35(5)aA	30(3)abA	37(4)aA	35(3)aA	37(3)aA
S86	32(1)aA	32(4)aA	27(3)aA	38(6)aA	36(4)aA	33(3)aAB	33(1)aA
B331	33(1)aA	31(3)aA	31(5)aA	34(7)aA	27(5)aA	29(4)aAB	30(3)aA
B301	27(5)abAB	30(2)abA	32(2)aA	25(3)abA	26(4)abA	24(3)abB	21(2)bB

4. Discussion

4.1 Effect of planting density

In this study, diameter at breast height (DBH) and individual volume (V) were negatively influenced by the planting density (PD), while slenderness index (SI) and stand volume (SV) were significantly positively influenced. Tree height on the other hand was not markedly affected by PD. These findings are consistent with previous studies on *Populus simonii* × *P. nigra* (Jiang et al. 2007), *Eucalyptus pilularis* (Alcorn et al. 2007), *Fraxinus excelsior* and *Acer pseudoplatanus* (Hein and Spiecker 2008), but contradict studies on *Populus trichocarpa* (Heilman and Peabody 1981) and *Populus alba* var. *pyramidalis* (Huang et al. 2017), where DBH and height were all markedly influenced by PD. The disagreement with these studies indicated that the effects of PD on height growth are more complicated and height growth is affected by multiple factors, such as species, age, site conditions, and the range of PD treatments (Daniel et al. 1979; Sun 1992; Hummel 2000). In an earlier study of the trial examined here, the height of *P. tomentosa* was significantly influenced by PD at the age of 2-3.5 years, while this effect was absent when the trees were four years old (Wang et al. 2012). It could thus be deduced that *P. tomentosa* showed notable differences in height growth only before 4 years of age, when canopy closure occurred. *P. tomentosa* is characterized by fast growth; for example, the rapid height growth stage of its triploid occurs before 8 years of age, and its height growth rate decreases thereafter (Zhu 2006), when less of a difference may be observed between PD treatments. This could also explain why significant difference was absent in height among the seven PD treatments at the age of 11-year-old trees in the present study.

Similar to DBH, crown diameter (CD) and the ratio of CD to DBH (k/d) were significantly negatively influenced by PD, while crown length (CL) and the crown ratio (CR) were not in the present study. These results differed to some extent from Akers et al.'s (2012) study on 12-year-old *Pinus taeda* plantations, which showed that CD and CL decreased markedly with increasing PD. These results were also slightly inconsistent with Wang et al.'s (2017) study on *Betula alnoides*, they found that CD, CL and CR differed considerably between the lowest PD treatment and the other four treatments, while significant difference was absent in k/d. In the present study, the CDs under the higher PD treatments (1111, 1667 and 2500 stems per hectare ($stems \cdot ha^{-1}$)) were much lower than those under the lower PD treatments, and only the CD under the lowest PD treatment (417 $stems \cdot ha^{-1}$) differed markedly from those under the two highest PD treatments (1667 and 2500 $stems \cdot ha^{-1}$). These discordances could be explained by the differences in the species involved in these studies. *B. alnoides* is a valuable species with a rotation period of more than 20 years, while *P. tomentosa* is a fast-growing species with a short rotation period of 5 to 10 years. These discordances might also result from differences in age. Johnson et al. (2015) found that the CD and CL of *Pinus taeda* differed significantly among different PD treatments at the age of 14 years but not at the age of 15 years.

Wang et al.'s (2017) study on *B. alnoides* showed that the live branch diameter (BD) and largest live branch diameter (LBD) of 14-year-old *B. alnoides* tended to decrease significantly with increasing PD, and the numbers of all (NAB), live (NLB) and dead branches (NDB) varied within narrow ranges. In the present study, only the live branch length (BL) of *P. tomentosa* was significantly affected by PD. The discordance of both studies might be caused by the fact that inter-tree competition for resources such as light and space intensified as tree age increased, which resulted in decreases in BL, BD and LBD with increasing PD. It was inferred that the BL of *P. tomentosa* showed quite strong plasticity in response to inter-tree competition compared to BD.

4.2 Effect of clone

Almost all examined traits differed significantly among the clones in the present study except for k/d, which was influenced greatly by PD rather than the clone. These results were in accordance with those of most previous studies that the branch attributes of *P. tomentosa* were mainly controlled by genetic factors in the present study. Taking branch traits as an example, BL, NAB and the live branch angle (BA) were also differed markedly among the poplar clones (Nelson et al. 1981; Ceulemans et al. 1990; Benomar et al. 2012). Some studies have also shown that NAB (Mäkinen et al. 2001) and BA (Vestøl et al. 1999) are subject to genetic control at moderate or strong levels. Among the four clones included in the present study, the three triploids performed better than the diploid in terms of height, DBH, HCB, SI, V, SV CD, BL, BD and LBD, demonstrating an obvious advantage of polyploidization. Diploid clone 1316 exhibited the most promising branch diameters values, but the lowest volume growth. The triploid clones exhibited higher volume production than the diploid clone. Given that the triploid clones performed better in most traits, they should be applied preferentially. Considering their branch diameter is larger, artificial pruning can be used to decrease related defects. B301 was the best triploid clone in terms of growth performance; however, given the effect of branch traits on knot-related defects, it is necessary to control the branches within the target height by artificial pruning in the management of plantations to meet multiple utilization requirements for *P. tomentosa*. Additionally, the considerable variation in most growth, crown and branch traits among the four *P. tomentosa* clones in the present study partly explains the insignificant differences among PD treatments.

5. Conclusion

Planting density (PD) was negatively influenced tree growth but did not significantly affect branch development; triploid clones showed great advantages in growth performance and exhibited larger branches than diploid clones, and there were significant interactions between the PD and clone in terms of individual volume, stand volume and the number of all branches. Therefore, the determination of optimal planting densities for different clones is critical for the efficient cultivation of *P. tomentosa*, based on the final wood production target. The pulpwood cultivation of *P. tomentosa* is suggested to be conducted under a higher planting density, such as 1667 stems·ha^{-1}, especially for triploid clone B301 (showing the highest SV). For high-quality sawn timber production, planting the *P. tomentosa* triploid clone S86 (showing the highest V and SV, smaller BD) under a lower density (e.g., 500 stems·ha^{-1}) would be much suitable.

