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基于蒙古国森林清查的异龄林立地质量评价

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摘要

立地质量的评估是异龄林林分生长动态的模拟与森林经营决策研究中不可或缺的部分。林木的树高信息通常间接反映了林分的立地质量。树高-胸径关系模型被广泛应用于蒙古森林调查中，用于替代或验证树高测量的工作。本研究基于蒙古全国森林资源清查的数据，针对寒带森林中七个主要树种分别建立立地评价体系。基于蒙古异龄林的林分结构特点，研究中共收集整理了基于群团抽样设计 3904 块圆形样地的数据信息。样地设置采用按胸径分组的同心圆设计方法。针对 5 种针叶与 2 种落叶阔叶树种，研究测试了 10 种树高-胸径关系模型，并在此过程中，对不同林分特征的变量进行了比较筛选。对多数树种而言，立地形模型最终选取了 Chapman-Richards 方程，且基准胸径设置为 20cm。基于 69 块固定样地中生长锥钻取的木芯信息，林分断面积、蓄积与生物量的连年生长量得以被计算，并用于森林生产力的评估，并与当前林分的蓄积量信息进行了对比。对多数林分而言，在树高-胸径模型中将优势高、林分平均胸径和 Shannon 多样性指数加入作为自变量后，模型拟合效果显著提升。本研究所开发的异龄林树高-胸径模型相比于蒙古传统林业调查规程中的模型，精确度也有着显著提升。研究涉及到林分其立地形的范围为 14-20m，不同树种间有着明显区别。西伯利亚落叶松多为纯林，其立地指数范围为 20-26m。多数指标都表明同等立地质量下混交林有着更高的林分生产力。然而，当前林分状态下纯林蓄积量整体高于混交林，这与不同林分所处的区域于土壤特征有关。本研究基于样地调查与生长锥木芯的数据，综合了立地形、立地指数、蓄积和生物量等多种方法建立起完整的立地质量模型评估体系，对蒙古不同区域、树种和林分类型进行了立地质量的评价和比较，不同评价方法尽管在量化结果上有所区别，但整体结论有着较高的一致性。

关键词：树高-胸径模型；直接法和间接法；立地质量；全国森林调查

ABSTRACT

Evaluation of site quality is essential for stand development and forest management decision in uneven-aged natural boreal forest. Height-diameter relationship models have been extensively used in Mongolia's forest inventory to avoid the time-consuming task of measuring heights of all individual trees. In this study, site quality evaluated different forest types in boreal forest based on Multi-purpose NFI (National Forest Inventory) data. The study involved various stand structures of uneven-aged boreal forest in Mongolia. One-time observation data were obtained from 3 904 permanent cluster sampling plots including three circle sub-plots. The trees were grouped and sampled within three different radii according to DBH (dimeter at breast height). Totally, ten height-diameter relationship base models are presented for five conifer and two broadleaf trees. New height-diameter relationship models were evaluated along with stand variables relying on statistical analysis. Indirect methods, including site form and site index, predicted based on height-diameter relationship models. Site form model was constructed based on Chapman-Richards model for different forest types and different regions. The reference diameter of site form was 20 cm for each species. Based on tree ring data from 69 permanent plots, site productivity were evaluated by calculating basal area increment, mean annual increment and biomass production. Meanwhile, current volume was estimated for all permanent sample plots. The height-diameter models with best performances included dominant height, mean quadratic diameter and Shannon index as independent variables. The height-diameter relationship models for seven trees in this study were more accurate than models developed in the past. The site form classes varied from 14m to 20m and the patterns were indicating species-specific differences in uneven-aged forest. Site index of Siberian larch stand varied from 20 m to 26 m. Comparison of site productivity demonstrated that mixed forests are more productive than pure stand. Meanwhile, the basal area increment of pure stand were lower than that of mixed stand, contrast mean annual increment of mixed stand lower than pure stand. And site productivity was highest in loamy sand and lowest in clay loamy soil. Otherwise, pure Siberian larch forest was more productive than mixed forest. The direct and indirect methods showed strong correlations with site productivity and site quality measures

KEY WORDS: height-diameter model, direct and indirect methods, site quality, NFI

Contents

CHAPTER 1. INTRODUCTION

Forest management planning based on assessment of site quality and future yield estimation which requires suitable inventory. The increasing availability of site information and growth and yield data from forest inventories that influence to an increased meshing of locally acquired information of site growth and yield relationships (Pretzsch 2009). Stand growth and yield projections require some evaluation of these site differences (Vanclay 1994), which means that models for growth and yield develop reliable tools for predicting stand characters. Diameter distribution models developed for growth and yield, while dominant tree heights predicted by diameter class (Burkhart and Tom´e 2012) that indicates height-diameter relationships are basic as input variables for prediction of stand growth and yield models.

Forest site quality affected by biological and physical factors that characterize tree growth ability in different site conditions. Forest site quality evaluation is an essential part of growth and yield modelling. Two main measures used in forest site evaluation are phytocentric (tree based attributes) and geocentric (physical site properties) (Vanclay 1994; Weiskittel et al. 2011). Phytocentric measures that attempt to characterize a site based on tree measurement and component of individual trees (Weiskittel et al. 2011) such as, site index, site form, plant indicators, maximum mean annual increment, growth index and reference diameter. Otherwise, various studies that have evaluated the relationship between site productivity and geocentric measures (soil properties, climate and position of site) that, soil depth and nitrogen content, annual temperature and precipitation, elevation, aspect and slope (Fontes et al. 2003). Various studies have developed height-diameter relationship models with geocentric variables that slope (Magalhães 2017).

Generally, forest site evaluation measures divided into direct and indirect methods that depending on the scale and how close to stand volume production (Skovsgaard and Vanclay 2008). In this case, production is direct phytocentric measures of forest site, while site index and site form are indirect phytocentric measure (Vanclay 1994; Weiskittel et al. 2011). Yield based measures that mean annual increment (MAI) and basal area increment were proposed site productivity (Pokharel and Froese 2009; Berrill and O'Hara 2014; Fu et al. 2017). MAI curves provide a part of the information needed for long-term estimation of forest management decision. Accurate estimation of total tree height are critical for estimating tree volume, forest productivity, site quality, and site index. Furthermore, tree height-diameter models are useful in simulation of forest dynamics, biomass estimation, growth and yield, and carbon budget (Vanclay 1994). In even-aged stand, dominant height of a stand reflects the productivity of a fully stocked, because the height growth of dominant trees is independent of stand density over a wide range of densities (Skovsgaard and Vanclay 2008; Berrill and O'Hara 2014). Dominant height of the stand is the main component of the indirect methods that site index and site form measures. The height determination at a known age that method are used to estimate site index and expected volume production. Site index is one of the most common measures of forest site quality, that dominant trees in stand are generally considered for site index. Due to, estimated site index is representative of the site, that selected trees should be undamaged. The dominant height and age on permanent plots provide the best source of data for fitting site index functions (Burkhart and Tom´e 2012). Weiskittel and others (2011) mentioned that, dominant trees have not experienced any suppression or other damages are easily identified. Generally, site index was developed for even aged and pure stands, due to it's difficult to precise site index in mixed species and uneven-aged stand (Harrington 1986). Otherwise, site index has been applied to mixed species and uneven-aged stand (Huang and Titus 1994). For example, site index measure is difficult to apply to uneven-aged and mixed species forest. The reason is sensitive errors on measurement due to competition between different species (Weiskittel et al. 2011).

In a natural uneven-aged forest, site productivity emphasizes the potential of timber or biomass production as a main indicator of a site (Fu and Sharma 2017). Last several decades, the strategies to manage uneven-aged forest were increasing, the purposes that timber production, and measures of site productivity are needed as indicators of sustainability and to predict rates of change (Berrill and O'Hara 2014). In uneven-aged stand mixed stand, size distribution widely varied that indicated species competition and mixing effects. Diameter distribution is determined as non-normal for individual diameter classes in uneven-aged stand (Woodall, Miles, and Vissage 2005), due to that different growth rate and shade tolerances among species.

1.1 Literature review of forest site evaluation

Generally, the previous studies have focused on finding the best functional form of the models for height prediction from measured diameter. Due to that, total height measurement is harder and time-consuming to measure, complex and expensive than diameter measurement (Larsen and Hann 1987; Wang and Hann 1988; Huang and Titus 1994; Sharma and Parton, 2007; Colbert et al 2002; Kershaw et al., 2008). For this reason, the DBH is measured for all the sampled trees, while height is measured only for a subsample of trees in inventory for forest management planning. Therefore, various model forms are generally used to height by growth functions, such as Chapman-Richards, exponential, modified logistic (Larsen and Hann, 1987; Zhang et al., 2002; Calama and Montero 2004; Westfall et al., 2006). Several studies have compared some linear and non-linear models in the H-D relationship studies (Huang and Titus, 1994; Temesgen and v. Gadow, 2004; Li et al., 2015; Liu et al., 2017).

In contrast, comparison studies tried to find the best models for all species in study forest stand or region (Larsen and Hann, 1987; Colbert et al. 2002). However, the height-diameter relationship strongly depends on site conditions within a given species. On the other hand, total tree height is strongly correlated with tree diameter at breast height, this relationship varies by species and stand conditions (Weiskittel et al. 2011). Therefore, some studies have used input variables of stand-level information into the basic models. Such as, stand density variables have been used by Larsen and Hann (1987), Staudhammer and LeMay (2000), Sharma and Zhang (2004) and Sharma and Parton (2007), position variables and stand density variables have been used by Temesgen and Gadow (2004), site index variables have been used by Larsen and Hann (1987) and Wang and Hann (1988). And, several variables of dominant and large trees are used for improving height static equation. For example, basal area in large trees, crown competition factor in large tree and dominant stand height have been used by Temesgen and Gadow (2004), Temesgen and other (2007), and Kershaw and other (2008), respectively. Various studies have used dummy variables of stand information into the height-diameter models (Magalhães 2017). The dummy variables are independent variables as a category, when it takes value of either 0 or 1, its coefficient is disappeared from the model (Garavaglia and Dun 2000). Stand variable and dummy variables application that can be applied to incorporate site-specific effects and account for the interregional variabilities (Magalhães 2017).

Various approaches have been used to evaluate site quality rely on site index, that is defined as the mean height of dominant and co-dominant trees in a stand at reference age of stand. Several studies have applied height-diameter relationship to estimate site quality for pure and mixed even-aged stands (Herrera-Fernández et al. 2004). But and cannot be to compare potential productivities between different species in natural mixed species stand. Sharma and Zhang (2004) mentioned, that results of height-diameter models could be more accurate with stand density and basal area than with site index as independent variables. In the fact that accurate estimate for site index depends on the past or future stand conditions and the model form. And a possible error in site index estimation is age determination (Reinhardt, 1982). Otherwise, the height of all trees in the stand may be affected by stand density more uneven-aged mixed natural stand than even-aged pure stand. And, basal area per hectare of all species in the mixed-species stand should be suitable with uneven-age structures. Because tree growth in mixed-species composition depends on the spatial arrangement (Pretzsch 2009b). Therefore, enough trees for each species in mixed-species stand must be measured (Harrington, 1986; Weiskittel, 2011; Huang et al., 1994). If the variation in stand density and site productivity has significant effects on tree height, they may be incorporated into the equation to provide better height prediction.

The most of site evaluation studies have been focused on even-aged or pure forest stands. Due to that tree and stand ages in such mixtures have very limited meaning, studies on growth and yield for mixed-species stands rarely involve the explicit use of age as an input variable (Huang et al. 1994). Otherwise, site form measure used as accurate measure to access site quality for uneven-aged and mixed forest stand Vanclay and Henry 1988; Huang and Titus 1994). Recently, this approach has been applied to natural uneven-aged Mongolian oak and Korean larch forest in Jilin, China (Fu and Sharma 2017). They had recommended site form measure based on height-diameter relationship model to estimation of site productivity of natural forests. And also, prediction accuracy site form was significantly higher than site index in mixed forest.

The quality of data has essential involvement for modelling effort. The different modelling approaches required different data forms from different sources. The inventory database contains the essential information about forest structure at the time of the last inventory along with important site characteristics. The permanent plots are best source of data for growth modelling. In traditionally, long-term experimental plots are distributed rather irregularly while most inventories follow a systematic grid (Pretzsch 2009). The advantage of systematic forest inventories is that this type of inventory may cover different range of site conditions and stand structures. Consecutive forest inventories on permanent plots provide information about stand and tree growth dynamics (Pretzsch 2009). There are difficulties associated with using temporary plots to model tree and stand dynamics. Otherwise, temporary plots require backdating to the start of the previous growth period those based on tree cores and stem analysis (Weiskittel et al. 2011; Laar and Akça 2007). Tree ring width measurement determining the annual diameter increment, basal area increment and mean annual increment. The growth of individual trees also is an effective measure of site productivity evaluation. Growth index ranks site productivity using individual-tree growth data collected from remeasured permanent plots (Weiskittel et al. 2011).

Forest inventories are considered as the most frequent way to obtain forest types and stand information with the highest accuracy. Forest types are classified as different groups of forest ecosystems with a generally similar composition that can be distinguished from other groups by their species composition, productivity and crown closure (Lu et al. 2017). The forest classification is composed predominantly of pure or mixed.

In Mongolia, some long-term analysis data are available form permanent plots that are long-term growth and yield experiments. However, such precise information has been rarely exploited for forest management planning. Otherwise, forest quality has been determined based on forest volume that the reason for calculation of timber production of major tree species in Mongolian boreal forest, but that has been conducted in selected regions. Hence, site quality is necessary to management plan of mixed boreal forest. In application, the height prediction models for site quality evaluation would helpful for future forest management decision in Mongolia

1.2 Objectives of the study

Various height-diameter models have been developed for site quality evaluation in boreal forest. However, most of the studies conducted in even-aged forest stand due to the restrictions that stand age prediction in uneven-aged forest. Otherwise, taller trees indicate that better site productivity and site quality. Therefore, classification of dominant height is accurate measure that can demonstrate stand site quality in uneven-aged mixed species forest. Direct method and indirect methods are based on production and tree attributes, respectively. However, both methods are using different approaches for site quality evaluation.

Therefore, the thesis attempts to evaluate site quality for uneven-aged forests by direct and indirect methods based on data from Multipurpose NFI 2014 of Mongolia with one-time observation. There are seven main tree species such as Siberian larch (*Larix sibirica* Ledeb.), Scots Pine (*Pinus sylvestris* L.), Siberian pine (*Pinus sibirica* Du Tour.), Siberian spruce (*Picea obovata* Ledeb.), Siberian fir (*Abies sibirica* Ledeb.), white birch (*Betula platyphylla* Sukaczev.), and aspen (*Populus tremula* L.).

The specific objectives of this study included the following:

1. to develop tree height-diameter relationship model for seven major tree species,
2. to apply stand variables and categorical stand variables into selected base models and to compare and analyze these new models,
3. to evaluate site quality of boreal forest based on site form and site index,
4. to calculate site productivities, and to compare with indirect methods

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CHAPTER 2. MATERIALS AND METHODS

2.1 NFI of Mongolia

Mongolia is geographically located between latitudes 41º N to 52º and longitudes 88º E to 120º E which covers an area of 1.56 million km^2. Mongolia is an upland country with greatest part lying above 1500 m sea level that ranges from 532 m to 4374 m. Mongolia has six natural eco-zones: Alpine, taiga forest, forest-steppe, steppe, desert-steppe and desert, that differing in altitude, landscape, soil, climate and vegetation (Altrell and Erdenejav 2016). The annual temperature ranges from -45ºC to 40ºC and annual precipitation ranges from 600 mm (northern mountain forest) to 100 mm (southern desert). Boreal forest of Mongolia spread in transition between the Siberian taiga forest and Asian dry steppe (Dorjsuren Ch 2012), functioning as a separator of great taiga and steppe, and protecting them of drying effect. And this boreal forest are situated along the three water basins in the world, and play an important ecological role in regulation of river's water resources, protection from soil erosion, softening the hard climate conditions, adsorption of greenhouse gasses, creating of suitable or pleasant conditions for growth of flora, fauna and microorganisms, and restricting of eternal frost (Munkhzorig D 2000). It shows that Mongolian boreal is special interest for studies of the impact of global warming due to that warming in central Asia significantly exceeded the global average, forest-steppe borderline already influenced by climate change, and tree growth in northern Mongolia is principally limited by drought (Dulamsuren et al. 2010).

Mongolian forested area divided into two types are northern conifer forest and southern Saxaul (*Haloxylon ammodendron*) forest. This study conducted northern conifer forest that is mountain forest that grows in north slope of the mountain because of growing under harsh conditions of the dry continental type of climate with low precipitation. Due to the forest situated high altitude and far from the influences of oceans. Totally, there are 9.1 million ha boreal forest stocked in Mongolia. The boreal forest in Mongolian is divided into four main mountain regions, including Khangai, Khentii, Khuvsgul and Altai mountain regions (Dorjsuren Ch 2012). The mountain forest of Mongolia covered by Siberian larch (*Larix sibirica* Ledeb.), Scots Pine (*Pinus sylvestris* L.), Siberian pine (*Pinus sibirica* Du Tour.), Siberian spruce (*Picea obovata* Ledeb.), Siberian fir (*Abies sibirica* Ledeb.), white birch (*Betula platyphylla* Sukaczev.), aspen (*Populus tremula* L.) and other broadleaved species. Siberian larch has the most dominant species and the most important socioeconomic value to local communities in Mongolia, which sell and use its by timber for construction. Forest growth rate is slow, due to the relatively harsh Central Asian climate that dry and windy weather with a short growing season (Batsukh 2000). And forest reforestation was generally poor, mainly due to influence of harsh climate. About 30%, 21% and 48% of total forest area belongs to area for protection, area designed for production purpose and utilization area, respectively. Forest resources in Mongolia have been increasingly degraded due to unregulated overexploitation and inadequate protection (Batsukh 2000; Altrell and Erdenejav 2016). Otherwise, according to forest statistics 1.7 million hectare confer forest replaced by birch and popular forest due to forest fire between 1974 and 2000 (Batsukh 2000; Tsogtbaatar 2013). Deciduous trees occur predominantly as pioneer species only, colonizing after forest fires, insect outbreaks and windfalls, or at special sites such as river terraces. And around 18.6% of the total forest area shows evidence of recent forest fire (Altrell and Erdenejav 2016) that is the most serious impact on the forest degradation.

Previous conventional forest inventories of Mongolia conducted five times from 1956. The purposes of the first and second inventories were forest extension mapping and corresponding statistics of forest characteristics. However, inventories were conducted nationwide, those were used conventional ocular estimation methods. And following inventories carried out at provincial levels that classified by administrations. The subnational inventories relied on taxation estimation sampling, that divided into forest permanent compartments for estimation of stocking density. These inventories sampling methods were not systematically and covered different parts of boreal forest of Mongolia.

Multipurpose National Forest Inventory (NFI) implemented nationwide in 2014, which is recommended for national and international reporting. The data used for this study were obtained by tree measurement on permanent plots of NFI. The permanent plots based on systematic sampling dot-grids, where national grid lines spacing of 9 km north to south and east to west. In some region denser grid with spacing 1.5 km and 4 km north to south and east to west was added, to better capture the relatively small forest area. As a result of this work, a network of 4211 permanent plots was installed in the boreal forest of Mongolia. Location of four mountain regions and buffer zone and permanent plot design illustrated in Figure 2-1.