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Conflict of interest

The authors declare no conflict of interest.

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Efficiency analysis of forest management units considering economics and carbon dynamic: A data envelopment analysis (DEA) approach

Effizienzanalyse von forstlichen Bewirtschaftungseinheiten unter Berücksichtigung wirtschaftlicher Faktoren und der Kohlenstoffdynamik: ein Data Envelopment Analysis (DEA) Ansatz

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Keywords: *Carbon dynamic, efficiency analysis, undesirable output, CO_2 emission, Hyrcanian forests, Fagus orientalis*

Schlüsselbegriffe: *Kohlenstoffdynamik, Effizienzanalyse, unerwünschte Folgen, CO_2-Emissionen, Hyrkanischer Wald, Fagus orientalis*

Abstract

The aim of this paper is to measure the relative performance of forest management units considering economics and carbon dynamic in Caspian forests of Iran. Data Envelopment Analysis (DEA) as a well-known and robust technique for measuring the relative efficiency of Decision Making Units (DMUs) was used for measuring the efficiencies of 33 forest management units or DMUs. The relative efficiency of DMUs was calculated using global technical efficiency (CCR) model using three scenarios for undesirable output, like CO_2 emission due to forest management activities. The main challenges that are considered in the modelling of the undesirable outputs were to consider the undesirable outputs in the modelling process along with the desirable outputs. The three scenarios were to ignore the undesirable output (scenario 1), to treat the undesirable outputs as inputs (scenario 2) and to apply a monotone decrea-

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sing transformation to the undesirable outputs and then to use the adapted variables as outputs (scenario 3). Results of input-oriented CCR model based on scenarios 1 and 2 showed that, 10 and 13 DMUs became efficient, respectively. Results of input-oriented and output-oriented CCR models based on scenario 3 indicated that 11 DMUs became efficient. By including the undesirable output in efficiency analysis of forest management units, this study shows how we can expand a new path in efficiency analysis of forest management units and provide important input to the forest organizations supervising the forestry sector.

Zusammenfassung

Ziel dieser Studie ist es, die relative Performance von forstlichen Bewirtschaftungseinheiten hinsichtlich wirtschaftlicher Aspekte und der Kohlenstoffdynamik zu untersuchen. Data Envelopment Analyse (DEA) ist eine weit verbreitete und robuste Methode um die relative Effizienz von Entscheidungseinheiten (DMU) und wurde hier verwendet, um die Effizienz von 33 forstlichen Bewirtschaftungseinheiten oder DMUs zu untersuchen. Die relative Effizienz der DMUs wurde mit einem global technical efficiency model (CCR) mittels drei Szenarien der unerwünschten Folgen berechnet, wie CO_2-Emissionen der Bewirtschaftungsmassnahmen. Eine wichtige Herausforderung in der Modellierung war es, die unerwünschten Folgen gemeinsam mit den erwünschten Folgen zu berücksichtigen. Die drei Szenarien sind die unerwünschten Folgen zu ignorieren (Szenario 1), die unerwünschten Folgen als Input zu verwenden (Szenario 2) und eine monoton abnehmende Transformation der unerwünschten Folgen zu verwenden und dann die so modifizierten Variablen als Input zu verwenden (Szenario 3). Die Ergebnisse der Input-orientierten CCR-Modelle unter Verwendung von Szenario 1 und 2 zeigten, dass 10 bzw. 13 DMUs effizient wurden. Hingegen waren bei einem Input- und Output-orientierten CCR-Modell (Szenario 3) 11 DMUs effizient. Wenn wir die unerwünschten Folgen in der Effizienzanalyse von forstlichen Bewirtschaftungseinheiten berücksichtigen, können wir neue Optimierungspotentiale aufzeigen und damit Forstbetriebe bei der Aufsicht des Waldbewirtschaftung unterstützen.

Introduction

The forests of Iran represent 7.5 % of the total size of the country. Iranian Caspian or Hyrcanian forests are located on the south coast of the Caspian Sea and the northern slopes of the Alborz Mountain range from sea level to 2,800 m. These forests grow in a strip 800 km in length and 20-70 km wide. These are the most valuable forests in Iran. Industrial harvesting occurs only in the Caspian forest. Because of the severe climatic conditions and forest degradation, forests in other regions are not exploited for industrial wood production. Forest industries in Iran produce sawnwood and wood-based panels as well as pulp and paper from hardwood species. Moderate volumes of forest products, mainly paper, are imported. Modest quantities of wood are burned as fuel (Mohammadi Limaei, 2010).

Efficiency measurement has received a great attention and has become increasingly important in many areas and organizations. Efficiency evaluation of a DMU is an important task for purpose of control, planning and benchmarking. Data envelopment analysis (DEA) developed by Charnes *et al.* (1978). DEA is a linear programming optimization to calculate the efficiency of multiple DMUs with multiple inputs and outputs. DEA is a nonparametric approach in operations research for estimation of production frontiers and used to measure productive efficiency of DMUs (Charnes *et al.*, 1978). DEA is a technique that widely applied to measure the relative efficiency of a set of production systems, or DMUs, which apply the same inputs to produce the same outputs. This method identifies DMUs with weak performance and thus highlights sources of inefficiency (Cardillo and Fortuna, 2000).

Traditional forest planning sought achievement of economic goals such as maximizing net present value through timber harvest or enhancing environmental protection. Less attention was given to multipurpose goals because, in many cases, these goals conflicted with each other (Mohammadi Limaei *et al.*, 2014). The efficiency measurement of forest management plans can be very complicated with considering multiple goals in forest management such as economic, ecological and social objectives. In the last few decades, forest management has been focussed on multifunction usage and general benefits of forests. Owing to the multiple benefits and advantages offered by the forest as well as the non-market nature of part of these outputs, measuring the efficiency in forestry is highly demanding (Sporcic *et al.*, 2009). Estimation of the accumulated biomass in the forest ecosystem is important for assessing the productivity and sustainability of the forest. It also gives us an idea of the potential amount of carbon that is emitted as CO_2 when forests are harvested or burned (Lu, 2006). Nowadays, the increasing environmental issues of forest management and logging operation is important due to greenhouse gas emissions and climate change issues. Therefore, it is necessary to assess the economic and environmental efficiency of forest management activities and forest industries.