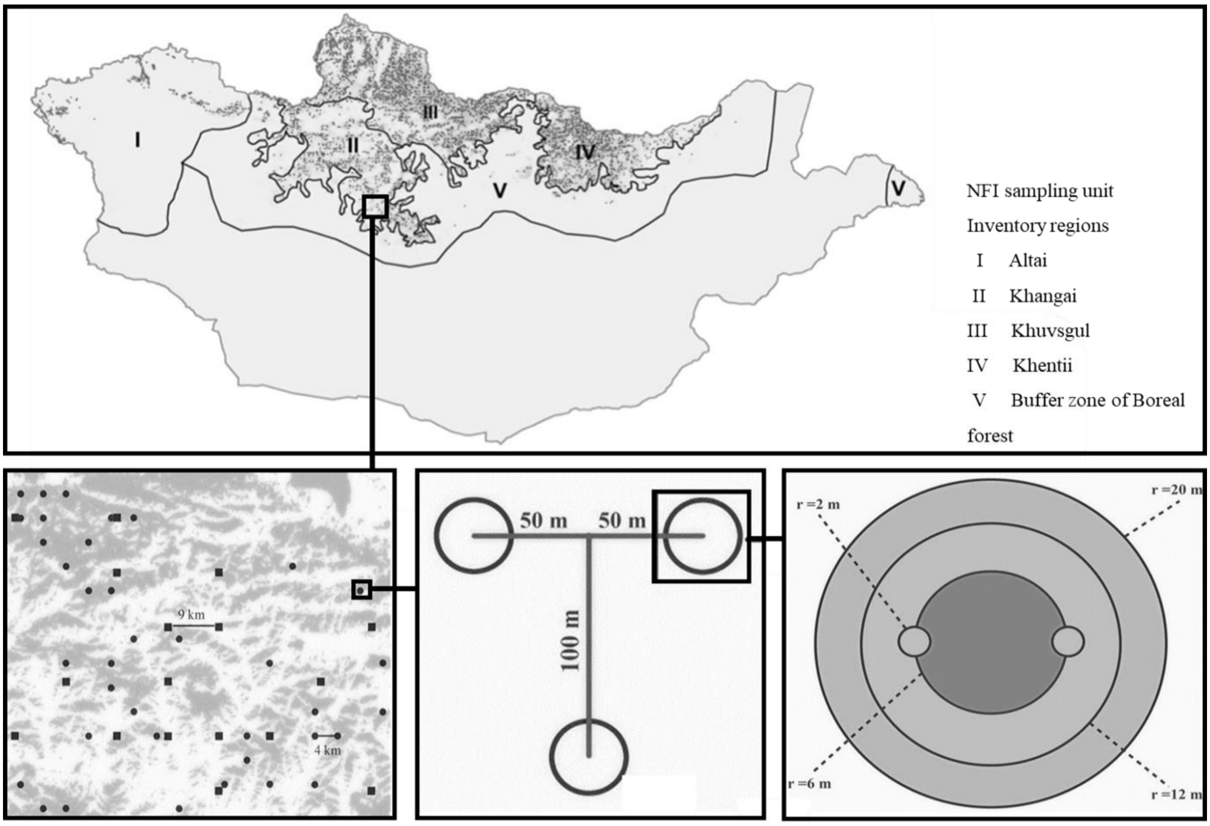

Figure 2-1. Sampling plot with a nested design

According to the aim of the inventory, the data required for generate unbiased statistics on stand, forest, and regional forestry resource were collected from stratified random sampling from sample plots. On average, Siberian larch (*Larix sibirica* Ledeb.) accounted for 80.7 percent of growing stock volume considered, Siberian pine (*Pinus sibirica* Du Tour.) for 6.7 percent, white birch (*Betula platyphylla* Sukaczev.) for 6.4 percent, Scotch pine (*Pinus sylvestris* L.) for 4.9 percent and another tree species for less than 2 percent (Altrell and Erdenejav 2016).

The stratified sampling is more convenient and efficient than simple sampling. Three circle sub-plots including one sampling cluster plot, in order to covering variation of stand densities and characteristics at one location. The sub-plot was nested with trees between 6 cm and 14.9 cm in diameter at breast height measured within a 0.034 ha (small circle - 6 m radius), trees between 15 cm and 29.9 cm in diameter measured within a 0.136 ha (medium circle - 12 m radius), and trees above 30.0 cm in diameter measured within a 0.377 ha (large circle - 20 m radius). Diameter measured over the bark for all sample trees, while total height measured for a subset of trees on every circle. Two trees, that are alive and with top of tree measured total height from every species and every circle. And stand observations were recorded each plot, such as forest structure, ground vegetation, landscape, slope, aspect of slope, soil horizon dept, soil texture, litter layer, and fore assessment. Tree ring core collected from 5 percent of permanent plots that were conducted during the growing season. In total, 30 cores were collected from three diameter size classes (large, medium and big).

2.2 Statistics of the NFI data

One-time observation data for developing height-diameter models acquired from 3904 permanent sample plots of the NFI. Sample plots were randomly located that provide a variety of height, stand structure, species and density in the boreal forest. The data for height-diameter relationship analysis of five conifer species and two broadleaved species came from uneven-aged natural forest. Species composition (based on basal area of the species in plot) for each species presented in Table 2-1, which was calculated for each species in each plot. Not every plot contained all species and generally two species recorded in sample plots of mixed stand. Siberian larch and Siberian fir were found to be highest (3521) and lowest (59) number of plots, respectively. On other hand, mean species composition was 90.6% Siberian larch (highest), 21.28% Siberian spruce (lowest). Plots with above than 80% and between 30% and 80% of stand basal area in a single species are considered pure and mixed stand, respectively.

Table 2-1. Summary statistics species composition

Species	Number of plots	Species composition (%)			
		Mean	S.D.	Min.	Max.
Siberian Larch	3521	90.60	17.83	0.50	100.00
Scotch Pine	424	64.23	31.39	0.08	100.00
Siberian Pine	786	41.39	28.87	0.04	100.00
Siberian spruce	253	21.28	18.15	0.09	99.26
Siberian fir	59	23.41	19.61	1.00	73.00
White birch	1446	30.30	31.41	0.05	100.00
Aspen	117	21.94	22.06	0.09	100.00

Note: S.D.=standard deviation; Min.=Minimum; and Max.=Maximum.

From each plot, total height-diameter of undamaged trees were selected for site quality evaluation by height-diameter relationship model and site form. The data set divided into plot-level and tree-level data. The plot level data contained categorical and calculated variables. Categorical data included stand observations such as, mountain region (five classes), slope (four classes by degree), aspect of slope (eight directions), and soil texture type (six classes). Geographical conditions are different growing conditions such as location, altitude, temperature and precipitation. Mountain regions that geographical conditions grouped NFI data set into Altai (AL), Khangai (KA), Khuvgsul (KU) and Khentii (KE) regions and buffer zone (BZ). Similarly, soil texture assigned sandy soil (S), loamy sandy soil (LM), sandy loamy soil (SL), loamy soil (L), clay loamy soil (CL), and clay soil (C). Stand level and tree level categorical variables applied to the model by dummy variables (Table 2-2). Other plot-level data that total basal area (BA /ha), quadric mean diameter (D_q /cm), number of stems (N /ha, trees with DBH greater than or equal to 6 cm), Shannon index (H_{sh}), and dominant height (H_d /m) were calculated for each plot. The tree-level data contained age class (six classes), total height (H, m), and diameter (D /cm at 1.3 m above ground) of trees on plots. Age of trees were classified the following 5 categories: less 20 years, 20 to 50 years, 50 to 100 years, 100 to 200 years and over 200 years (Table 2-2).

Table 2-2. Description of dummy variables for each species

Species	Aspect of slope							
	N	NE	E	SE	S	SW	W	NW
Siberian larch	14202	9410	3379	2511	1328	2497	3464	9321
Species	Age							
	20 >	20-50	50-100	100-200	>200			
Siberian pine		1757	1997	1851	305			
Siberian spruce	39	463	505	279	67			
White birch	1055	3759	3613	1107	68			
Species	Soil texture type							
	S	LM	SL	L	CL	C		
Siberian pine	32	437	1513	2890	958	145		
Species	Region							
	AL	KA	KU	KE	BZ			
Siberian larch	3806	9788	24799	6275	1716			
Scots pine			554	1987	112			
Siberian pine	21	593	2509	2908	142			
Siberian spruce	235	35	703	379	24			
White birch		195	5077	4103	217			
Aspen			99	286				
Species	Slope							
	0-10	10-20	20-30	30 <				
Siberian larch	16155	19886	8380	1963				
Scots pine	832	1306	472					
Siberian pine	1770	2715	1355					
Siberian spruce	606	397	330	43				
Aspen	115	214	70					

Another hand, the data were randomly divided into two group sets for model fitting and model cross-validation. Summary statistics of observed and calculated variables presented by two groups for fitting and validation (Table 2-3). D ranged from 18.4 cm (white birch) to 29.5 cm (Scots pine), H ranged from 12.3 m (white birch) to 16.8 m (Scots pine), BA ranged from 16.6 m^2/ha (aspen) to 27.1 m^2/ha (Siberian pine), N ranged from 593.9 stem/ha (Scots pine) to 914.5 stem/ha (aspen), D_q ranged from 25.3 cm (Siberian spruce) to 29.0 cm

(Siberian fir), H_d ranged from 16.9 m (white birch) to 21.7 m (Scots pine) and H_{sh} ranged from 0.3 (Siberian larch) to 1.0 (Siberian fir).

Table 2-3. Summary statistics of observed diameter and height of two groups for seven species

Species	Group 1							Group 2						
	D /cm	H /m	BA m^2/ha	N /ha	D_q /cm	H_d /m	H_{sh}	D /cm	H /m	BA m^2/ha	N /ha	D_q /cm	H_d /m	H_{sh}
Siberian larch														
Mean	25.3	14.9	21.0	768.6	28.0	21.6	0.3	25.3	14.9	20.9	761.3	28.1	21.5	0.2
S.D.	12.8	5.5	8.8	432.1	5.9	4.2	0.3	12.9	5.4	9.1	430.6	5.6	4.1	0.3
Min	6.0	2.0	1.3	18.6	7.7	5.1	0.0	6.0	2.0	1.9	36.5	9.6	6.4	0.0
Max	102.4	50.8	55.8	3172.8	66.1	50.8	1.6	109	54.1	84.3	2590.1	54.8	54.1	1.8
Scotch Pine														
Mean	29.5	16.8	17.5	593.9	28.6	21.7	0.7	29.8	17	17.6	587.4	28.8	21.8	0.7
S.D.	13	5.2	8.1	376.1	5.5	3.8	0.4	13	5.2	8.1	368.7	5.4	3.8	0.4
Min	6.0	2.0	1.3	31.2	7.7	4.6	0.0	6.0	3.0	1.6	31.2	13.4	6.1	0.0
Max	85	32.4	45.3	2420.0	45.5	32.5	1.8	84.3	32.5	45.3	2347.2	45.5	32.5	1.8
Siberian pine														
Mean	23.2	12.8	21.7	814.0	27.3	18.0	0.7	23.2	12.9	21.7	818.2	27.2	18.0	0.7
S.D.	12	4.9	9.1	430.6	4.9	4.1	0.3	11.9	5.0	9.1	432.7	4.9	4.1	0.3
Min	6.0	2.0	3.4	72.5	11.1	4.1	0.0	6.0	2.0	3.4	36.5	11.1	4.1	0.0
Max	112	29.6	55.8	2662.3	50.5	41.7	1.8	116.3	41.7	55.8	2662.3	50.5	41.7	1.8
Siberian spruce														
Mean	19.8	12.9	20.0	914.5	25.3	18.2	0.8	19.5	12.8	20.0	904.6	25.5	18.3	0.8
S.D.	10.4	5.1	8.6	497.0	4.6	4.4	0.3	9.9	5.3	8.6	494.7	4.7	4.4	0.3
Min	6.1	3.7	4.0	94.9	13.6	5.0	0.1	6.0	2.7	4.0	81.3	13.6	5.0	0.1
Max	80.3	26.8	52.0	3135.4	42.9	26.8	1.8	62.8	26.4	52.0	3135.4	42.9	26.8	1.8
Siberian fir														
Mean	22.1	15	18.0	599.1	29.0	18.4	1.0	20.6	14.2	17.5	590.4	28.8	18.1	1.0
S.D.	10.6	4.8	8.1	245.3	3.7	4.5	0.3	9.6	5.0	8.2	248.9	3.6	4.7	0.3
Min	7.1	6.1	6.3	188.0	21.2	6.1	0.1	6.5	4.4	6.3	133.0	18.8	4.5	0.2
Max	50.2	25.7	52.0	1327.0	45.5	26.1	1.8	45.1	26.1	52.0	1327.0	38.7	26.1	1.8
White birch														
Mean	18.4	12.3	17.7	661.2	27.4	16.9	0.6	18.2	12.2	17.6	660.0	27.4	16.8	0.6
S.D.	9.1	4.5	7.6	330.8	5.9	3.9	0.3	9.0	4.5	7.7	333.8	5.9	3.9	0.3
Min	6.0	2.0	1.2	25.3	6.8	4.1	0.0	6.0	2.0	1.2	25.3	6.8	4.1	0.0
Max	57.1	35	48.9	2420.0	52.0	35.0	1.8	79.0	30.4	48.9	2420.0	52.0	35.0	1.8
Aspen														
Mean	20.2	13.8	16.6	658.8	27.0	17.3	0.9	20.5	13.7	16.6	681.0	26.7	17.2	0.9
S.D.	10.8	5.5	7.8	383.4	6.4	5.1	0.3	11.2	5.2	8.0	406.6	6.3	5.0	0.3
Min	6.0	2.0	2.5	113.8	6.8	4.5	0.0	6.0	3.0	2.5	111.7	6.8	4.9	0.0
Max	60.3	27	35.0	2420.0	42.5	27.0	1.6	71.7	24.4	35.0	2590.1	39.6	27.0	1.6

Note: S.D.=standard deviation; Min.=Minimum; and Max.=Maximum.

Totally 1181 tree core samples from 68 permanent plots were measured. The annual radial growth increment was divided into diameter size classes by 5 cm intervals. The sample collection was carried out during vegetation period of 2014, when the growth had not completed. Due to the radial growth of trees were measured from 2013. Site index and mean annual production used exact tree age and radial growth of sample plots form tree core samples. Diameter distribution of trees in sample plots were presented by different regions in Table 2-4.

Table 2-4. Collected diameter increment cores of Siberian larch by diameter size class

Region	Size class, cm							
	<10	10-15	15-20	20-25	25-30	30-35	35-40	>40
Altai	33	39	43	28	12	15	2	6
Khangai	10	43	39	34	22	15	6	1
Khuvsgul	43	138	114	87	100	40	15	9
Khentii	33	61	57	51	38	33	5	9

2.3 Methods

Generally, forest site evaluation methods divided to direct and indirect measures that depending on how close to stand volume production (Skovsgaard and Vanclay 2008). In this study, direct and indirect measures are proposed to evaluate forest site quality for uneven-aged forest based on one-time observation data of NFI (Figure 2-2). The direct methods were included stand volume and biomass production and current volume that based on tree radial growth measurement and volume equation. Another hand, indirect methods were relied on height-diameter relationship model and age of the dominant trees. The output that, forest site evaluation presented by different scale, forest type and comparison of different methods.

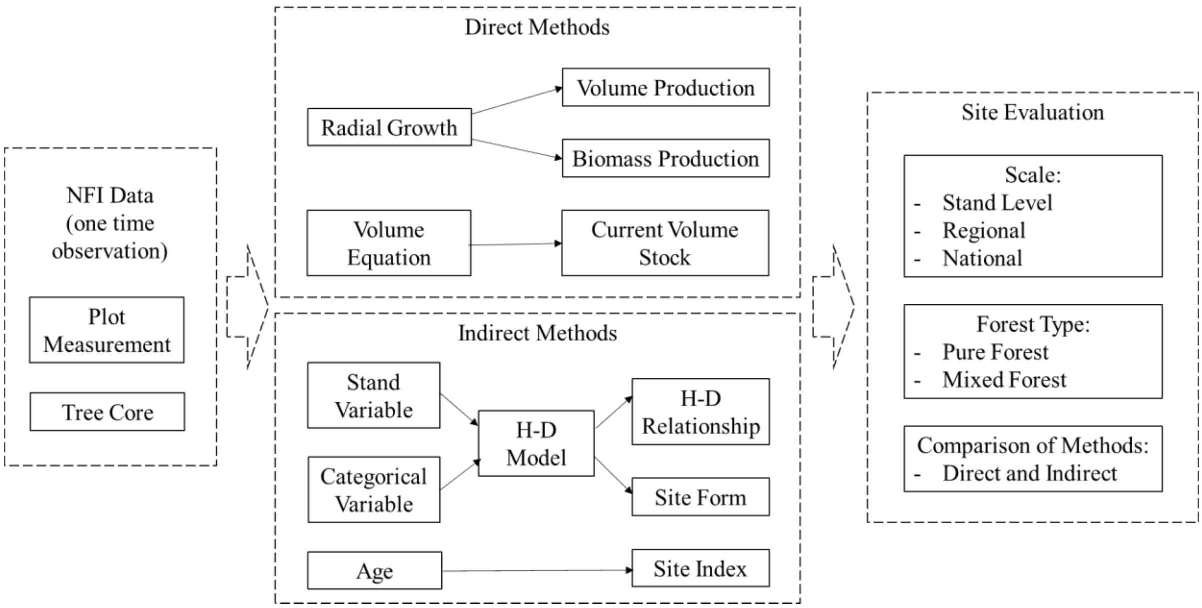

Figure 2-2. Flowchart of site evaluation for uneven-aged forests based on NFI data

2.3.1 Selection of base models

Height-diameter relationships are generally described using nonlinear modelling approach. Therefore, the following 10 candidate nonlinear models were selected for evaluation: Larsen and Hann (Model 1), Chapman-Richards (Model 2), Ratkowsky (Model 6), logistic (Model 4 and 10), and exponential (Model 3, 5, 7, and 9). All models have been commonly used in application studies. The height-diameter relationships models were included following sources and general form (Table 2-5).

Table 2-5. Height-diameter models

Model form	Source	Model
$H = 1.3 + e^{(a+bD^c)}$	(Larsen and Hann, 1987; Wang, 1998)	1
$H = 1.3 + a * (1 - e^{(-bD)})^c$	(Huang, 1994; Temesgen et al, 2007; Peng, 2004)	2
$H = 1.3 + e^{(a+\frac{b}{D+1})}$	(Temesgen, 2004; Calama and Montero 2004)	3
$H = 1.3 + (\frac{a}{1+b^{-1}*D^{-c}})$	(Nunung 2014)	4
$H = 1.3 + a * e^{(\frac{b}{D+c})}$	(Nunung 2014)	5
$H = 1.3 + e^{(a+b/(D+c))}$	(Temesgen et al. 2004)	6
$H = 1.3 + a * e^{(\frac{b}{D})}$	(Calama and Montero 2004)	7
$H = 1.3 + a * D^b$	(Temesgen et al. 2004; and Hui and Gadow 1993)	8
$H = 1.3 + a * e^{(\frac{b}{D+1})}$	(Temesgen et al. 2004; and Hui and Gadow 1993)	9
$H = 1.3 + (\frac{a}{1+e^{(b+c*\ln(D+1))}})$	(Ratkowsky 1990)	10

Notes: H = estimated total tree height (m); D = diameter at breast height (cm); 1.3 is a constant used to account that D is measured at 1.3 m (in height from the ground); e = e raised to the particular i^{th} power; $\ln$ = natural logarithm; and a, b, and c = parameters to be estimated.

2.3.2 Selection of stand variables and backward elimination

In this study, we added stand variables into base models in order to improve the accuracy of models. The additional stand variables include dominant height (H_d), basal area (BA), density (N), Shannon index (H_{sh}) and mean quadratic diameter (D_q). It has been reported that stand density variables, such as BA and N resulted in the most accurate relationship of height-diameter (Larsen and Hann, 1987; Temesgen, Hann and Monleon, 2007; Sharma and Parton, 2007). Dominant height based height-diameter equations developed by Kershaw and others (2008) showed that asymptotic maximum height should be related to dominant canopy height. Therefore, we evaluated diameter measure of stand (mean quadratic diameter, cm), height measure of stand (dominant height, m), stand mixture measure (Shannon index), and stand density measures (basal area, m^2/ha and number of trees, stem/ha) for improving the accuracy of selected models. In this study, H_d was calculated as the average height of a specified number per unit area of the trees in a stand with the largest diameter (West 2015). In boreal mixed forests, tree height growth may be affected by species composition (Huang and Titus 1994). Thus, we also considered Shannon index which is defined as quantifying species diversity based on frequency of species:

$$\mathrm{H}_{sh} = -\sum_{k=0}^{S} pi * lnpi \tag{11}$$

where: S represents the number of species in the stand, pi the proportion of a species in the population. $pi = n_i/N$, n_i the number of individuals of a species i, and N the total number of individuals (Pretzsch 2009).