There are several studies dealt with efficiency analysis in forestry and forest industries such as Kao and Yang, 1991; Bogetoft *et al.* 2003; Hailu and Veeman, 2003; Salehirad and Sowlati, 2007; Helvoigt and Adams, 2008; Mohammadi Limaei, 2013; Wu and Zhou, 2014; Zadmirzaei *et al.*, 2015, 2016, 2017 and 2019.

In these studies evaluating the efficiency of forestry and forest industries, there was less attention to the environmental issues such CO_2 emission during logging operation as well as environmentally services such as carbon sequestration. Ignoring undesirable output may give high score of efficiency of some DMUs. Hence, the aim of this research is to determine the efficiency of some forest management plans in Iranian Caspian forests with considering CO_2 emission during the logging operation as an undesirable output. In addition, carbon sequestration will be considered as a desirable output.

Material and methods

Study area

The needed data was collected from 33 forest management plans in Shafaroud forest, north of Iran (Fig. 1). The names of forest management plans are shown in Table 1. The dominant tree species in this region is beech (*Fagus orientalis*). Other frequent tree species are hornbeam (*Carpinus betulus*), Persian maple (*Acer velutinum*), Cappadocian maple (*Acer cappadocicum*), largeleaf linden (*Tilia platyphyllos*), smooth leaved elm (*Ulmus minor*), wych elm (*Ulmus glabra*) and sweet cherry (*Cerasus avium*) (Sagheb-Talebi *et al.* 2013).

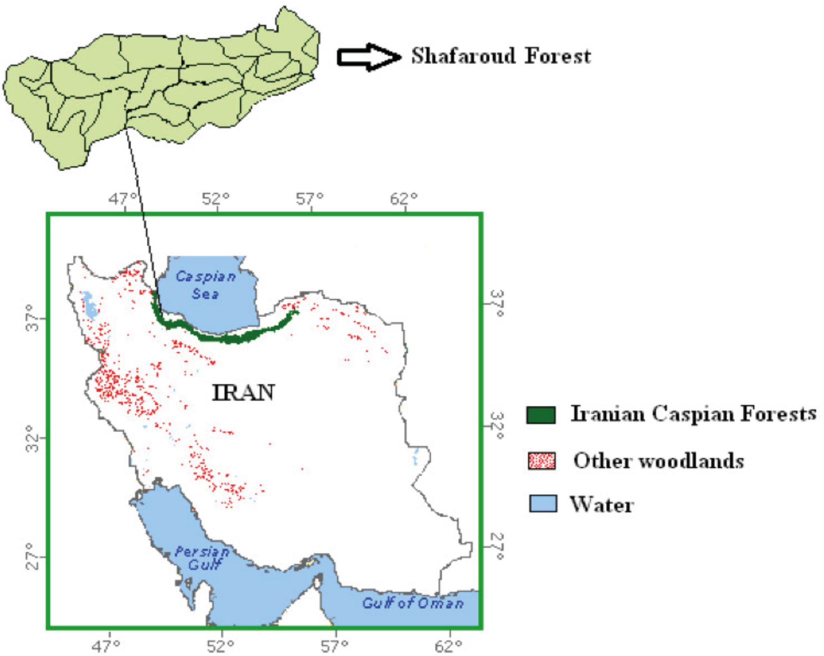

Figure 1: Iranian forests map (FAO, 1999, Global Forest Cover map) and the study area (Shafaroud forest).

Abbildung 1: Karte der Iranischen Wälder (FAO, 1999, Global Forest Cover map) und des Untersuchungsgebiets (Shafaroud Wald).

Table 1: Names of forest management plans.

Tabelle 1: Namen der forstlichen Bewirtschaftungseinheiten.

DMUs	Forest management plans	DMUs	Forest management plans
1	Avardim-9	18	Nav district 1
2	Siyahbil-8, Lomer	19	Lomer district 1
3	Dasht-daman-8	20	Chojeyeh district 2
4	Nave-Asalam	21	Siyahbil district 2
5	Raze-darposht	22	Khjedareh district 2
6	Janbe-sara	23	Chafroud district 4
7	District 16, region 9	24	Shanderman district 2
8	District 5, region Shanderman	25	Liyashi-sara district 8
9	District 3, region Chafrood	26	Changol district 6
10	Shafaroud district 17	27	Fiyab district 5
11	Shafaroud district 14	28	Siyahroud district 7
12	Shafaroud district 11	29	Poya-sepidar district 4
13	Shafaroud district 9	30	Poya-sepidar district 1
14	Nav district 14	31	Narmash district 2
15	Nav district 12	32	Narvan district 10
16	Nav district 3	33	Laeil district 2
17	Nav district 2		

Data collection

Booklets of Forest Management Plans were used to collect the data such as volume per hectare (stock), fixed cost, variable cost and harvesting revenue (Guilan Department of Natural Resources, 2018). It should be noted that the length of forest management plans period were 10 years. Hence, the average data of a ten-year period were considered. The monetary values were deflated using consumer price index (CPI) of Iran based on the base year of 2016 (Central Bank of Iran, 2018).

The following data were considered:

Stock 1: The volume before starting forest management plan (before harvesting) (year zero).

Stock 2: The volume after forest management plan (after harvesting) (10 years later).

Sequestered carbon in stock 1: The amount of carbon sequestered in stem wood volume before harvesting using the methodology of Mohammadi *et al.* (2017).

Sequestered carbon in stock 2: The amount of carbon sequestered in stem wood volume after harvesting.

Costs and revenues: Real fixed costs, variable costs and real harvested revenue (Iranian million Rials).

CO_2 emission: Since there was not any data about CO_2 emission in forest logging using chainsaw in Iranian Caspian forests, I used the amount of CO_2 emission during the logging operation using chainsaw in forest management plans according to Dias (2007).

Sequestered carbon in wood products: The sequestered carbon in harvested timber in ton carbon per hectare was determined according to Mohammadi *et al.* (2017).

Forest protection task: Some questionnaires were distributed between the experts of Natural Resources office at Guilan province in Iran for rating scale of forest protection activities (i.e. regeneration) during the implementation of each forest management plan (the score in questionnaires was from 1 to 5 based on Likert scale) (Zadmirzaei *et al.*, 2019).