Stand variables were eliminated by backward elimination, which involved starting with all variables in equation and testing the deletion of each variable used statistical insignificant deterioration and index of the model fit, such as residual standard error (RSE) and Akaike's Information Criterion (AIC). The variables applied to selected models 2, 5 and 10 from base (without any variables) model selection part and expanded version of the models given in model 12, 13, and 14, respectively.

$$H = 1.3 + (a_1 + a_2 * BA + a_3 * N + a_4 H_d + a_5 * D_q + a_6 * H_{sh}) * (1 - e^{(-bD)})^c \tag{12}$$

$$H = 1.3 + (a_1 + a_2 * BA + a_3 * N + a_4 H_d + a_5 * D_q + a_6 * H_{sh}) * e^{(\frac{b}{D+c})} \tag{13}$$

$$H = 1.3 + (\frac{a_1 + a_2 * BA + a_3 * N + a_4 H_d + a_5 * D_q + a_6 * H_{sh}}{1 + e^{(b + c * \ln(D+1))}}) \tag{14}$$

where: H - estimated total tree height (m), D - diameter at breast height (cm), 1.3 is a constant used to account that D is measured at 1.3 m (in height from the ground), e - e raised to the particular i^{th} power, $a_1, b\ and\ c$ - parameters to be estimate height of the individual tree, a_{2-i} – parameters of stand variables, BA = Basal area (m^2/ha), N = Number of tree (n/ha), H_d=Dominant Height (m), D_q= Quadratic Mean Diameter (cm), and H_{sh}= Shannon Index.

2.3.3 Stand variables and dummy variables

The expanded models formulated based on Chapman Richards base model (model 2). Various growth and yield studies described that model 2 were the most flexible model for empirical modelling approach (Huang and Titus 1994; Sharma and Parton 2007). The most of studies applied stand variables to parameter a. The parameters of model 2 controls different functions that parameter a, b, and c are control the asymptote, rate, and shape, respectively (Hanus, Marshall, and Hann 1999; Huang and Titus 1994; Sharma and Parton 2007). Therefore, stand variables that tested by different parameters. The most accurate stand variables that H_d, D_q, and H_{sh} selected from the result of backward elimination. The models with stand variables in different parameters can be expressed as follows:

$$H = 1.3 + (a_1 + a_2 * H_d + a_3 * D_q + a_4 * H_{sh}) * (1 - e^{(-bD)})^c \quad (15)$$

$$H = 1.3 + a * \left(1 - e^{(-(b_1+b_2*H_d+b_3*D_q+b_4*H_{sh})*D)}\right)^c \quad (16)$$

$$H = 1.3 + a * (1 - e^{(-bD)})^{c_1+c_2*H_d+c_3*D_q+c_4*H_{sh}} \quad (17)$$

where: H - estimated total tree height (m), D - diameter at breast height (cm), 1.3 is a constant used to account that D is measured at 1.3 m (in height from the ground), e - e raised to the particular i^{th} power, $a, b\ and\ c$ - parameters to be estimate height of the individual tree, H_d= dominant Height (m), D_q= mean quadratic diameter (cm), and H_{sh}= Shannon Index.

A height-diameter model was developed using a dummy variable modelling approach. Dummy variables are independent variables which indicates categorical data (Garavaglia and Dun 2000) and the variables take a value of 1 if the observation comes class number one and 0 if it comes from another classes. Site specific effects are adding to the base models as dummy variables (Magalhães 2017) and it classifies data into growing different conditions. Model 2 with dummy variables was carried out every seven species. The dummy variables that were included regional (mountain region), site condition (soil type), geographic (slope degrees and aspect of slope) and age (age classes) categorical variables. All dummy variables applied to parameter a that controls asymptotic height of the stand (Hanus, Marshall, and Hann 1999; Huang and Titus 1994; Sharma and Parton 2007). The expanded version of model 2 with dummy variables can be expressed as follows:

$$H = 1.3 + (a_1 + a_2AL + a_3KA + a_4KU + a_5KE) * (1 - e^{(-bD)})^c \quad (18)$$

All data fitted into five mountain regions were defined as: if data comes from the Altai region (AL), all other indicator variables are zero ($a_{2-i} = 0$) ; if data comes from the Khangai region (KA), all other indicator variables $a_{2-i} = 0$; if data comes from the Khuvsgul region (KU), all other indicator variables $a_{2-i} = 0$; and if data comes from the Khentii region (KE) , all other indicator variables $a_{2-i} = 0$. When all other indicator variables $a_{2-i} = 0$ the model predicts height in buffer zone (BZ), due to that the model wasn't including dummy variable from BZ.

$$H = 1.3 + (a_1 + a_2SL_{0-10} + a_3SL_{10-20} + a_4SL_{20-30}) * (1 - e^{(-bD)})^c \quad (19)$$

The slope of the forest area divided into four classes that indicate the following dummy variables: if slope of plot area 0 to 10 degree (SL_{0-10}), all other indicator variables are zero ($a_{2-i} = 0$); if slope of plot area 10 to 20 degree (SL_{10-20}), all other indicator variables $a_{2-i} = 0$; and if slope of plot area 20 to 30 degree (SL_{20-30}), all other indicator variables $a_{2-i} = 0$. When all other indicator variables $a_{2-i} = 0$ the model predicts height with > 30 degree ($SL_{>30}$). Therefore, the expanded model wasn't including dummy variable with $SL_{>30}$.

$$H = 1.3 + (a_1 + a_2N + a_3NE + a_4E + a_5SE + a_6SW + a_7W + a_8NW) * (1 - e^{(-bD)})^c \quad (20)$$

The aspect of slope recorded by directions were defined as: if slope of area to north (N), all other indicator variables are zero ($a_{2-i} = 0$); if slope of area to north east (NE), all other indicator variables $a_{2-i} = 0$; if slope of area to east (E), all other indicator variables $a_{2-i} = 0$; if slope of area to south east (SE), all other indicator variables $a_{2-i} = 0$; if slope of area to south west (SW), all other indicator variables $a_{2-i} = 0$; if slope of area to west (W), all other indicator variables $a_{2-i} = 0$; and if slope of area to north west (NW), all other indicator variables $a_{2-i} = 0$. The model predicts height with south (S), when all other indicator variables $a_{2-i} = 0$. Therefore, the expanded model wasn't including dummy variable with S.

$$H = 1.3 + (a_1 + a_2LM + a_3SL + a_4L + a_5CL + a_6C) * (1 - e^{(-bD)})^c \quad (21)$$

To determinate differences among site condition, the following forest soil texture predictor variables are created: if stand grows in loamy sand soil (LM), all other indicator variables are zero ($a_{2-i} = 0$); if stand grows in sandy loam soil (SL), all other indicator variables $a_{2-i} = 0$; if stand grows in loam soil (L), all other indicator variables $a_{2-i} = 0$; if stand grows in clay loam soil (CL), all other indicator variables $a_{2-i} = 0$; and if stand grows in clay soil (S), all other indicator variables $a_{2-i} = 0$. When all other dummy variables $a_{2-i} = 0$ the model predicts height of trees in sandy soil (S), because the model wasn't including dummy variable from S.

$$H = 1.3 + (a_1 + a_2Age_{<20} + a_3Age_{20-50} + a_4Age_{50-100} + a_5Age_{100-200}) * (1 - e^{(-bD)})^c \quad (22)$$

where: H - estimated total tree height (m), D - diameter at breast height, 1.3 is a constant used to account that D is measured at 1.3 m (in height from the ground), e - e raised to the particular i^{th} power, a_1, b and c - parameters to be estimate height of the individual tree, and a_{2-i} – parameters of dummy variables.

Age of individuals recorded by five age classes were defined as: if age of tree less than 20 years ($Age_{<20}$), all other indicator variables are zero ($a_{2-i} = 0$); if age of tree 20 to 50 years (Age_{20-50}), all other indicator variables $a_{2-i} = 0$; if age of tree 50 to 100 years (Age_{50-100}), all other indicator variables $a_{2-i} = 0$; and if age of tree 100 to 200 years ($Age_{100-200}$), all other indicator variables $a_{2-i} = 0$. All other indicator variables $a_{2-i} = 0$, when the model predicts height with age over than >200 ($Age_{>200}$). Therefore, the expanded model wasn't including dummy variable with $Age_{>200}$.

2.3.4 Site form, site index, or site productivity

Diameter of trees are same that growing different site conditions would be different height and different site productivity. Site form defined as the average height of dominant and codominant trees at reference diameter at breast height (Huang and Titus 1994). Which expressed trees that commonly occur in the uneven-aged stand (Vanclay and Henry 1988). Site form is the convenient measure for site productivity assessment in uneven-aged and mixed species stands (Huang and Titus 1994). Stand height-diameter relationship of the dominant and codominant trees was used to evaluation of site productivity for uneven-aged and mixed forest (Fu and Sharma 2017). Site form is the expected height at reference diameter that chosen 20 cm diameter for each species in this study. The reference 20 diameter corresponds to 50 years reference age in boreal forest (Huang and Titus 1994). Forest site form model developed based on algebraic approach of Chapman-Richards models (25) that selected from the result of model selection and validation. The parameters (a, b, and c) estimated Chapman-Richards model (2) that used observed individual tree diameter and height in the stands.

$$H_{d1} = 1.3 + a * (1 - e^{(-bD_{d1})})^{c} \tag{23}$$

$$H_{d2} = 1.3 + a * (1 - e^{(-bD_{d2})})^{c} \tag{24}$$

The equation that parameter b isolated in the model (23) and (24) and expression of H_{d2} given by:

$$H_{d2} = 1.3 + a * \left[1 - \left(1 - \frac{H_{d1} - 1.3}{a}\right)^{\frac{D_{d2}}{D_{d1}}}\right]^{c} \tag{25}$$

where H_{d1} and H_{d2} ($H_{d1} < H_{d2}$) are two succeeding mean diameter of stand and the corresponding mean quadratic diameter D_{d1} and D_{d2} ($D_{d1} < D_{d2}$).

Site index is the most common measure to evaluate site quality that the expected height at reference age in even-aged forest. The reference age typically 25, 50 and 100 years, depending on the lifespan (Larsen and Hann 1987). Age and site index are not described for all sample plot in this study because age is one of most time consuming and difficult variables to measure in uneven-aged stand. Individual tree height was predicted using model 2a and diameter was calculated based on radial growth measurement. The site index equation followed Hammer's (1981 Equation II) that was of the following form:

$$H = 1.3 + (a * SI - b) * (1 - exp(-c * A)) \quad (26)$$

where H is individual tree height (m), A is breast high age (years), and SI is site index that height (m) at reference age 100. This equation was based on the several dominant and codominant trees in each of 69 sample plots. Due to that exact age described in 69 sample plots based on tree ring core measurement.

Site productivity is generally expressed by volume per unit area that one of phytocentric direct method (Vanclay 1994). Stand mean annual production based on radial growth measurements of 1181 tree sample cores that collected from 69 permanent plots. Stand productivity assessment calculated in different estimates that basal area increment (BI), mean annual increment (MAI) and biomass production (Bio). Around 90% (3521 plots) of total permanent plots contain Siberian larch forest. The long-term site productivities (BI, MAI and Bio) are expressed better by MAI (Pretzsch 2009) that production at a given time is divided by age of individual tree. MAI expressed as follow:

$$MAI = yield_n / time_n \quad (27)$$

where $yield$ – standing volume, n – given time and $time$ – total age of tree.

Total tree height predicted for each radial growth samples based on best height prediction model 2a. Above ground biomass equation established for Mongolian boreal forest (Altrell and Erdenejav 2016) that used in this calculation. Individual tree volume and biomass equations expressed as follows:

$$V = a * D^b * H^c \quad (28)$$

$$Bio = a * D^b * H^c \quad (29)$$

where V- volume, a, b and c – species specific parameters for Siberian larch (0.229067, 1.75631439 and 1.04530318). And B- above ground biomass, a, b and c – species specific parameters for Siberian larch (0.148867, 1.9992 and 0.2446, respectively) and parameters for white birch (0.11074, 1.9047 and 0.5398, respectively).

2.3.5 Model fitting and validation

The model fitting and cross-validation were used nonlinear function in R version 3.5.2. Relied on model fitting statistics and validation statistics, models that the best performance were selected for further analysis. The fits of models were evaluated using residual standard error (RSE), root mean square error (RMSE), and coefficient of determination (R^2). RSE was analyzed precision of estimates for regression in of R studio software. RMSE is a measure of accuracy of the prediction, that is the lowest may be taken to be the most accurate model supported by the data. Fits of model resulting in significance of the parameters, the largest R^2, and lowest RSE and RMSE for height-diameter relationship model selected as the best model for each species. The expressions for fitting statistics are as follow:

$$RSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-2}} \tag{30}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}} \tag{31}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y}_i)^2} \tag{32}$$

where Y_i is the observed data of the i^{th} sample, $\bar{Y}$ is the observed mean data, $\hat{Y}_i$ is the estimated data of the i^{th} sample, and n is the number of samples (H. Temesgen and v. Gadow 2004; Colbert et al 2002; Sharma and Parton 2007; Temesgen et al 2007).

Models with different number of parameters were compared by Akaike's Information Criterion (AIC), and Schwarz's Bayesian information criteria (BIC). AIC and BIC of base models were compared to corresponding expanded models with parameters. The models that provided the lowest AIC and BIC may be taken to be the most accurate model supported by the data (Fulton 1999; Sharma and Parton 2007; Duan et al. 2018).

$$AIC = C\, ln\left(\frac{RSS}{C}\right) + 2\, p \tag{33}$$

$$BIC = C\, ln\left(\frac{RSS}{C}\right) + (log\, n)\, p \tag{34}$$

where C is the number of observed data, RSS is residual sum of square, and p is the number of parameters of the model (e.g. Temesgen and v. Gadow, 2004; Temesgen, Hann and Monleon, 2007; Nugroho, 2014; and Huang *et al.*, 2009; Crecente-Campo et al. 2010).

To describe more accurate models with relationship between height-diameter of individual trees that accessed with Bias, the standard error of estimate in actual unit (Se), and the coefficient of variation (CV) in model validation.

$$Bias = \left(\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)}{n}\right) \tag{35}$$

$$S_e = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{(n-p)}} \tag{36}$$

$$CV = \left(\frac{S_e}{\bar{Y}}\right) * 100 \tag{37}$$

where Y_i is the observed data of the i^{th} sample, $\hat{Y}_i$ is the estimated data of the i^{th} sample, n is the number of samples, and and p is the number of parameters of the model (Temesgen and v. Gadow, 2004; Colbert et al 2002; Sharma and Parton 2007).

CHAPTER 3. RESULTS

3.1 Height-diameter base models

The height models, which have been developed for particular species in different areas, analyzed for seven tree species in Mongolia. Totally, 10 base models evaluated for height-diameter relationship were given in Table 2-5. The results of estimated parameters were significant at $p > 0.05$ and fit statistics (Se, RMSE, R^2, BIAS, and CV) of 10 base models are presented in Table 3-1 and 3-2 for each species. All models provided adequate performance across all species. However, several models marked bold, such as Eq 2, Eq 5, and Eq 10, which provided the highest R^2; and lowest Se, CV, RMSE, and BIAS for each species. The model 8 had the lowest fits for conifer (Table 3-1). The coefficient of R^2 varied from 0.59 (Siberian pine) to 0.72 (Siberian fir), RMSE varied from 2.59 (Siberian fir) to 3.36 (Siberian larch) and CV varied from 17.4 (Scots pine) to 24.57 (Siberian pine).

Table 3-1. Fit statistics of height-diameter relationship models with conifer species

Models	Parameters			Fitting statistics					
	a	b	c	S_e	RMSE	R^2	BIAS	CV	
Siberian larch									
1	3.387	-9.062	-0.800	3.21	3.21	0.66	0.01	21.52	*
2	**21.100**	**0.060**	**1.397**	**3.20**	**3.20**	**0.66**	**0.00**	**21.46**	*
3	3.270	-14.701		3.21	3.21	0.66	0.02	21.52	*
4	23.950	0.012	1.518	3.20	3.20	0.66	0.01	21.47	*
5	**27.545**	**-17.025**	**2.490**	**3.21**	**3.21**	**0.66**	**0.00**	**21.50**	*
6	3.316	-17.025	2.490	3.21	3.21	0.66	0.00	21.50	*
7	25.464	-13.185		3.22	3.22	0.66	0.03	21.58	*
8	2.123	0.586		3.36	3.36	0.63	-0.06	22.53	*
9	26.303	-14.701		3.21	3.21	0.66	0.02	21.52	*
10	**23.451**	**4.824**	**-1.652**	**3.20**	**3.20**	**0.66**	**0.01**	**21.46**	*
Scots pine									
1	3.419	-10.232	-0.838	2.95	2.95	0.68	0.00	17.42	*
2	**22.627**	**0.055**	**1.358**	**2.95**	**2.95**	**0.68**	**0.00**	**17.41**	*
3	3.335	-15.671		2.95	2.95	0.68	0.01	17.42	*
4	25.471	0.011	1.521	2.95	2.94	0.68	0.00	17.40	*
5	**28.883**	**-17.211**	**2.074**	**2.95**	**2.95**	**0.68**	**0.03**	**17.41**	*
6	3.363	-17.211	2.074	2.95	2.95	0.68	0.00	17.41	*
7	27.349	-14.269		2.96	2.95	0.67	0.02	17.45	*
8	2.474	0.552		3.11	3.10	0.64	-0.04	18.35	*
9	28.090	-15.671		2.95	2.95	0.68	0.01	17.42	*
10	**25.022**	**4.889**	**-1.641**	**2.95**	**2.94**	**0.68**	**0.00**	**17.40**	*
Siberian pine									
1	3.061	-13.562	-1.051	2.97	2.96	0.64	0.01	23.03	*
2	**17.010**	**0.088**	**1.863**	**2.95**	**2.95**	**0.64**	**0.01**	**22.88**	*
3	3.123	-13.791		2.97	2.97	0.64	0.00	23.04	*
4	18.540	0.007	1.844	2.95	2.95	0.64	0.01	22.92	*
5	**22.102**	**-12.559**	**0.181**	**2.97**	**2.96**	**0.64**	**0.00**	**23.03**	*

Continue Table 3-1. Fit statistics of height-diameter relationship models with conifer species

6	3.096	-12.559	0.181	2.97	2.96	0.64	0.00	23.03	*
7	21.965	-12.291		2.97	2.96	0.64	0.01	23.03	*
8	1.940	0.581		3.16	3.16	0.59	-0.06	24.57	*
9	22.722	-13.791		2.97	2.97	0.64	0.00	23.04	*
10	**18.270**	**5.489**	**-2.014**	**2.95**	**2.95**	**0.64**	**0.01**	**22.91**	*
Siberian spruce									
1	3.469	-8.595	-0.746	2.96	2.96	0.68	0.01	23.07	*
2	**20.788**	**0.065**	**1.518**	**2.95**	**2.94**	**0.68**	**0.01**	**22.97**	*
3	3.275	-15.041		2.96	2.96	0.68	0.02	23.07	*
4	23.934	0.011	1.553	2.95	2.94	0.68	0.01	22.99	*
5	**28.590**	**-18.506**	**2.947**	**2.96**	**2.95**	**0.68**	**0.00**	**23.03**	*
6	3.353	-18.506	2.947	2.96	2.95	0.68	0.00	23.03	*
7	25.356	-13.333		2.97	2.97	0.67	0.04	23.16	*
8	1.607	0.673		3.09	3.09	0.65	-0.06	24.08	*
9	26.453	-15.041		2.96	2.96	0.68	0.02	23.08	*
10	**23.282**	**4.982**	**-1.704**	**2.95**	**2.94**	**0.68**	**0.01**	**22.97**	*
Siberian fir									
1	3.895	-5.810	-0.503	2.63	2.59	0.72	0.01	18.00	*
2	**23.774**	**0.047**	**1.120**	**2.62**	**2.59**	**0.72**	**0.00**	**17.95**	*
3	3.303	-14.045		2.65	2.62	0.72	0.03	18.17	*
4	29.798	0.021	1.224	2.62	2.59	0.72	0.01	17.96	*
5	**32.463**	**-22.878**	**6.212**	**2.62**	**2.59**	**0.72**	**0.00**	**17.95**	*
6	3.480	-22.878	6.212	2.62	2.59	0.72	0.00	17.95	*
7	26.196	-12.499		2.67	2.64	0.71	0.04	18.30	*
8	1.958	0.635		2.67	2.64	0.71	-0.02	18.32	*
9	27.188	-14.045		2.65	2.62	0.72	0.03	18.17	*
10	**28.386**	**4.203**	**-1.353**	**2.62**	**2.59**	**0.72**	**0.01**	**17.95**	*

Notes: S_e = Standard error in actual unit, RMSE = Root mean square error, and CV = Coefficient of Variation. **Bold** indicates the smallest three S_e, RMSE, CV, and BIAS; and highest R^2 values. An asterisk (*) indicates significant with $p < 0.05$.