Livestock resettlement: Livestock resettlement is the withdrawal of animal husbandry units out of the forest and is one of the major socioeconomics problem in Iranian forests. This score was obtained using questionnaires based on Likert approach (Zadmirzaei *et al.*, 2019).

A summary of sources in data collection and numerical data are shown in Table 2 and 3, respectively.

In this research, four inputs (stock 1, sequestered carbon in stock 1, fixed costs, variable costs) and seven outputs (harvesting revenue, stock 2, sequestered carbon in stock 2, forest protection task, livestock resettlement task, CO_2 emission) were considered (Fig. 2). At least 33 forest management plans should be selected using the following rule of thumb in DEA approach:

$$n = 3\ (m + s)$$

where *n* is number of DMUs, *m* is number of inputs, and *s* is number of outputs. Afterwards, it is assumed that this (or other) degrees of freedom conditions are satisfied and no further consideration are needed in this regard (Cooper *et al.* 2011).

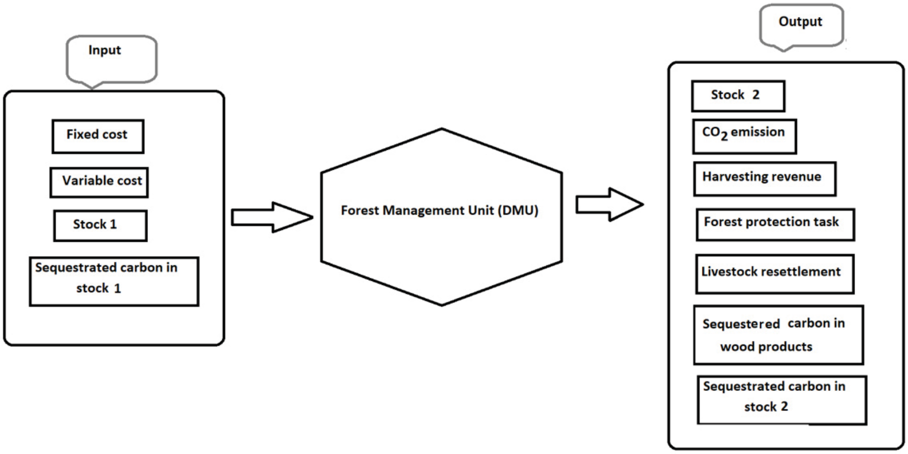

Figure 2: Production system of the forest management units consisting four input and seven output.

Abbildung 2: Produktionssystem der forstlichen Bewirtschafungseinheiten mit vier Inputs und sieben Outputs.

Table 2: A summary of sources used for data collection.

Tabelle 2: Zusammenfassung der Datenquellen.

Data	References
Stock, fixed cost, variable cost, harvesting revenue	Guilan Department of Natural Resources (Booklets of Forest Management Plans)
Sequestered carbon	Mohammadi et al., 2017.
Forest protection task, Livestock resettlement	Zadmirzaei et al., 2019.
CO_2 emission (kg/ha)	Dias et al., 2007.

Estimation of sequestered carbon

Mohammadi *et al.* (2017) estimated the amount of sequestered carbon in stem wood using Eq. (1). For further information about the carbon model and growth function see Mohammadi *et al.* (2017, 2018).

$$\text{Ton c} = \text{Wood density} \times 0.5 \times \text{wood volume} \quad (1)$$

Due to lack of data about logging residues and wood processing residues, the amount of sequestered carbon in wood products also estimated using Eq. (1).

The average wood density is needed for Eq. (1). Average wood density of the species in the study area was taken from the literature (Parsa Pajouh, 1995). The wood density of hornbeam, beech and the other species (maple, ash, elm, etc.) are 0.670, 0.621 and 0.700, respectively. Therefore, their average wood density is 0.664. The wood volume data (stock 1, stock 2 and wood products) was collected from Booklets of Forest Management Plans (Guilan Department of Natural Resources, 2018) and used in Eq. 1 (Table 3). Stock 2 is larger than stock 1 in some DMUs in Table 3, since the amount of harvesting in some DMUs were lower than the increment during the forest management period of 10 years.

Estimation of CO_2 emission

There was no suitable data available about CO_2 emission by forest logging in Iranian Caspian forests. Therefore, the amount of CO_2 emissions was estimated during the logging operation using chainsaw in different forest management plans. According to Dias *et al.* (2007) the average CO_2 emission in operation curried out during the logging by using chainsaw including cutting and processing (felling, limbing, bucking, debarking), extraction and log loading onto trucks in Portugal for eucalypt and maritime pine stands was 4377.5 g CO_2/m^3. Hence, the amount of wood production in different forest management units was multiplied to 4377.5 and the amount of carbon emission was estimated. It should be noted that Caspian forests are temperate broadleaf and mixed forests, and are quite different from eucalypt and pine stands in Portugal, but the similarity of forest logging using chainsaw in both regions was the main reason to use the results of Dias *et al.* (2007) as a reference for the estimation of CO_2 emission in this study.

Table 3: Input and output of 33 DMUs (forest management units) from Shafaroud forest.

Tabelle 3: Input und Output der 33 DMUs (forstlichen Bewirtschaftungseinheiten) im Shafaroud Wald.