Table 3-2 displays fit statistics and predicted parameters of height fitting for broadleaved species. Model 8 had the lowest fits among these ten models for broadleaved and conifer species, among these 10 models. While the best fits of models marked bold that are model 2, 5 and 10 for broadleaved trees. The lowest RMSE and highest coefficient of R^2 reported with model 10 for white birch and aspen (2.55 and 0.74, respectively).

Table 3-1. Fit statistics of height-diameter relationship models with broadleaved species

Models	Parameters			Fitting statistics					
	a	b	c	S_e	RMSE	R^2	BIAS	CV	
White birch									
1	3.262	-8.419	-0.818	2.56	2.56	0.68	0.01	20.90	*
2	**18.188**	**0.079**	**1.545**	**2.55**	**2.55**	**0.68**	**0.00**	**20.84**	*
3	3.161	-13.006		2.56	2.56	0.68	0.01	20.89	*
4	20.690	0.014	1.591	2.56	2.55	0.68	0.00	20.84	*
5	**24.472**	**-14.460**	**1.882**	**2.56**	**2.56**	**0.68**	**0.00**	**20.88**	*
6	3.198	-14.460	1.882	2.56	2.56	0.68	0.00	20.88	*
7	22.590	-11.404		2.57	2.57	0.67	0.02	20.95	*
8	1.772	0.638		2.68	2.68	0.65	-0.04	21.86	*
9	23.591	-13.006		2.56	2.56	0.68	0.01	20.89	*
10	**20.160**	**4.824**	**-1.762**	**2.55**	**2.55**	**0.68**	**0.01**	**20.83**	*
Aspen									
1	3.518	-7.175	-0.690	2.78	2.76	0.73	0.01	20.15	*
2	**21.054**	**0.067**	**1.420**	**2.75**	**2.73**	**0.74**	**0.01**	**19.95**	*
3	3.271	-13.590		2.78	2.76	0.73	0.04	20.18	*
4	24.546	0.015	1.478	2.76	2.74	0.74	0.02	20.00	*
5	**29.059**	**-18.028**	**3.618**	**2.76**	**2.74**	**0.74**	**0.01**	**20.06**	*
6	3.369	-18.028	3.618	2.76	2.74	0.74	0.01	20.06	*
7	25.306	-11.975		2.80	2.78	0.73	0.05	20.33	*
8	1.951	0.629		2.91	2.89	0.71	-0.06	21.15	*
9	26.347	-13.590		2.78	2.76	0.73	0.04	20.18	*
10	**23.788**	**4.683**	**-1.637**	**2.75**	**2.73**	**0.74**	**0.02**	**19.97**	*

Notes: S_e = Standard error in actual unit, RMSE = Root mean square error, and CV = Coefficient of Variation. **Bold** indicates the smallest three S_e, RMSE, CV, and BIAS; and highest R^2 values. An asterisk (*) indicates significant with $p < 0.05$.

3.1.1 Backward elimination of input variables

Stand variables tested by deletion of variable and statistic index deterioration of the model fit statistics presented in Table 3-3 to 3-6. Five stand variables (BA, N, D_q, H_{sh} and H_d) have applied into selected three base models that based on fit statistics of ten base models (Table 3-1 and 3-2).

Firstly, variables deleted by statistical insignificant deterioration and an asterisk (*) recorded significant with p < 0.05. The result was insignificant for most of extended models with Siberian spruce, Siberian fir, aspen and white birch. RSE was increasing by deletion of H_d for each species. This result strongly indicated that the variable H_d is the most convenient variable with model 2 (Table 3-3).

Table 3-3. Residual standard error of variable backward elimination for model 2 for each species

Variables					Siberian larch		Siberian pine		Siberian spruce		Aspen		Scots pine		Siberian fir		White birch	
					3.20	*	**2.95**	*	**2.95**	*	**2.74**	*	**2.95**	*	**2.60**	*	**2.55**	*
BA	N	D_q	H_{sh}	H_d	2.74	*	2.22		2.50	*	2.20		2.47		2.30		2.32	
	N	D_q	H_{sh}	H_d	2.74		2.22	*	2.51		2.19		2.47	*	2.33		2.32	
BA		D_q	H_{sh}	H_d	2.74	*	2.23	*	2.51		2.20		2.47	*	2.35		2.32	
BA	N		H_{sh}	H_d	2.75	*	2.23	*	2.51		2.20		2.47	*	2.37		2.32	
BA	N	D_q		H_d	2.75	*	2.24		2.51	*	2.20		2.47	*	2.29		2.32	
$\boldsymbol{BA}$	$\boldsymbol{N}$	$\boldsymbol{D_q}$	$\boldsymbol{H_{sh}}$		**3.08**	*	**2.85**		**2.88**		**2.65**		**2.90**	*	**2.42**		**2.55**	
	N	D_q	H_{sh}	H_d	2.74		2.22	*	2.51		2.19		2.47	*	2.33		2.32	
		D_q	H_{sh}	H_d	2.74	*	2.23	*	2.51		2.23		2.47	*	2.34		2.32	
	N		H_{sh}	H_d	2.75	*	2.24		2.51		2.20		2.47		2.37		2.32	
	N	D_q		H_d	2.75	*	2.24	*	2.51		2.19		2.47	*	2.32	*	2.32	
	$\boldsymbol{N}$	$\boldsymbol{D_q}$	$\boldsymbol{H_{sh}}$		**3.11**	*	**2.86**		**2.91**	*	**2.67**		**2.91**		2.44		**2.55**	
		D_q	H_{sh}	H_d	2.74	*	2.23	*	2.51		2.23		2.47	*	2.34		2.32	
			H_{sh}	H_d	2.75	*	2.24	*	2.51		2.22		2.47	*	2.38		2.32	
		D_q		H_d	2.75	*	2.24	*	2.51		2.22		2.47	*	2.34	*	2.32	
				H_d	2.76	*	2.26	*	2.51	*	2.22		2.48	*	2.37	*	2.32	*

Notes: BA = Basal area (m^2/ha), N = Number of tree (n/ha), H_d=Dominant Height (m), D_q= Quadratic Mean Diameter (cm), H_{sh}= Shannon Index, an asterisk (*) indicates significant with $p <$ 0.05, and **Bold** indicates the highest RSE.

The result of variable backward elimination for model 5 provided negligible for most of species except Siberian larch. Model 5, deletion of H_d was increased RSE for each species. RSE were lowest in extended models with H_d for broadleaved trees are 2.25 (aspen) and 2.33 (white birch). For Siberian larch, the lowest RSE that was 2.75 for model with all variables. These results provided that application of stand variables into base model 5 wasn't improve the accuracy of model for all species (Table 3-4)

Table 3-4. Residual standard error of variable backward elimination for model 5 for each species

Variables					Siberian larch		Siberian pine		Siberian spruce		Aspen		Scots pine		Siberian fir		White birch	
					3.21	*	**2.97**		**2.96**		**2.75**	*	**2.95**	*	**2.60**	*	**2.56**	*
BA	N	D_q	H_{sh}	H_d	2.75	*	2.24		2.52		2.22		2.48		2.31		2.33	
	N	D_q	H_{sh}	H_d	2.76	*	2.24		2.53		2.22		2.48		2.33		2.33	
BA		D_q	H_{sh}	H_d	2.76	*	2.25		2.52		2.23		2.48		2.35		2.33	
BA	N		H_{sh}	H_d	2.76		2.25		2.52		2.22		2.49		2.38		2.33	
BA	N	D_q		H_d	2.76	*	2.26		2.52		2.22		2.48		2.30	*	2.33	
$\boldsymbol{BA}$	$\boldsymbol{N}$	$\boldsymbol{D_q}$	$\boldsymbol{H_{sh}}$		**3.09**	*	**2.87**		**2.89**		**2.66**		**2.90**		2.42		**2.55**	
	N	D_q	H_{sh}	H_d	2.76	*	2.24		2.53		2.22		2.48		2.33	*	2.33	
		D_q	H_{sh}	H_d	2.76	*	2.25		2.53		2.25		2.48		2.35		2.33	
	N		H_{sh}	H_d	2.76	*	2.26		2.53		2.22		2.49		2.37		2.33	
	N	D_q		H_d	2.77	*	2.26		2.53		2.22		2.48		2.33		2.33	
	$\boldsymbol{N}$	$\boldsymbol{D_q}$	$\boldsymbol{H_{sh}}$		**3.12**	*	**2.87**		**2.93**	*	**2.69**		**2.91**		2.44		**2.56**	
		D_q	H_{sh}	H_d	2.76	*	2.25		2.53		2.25		2.48		2.35		2.33	
			H_{sh}	H_d	2.76	*	2.26		2.53		2.25		2.49		2.38		2.33	
		D_q		H_d	2.77	*	2.26		2.53		2.25		2.49		2.35		2.33	
				H_d	2.77	*	2.28		2.53		2.25	*	2.49		2.38		2.33	*

Notes: BA = Basal area (m^2/ha), N = Number of tree (n/ha), H_d=Dominant Height (m), D_q= Quadratic Mean Diameter (cm), H_{sh}= Shannon Index, an asterisk (*) indicates significant with $p < 0.05$, and **Bold** indicates the highest RSE.

The extended model with only H_d performed significant and RSE were lower than base model for Aspen and white birch. RSE of extended model with D_q, H_{sh} and H_d were 2.75, 2.23, and 2.47 for Siberian larch, Siberian pine, and Scots pine, respectively, that were much lower than base model. In contrast the model 10 for Siberian spruce was provided significant and resulted low RSE (2.50) with extended model all variables. RSE of model 10 were increased by deletion of H_d for each species that same as model 2 and 5 (Table 3-5).

Table 3-5. Residual standard error of variable backward elimination for model 10 for each species

Variables					Siberian larch		Siberian pine		Siberian spruce		Aspen		Scots pine		Siberian fir		White birch	
					3.20	*	**2.95**	*	**2.95**	*	**2.74**	*	**2.95**	*	**2.60**	*	**2.55**	*
BA	N	D_q	H_{sh}	H_d	2.74	*	2.23		2.50	*	2.21		2.47		2.30		2.32	
	N	D_q	H_{sh}	H_d	2.75		2.23	*	2.51		2.20		2.47		2.33		2.32	
BA		D_q	H_{sh}	H_d	2.74	*	2.23	*	2.51		2.21		2.47		2.35		2.32	
BA	N		H_{sh}	H_d	2.75	*	2.23	*	2.51		2.21		2.48		2.38		2.32	
BA	N	D_q		H_d	2.75	*	2.24		2.51	*	2.21		2.47	*	2.30		2.32	
$\boldsymbol{BA}$	$\boldsymbol{N}$	$\boldsymbol{D_q}$	$\boldsymbol{H_{sh}}$		**3.09**	*	**2.85**		**2.88**		**2.65**		**2.90**	*	2.42		**2.54**	
	N	D_q	H_{sh}	H_d	2.75		2.23	*	2.51		2.20		2.47		2.33		2.32	
		D_q	H_{sh}	H_d	2.75	*	2.23	*	2.51		2.24		2.47	*	2.35		2.32	
	N		H_{sh}	H_d	2.75	*	2.24		2.51		2.21		2.48		2.37		2.32	
	N	D_q		H_d	2.75	*	2.24	*	2.51		2.20		2.47	*	2.32	*	2.32	
	$\boldsymbol{N}$	$\boldsymbol{D_q}$	$\boldsymbol{H_{sh}}$		**3.11**	*	**2.86**		**2.92**	*	**2.67**		**2.91**		2.44		**2.55**	
		D_q	H_{sh}	H_d	2.75	*	2.23	*	2.51		2.24		2.47	*	2.35		2.32	
			H_{sh}	H_d	2.75	*	2.24	*	2.51		2.23		2.48	*	2.38		2.32	
		D_q		H_d	2.75	*	2.24	*	2.51		2.23		2.47	*	2.34	*	2.32	
				H_d	2.76	*	2.26	*	2.51	*	2.23	*	2.48	*	2.37	*	2.32	*

Notes: BA = Basal area (m^2/ha), N = Number of tree (n/ha), H_d=Dominant Height (m), D_q= Quadratic Mean Diameter (cm), H_{sh}= Shannon Index, an asterisk (*) indicates significant with $p <$ 0.05, and **Bold** indicates the lowest RSE.

Comparation of AIC of base models and expanded models with different number of stand variables were provided in Table 3-6. AIC decreased from base model to expanded model with five stand variables. The significant and the lowest AIC resulted on expanded models for each species in three models (model 2, 5, and 10). The bold indicates the lowest AIC with significant with p < 0.05 for each species and model. The expanded models have smaller AIC than base models, which indicated improvement of model accuracy.

Table 3-6. Akaike's Information Criterion (AIC) by different number of stand variables with model 2, 5 and 10 for each species

Model	Variables	AIC						
		Larch	Cedar	Spruce	Aspen	Pine	Fir	Birch
2	BA N H_{sh} D_q H_d	**225045** *	27421	**6437** *	1845	12332	1059	43664
	N H_{sh} D_q H_d	225209	**27419** *	6447	1843	**12334** *	1063	43668
	H_{sh} D_q H_d	225567 *	27439 *	6445	1854	12337 *	1066	43683
	D_q H_d	225837 *	27510 *	6446 *	**1852** *	12378 *	**1064** *	**43683** *
	H_d	226076 *	27587 *	6445	1850	12347 *	1070 *	43681
		239942 *	30886 *	6884 *	2024 *	13299 *	1112 *	45542 *
5	BA N H_{sh} D_q H_d	**225518** *	27529	6453	1855	12358 *	1061	43776
	N H_{sh} D_q H_d	225723 *	27527	6464	1853	12361 *	1064	43784
	H_{sh} D_q H_d	226087 *	27549	6462	1864	12367 *	1067	43798
	D_q H_d	226357 *	27625	6462	1862	12372 *	1065	43799
	H_d	226660 *	27721	6461	**1860** *	**12381** *	1070	**43798** *
		240121 *	30968	6892	2028 *	13278 *	1112 *	45583 *
10	BA N H_{sh} D_q H_d	**225142** *	27430	**6438** *	1849	12335	1060	43674
	N H_{sh} D_q H_d	225319	**27429** *	6448	1847	12337	1064	43679
	H_{sh} D_q H_d	225678 *	27449 *	6446	1858	**12341** *	1067	43694
	D_q H_d	225948 *	27522 *	6447	1856	12346 *	**1065** *	43694
	H_d	226208 *	27604 *	6446 *	**1854** *	12352 *	1070 *	**43692** *
		239962 *	30901 *	6885 *	2025 *	13275 *	1112 *	45538 *

Notes: An asterisk (*) indicates significant with p < 0.05; and **Bold** indicates the lowest RSE.

These results indicated that improvement of model accuracy for model 2 and 10 for each species, while application of stand variables into base model 5 wasn't convenient. On the other hand, increase of RSE reported that H_d was the most convenient stand variable for application into parameter a of base models. The result of RSE indicated that expanded models were better than the base models. Therefore, based on the result of backward elimination, the expanded models of model 2 and 10 has chosen to evaluation of height-diameter relationship models.

3.1.2 Model validation

Expanded model formulated in Table 3-7 rely on result of model fitting statistics and backward elimination of variables. The extended models that included D_q, H_{sh} and H_d variables and based on the Chapman-Richards and Logistic models (model 2 and model 10, respectively).

Table 3-7. Selected height-diameter models with stand variables

Model	Equation	Form
2	Model 2	$H = 1.3 + a * (1 - e^{(-bD)})^c$
10	Model 10	$H = 1.3 + \left(\frac{a}{1 + e^{(b+c*\ln(D+1))}}\right)$
2a	Model 2 with H_d	$H = 1.3 + a * (1 - e^{(-bD)})^c; a = a_1 + a_2 * H_d$
10a	Model 10 with H_d	$H = 1.3 + (\frac{a}{1 + e^{(b+c*\ln(D+1))}}); a = a_1 + a_2 * H_d$
2b	Model 2 with H_d and D_q	$H = 1.3 + a * (1 - e^{(-bD)})^c; a = a_1 + a_2 * H_d + a_3 * D_q$
10b	Model 10 with H_d and D_q	$H = 1.3 + (\frac{a}{1 + e^{(b+c*\ln(D+1))}}); a = a_1 + a_2 * H_d + a_3 * D_q$
2c	Model 2 with H_d and H_{sh}	$H = 1.3 + a * \left(1 - e^{(-bD)}\right)^c; a = a_1 + a_2 * H_d + a_3 * H_{sh}$
10c	Model 10 with H_d, and H_{sh}	$H = 1.3 + (\frac{a}{1 + e^{(b+c*\ln(D+1))}}); a = a_1 + a_2 * H_d + a_3 * H_{sh}$
2d	Model 2 with H_d, D_q and H_{sh}	$H = 1.3 + a * (1 - e^{(-bD)})^c; a = a_1 + a_2 * H_d + a_3 * D_q + a_4 * H_{sh}$
10d	Model 10 with H_d, D_q and H_{sh}	$H = 1.3 + (\frac{a}{1 + e^{(b+c*\ln(D+1))}}); a = a_1 + a_2 * H_d + a_3 * D_q + a_4 * H_{sh}$

Notes: H = estimated total tree height (m), D = diameter at breast height (cm), 1.3 is a constant used to account that D is measured at 1.3 m (in height from the ground), e = e raised to the particular i^{th} power, ln = natural logarithm, a, b and c = parameters to be estimated, H_d=Dominant Height, D_q= Quadratic Mean Diameter, and H_{sh}= Shannon Index.

The expanded models provided lower RMSE and BIAS, and higher R^2 values than base models. The result from validation of model 10c (model with D_q and H_d) were performed best for Siberian larch and Siberian pine. While result of model 10a (model with H_d) reported best for Scots pine, and Siberian spruce, aspen and white birch. In contrast, validation statistic of base model 10 provided the best for Siberian fir (Table 3-8).

Table 3-8. Comparison of model validation statistics for each species

Species	RMSE									
	2	10	2a	10a	2b	10b	2c	10c	2d	10d
Siberian larch	3.173	3.157	2.737	2.735	2.734	4.727	2.731	**2.724**	4.698	4.660
Scots pine	2.962	2.949	2.492	**2.477**	2.493	5.079			4.990	
Siberian pine	2.965	2.949	2.282	2.261	2.245		2.260	**2.245**		
Siberian spruce	2.979	2.943	2.528	**2.506**						
Aspen	2.778	2.769	2.294	**2.281**						
White birch	2.560	2.553	2.324	**2.321**						
Siberian fir	2.860	**2.641**	2.872	2.961						
	R^2									
Siberian larch	0.664	0.667	0.750	0.750	0.750	0.254	0.751	**0.752**	0.263	0.275
Scots pine	0.672	0.675	0.768	**0.771**	0.768	0.036			0.070	
Siberian pine	0.638	0.642	0.786	0.790	0.793		0.790	**0.793**		
Siberian spruce	0.672	0.680	0.764	**0.768**						
Aspen	0.730	0.731	0.816	**0.818**						
White birch	0.676	0.678	0.733	**0.734**						
Siberian fir	0.662	**0.712**	0.659	0.638						
	BIAS									
Siberian larch	0.24	0.00	0.21	0.00	0.04	-2.75	0.18	**0.01**	-2.76	-2.70
Scots pine	0.06	-0.07	-0.19	**0.00**	0.10	-3.43			-3.30	
Siberian pine	0.21	0.00	-0.27	0.00	0.13		0.32	**0.02**		
Siberian spruce	-0.04	-0.04	-0.12	**0.01**						
Aspen	0.19	0.02	-0.27	**0.09**						
White birch	-0.11	0.02	-0.10	**0.05**						
Siberian fir	1.23	**0.51**	1.47	1.67						

Notes: RMSE= Root Mean Square Error; and **Bold** indicates the lowest RMSE and BIAS, and highest R^2

Height curves and corresponding residual plots were illustrated for each species in Figure 3-1 and Figure 3-2 that were best expended models in Table 3-8. The best equations contained base model 10 with H_d that illustrated height curve by changes of the H_d of stand.

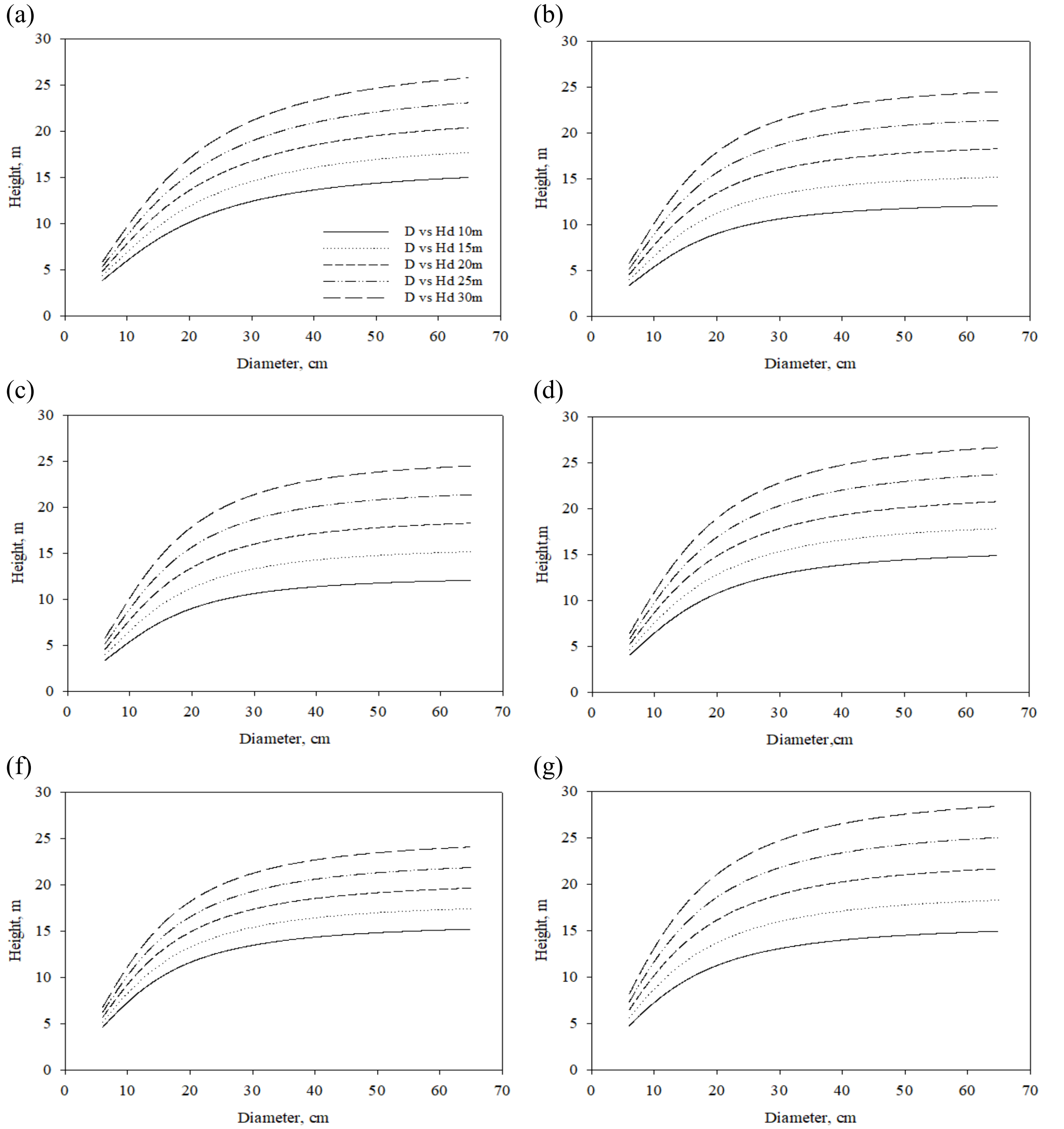

Figure 3-1. Individual height-diameter curve with different dominant height by tree species: Siberian larch (a), Scots pine (b), Siberian pine (c), Siberian spruce (d), white birch (f), and aspen (g).

Plot of the diameter versus different H_d curve (H_d=10m, 15m, 20m, 25m and 30m) that selected models from validation statistics are illustrated in Figure 3-1 by different species. The pattern indicated that accurate and strong correlation between observed and predicted height. The residual plots based on results of model validation illustrated in Figure 3-2. The residuals were scattered randomly and equally dispersed around horizontal axis, which indicated that height predictions for each species were well.

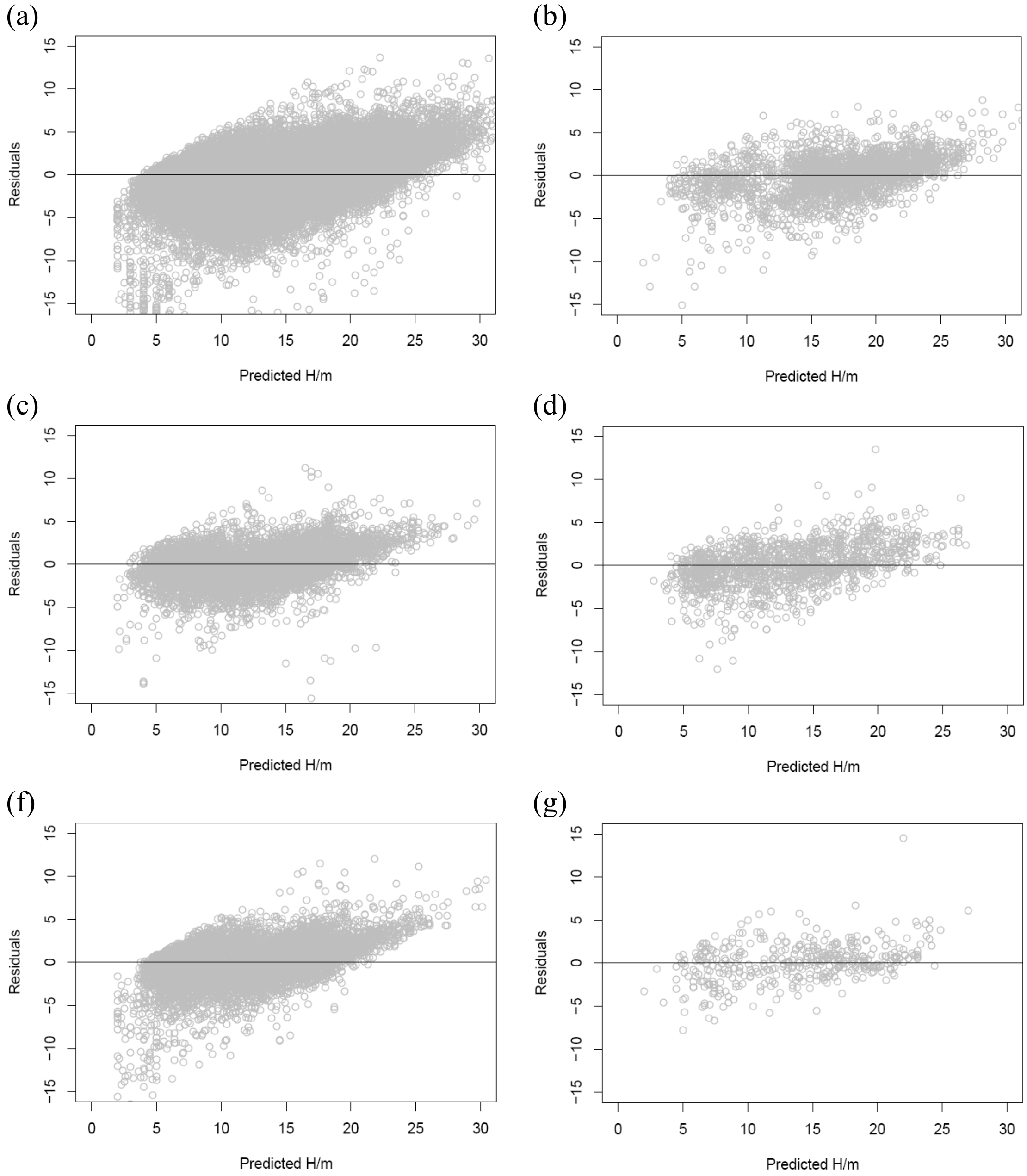

Figure 3-2. Residuals of the height prediction models for each species: model 10c for Siberian larch (a) and Siberian pine (c); model 10a for Scots pine (b), Siberian spruce (d), white birch (f) and aspen (g).

3.1.3 Comparison of base and expanded models

Fit statistics improved cross base and expanded (base with H_d) models for conifer and broadleaved species (Table 3-9 and 3-10). Decreased values of RSE, RMSE, AIC and BIC and increased values of R^2 were indicated that improvement fit statistics for each species. The decreases AIC and BIC varied from 7% (Scots pine and Siberian fir) to 40% (Siberian larch) for models with different number of parameters. On the other hand, increases of R^2

and decreases of and RMSE varied from 6% (Siberian fir) to 18% (Siberian pine), and from 8% (Siberian fir) to 23% (Siberian pine), respectively (Table 3-10). The R^2 increased 6% (white birch) and 11% (aspen), while RMSE decreased 6% (white birch) and 19% (aspen). Similarly, AIC and BIC decreased around 4% and 10 percent for white birch and aspen, respectively. Therefore, those expanded 2a and 10a models were the best for conifer and broadleaved species (Table 3-9). Predicted height versus observed height plots were constructed for base models (2 and 10) and expanded models (2a and 10a) for each species. The figure illustrated that pattern of expanded models spread closer to line than base models. Which indicated that height prediction models improved by stand H_d variable (Figure 5-1)

Table 3-9. Comparison of base and expanded height-diameter relationship models on broadleaved trees

	Model 2		Model 2a		Model 10		Model10a	
White birch								
a1	18.188	(0.172)	8.957	(0.198)	20.160	(0.275)	9.732	(0.231)
a2			0.436	(0.009)			0.469	(0.010)
b	0.079	(0.003)	0.098	(0.003)	4.824	(0.072)	4.944	(0.080)
c	1.545	(0.044)	1.688	(0.050)	-1.762	(0.036)	-1.926	(0.038)
RSE	2.55		2.32		2.55		2.32	
RMSE	2.55		2.32		2.55		2.32	
R^2	0.68		0.73		0.68		0.73	
AIC	45580.7		43681.0		45576.8		43692.3	
BIC	45609.4		43716.9		45605.5		43728.2	
Aspen								
a1	21.054	(0.906)	8.236	(0.813)	23.788	(1.544)	9.255	(0.995)
a2			0.584	(0.039)			0.649	(0.050)
b	0.067	(0.010)	0.076	(0.010)	4.683	(0.294)	4.173	(0.300)
c	1.420	(0.170)	1.259	(0.154)	-1.637	(0.148)	-1.582	(0.147)
RSE	2.74		2.22		2.74		2.23	
RMSE	2.73		2.21		2.73		2.22	
R^2	0.74		0.83		0.74		0.83	
AIC	2023.6		1849.9		2024.5		1854.0	
BIC	2039.8		1870.0		2040.6		1874.1	

Table 3-10. Comparison of base and expanded height-diameter relationship models on conifer trees

	Model 2		Model 2a		Model 10		Model10a	
Siberian larch								
a1	21.100	(0.089)	6.342	(0.125)	23.451	(0.149)	6.956	(0.140)
a2			0.619	(0.006)			0.670	(0.006)
b	0.060	(0.001)	0.075	(0.001)	4.824	(0.036)	5.171	(0.043)
c	1.397	(0.019)	1.631	(0.024)	-1.652	(0.017)	-1.851	(0.019)
RSE	3.20		2.69		3.20		2.70	
RMSE	3.20		2.69		3.20		2.70	
R^2	0.66		0.77		0.66		0.77	
AIC	239941.9		140069.8		239962.3		140186.7	
BIC	239976.8		140111.2		239997.3		140228.1	
Scots pine								
a1	22.627	(0.346)	8.003	(0.411)	25.022	(0.583)	8.659	(0.456)
a2			0.585	(0.017)			0.625	(0.019)
b	0.055	(0.003)	0.073	(0.003)	4.889	(0.156)	5.345	(0.155)
c	1.358	(0.074)	1.631	(0.083)	-1.641	(0.066)	-1.899	(0.063)
RSE	2.95		2.48		2.95		2.48	
RMSE	2.95		2.47		2.94		2.48	
R^2	0.68		0.77		0.68		0.77	
AIC	13298.8		12347.5		13295.9		12352.2	
BIC	13322.4		12376.9		13319.4		12381.6	
Siberian pine								
a1	17.010	(0.149)	4.608	(0.189)	18.270	(0.232)	4.908	(0.205)
a2			0.648	(0.010)			0.690	(0.012)
b	0.088	(0.003)	0.095	(0.003)	5.489	(0.123)	5.533	(0.102)
c	1.863	(0.078)	1.920	(0.066)	-2.014	(0.053)	-2.082	(0.044)
RSE	2.95		2.26		2.95		2.26	
RMSE	2.95		2.25		2.95		2.26	
R^2	0.64		0.79		0.64		0.79	
AIC	30886.5		27586.5		30900.8		27604.0	
BIC	30913.4		27620.2		30927.7		27637.6	
Siberian spruce								
a1	20.788	(0.617)	7.393	(0.549)	23.282	(0.977)	8.023	(0.625)
a2			0.597	(0.026)			0.648	(0.030)
b	0.065	(0.006)	0.084	(0.006)	4.982	(0.189)	5.189	(0.195)
c	1.518	(0.112)	1.710	(0.120)	-1.704	(0.092)	-1.905	(0.090)
RSE	2.95		2.51		2.95		2.51	
RMSE	2.94		2.51		2.94		2.51	
R^2	0.68		0.77		0.68		0.77	
AIC	6892.3		6445.1		6893.1		6446.1	
BIC	6913.2		6471.2		6914.0		6472.2	
Siberian fir								
a1	23.774	(2.358)	15.078	(1.538)	28.386	(4.343)	17.616	(2.427)
a2			0.361	(0.054)			0.419	(0.072)
b	0.047	(0.014)	0.056	(0.014)	4.203	(0.354)	4.144	(0.384)
c	1.120	(0.2)	1.150	(0.201)	-1.353	(0.212)	-1.417	(0.208)
RSE	2.60		2.37		2.60		2.37	
RMSE	2.59		2.35		2.59		2.35	
R^2	0.72		0.77		0.72		0.77	
AIC	1112.1		1069.5		1112.0		1069.8	
BIC	1125.9		1086.8		1125.8		1087.1	

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3.2 Height-diameter model with stand and dummy variables

Selected three stand variables (D_q, H_{sh} and H_d) relied on the result of backward elimination that applied to different parameters of model 2 (Chapman-Richards model). The result provided that significant performance with parameters a, b, and c for three species (Siberian larch, Scots pine and Siberian pine). While application of stand variables into parameters b and c resulted insignificant deterioration for other species.

3.2.1 Model fitting

Results of the fit are presented in Table 3-11 that compared different models within three tree species. Variable H_d applied to only parameter a, while other parameters applying to parameter b and c. Due to, parameter a controls asymptote height (Hanus et al 1999) result of application of H_d into parameter a was significant, lower RMSE (2.727) and higher R^2 (0.752) than H_d with parameter b and c. And most convenient for Chapman-Richards model. The lowest RMSE and the highest R^2 recorded in models, which had variable H_d with a parameter, variable D_q and H_{sh} with a, b, and c for each species.

Table 3-11. Comparison of model fitting summary statistics into a, b, and c parameters

Parameter			Siberian larch			Scots pine			Siberian pine		
a	b	c	RMSE	R^2		RMSE	R^2		RMSE	R^2	
H_d			2.727	0.752	*	2.473	0.772	*	2.254	0.791	*
D_q			3.119	0.675	*	2.911	0.683	*	2.945	0.643	*
D_q and H_{sh}			3.097	0.680	*	2.905	0.685	*	2.854	0.665	*
H_d and D_q			2.723	0.752	*	2.470	0.772	*	2.240	0.794	*
H_d, D_q and H_{sh}			**2.715**	**0.754**	*	**2.466**	**0.773**	*	**2.227**	**0.796**	*
	H_d		3.124	0.674	*	2.922	0.681	*	2.945	0.643	*
	D_q		3.107	0.678	*	2.914	0.683	*	2.889	0.657	*
H_d	D_q		2.718	0.753	*	2.461	0.774	*	2.231	0.795	*
H_d	**D_q and H_{sh}**		**2.714**	**0.754**	*	**2.457**	**0.774**	*	**2.225**	**0.796**	*
		H_d	3.134	0.672	*	2.934	0.678	*	2.945	0.643	*
		D_q	3.122	0.675	*	2.928	0.680	*	2.906	0.652	
H_d		D_q	2.720	0.753	*	2.459	0.774	*	2.233	0.795	
Hd		**Dq** and **Hsh**	**2.718**	**0.753**	*	**2.457**	**0.775**	*	**2.230**	**0.795**	*
H_d	**D_q**	**H_{sh}**	**2.716**	**0.754**	*	**2.459**	**0.774**	*	**2.227**	**0.796**	*
H_d	**H_{sh}**	**D_q**	**2.716**	**0.754**	*	**2.227**	**0.569**	*	**2.227**	**0.796**	*

Notes: H_d=Dominant Height (m); D_q= Quadratic Mean Diameter (cm); H_{sh}= Shannon Index, and RMSE= Root Mean Square Error. An asterisk (*) indicates significant with $p < 0.005$.

The categorical variables applied to model 2 that models with asymptote height (parameter a) tested in previous results. Five dummy variables were applied into base model 2 that fitted to each species. Due to speciality of data base, some species were significant with the dummy variables. Such as, Siberian larch with region, slope and aspect; Scots pine with region and slope; Siberian pine with region, age, slope and soil; Siberian spruce with region, age and slope; white birch with region and age; and aspen with region and slope variables. In contrast, Siberian fir was insignificant with all dummy variables due to that Siberian fir recorded just few plots in forested area.