DMUs	Input				Output						
					Desirable output						Undesirable output
	Stock 1 (m^3/ha)	Sequestered carbon in stock 1 (tons/ha)	Real Fixed costs, deflated (Iranian million Rials)	Real variable costs (Iranian million Rials	Real harvesting revenues, deflated (Iranian million Rials)	Stock 2 (m^3/ha)	Sequestered carbon in stock 2 (tons/ha)	Sequestered carbon in wood products(tons/ha)	Forest protection task	Livestock resettlement	CO_2 emission (kg/ha)
1	451.01	148.8333	11723.05	8573.98	15257.15	430.5	142.065	26.6442	3.25	3.84	353.4394
2	183.5	60.555	61441.14	8800.88	11262.38	210.45	69.4485	10.9824	3.46	4.26	145.6832
3	214.96	70.9368	56566.28	11083.61	8037.68	226	74.58	16.2327	4.23	4.35	215.3292
4	617.5	203.775	12410.62	8436.47	31415.02	550	181.5	42.1509	2.69	2.37	559.1381
5	224.5	74.085	7797.03	16357.26	12245.6	251.81	83.0973	10.8636	2.72	3.66	144.1073
6	138.4	45.672	25928.22	27770.9	7852.04	156	51.48	14.0679	1.59	2.55	186.6128
7	179	59.07	10134.76	17808.03	59680.97	187.63	61.9179	17.028	3.64	4.36	225.879
8	288	95.04	43351.21	36833.06	58500	295	97.35	17.5659	4.6	4.26	233.0143
9	217	71.61	61633.66	21885.31	52780.31	231.75	76.4775	15.0084	1.66	1.53	199.0887
10	210.52	69.4716	47271.93	37996.15	97455.03	226.46	74.7318	14.6157	1.53	1.6	193.8795
11	170.38	56.2254	51981.02	44906.56	313428.7	205.36	67.7688	8.3325	4.33	4.26	110.5319
12	293.74	96.9342	45141.09	43666.8	617356.23	289.84	95.6472	21.1629	4.4	4.26	280.7291
13	297.81	98.2773	42858.22	40682.55	459643.84	323.71	106.8243	11.3289	1.46	1.53	150.2796
14	255.4	84.282	41341.72	31088.15	254116.2	307.94	101.6202	2.5377	2.46	2.46	33.66298
15	155.43	51.2919	60309.75	45101.83	208728.41	188.57	62.2281	8.9397	1.46	1.53	118.5865
16	273.81	90.3573	65465.14	524275.58	979189.36	293.31	96.7923	13.4409	4.46	4.4	178.2956
17	219.62	72.4746	52603.07	40751.17	719567.52	254.12	83.8596	8.4909	1.46	1.53	112.6331
18	246.23	81.2559	45727.79	44166.25	490447.74	257.25	84.8925	16.2393	4.33	4.44	215.4168
19	432	142.56	60166.67	40776.75	925389.85	276.46	91.2318	71.2041	2.46	1.53	944.5332
20	231.77	76.4841	42118.54	41427.6	155192.04	226.59	74.7747	21.5853	2.33	4.44	286.3323
21	196.71	64.9143	51354.92	49990.51	211587.6	198.31	65.4423	19.3479	1.53	2.33	256.6528
22	197.246	65.09118	49852.1	49292.15	294463.9	215.58	71.1414	13.82568	1.53	2.46	183.3997
23	349.189	115.2324	30675.06	28668.73	174309.47	292.76	96.6108	38.49747	2.46	1.6	510.6748
24	213.5	70.455	42979.3	32181.66	206346.81	196.26	64.7658	25.5651	1.46	1.8	339.1249
25	241.558	79.71414	50606.99	48958.33	344301.64	250.06	82.5198	17.07024	2.4	2.53	226.4393
26	197.516	65.18028	21531.22	125556.11	230687.78	214.75	70.8675	14.18868	4.26	1.53	188.215
27	236.904	78.17832	43114.69	269325.63	339602.31	275	90.75	7.30422	4.4	2.53	96.89159
28	255.86	84.4338	49183.44	48145.83	268700.98	254.06	83.8398	20.4699	4.26	4.33	271.5363
29	289.45	95.5185	58103.41	43482.88	366840.42	328.97	108.5601	6.8343	4.4	4.2	90.65802
30	208.93	68.9469	43746.56	40000	239379.33	174.21	57.4893	31.3335	1.53	1.6	415.6436
31	193.77	63.9441	50385.04	43457.99	152691.76	218.42	72.0786	11.7414	2.46	2.33	155.7515
32	180.5	59.565	51498.9	47234.6	260786.72	210.3	69.399	10.0419	1.6	1.66	133.2073
33	159.67	52.6911	9973.47	68574.46	471496.59	138.71	3291.245	22.62957	4.2	4.4	68.57446

Data analysis

Data Envelopment Analysis (DEA)

DEA, which was introduced by Charnes *et al.* (1978), is a well-known and non-parametric method for measuring the relative efficiency of DMUs with multiple inputs and outputs. The basic DEA model for measuring the efficiency of DMU *k* is given below:

$$E_k = Max \frac{\sum_{r=1}^{s} u_r Y_{rk}}{\sum_{i=1}^{m} v_i X_{ik}}; s.t \frac{\sum_{r=1}^{s} u_r Y_{rj}}{\sum_{i=1}^{m} v_i X_{ij}} \leq 1;$$

$$j = 1,\ldots,n; v_i, u_r \geq \varepsilon, i = 1,\ldots m; r = 1,\ldots,s \qquad (2)$$

E_k = the relative efficiency of DMU *k*. v_i = the weight given to input *i*. u_r = the weight given to output *r*. The *k*th DMU utilizes *m* inputs $X_{ik} = 1, m$ to produce *s* outputs Y_{rk}, r = 1,. . . , s. If $E_k = 1$, DMU *k* is efficient and if $E_k < 1$, DMU *k* is inefficient.

CCR Model

DEA model introduced by Charnes, Cooper and Rhodes in 1978 is called CCR model. DEA is an effective technique for measuring the relative efficiency of a set of DMUs using the same inputs to produce the same outputs. Suppose there are *n* DMUs. The *k*th DMU uses m inputs $X_{ik} = 1, m$ to produce s outputs Y_{rk}, r = 1,. . . , s. Its efficiency E_k is calculated through the following CCR model (Charnes *et al.*, 1978):

$$\boldsymbol{E_k} = Max \sum_{r=1}^{s} u_r Y_{rk}$$

$$s.t \qquad \sum_{i=1}^{m} v_i X_{ik} = 1$$

$$\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \leqslant 0.\ j = 1.\ldots.n. \qquad (3)$$

$$u_r . v_i \geqslant \varepsilon. r = 1.\ldots.s; i = 1.\ldots.m.$$

X_{ij} = amount of input *i* used by unit *j*. Y_{ij} = amount of output *r* produced by unit *j*. v_i = the weight given to input *i*. u_r = the weight given to output *r*. Where u_r and v_i are the most favorable multipliers to be applied to *r*th output and *i*th input for DMUk in calculating its efficiency E_k and *e* is a small non- Archimedean quantity (Charnes *et* *al.*, 1978; Charnes and Cooper, 1984) which prohibits any input/output factor to be ignored. CCR model is a constant return to scale model. The model run *n* times to determine the relative efficiency scores of all the DMUs. Each DMU selects a set of input weights v_i and output weights u_r that maximize its efficiency score. A DMU is efficient, if it obtains the maximum score of 1, otherwise it is not efficient.