Comparison of fitting and validation statistics represented by different dummy variables in Table 3-13 to 3-17. Height-diameter model with region variable predicted with all species except Siberian fir because most of plots recorded in Khentii region and several plots in Khuvsgul region. The RMSE of model validation varied from 2.54 (white birch) to 3.1 (Siberian larch) and the R^2 of model validation varied from 0.65 (Siberian pine) to 0.74 (aspen) (Table 3-13). Age class variable applied to height prediction model for Siberian pine, Siberian spruce and white birch. The RMSE of model validation varied from 2.55 (white birch) to 2.94 (Siberian pine) and the R^2 of model validation varied from 0.65 (Siberian pine) to 0.69 (Siberian spruce) (Table 3-14). The slope dummy variable was insignificant with Siberian fir and white birch. The RMSE of model validation varied from 2.76 (aspen) to 3.14 (Siberian larch) and the R^2 of model validation varied from 0.65 (Siberian pine) to 0.73 (aspen) (Table 3-15). The aspect and soil dummy variables were significant with only Siberian larch and Siberian pine, respectively (Table 3-16 and 3-17). Decrease values of RMSE and increase values of R^2 were indicated that improvement fit statistics for each variable. The decreases of RMSE were 1.2% with region and age variable, and 2% with slope variable

3.2.2 Model validation

The statistical analysis of model validation resulted that variable H_d with parameter a (asymptote) and variables D_q and H_{sh} with parameters b (rate) and c (shape), and a were applied into Chapman-Richards model (2) for Siberian larch, Scots pine, and Siberian pine, respectively (Table 3-12). Statistic indexes indicated that variable H_d with parameter a, and variable D_q and H_{sh} with parameter b were the best for Siberian larch, variable H_d with parameter a and variable D_q and H_{sh} with parameter c were the best for Scots pine, and variable H_d with parameter a and variable D_q and H_{sh} with parameter a were more accurate than other variants.

Table 3-12. Summary statistics of application of variables into a, b, and c parameters

Parameters a	b	c	Se	CV	BIAS	RMSE	R2
Siberian larch							
H_d, D_q and H_{sh}			2.824	18.962	-0.698	2.826	0.733
$\boldsymbol{H_d}$	**$\boldsymbol{D_q}$ and $\boldsymbol{H_{sh}}$**		**2.715**	**18.232**	**0.008**	**2.717**	**0.754**
H_d		D_q and H_{sh}	2.719	18.255	0.007	2.720	0.753
H_d	D_q	H_{sh}	2.717	18.244	0.008	2.719	0.753
H_d	H_{sh}	D_q	2.717	18.242	0.007	2.718	0.753
Scots pine							
H_d, D_q and H_{sh}			0.590	3.486	-0.001	2.470	0.772
H_d	D_q and H_{sh}		0.627	3.703	-0.040	2.624	0.743
$\boldsymbol{H_d}$		**$\boldsymbol{D_q}$ and $\boldsymbol{H_{sh}}$**	**0.588**	**3.470**	**0.000**	**2.459**	**0.774**
H_d	D_q	H_{sh}	0.646	3.812	0.006	2.702	0.727
H_d	H_{sh}	D_q	0.602	3.555	0.019	2.520	0.763
Siberian pine							
$\boldsymbol{H_d}$, $\boldsymbol{D_q}$ and $\boldsymbol{H_{sh}}$			**0.813**	**6.315**	**-0.001**	**2.230**	**0.795**
H_d	D_q and H_{sh}		0.816	6.334	0.001	2.237	0.794
H_d		D_q and H_{sh}	0.815	6.328	0.002	2.235	0.795
H_d	D_q	H_{sh}	0.817	6.342	0.000	2.239	0.794
H_d	H_{sh}	D_q	0.835	6.485	-0.033	2.290	0.784

Notes: S_e = Standard error in actual unit; RMSE= Root Mean Square Error; CV = Coefficient of Variation; H_d=Dominant Height (m); D_q= Quadratic Mean Diameter (cm); and H_{sh}= Shannon Index.

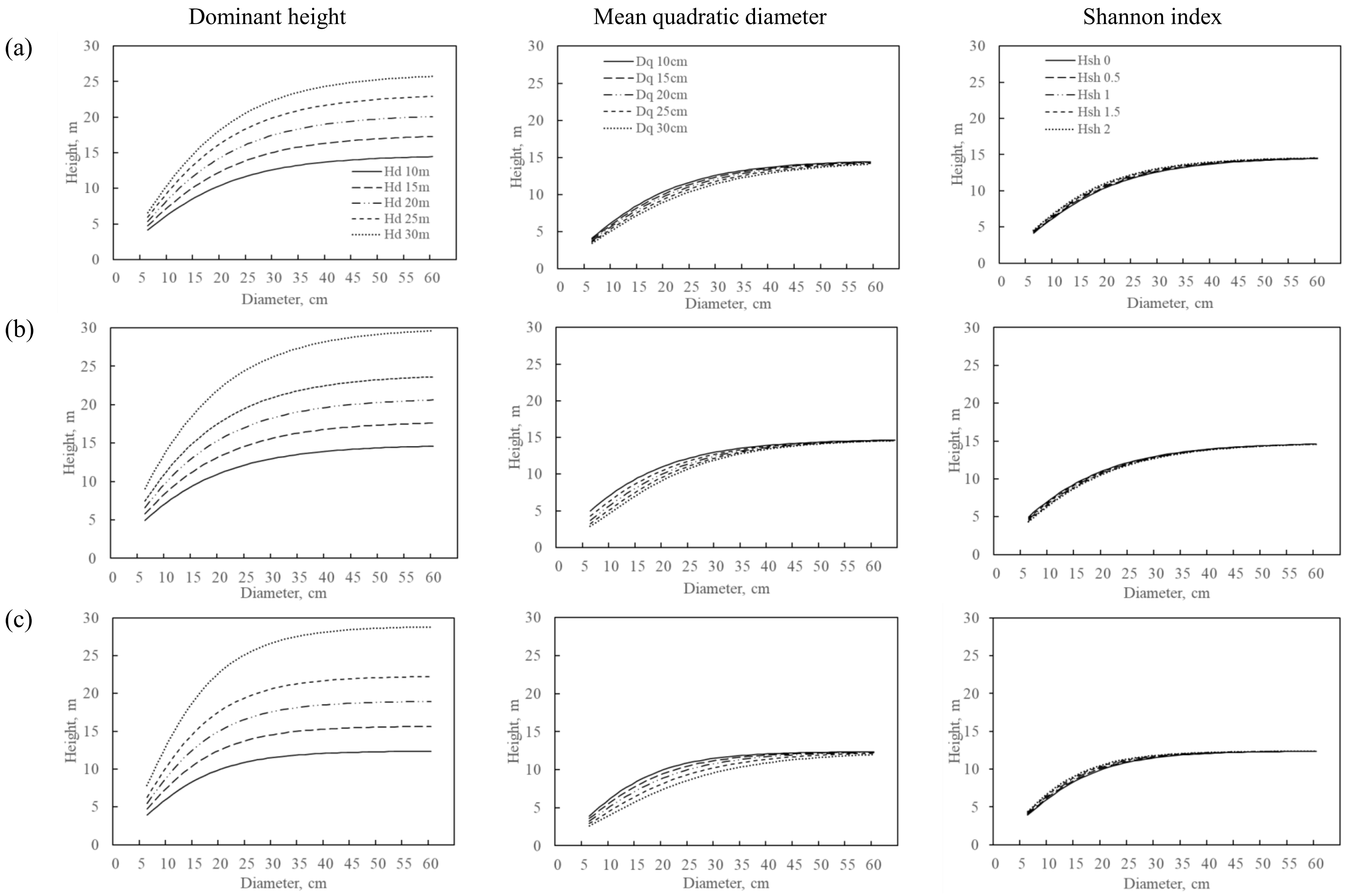

Figure 3-3. Height-diameter curve by different stand variables with Siberian larch (a), Scots pine (b), and Siberian pine (c)..

The difference between stand variables examined by changes of one variable in expanded best models of each species in Figure 3-3. That was defined as, if H_d is changing, others D_q and H_{sh} fixed; if D_q is changing, others H_d and H_{sh} fixed; and if H_{sh} is changing, others D_q and H_d fixed. Changes of H_d revealed that different H_d of stand is more effective with height-diameter relationship model than stand D_q and H_{sh}.

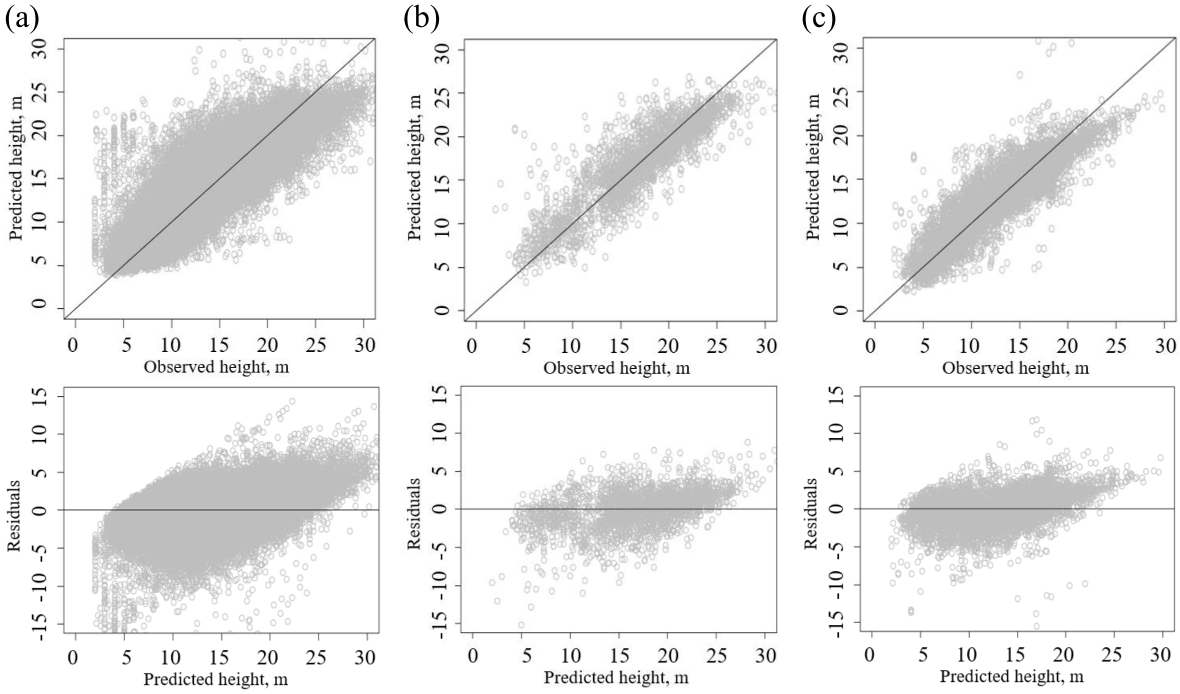

Figure 3-4. Observed vs predicted values and corresponding residuals in the cross-validation of height prediction model 2 for Siberian larch (a), Scots pine (b), and Siberian pine (c).

Comparison of height curve illustrated that dominant height was more accurate and improving height-diameter relationship model than mean quadratic diameter and Shannon index. Plot of the observed heights versus predicted heights were illustrated in Figure 3-4, that the best models selected from validation (Table 3-12). The pattern illustrated dispersion around horizontal axis that indicated well correlation between observed and predicted height. The residuals were dispersed around horizontal axis, which indicated that height predictions were well.

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Table 3-13. Summary statistics of fitting and validation with Region variable

Species	Parameters							Fitting statistics				Validation statistics		
	a1	a2	a3	a4	a5	b	c	RMSE	R2	RSE		RMSE	R2	BIAS
Siberian larch	18.6	1.668	1.723	2.687	2.872	0.0622	1.417	3.11	0.68	3.11	*	3.10	0.68	0.0039
Scots pine	20.4309	2.33689	2.22178			0.05552	1.36403	2.93	0.68	2.93	*	2.93	0.68	-0.0001
Siberian pine	15.6297	1.04225	2.07554			0.086	1.81223	2.90	0.65	2.90	*	2.90	0.65	0.0007
Siberian spruce	21.5644	-1.469	-0.7997			0.06547	1.51194	2.92	0.68	2.93	*	2.93	0.68	0.0001
White birch	18.2609	-7.8357	-2.5603	-0.1766		0.07966	1.54682	2.54	0.68	2.54	*	2.54	0.68	0.0009
Aspen	18.998	2.28353				0.06709	1.36853	2.68	0.75	2.69	*	2.71	0.74	0.00003

Table 3-14.Summary statistics of fitting and validation with Age class variable

Species	Parameters							Fitting statistics				Validation statistics		
	a1	a2	a3	a4	a5	b	c	RMSE	R2	RSE		RMSE	R2	BIAS
Siberian pine	14.7341	1.39474	2.11328	2.06536		0.09158	1.68596	2.93	0.65	2.93	*	2.94	0.65	0.0005
Siberian spruce	20.8724	-4.3998	-4.1262	-3.1492	-2.1747	0.08515	1.6398	2.90	0.69	2.91	*	2.92	0.69	0.0001
White birch	18.7854	-2.6588	-1.882	-1.0461	-0.8345	0.08168	1.46304	2.54	0.68	2.54	*	2.55	0.68	0.0008

Table 3-15.Summary statistics of fitting and validation with Slope variable

Species	Parameters						Fitting statistics				Validation statistics		
	a1	a2	a3	a4	b	c	RMSE	R2	RSE		RMSE	R2	BIAS
Siberian larch	19.49	1.278	1.54	1.646	0.06216	1.422	3.15	0.67	3.15	*	3.14	0.67	0.00151
Scots pine	21.8529	1.03452	0.88219		0.05536	1.36302	2.94	0.68	2.94	*	2.94	0.68	-0.00003
Siberian pine	16.3664	0.84846	1.27442		0.0872	1.84791	2.92	0.65	2.93	*	2.93	0.65	0.00088
Siberian spruce	18.6786	2.12953	1.69387	2.64338	0.06536	1.52505	2.93	0.68	2.93	*	2.94	0.68	0.00010
Aspen	22.4764	-2.2208	-1.2816		0.06424	1.36143	2.70	0.74	2.72	*	2.76	0.73	-0.00005

Table 3-16. Summary statistics of fitting and validation with Aspect variable

Species	Parameters										Fitting statistics				Validation statistics		
	a1	a2	a3	a4	a5	a6	a7	a8	b	c	RMSE	R2	RSE		RMSE	R2	BIAS
Siberian larch	20.068	0.679	0.82	1.289	1.274	1.182	0.682	0.8744	0.062	1.424	3.15	0.67	3.15	*	3.15	0.67	0.002

Table 3-17. Summary statistics of fitting and validation with Soil variable

Species	Parameters								Fitting statistics				Validation statistics		
	a1	a2	a3	a4	a5	a6	b	c	RMSE	R2	RSE		RMSE	R2	BIAS
Siberian pine	15.4936	1.52974	1.63064	1.8026	0.78524	1.77387	0.08734	1.855244	2.93	0.65	2.93	*	2.93	0.65	0.001

Notes: RMSE= Root Mean Square Error and RSE = Residual Standard Error. An asterisk (*) indicates significant with $p < 0.005$.

3.3 Comparisons of site form, site index, and site productivity

3.3.1 Application of site form

The site form was predicted for each stand using model 25 (b parameter isolated with Chapman-Richards). Figure 3-5 illustrated that relationship between height-diameter for range of site form by classes 14 m to 20 m. The site form varied different by species that Siberian larch stand from 5.7 m to 13.6 m, Scots pine stand from 9.1 m to 16.5 m, Siberian pine stand from 6.3 m to 16.0 m, Siberian spruce stand from 9.1 m to 18.6 m, Siberian fir stand from 9.9 m to 19.3 m, white birch stand from 12.4 m to 19.4 m, and aspen stand from 9.1 m to 18.6 m at 20 cm diameter. For comparison between different species, height at 50 cm diameter were highest with Siberian larch and Scots pine. However, the height at 20 cm diameter of these species were lower than other conifer and broadleaved trees.

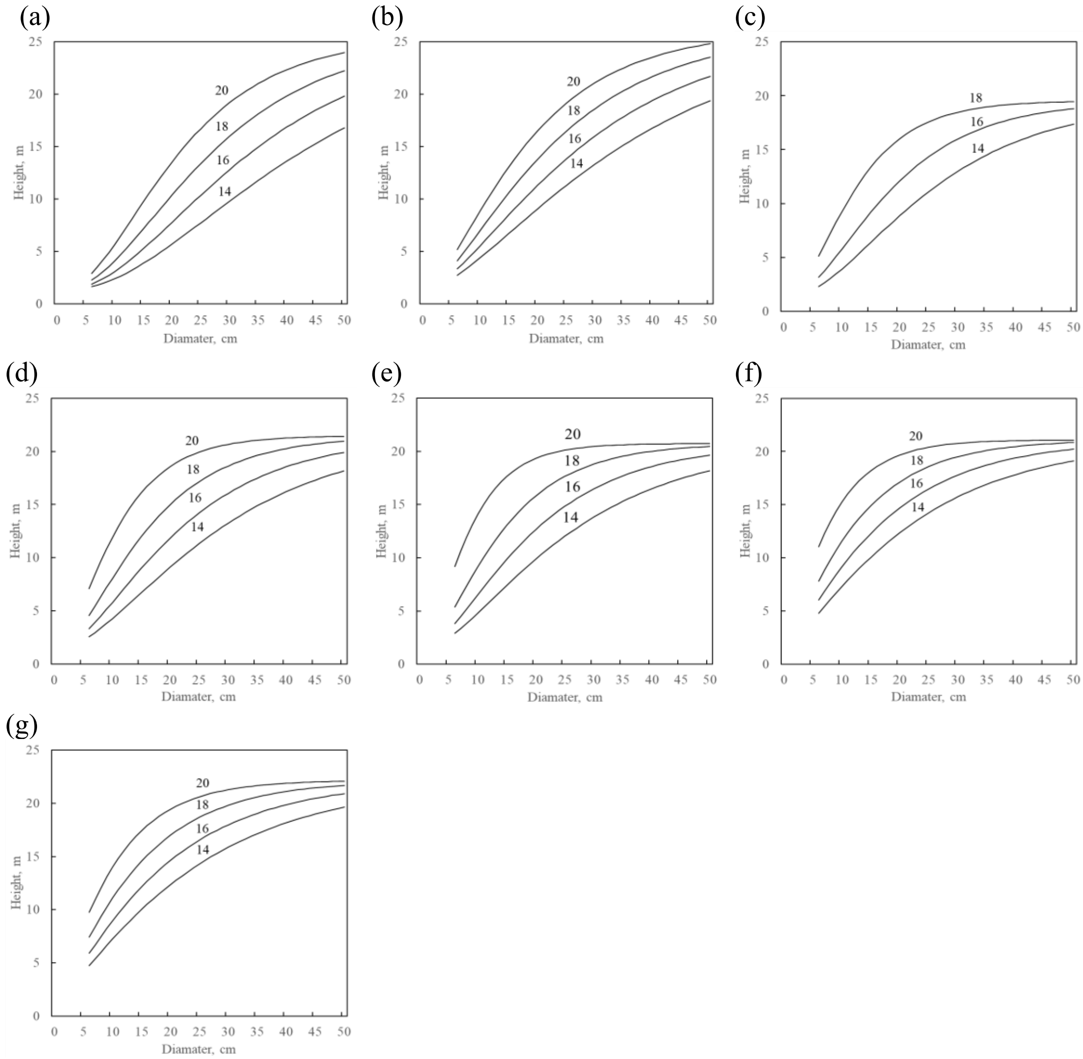


Figure 3-5. Site form curves for Siberian larch (a), Scots pine (b), Siberian pine (c), Siberian spruce (d), Siberian fir (e), White birch (f), and Aspen (g).

The fit statistics presented that MSE varied from 9.29 (Scots pine) to 16.29 (Siberian larch), RSE varied from 3.05 (Scots pine) to 4.04 (Siberian larch) and R^2n varied from 0.19 (Siberian larch) to 0.65 (aspen) (Table 3-18).

Table 3-18. Coefficients for site form prediction

Species	Value				MSE	RSE	R^2	
	a		c					
Siberian larch	24.21253	0.399	2.63699	0.074	16.29	4.04	0.19	*
Scots pine	24.7616	0.538	1.73331	0.053	9.29	3.05	0.55	*
Siberian pine	18.2437	0.336	2.4271	0.148	14.78	3.84	0.48	*
Siberian spruce	20.1732	0.804	2.0508	0.192	11.25	3.35	0.59	*
Siberian fir	19.4355	1.805	1.9253	0.473	11.73	3.42	0.56	*
White birch	19.79107	0.347	1.30949	0.026	9.36	3.06	0.56	*
Aspen	20.86223	1.442	1.27955	0.086	12.31	3.51	0.65	*

The site form was predicted by different regions that showed different pattern within species (Table 3-19). And height at 50 cm diameter of Siberian larch (a) in Altai and Khangai region and Siberian pine (c) in Khangai and Khuvsgul region were lower than other regions. However, the height of the broadleaved species (f and g) were quite similar in all regions (Figure 5-2).

Table 3-19. Site form by region

Species	Region 1		Region 2		Region 3		Region 4		Region 5	
Siberian larch										
a	18.825	(0.428)	19.393	(0.477)	21.332	(0.117)	23.695	(1.027)	23.079	(1.300)
b	0.049	(0.004)	0.058	(0.005)	0.064	(0.001)	0.048	(0.008)	0.043	(0.008)
c	1.129	(0.066)	1.230	(0.083)	1.490	(0.028)	1.331	(0.197)	1.117	(0.123)
Hm	11.6		12.8		14.3		14.4		13.1	
RSE	3.103		3.148		3.169		3.270		3.162	
Siberian pine										
a	21.658	(5.023)	15.827	(0.425)	15.968	(0.195)	18.577	(0.287)	21.659	(4.772)
b	0.039	(0.021)	0.081	(0.008)	0.108	(0.006)	0.069	(0.004)	0.033	(0.019)
c	1.305	(0.360)	1.719	(0.183)	2.368	(0.178)	1.469	(0.080)	1.000	(0.246)
Hm	11.2		11.2		13.3		13.4		9.2	
RSE	1.210		2.345		3.297		2.635		2.596	
White birch										
a			17.823	(2.718)	16.579	(0.157)	20.903	(0.422)	17.799	(1.839)
b			0.064	(0.025)	0.110	(0.004)	0.053	(0.003)	0.057	(0.019)
c			1.482	(0.379)	2.094	(0.091)	1.192	(0.044)	1.142	(0.238)
Hm			9.6		12.9		10.8		11.9	
RSE			2.782		2.622		2.364		2.652	
Aspen										
a					27.104	(5.612)	20.764	(0.921)	13.712	(1.137)
b					0.036	(0.017)	0.072	(0.013)	0.148	(0.071)
c					1.134	(0.206)	1.403	(0.223)	2.507	(1.761)
Hm					10.7		13.7		12.9	
RSE					2.179		2.746		2.032	

3.3.2 Applications of site index

Site index was defined as height (m) of dominant and co-dominant trees at age 100 years in this study. The model fitting was significant with Siberian larch forest. The RSE, RMSE and R^2 resulted 3.17, 3.16 and 0.8, respectively Table 3-20.

Table 3-20. Summary statistics of model fitting

Parameters				RSE	RMSE	R^2
a	1.047663	(0.105)	*	3.17	3.16	0.80
b	-3.26869	(0.970)	*			
c	0.0136	(0.001)	*			

Notes: An asterisk (*) indicates significant with $p < 0.005$.

The site index curve was fitted Siberian larch forest using Hammer's model (model 26). Figure 3-6 illustrated that relationship between height-age for range of site index by classes 20 m to 26 m for Siberian larch stand.

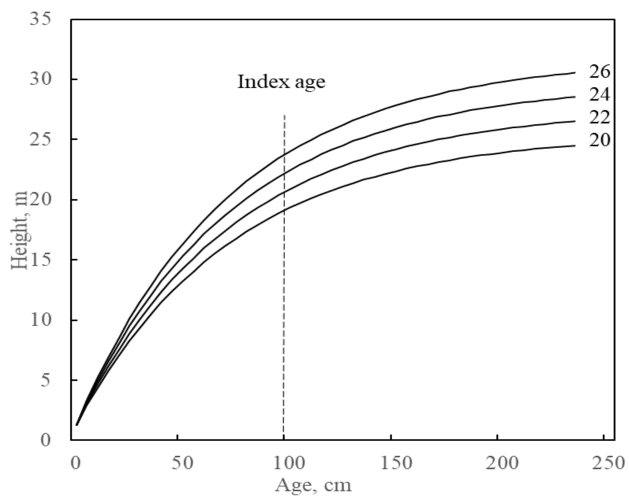


Figure 3-6. Site index curve of Siberian larch forest

3.3.3 Applications of site productivity

Mean annual productivity results based on radial growth measurements of 1181 cores from 69 permanent plots. Stand productivity assessment resulted in different estimates that basal area increment (m^2/ha/year), MAI (m^3/ha/year) and biomass production (kg/ha/year) by comparison of pure and mixed Siberian larch stand (Table 3-21). Pure forest distribution that 92% and 90% of permanent plots were pure stand in Altai and Khangai regions, respectively. The highest basal area increment (0.530 m^2/ha/year), MAI (2.885 m^3/ha/year) and biomass production (1810.0 kg/ha/year) resulted in mixed forest of Khentii and Khuvsgul regions. In contrast, the lowest mean annual productivities resulted in pure stand of Khangai and Khentii regions.

Table 3-21. Mean annual productivity by mountain regions in pure and mixed Siberian larch forest

	Pure				Mixed			
BAI, m^2/ha/year								
Region	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Altai	0.378	0.467	0.099	1.304	0.0	0.0	0.0	0.0
Khangai	0.308	0.117	0.161	0.461	0.0	0.0	0.0	0.0
Khuvsgul	0.340	0.194	0.114	0.888	0.530	0.329	0.043	0.995
Khentii	0.309	0.243	0.022	0.799	0.496	0.204	0.230	0.795
MAI, m^3/ha/year								
Region	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Altai	2.289	2.667	0.451	7.418	0.0	0.0	0.0	0.0
Khangai	2.027	0.882	1.060	3.604	0.0	0.0	0.0	0.0
Khuvsgul	2.034	1.232	0.450	4.869	2.592	1.781	0.317	5.255
Khentii	1.949	1.501	0.172	5.379	2.885	1.678	0.847	5.426
Biomass production, kg/ha/year								
Region	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Altai	1327.5	1589.0	333.8	4450.2	0.0	0.0	0.0	0.0
Khangai	1123.5	420.7	596.7	1648.2	0.0	0.0	0.0	0.0
Khuvsgul	1208.9	673.4	386.9	2997.9	1810.0	1109.9	163.8	3116.2
Khentii	1116.0	868.2	85.6	2920.4	1754.9	786.6	721.1	2917.8

Frequency of BAI and MAI illustrated by different species structure of Siberian larch forest. The highest frequency of BAI was 0.3 m^2/ha/year and 0.6 m^2/ha/year in pure and mixed stand, respectively (Figure 3-1a). In contrast, the highest frequency of MAI was 3 m^3/ha/year and 2 m^3/ha/year in pure and mixed stand respectively (Figure 3-1b).

(a) (b)

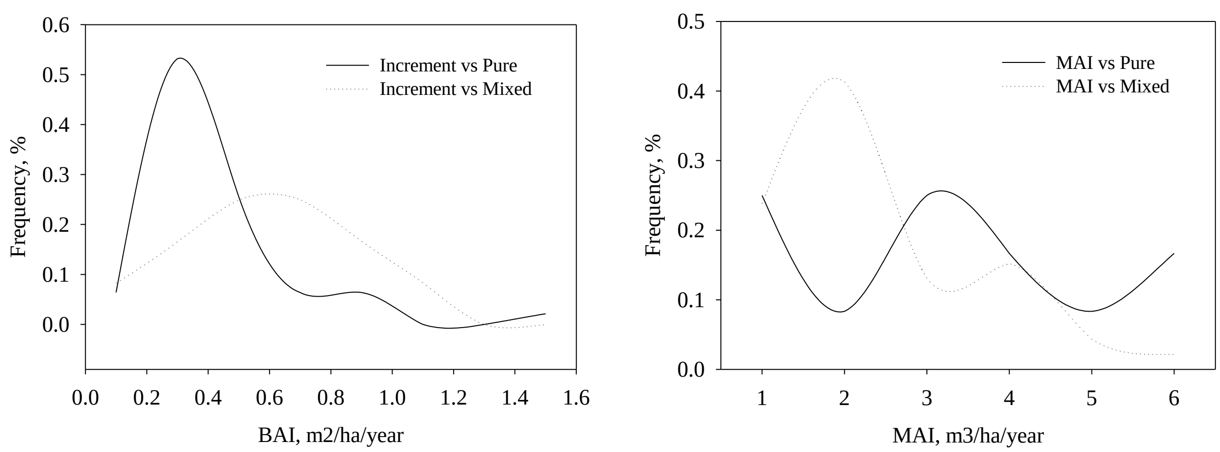


Figure 3-1. Mean annual basal area increment in pure and mixed Siberian larch forest

The mean annual productivities compared by different densities pure and mixed stand (Table 3-22). The basal area increment varied from 0.421 m^2/ha/year (pure stand) to 0.580 m^2/ha/year (mixed stand), MAI varied from 2.801 m^3/ha/year (pure stand) to 3.509 m^3/ha/year (mixed stand) and biomass production varied from 1526.7 kg/ha/year (pure stand) to 2081.2 kg/ha/year (mixed stand) in forest that density 500 to 1000 stem/ha. These results indicated that the highest mean annual productivity resulted in mixed medium density (500 to 1000 stem/ha) forest.

Table 3-22. Mean annual productivity by density in pure and mixed Siberian larch forest

	Pure				Mixed			
BAI, m^2/ha/year								
Density	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
<500	0.296	0.242	0.077	1.304	0.549	0.401	0.220	0.995
500-1000	0.421	0.223	0.184	0.888	0.580	0.148	0.425	0.805
>1000	0.430	0.237	0.398	0.461	0.411	0.339	0.043	0.795
MAI, m^3/ha/year								
Density	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
<500	1.769	1.379	0.226	7.418	1.790	1.056	0.656	2.748
500-1000	2.801	1.474	0.744	5.379	3.509	1.213	2.229	5.255
>1000	2.267	1.219	2.116	2.418	2.415	2.335	0.317	5.426
Biomass production, kg/ha/year								
Density	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
<500	1054.3	829.5	236.3	4450.2	1746.5	1244.0	686.7	3116.2
500-1000	1526.7	784.8	636.7	2997.9	2081.2	558.7	1532.8	2933.0
>1000	1470.2	806.6	1363.2	1577.3	1449.9	1243.5	163.8	2917.8

On the other hand, mean annual productivity differenced by soil texture (Table 3-23). The basal area increment varied from 0.277 m^2/ha/year (pure stand) to 0.865 m^2/ha/year (mixed stand), MAI varied from 1.981 m^3/ha/year (pure stand) to 4.476 m^3/ha/year (mixed stand) and biomass production varied from 1040.5 kg/ha/year (pure stand) to 2989 kg/ha/year (mixed stand) in forest that grows loamy sand soil. These results indicated the highest mean annual productivity resulted in mixed forest that grows loamy sand soil.

Table 3-23. Mean annual productivity by soil texture in pure and mixed Siberian larch forest

	Pure				Mixed			
BAI, m^2/ha/year								
Soil texture	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Loamy sand	0.277	0.124	0.118	0.463	0.865	0.113	0.795	0.995
Sandy loam	0.386	0.235	0.161	0.888	0.0	0.0	0.0	0.0
Loam	0.312	0.279	0.022	1.304	0.400	0.196	0.043	0.639
Clay loam	0.215	0.090	0.102	0.297	0.0	0.0	0.0	0.0
MAI, m^3/ha/year								
Soil texture	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Loamy sand	1.981	1.092	0.450	3.402	4.476	1.500	2.748	5.426
Sandy loam	2.355	1.439	0.744	5.379	0.0	0.0	0.0	0.0
Loam	1.865	1.664	0.172	7.418	2.127	1.306	0.317	4.135
Clay loam	1.465	0.556	0.715	1.974	0.0	0.0	0.0	0.0
Biomass production, kg/ha/year								
Soil texture	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Loamy sand	1040.5	485.3	386.9	1733.5	2989.0	110.4	2917.8	3116.2
Sandy loam	1380.8	819.0	589.7	2997.9	0.0	0.0	0.0	0.0
Loam	1103.1	959.4	85.6	4450.2	1386.4	713.5	163.8	2337.2
Clay loam	789.8	320.3	376.3	1082.2	0.0	0.0	0.0	0.0

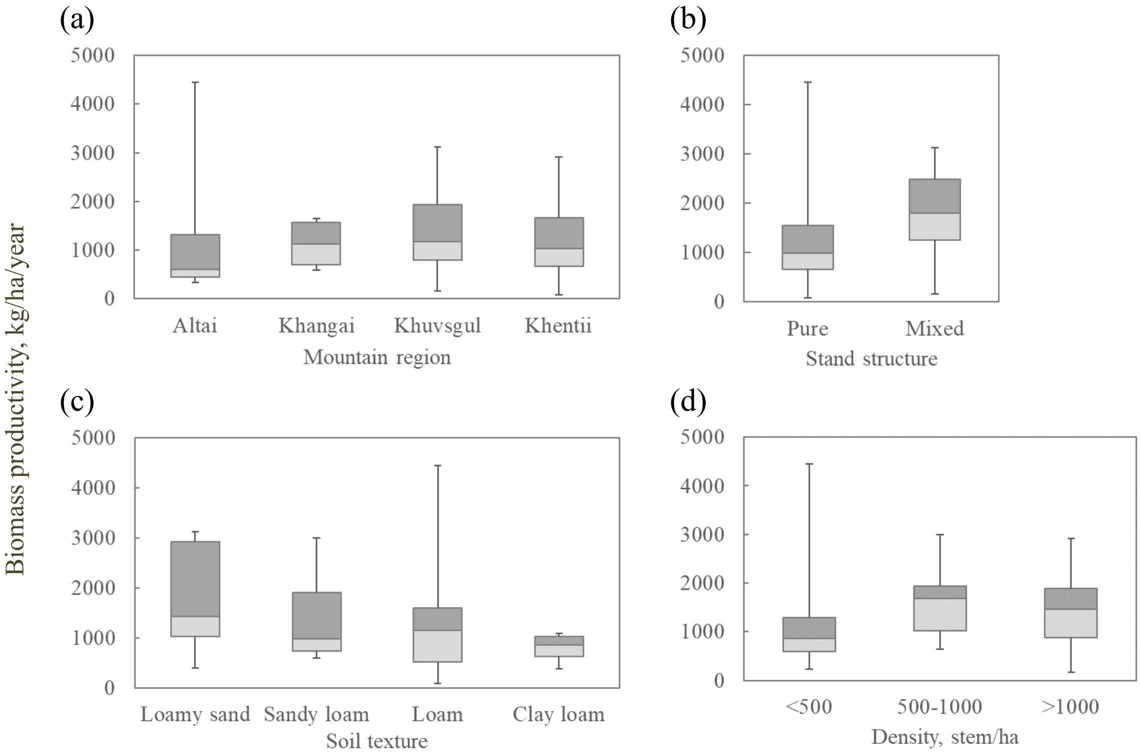


Figure 3-2. Mean annual biomass productivity in Siberian larch forest

Comparison of mean annual biomass production of Siberian larch forest are illustrated in Figure 3-2. In this case, regional differences of mean annual biomass production illustrated by four mountain regions (Figure 3-2a). The biomass productivity was highest in

Khuvsgul region and lowest in Altai region. The differences of biomass productivity in pure and mixed larch stand provided that the pure larch stand was lower productivity than mixed stand (Figure 3-2b). On the other hand, annual biomass production varied by different soil textures such as loamy sand, sandy loam, loam and clay loam. Forest biomass production was varied the highest in loam sand. In contrast, mean biomass production in loam sand was lower than loamy sand soil (Figure 3-2c). Similarly, mean productivity of sparse stand was the lowest but, varied the highest. The mean biomass productivity was the highest in medium dense stand (500 to 1000 stem/ha) (Figure 3-2d).

(a) (b)

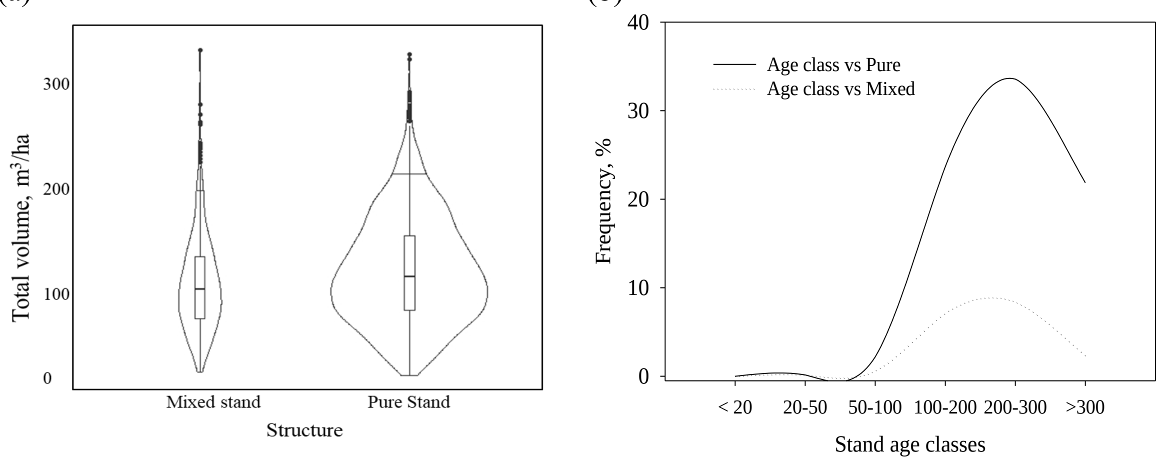


Figure 3-3. Stand total volume of pure and mixed Siberian larch forest

Stand total volume illustrated by different stand structure that varied similar volume. Otherwise, mean and 95% volume of total plots for each stand structure indicated that total volume of pure stand was higher than mixed stand (Figure 3-3a). Total volume frequency of plots illustrated by age classes. The highest frequency of total volume of mixed and pure stand were same in mature stand (100 to 200 years and 200 to 300 years) (Figure 3-3b).

The total volume in boreal Siberian larch stand varied from 11.2 m^3/ha to 146.0 m^3/ha (pure stand). Otherwise, total volume in mixed young stands (age class 20-50 and 50-100) were higher and mature stands (age class 20-50) were lower than pure stand (Table 3-24).

Table 3-24. Total volume of Siberian larch forest

Age class	Mixed				Pure			
	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
20-50	93.6	110.9	15.7	220.6	15.3	11.2	2.9	27.1
50-100	40.1	28.8	5.3	107.3	32.1	28.4	1.9	137.3
100-200	86.1	50.1	5.8	371.7	95.5	51.0	3.8	324.1
200-300	121.5	51.5	15.7	309.8	128.8	56.1	9.9	367.4
>300	128.2	53.8	22.4	298.3	146.0	62.2	10.6	361.5

Notes: SDI= Stand density index

Table 3-25 and 3-26 reveals that direct and indirect methods correlations with other measures od site productivity and site quality. The correlations between site form and current volume was the best with Siberian larch stand (0.35). This result indicated that good correlations between direct and indirect methods. The correlation between site form and dominant height were the best with each species and between site form and stand density were the lowest. While current volume was high correlated with basal area than site form.