Eq. (3) is called an input-oriented model that minimize the inputs for a desired level of output to be achieved and it focuses on minimizing the level of inputs with an assumption of fixed level of outputs. In contrast, an output-oriented DEA model maximize the outputs although input kept at a constant level. Hence, the difference between output-oriented CCR model with input-oriented one is that instead of maximizing output, input is minimized and the output is assumed equal 1 for the same DMU under investigation. The other constraints remain unchanged as below:

$$\boldsymbol{E_k} = Min \sum_{i=1}^{m} v_i X_{ik}$$

$$s.t \qquad \sum_{r=1}^{s} u_r Y_{rk} = 1$$

$$\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \leqslant 0.\ j = 1.\dots.n. \qquad (4)$$

$$u_r\ .v_i \geqslant \varepsilon.r = 1.\dots.s; i = 1.\dots.m.$$

Undesirable output model

There are some outputs, that are undesirable such as CO_2 emission during the production process or tax payments in financial firms or interest payments to the depositors in a bank. The main challenges that are considered in the modeling of the undesirable outputs is to consider the undesirable outputs in the modeling process along with the desirable outputs. In addition, we need to reduce the undesirable outputs while the desirable outputs be increased in order to increase the efficiency of DMU.

Seiford and Zhu (2002) defined five possibilities to deal with undesirable outputs in the DEA-BCC framework:

- "The first possibility is just simply to ignore the undesirable outputs.
- The second is to treat the undesirable outputs in the non-linear DEA model.
- The third is to treat the undesirable ones as outputs and to adjust the distance measurement in order to restrict the expansion of the undesirable outputs (see

the weak disposability model in Färe *et al.*, 1989).

- The fourth is to treat the undesirable outputs as inputs. However, this does not reflect the true production process.

- The fifth is to apply a monotone decreasing transformation (e.g. 1 = *yb*) to the undesirable outputs and then to use the adapted variables as outputs. The use of linear transformation preserves the convexity relations and it is a good choice for a DEA model".

In this research, the following three scenarios considered to treat with undesirable output of CO_2 emission:

Scenario1 = Ignore the undesirable output

Scenario 2 = Treat the undesirable outputs as inputs

Scenario 3 = Apply a monotone decreasing transformation to the undesirable outputs and then to use the adapted variables as outputs.

LINGO software was used for analysis of efficiency score in DEA models under three above-mentioned scenarios.

Sensitivity analysis of DEA models

Sensitivity analysis in DEA studies is used to investigate how sensitive the solution values and efficiency scores of the DMUs are to the numerical input and output data. A developed analytical method for studying the sensitivity of DEA results to variations in the data is explained by Cooper *et al.* (2011). The results of sensitivity analysis can be a guideline for inefficient DMUs in order to be able to improve their efficiency scores and reach to the efficiency frontier or efficient DMUs. It is not possible to find which of the input parameters has the strongest effect on the results of efficiency score because the assumption is that all input and output have the same weight in DEA analysis. DEA uses linear programming approach to measure the relative efficiency of DMUs with multiple inputs and outputs whereas each variable (input and output) considered as a decision variables. The aim is to maximize output or minimize input (based on the objective function). However, if we give weight for each variable based on a qualitative method such as Analytical Hierarchy Process (AHP), then we can priorities the input and output variables in order to investigate which variable is more important and has strongest effect on the results of DEA analysis.

An increase of any output or a decrease of any input can not worsen the efficiency of DMUs. Therefore we restrict our attention to decrease in outputs and increase in inputs for DMUS (Seiford and Zhu, 1998). In order to simultaneously considering the data changes for the other DMUs, they suppose increased output and decreased input for all other DMUs. Hence, the suggested approach by Seiford and Zhu (1998) was used for sensitivity analysis in this research whereas 10 % output increased and 10 % input reduced to analyse the changes of data on efficiency scores.

T-test

The t-test using Excel software performed to determine if the means of efficiency scores are significantly different from each other.

Analysis of Variance (ANOVA)

One way Analysis of Variance (ANOVA) using Excel software performed to investigate, if there is any significance among the means of efficiency scores of various DMUs (33 forest management plans) in three scenarios.

Results

DEA analysis

Scenario 1 - Ignoring the undesirable output.

Here the input-oriented CCR model (Eq. 3) was used to determine the efficiency of forest management, ignoring the CO_2 emission. According to the results (Table 4), 10 DMUs are efficient as their efficiency score is 1 and the others are inefficient with efficiency score lower than 1.

Scenario 2 - Treat the undesirable outputs as input

Here the input-oriented CCR model (Eq. 3) was used to determine the efficiency of forest management considering undesirable outputs (CO_2 emission) as an input. According to the results (Table 4), 13 DMUs are efficient and the others are inefficient.

There are some differences between the results of scenario 2 and scenario 1 as in scenario 2 four more DMUs are efficient (13, 14, 19 and 29).

Scenario 3 - Apply a monotone decreasing transformation to the undesirable outputs and then to use the adapted variables as outputs

Here a monotone decreasing transformation was performed to the CO_2 emission as an undesirable output. Then the adapted variables (CO_2 emission) was used as an output in the input-oriented CCR model (Eq. 3) and output-oriented CCR model (Eq. 4). Results showed that in both input–oriented and output-oriented models, 11 DMUs are efficient (Table 4).

The results of scenario 3 is rather similar to the results of the scenario 1 in term of efficient DMUs, the only difference is that DMU 14 is efficient in scenario 3 whereas it is inefficient in the scenario 1. However, there are some differences in the score of inefficient DMUs in both scenarios 1 and 3.

Regarding to the results of DMUs efficiencies (Table 4), the inefficient DMUs (i.e. DMUs 6, 8, 9, 10 etc.) should reduce their input in input-oriented CCR model (scenarios 1 and 2) in order to enhance their efficiencies. In output-oriented CCR model, the DMUs should increase their output (scenario 3) in order to enhance their efficiencies. In fact, the deficient forest management units can become efficient if they reduce their inputs or increase their output. It is possible to determine the virtual input and output for each DMUs using shadow price to investigate how much an inefficient DMU should reduce its input or increase its output in order to become efficient, but it was not the aim of this research (see Mohammadi Limaei, 2013).