Table 3-25. Correlations between estimates of site quality for conifer species

Measure	Siberian larch		Scots pine		Siberian pine		Siberian spruce	
	Site form	Current volume	Site form	Current volume	Site form	Current volume	Site form	Current volume
Site form	1.0	0.35	1.0	0.14	1.0	0.13	1.0	0.21
Current volume (m3/ha)	0.35	1.0	0.14	1.0	0.13	1.0	0.21	1.0
Dominant height (m)	0.43	0.48	0.74	0.18	0.69	0.12	0.77	0.23
Dominant diameter (cm)	0.93	0.32	0.94	0.16	0.89	0.15	0.94	0.18
SDI	0.30	0.72	0.05	0.72	0.05	0.74	0.11	0.72
Density (stem/ha)	0.01	0.31	-0.16	0.40	-0.04	0.39	0.00	0.35
Basal area (m2/ha)	0.31	0.94	0.08	0.95	0.09	0.94	0.15	0.92
Biomass (tn/ha)	0.33	0.98	0.12	0.99	0.13	0.98	0.20	0.96

Notes: SDI= Stand density index

Table 3-26. Correlations between estimates of site quality

Measure	Siberian fir		White birch		Aspen	
	Site form	Current volume	Site form	Current volume	Site form	Current volume
Site form	1.0	0.09	1.0	0.12	1.0	0.22
Current volume (m3/ha)	0.09	1.0	0.12	1.0	0.22	1.0
Dominant height (m)	0.75	0.24	0.75	0.14	0.80	0.24
Dominant diameter (cm)	0.93	0.05	0.95	0.10	0.97	0.20
SDI	-0.06	0.78	0.02	0.76	-0.06	0.72
Density (stem/ha)	-0.20	0.48	-0.09	0.32	-0.27	0.20
Basal area (m2/ha)	0.03	0.97	0.08	0.95	0.11	0.91
Biomass (tn/ha)	0.08	0.99	0.14	0.99	0.20	0.98

Notes: SDI= Stand density index

CHAPTER 4. DISCUSSION AND CONCLUSIONS

Systematically sampling design of multipurpose NFI are covered various stand structure of boreal forest of Mongolia. This study focused on evaluation of forest site quality in boreal forest, using different approaches that height-diameter relationship, site form, site index and site productivity. New height prediction models for commercial trees in this study were developed more accurately than model developed in the past. Site form was predicted based on height-diameter model for different forest types and different regions. And most common indirect measure that site index was defined as dominant height at age 100 years based on tree ring data. Another hand, stand productivity calculated in different estimates that basal area increment, mean annual increment, biomass production and current volume. Those measures evaluated for boreal site quality by different scales and different forest types.

4.1 Discussion

The height growth increases with increasing site quality (Sharma and S. Y. Zhang 2004), therefore site quality evaluated by height-diameter relationship models. Otherwise, accurate height-diameter relationship models are critical for forest growth and yield estimation. Ten nonlinear models were proposed as possible candidates for base nonlinear height-diameter relationship models (Table 2-5). The base models fitted to same data sets of seven commercial species that presented significant and similar fit statistics across all species (Table 3-1 and 3-2). Height-diameter models modify accurate local model with stand variables (Huang et al 2000; Kershaw et al 2008). The locally acquired height prediction models developed with stand variables such as dominant height, basal area in large trees, crown competition factor, stand density and other stand variables (Larsen and Hann, 1987; Staudhammer and LeMay, 2000; Sharma and Zhang, 2004; Temesgen and Gadow, 2004; Temesgen*et al.*,2007; and Kershaw *et al.*, 2008). The stand variables were tested in fit statistics for each species by backward elimination method. The mean quadratic diameter, Shannon index and dominant height were significant influence with height-diameter relationship model. Furthermore, the most accurate variable for new model development was dominant height (Table 3-3 to 3-5). Many studies found result that dominant height were described height prediction models was proposed. The base and expanded (with dominant height) models were compared by statistic results that provided by development locally acquired from base models (Table 3-9 to 3-10 and Figure 5-1).

Various growth and yield studies described that Chapman-Richards model were the most flexible model for empirical modelling approach (Huang and Titus 1994). In the most of height-diameter relationship modelling studies, stand variables are applied to parameter that controls asymptotic height. In this study the variables applied to asymptote, rate and shape parameters of Chapman-Richards model. Analysis of variable application resulted that dominant height was significant with only parameter a that controls asymptote height (Hanus, Marshall, and Hann 1999; Huang and Titus 1994; Sharma and Parton 2007). Otherwise, both mean quadratic diameter and Shannon index provided the best performance with different parameters for different species. The analysis resulted significant and adequate performance for different species (Table 3-12). On the other hand, geocentric measures were previously proposed with height-diameter relationship for site quality assessment (Stage 1976; Coble and Marshall 2002; Fontes et al. 2003; Stage and Salas 2007). Dummy variables have the advantage that models including variables defining the between-site variability (Magalhães 2017). Dummy variable application shows all dummy variables were not significant across all species. For example, the aspect and soil variables were significant with only Siberian larch and Siberian pine, respectively. It might be for several reasons that (1) the significance of the parameters of the models depend on range of the data, (2) Mongolian forest is mountain forest that generally grows in the north slope of mountain and south and plains and depression is in the east and the south slope, and (3) on average, pure Siberian larch forest accounted for 62.4 percent of total forest area considered, mixed conifer forest for 9.9 percent, mixed forest 9.7 percent and another forest types for less than 6 percent (Altrell and Erdenejav 2016).

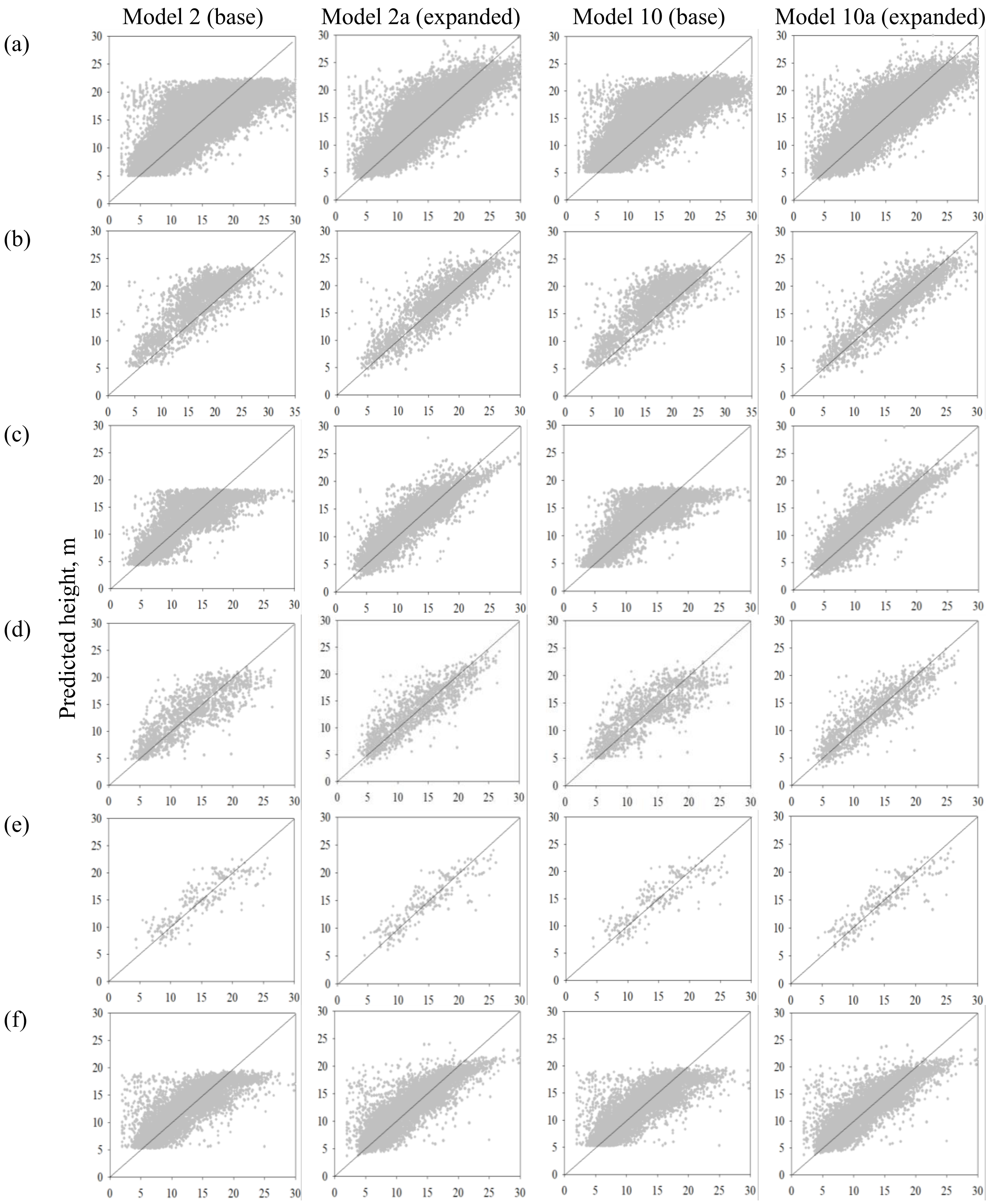
The height-diameter relationships have potential to indicate forest site quality in natural forest (Herrera et al 2004). Site form predicted in this study that relied on algebraic approach of height-diameter relationship models. The reference diameter of site form was chosen 20 cm for each species. Site form measure provides simple and reasonable index of site productivity for uneven-aged and mixed stand (Huang and Titus 1994). Figure 3-5 illustrating polymorphic form that relationship between dominant height and corresponding diameter range of site form. The site form classes are varied between 14 m to 20 m in uneven-aged different forest types. The patterns were indicating differences between species specific differences and regional differences that demonstrating site differences by growing conditions (Figure 5-2 and Table 3-19). Site index is often used as proxy for wood volume production that height is measured at known age and it is converted to yield class (Vanclay 1994). In this study, reference age chosen 100 years for Siberian larch forest based on radial growth measurements. Due to that harsh growing condition, radial growth of the Siberian larch tree quite low in boreal forest of Mongolia. The site index equation was based on the several dominant and codominant trees in 69 permanent sample plots. Site index model fitted to Siberian larch forest with significant (Table 3-20) and site index curve illustrated various height-age for range of Siberian larch stand (Figure 3-6).

Site productivity provide critical information to forecast rates of change that is necessary for forest management planning (Berrill and O'Hara 2014). Site productivity demonstrated by pure and mixed Siberian larch stand as basal area increment, mean annual increment and biomass production (Table 3-21 to 23). Due to the presence of interspecific interactions, the growth–density relationships in mixed stands will most probably be different from those generally observed in pure stands (del Río et al. 2015). The result showed that mixed forests are more productivity than pure forest. We tried to avoid site conditions and stand density effects therefore, productivities classified different regions, density classes and soil properties. Comparison of productivity illustrated basal area increment of pure stand were lower than mixed stand, contrast mean annual increment of mixed stand lower than pure stand (Figure 3-8b). The site productivity is estimated through either geocentric method, such as soil and site properties (Berrill and O'Hara 2014). Biomass productivity ranged highest in loamy sand to lowest in clay loamy soil (Figure 3-8c). And similar biomass productivity resulted in forest that density 500 to100 stems/ha and over 1000 stems/ha. Stand total volume of pure stand was higher than mixed stand (Figure 3-8d). The different species in mixed forests may show differences in growth habit, and species-specific growth rates that may impede the use of volume as a direct measure of site productivity (Vanclay 1994). Otherwise, Figure 3-9 illustrated that around 95 percent of boreal forest of Mongolia is over than 100 years and around 80 percent total forest are pure stand. The current volume stock was high in pure and mixed forest that over 200 years old (Table 3-24). The comparison of direct and indirect methods resulted good correlations with site productivity and site quality measures (Table 3-25 to 3-26).

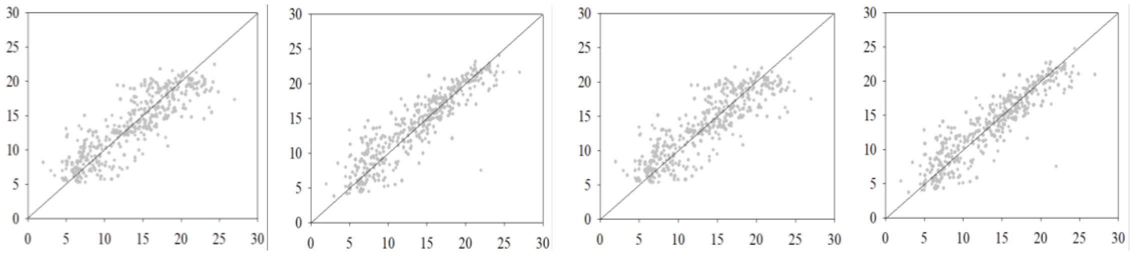
4.2 Conclusion

In this study, site quality evaluated different forest types with various stand structures of uneven-aged boreal forest. Height-diameter relationship models with stand variables are presented for five conifer and two broadleaf trees. The best predictions of height were obtained by a logistic model with stand dominant height variable. Height-diameter relationship models are essential for forest growth and yield estimation. Furthermore, site form predicted based on Chapman-Richards model for different forest types and different regions. The reference diameter of the site form was chosen 20 cm for each species. Site form measure provides simple and reasonable index of site productivity. Another hand, reference age of site index measure chosen 100 years for Siberian larch forest. The site index equation was fitted to several dominant and codominant trees of stand. Based on tree ring data from 69 permanent plots, site productivity was evaluated by calculating annual increment. The productivity resulted by different classes due to that we tried to avoid site conditions and stand density effects. According to the result, mixed Siberian larch stand are more productivity than pure stand. Another hand, comparison of productivity presented that basal area increment of pure stand was lower than mixed stand based on radial growth increment. Site form is comparable with other site productivity measures. In Siberian larch forest, site form more correlated with current volume of the stand than other species.

APPENDIX


Model 2 (base)
Model 2a (expanded)
Model 10 (base)
Model 10a (expanded)
(a)
(b)
(c)
(d)
(e)
(f)
Predicted height, m

(g)



Observed height, m

Figure 5-1. Comparison of base and expanded models by plots of observed and predicted values in cross-validation of height prediction models. Siberian larch (a), Scots pine (b), Siberian pine (c), Siberian spruce (d), Siberian fir (e), white birch (f), and aspen (g).

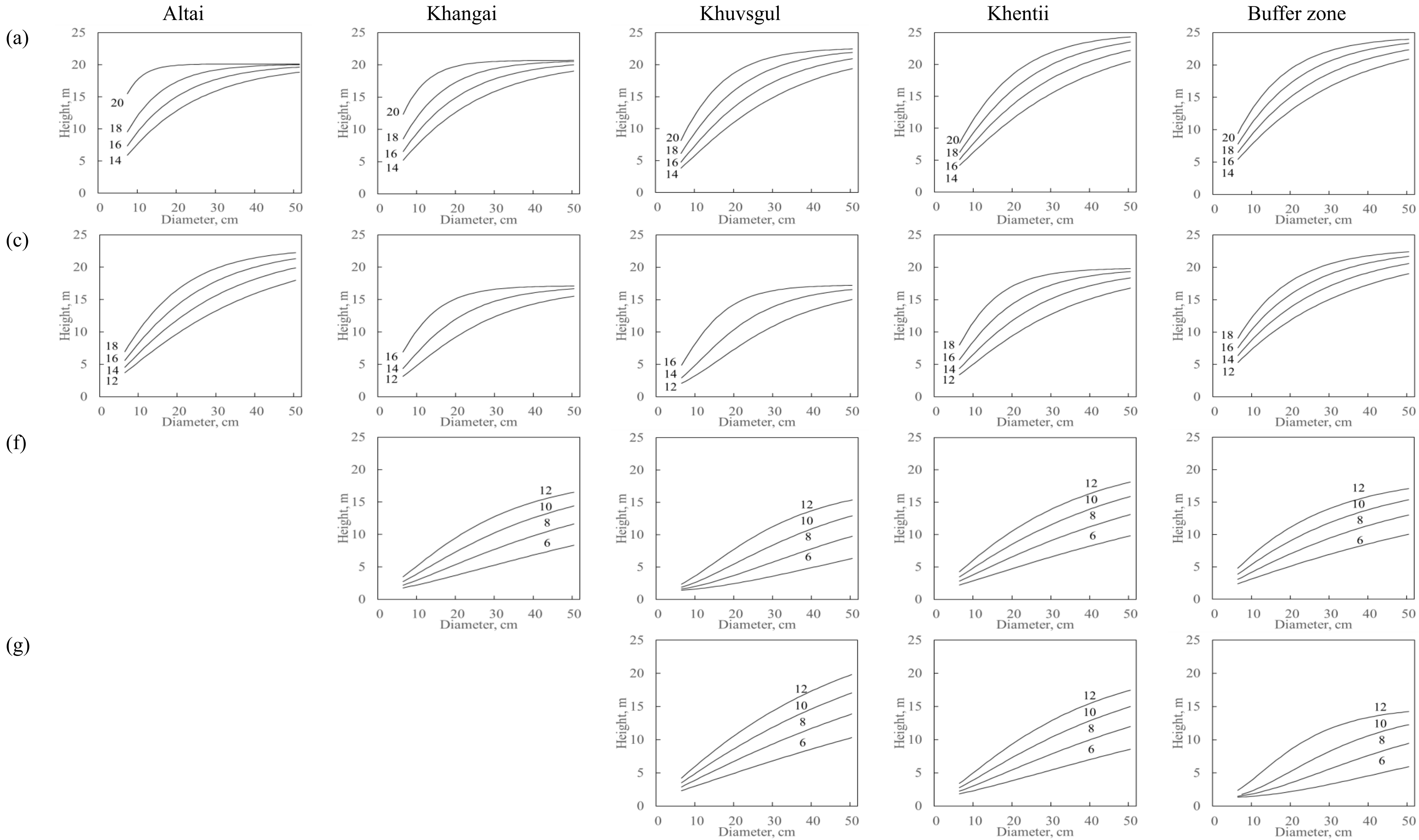


Figure 5-2. Site form by 5 regions for Siberian larch (a), Siberian pine (c), White birch (f), and Aspen (g)

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Title of qualification awarded	Master of science in forestry (Mongolia)
Research work of graduate	Carbon stock estimation of living trees and standing dead wood
dates (from - to)	2015 March 4-12
Name and type of organisation	4th Asian Dendrochronological Conference, Kathmandu, Nepal
Providing education and training	Some result of Dendro-dating Saridag Monastery, Mongolia, Poster presentation
dates (from - to)	2015 March 21
Name and type of organisation	International day of forest 2016, Ulaanbaatar, Mongolia
Providing education and training	Carbon stock estimation of living trees and standing dead wood, Poster presentation

dates (from - to)	2016 May 25-30
Name and type of organisation	German Agency for International Cooperation
Providing education and training	Forest Mask on QGIS and Rstudio.
dates (from - to)	2016 October 23-27
Name and type of organisation providing	IUFRO Regional Congress for Asia and Oceania 2016, Beijing, China
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ADDITIONAL INFORMATION

Publications

- "Carbon estimation of living and standing dead trees" in Journal of "Khurel togoot- 2015"
- "Above ground forest carbon estimation of Northern Mongolia" in Journal of "MUST"
- "Climate and radial growth of artificial forest " in Journal of "MUST"

Presentations

- "Carbon estimation of living and standing dead trees"
- "Climate and radial growth of artificial forest "
- “Forest carbon stock estimation of Mongolia case study on different forest regions”

Projects

- Multi-Purposed National Forest Inventory
- Climate and human history of Mongolian Empire

Conferences

- 4th Asian Dendrochronological Conference, Kathmandu, Nepal in 2015 March 4-12
- International day of forest 2016, Ulaanbaatar, Mongolia in 2016 March 21
- IUFRO Regional Congress for Asia and Oceania 2016, Beijing, China in 2016 October 23-27

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