Optimal relative efficiency and benchmarking

DEA analysis determine the optimal relative efficient DMUs as a base-line or benchmark for inefficient DMUs and provide information on how much inputs can be decreased or outputs increased to increase the efficiency of inefficient DMUs to reach the benchmarks (efficient DMUs). Inefficient DMUs can continuously improve their efficiencies based on efficient DMUs as they are specific targets for improvement over time. According to the results in Table 4, DMUs 1 to 5, 7, 12, 17, 19, 33 are benchmark for other DMUS in scenario 1. More DMUs became benchmark in scenarios 2 and 3.

Efficiency distributions of three scenarios (1, 2 and 3) based on CCR model is shown in Fig. 3. The scores in various scenarios have rather similar trends and they fluctuates between 0.34 and 1.

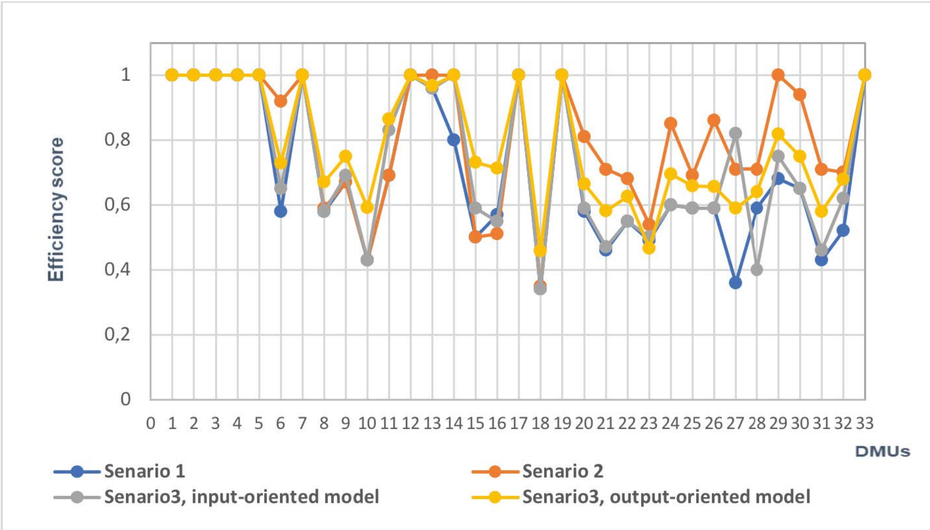

Figure 3: Efficiency distributions of various scenarios based on CCR model.

Abbildung 3: Verteilung der Effizienz nach den drei Szenarien des CCR-Modells.

Table 4: Efficiency scores of forest management units (DMUs) based on CCR model in three scenarios.

Tabelle 4: Effizienz der forstlichen Bewirtschaftungseinheiten (DMUs) berechnet mit dem CCR-Modell und drei Szenarien.

DMUs	Scenario 1	Scenario 2	Scenario 3	
			Input-oriented model	Output-oriented model
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1
6	0.58	0.92	0.65	0.73
7	1	1	1	1
8	0.58	0.59	0.58	0.67
9	0.67	0.67	0.69	0.75
10	0.43	0.43	0.43	0.59
11	0.69	0.69	0.83	0.87
12	1	1	1	1
13	0.96	1	0.96	0.97
14	0.8	1	1	1
15	0.5	0.5	0.59	0.73
16	0.57	0.51	0.55	0.71
17	1	1	1	1
18	0.34	0.35	0.34	0.46
19	1	1	1	1
20	0.58	0.81	0.59	0.67
21	0.46	0.71	0.47	0.58
22	0.55	0.68	0.55	0.63
23	0.49	0.54	0.5	0.47
24	0.6	0.85	0.6	0.69
25	0.59	0.69	0.59	0.66
26	0.59	0.86	0.59	0.66
27	0.36	0.71	0.82	0.59
28	0.59	0.71	0.4	0.64
29	0.68	1	0.75	0.82
30	0.65	0.94	0.65	0.75
31	0.43	0.71	0.46	0.58
32	0.52	0.7	0.62	0.68
33	1	1	1	1

Sensitivity analysis of DEA models

Sensitivity analysis is used to investigate the sensitivity of the efficiency scores of the DMUs to the numerical input and output data. The suggested new model examines the robustness of DEA efficiency scores by changing the reference set of DMUs (Agarwal *et al.*, 2014). Due to the similarity of sensitivity analysis in various scenarios, sensitivity analysis (10 % output increased and 10 % input reduced in all DMUs) was done in the scenario 3 with output-oriented CCR model. As results shown in Table 5, the number of efficient DMUs increased and DMU 13 became efficient. In addition, the efficiency score of all DMUs increased.

Table 5: Efficiency scores of forest management units from sensitivity analysis using the scenario 3 with output-oriented CCR model.

Tabelle 5: Effizienz der forstlichen Bewirtschaftungseinheiten aus der Sensitivitätsanalyse von Szenario 3 mit dem Output-orientierten CCR-Modell.

DMUs	Efficiency score	DMUs	Efficiency score
1	1	18	0.98
2	1	19	1
3	1	20	0.78
4	1	21	0.71
5	1	22	0.73
6	0.82	23	0.78
7	1.00	24	0.78
8	0.70	25	0.71
9	0.76	26	0.74
10	0.63	27	0.65
11	1	28	0.76
12	1	29	0.84
13	1	30	0.78
14	1	31	0.69
15	0.78	32	0.74
16	0.77	33	1
17	1		

Statistical analysis

The results of t-test between scenario 1 (ignoring the CO_2 emission) and scenario 2 (considering the undesirable outputs as input) shown in Table 6. Results indicated that there is a significant difference at significance level of 0.05 in the efficiency scores of scenarios 1 and 2 in both one-tailed and two-tailed tests.

Table 6: Results of paired t-test between scenarios 1 and 2.

Tabelle 6: Ergebnis des paarweisen t-Tests zwischen Szenarien 1 und 2.

	Scenario 1	Scenario 2
Mean	0.703333333	0.805151515
Variance	0.052347917	0.040075758
Observations	33	33
Pearson Correlation	0.827008255	
Hypothesized Mean Difference	0	
df	32	
P(T<=t) one-tail	3.86338E-05	
t Critical one-tail	1.693888748	
P(T<=t) two-tail	7.72676E-05	
t Critical two-tail	2.036933343	

The results of t-test to compare the average score of input-oriented and output-oriented CCR models between scenario 1 and scenario 3 (applying a monotone decreasing transformation to the undesirable outputs and then to use the adapted variables as outputs) shown in Table 7. Results indicated that there is a significant difference at significance level of 0.05 in the efficiency scores of scenarios 1 and 3 in both one-tailed and two-tailed tests.

Table 7: Results of paired t-test between scenarios 1 and 3.

Tabelle 7: Ergebnis des paarweisen t-Tests zwischen Szenarien 1 und 3.

	Scenario 1	Scenario 3
Mean	0.703333	0.758961
Variance	0.052348	0.040298
Observations	33	33
Pearson Correlation	0.942716	
Hypothesized Mean Difference	0	
df	32	
t Stat	-4.10873	
P(T<=t) one-tail	0.000129	
t Critical one-tail	1.693889	
P(T<=t) two-tail	0.000258	
t Critical two-tail	2.036933	

Results of t-test indicated that there is a significant difference at significance level of 0.05 in the efficiency scores of scenarios 2 and 3 (average score of input-oriented and output-oriented CCR models) in both one-tailed and two-tailed tests (Table 8).

Table 8: Results of paired t-test between scenarios 2 and 3.

Tabelle 8: Ergebnis des paarweisen t-Tests zwischen Szenarien 2 und 3.

	Scenario 2	Scenario 3
Mean	0.805152	0.758961
Variance	0.040076	0.040298
Observations	33	33
Pearson Correlation	0.836161	
Hypothesized Mean Difference	0	
df	32	
t Stat	2.31227	
P(T<=t) one-tail	0.013675	
t Critical one-tail	1.693889	
P(T<=t) two-tail	0.027351	
t Critical two-tail	2.036933	

One way Analysis of Variance (ANOVA) using Excel software was used to investigate, if there is any significance among the means of efficiency scores of various DMUs (33 forest management plans) in three scenarios. Results indicated that there is a significant difference at the significance level of 0.05 in efficiency scores of various DMUs (Table 9).

Table 9: Results of ANOVA (single factor) among the various DMUs under three scenarios.

Tabelle 9: Ergebnisse der ANOVA (single factor) zwischen den DMUs und den drei Szenarien.

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.095847	32	0.159245	20.79003	2.75E-31	1.560421
Within Groups	0.758309	99	0.00766			
Total	5.854156	131				

Discussion

The current research deals with desirable and undesirable factors in forest management units using DEA approach. DEA is used for benchmarking of DMUs and provides information on how much the input of an inefficient DMU can be decreased or its outputs can be increased to make the unit efficient.

It is not appropriate to increase all output for increasing the efficiency score, when there is undesirable output such as CO_2 emission during logging operation in forests. Therefore, in this study three scenarios considered to treat with undesirable output such as scenario 1) ignoring the undesirable output, scenario 2) treating the undesirable outputs as inputs, scenario 3) applying a monotone decreasing transformation to the undesirable outputs and then to use the adapted variables as outputs (Seiford and Zhu, 2002). It was shown that the CCR model can be used to improve the efficiency of DMUs through increasing the desirable outputs and decreasing the undesirable outputs. Results of CCR model showed that with ignoring the undesirable output (scenario 1) and considering the undesirable outputs as inputs (scenario 2), 10 and 13 DMUs became efficient, respectively. Furthermore, results of DEA model with considering a monotone decreasing transformation to the CO_2 emission and using the adapted variables as outputs (scenario 3) indicated that 11 DMUs became efficient. There is similarity between the results of this study and finding in Seiford and Zhu (2002) that they applied a linear monotone decreasing transformation to treat the undesirable outputs in some paper mills.

The t-test used to determine if the means of efficiency scores are significantly different from each other in three scenarios. Results indicated that there is a significant difference at the efficiency scores of various scenarios in pair at the significance level of 0.05 (Tables 6 to 9). In addition, there are differences in ranking of DMUs performances. Hence the results of this research is in line with finding Färe *et al.* (1989) that failure to credit mills for pollution reduction can severely distort the ranking of mill performance.

Sensitivity analysis was done in scenario 3 with output-oriented CCR model to investigate how sensitive the efficiency scores of the DMUs are to the numerical input and output data. Results of sensitivity analysis showed that the number of efficient DMUs increased and the efficiency score of all DMUs increased.

Kao and Yang (1991) were the first researchers used DEA for performance measurement of forest industries. Their method applied and developed by several authors as it was reviewed in introduction. In all of the previous studies to evaluate the efficiency of forestry and forest industries, there was less attention to the carbon dynamic such as carbon sequestration and CO_2 emission. Ignoring the undesirable (CO_2 emission) output may give high efficiency score to some DMUs and will advise the DMUs to increase their efficiency score only by adjusting their economics variables such as cost and revenue. In addition, the amount of sequestered carbon in stem wood volume before and after harvesting as well as the sequestered carbon in harvested timber was considered in this study.

Hence, the results of this study can be a guideline for forest management units to become more efficient considering both economics and carbon dynamics.

Conclusion

Estimating the efficiency of forest management units considering desirable and undesirable output will be an appropriate benchmark for inefficient DMUs to increase their efficiency as well as for governmental organizations to oversight the management units considering economics and environmental objectives which is in line with sustainability issues. This research was a first attempt to consider CO_2 emission as an undesirable output in estimating the efficiency of forest management units using DEA approach. In the future studies, more undesirable output could be included in the DEA model such as soil erosion in forest harvesting for increasing the accuracy of the efficiency analysis and giving more weight to the environmental issues. To sum up, the classical approach of efficiency measurement is not an appropriate approach to deal with undesirable output, while the presented approach in scenario 3 (applying a monotone decreasing transformation to the undesirable outputs and then using the adapted variables as outputs) can be considered as a possible appropriate approach in which to make forest management units more sustainable and provide effective guidance on how to tackle undesirable output in forest production systems.

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