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RESEARCH COMMUNICATIONS 2003

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Original article (in French): [2003]
Translated: November 2003

Published: 16 December 2003

Related SFM Network Project:
gauthiersdeve6
Development and experimentation of ecosystem management in the eastern boreal forest of Québec

This Research Communication is an authorized translation of:

Boucher D, De Grandpré L, Gauthier S.
Développement d'un outil de classification de la structure des peuplements et comparaison de deux territoires de la pessière à mousses du Québec.
The Forestry Chronicle 2003 mars/avril; 79(2): 318-328.

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Development of a statistical tool for classifying stand structure and comparison of two territories in the black spruce-moss forest region of Québec

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Forest stand structure is an important element for biodiversity and, from a sustainable forest management perspective, uneven-sized stands should be managed in order to maintain the structural diversity over the landscape. The first objective of this study is to develop a statistical tool to characterize stand structure that can be used in forest management planning. The second objective is to classify the stand structure of two regions to illustrate a possible use for the tool. The statistical tool for characterizing stand structure has been developed from forest inventory data gathered by the Ministère des Ressources naturelles du Québec (MRNQ), using discriminant analysis. The analysis makes it possible to classify the stands into three types of structure, even-sized, uneven-sized and inverse J-shaped, with an error rate estimated at only 7 per cent. Proportions of different structure types in Quebec's eastern black spruce forest region have been compared with those found in the western black spruce forest region. Nearly 90 per cent of the western black spruce forest region is composed of pure black spruce stands, contrary to the eastern black spruce region, where there are more pure fir and mixed spruce-fir stands. Most of the western black spruce forest stands are even-sized (62 per cent), while almost 70 per cent of the eastern black spruce forest stands are uneven-sized or inverse J-shaped. Pure black spruce stands are more even-sized than pure fir stands, but regional differences are also found within pure black spruce stands. Our results show that it is possible to develop a robust tool that makes it possible to classify thousands of stands rapidly. Such tools are required if we want to consider stand structure for appropriate management prescriptions in the boreal forest.

Key words: Even- and uneven-sized structure; fire regime; *Picea mariana*; *Abies balsamea*; boreal forest; structural diversity.

La structure des peuplements forestiers constitue un élément clé pour le maintien de la biodiversité, et dans une perspective d'aménagement forestier durable, les peuplements irréguliers devraient être aménagés de façon à maintenir la diversité des peuplements à l'échelle du paysage. La présente étude a pour premier objectif de développer un outil permettant de caractériser la structure des peuplements et pouvant être utilisé lors du processus de planification d'aménagements forestiers. Le deuxième objectif est de classifier la structure des peuplements de deux régions afin d'illustrer une utilisation possible de cet outil. L'outil de caractérisation de la structure a été développé à partir des données d'inventaire recueillies par le ministère des Ressources naturelles du Québec, en utilisant une analyse discriminante. L'analyse permet de classer les placettes d'inventaire parmi trois types de structure, soit la structure régulière, irrégulière et en « J » inversé, avec un taux d'erreur estimé à 7 % seulement. Les proportions des différents types de structure de la pessière de l'est ont été comparées à celles de la pessière de l'ouest. La pessière de l'ouest est composée à près de 90 % de pessières pures, contrairement à la pessière de l'est où l'on retrouve beaucoup plus de sapinières et de peuplements mélangés épinette-sapin. La majorité des peuplements de la pessière de l'ouest présente une structure régulière (62 %), alors que dans la pessière de l'est, les structures irrégulières et en « J » inversé constituent près de 70 % des peuplements. Les pessières pures sont davantage régulières que les sapinières, mais la différence de structure entre les deux régions s'observe même parmi les pessières pures. Nos résultats montrent qu'il est possible de développer un outil de classification robuste qui permet de classer rapidement des milliers de peuplements. De tels outils sont requis si l'on veut tenir compte de la structure des peuplements afin de prescrire des aménagements appropriés en forêt boréale.

Mots-clés : Structures de taille régulière et irrégulière; régime de feux; *Picea mariana*; *Abies balsamea*; forêt boréale; diversité structurale.

Introduction

In a context where sustainable forest management criteria must be met, it becomes particularly important to develop forestry practices aimed at preserving biological diversity. In the boreal forest, a number of key characteristics for maintaining biodiversity have been proposed, one of which is stand structure (Hunter 1990; Kimmins 1997; Kuuluvainen 2002). The structural complexity of uneven-sized stands appears to provide a greater variety of habitats compared to even-sized stands, thereby supporting more animal and plant species (Hansen et al. 1991; McComb et al. 1993). Several factors that may influence stand structure have been identified, but the time since the last major disturbance, such as a fire or major windthrow, is by far the factor most often cited in the literature. Stands that have undergone such a disturbance in the recent past generally have an even-sized structure, while stands whose last major disturbance occurred in the more distant past appear to exhibit a more uneven-sized structure or an inverse "J"-shaped distribution (Oliver and Larson 1996; Smith et al. 1997). Other factors recognized as influencing stand structure include secondary disturbances, such as insect outbreaks and small windthrow, which appear to promote the formation of uneven-sized structures in the prolonged absence of fires (Heinselman 1981; Hunter 1990; Fajvan and Seymour 1993). In addition, the characteristics of the physical environment (deposits, drainage, topography, relief, climate) influence stand composition and could also affect their structure or even the rate of structural change (Lindenmayer et al. 1999; Bebi et al. 2001). However, the exact role played by the physical environment on stand structure is poorly documented for the boreal forest.

At the landscape level, the various stand structure types can be expected to occur in proportions which vary from one region to another depending on the disturbance regime and environmental conditions. Since a large part of the boreal forest is characterized by a fire cycle that is shorter than the average longevity of the dominant species (Heinselman 1981), it is dominated by even-aged stands with an even-sized diameter structure (Johnson 1992; Oliver and Larson 1996). Conversely, certain regions of the boreal forest are subject to longer fire cycles, on the order of 200 years or more (Heinselman 1981; Cogbill 1985; Foster 1985). For example, the eastern boreal forest of Quebec and Labrador, characterized by a maritime climate (Grondin 1996), has a fire cycle estimated at between 300 and 500 years (Heinselman 1981; Foster 1985). Disturbances of lesser intensity appear to dominate the forest dynamics of these regions (Blais 1983; Bergeron et al. 1995; Oliver and Larson 1996; Ruel 2000) and one would therefore expect to find a significant proportion of uneven-aged stands that have developed an uneven-sized diameter structure over the years (De Grandpré et al. 2000; Bergeron et al. 2001).

Since stand heterogeneity at the landscape level is important to biodiversity, it should be taken into account in sustainable forest management (Hansen et al. 1991; Bergeron et al. 2001; Gauthier et al. 2001; Kuuluvainen 2002). Stands should be managed in such a way as to maintain their structural characteristics, in order to preserve the proportions of the various structure types in the landscape and thereby reduce the risk of biodiversity loss (Hansen et al. 1991; McComb et al. 1993; Bergeron et al. 1999; Landres et al. 1999; Harvey et al. 2002). However, the forest practices currently used in Quebec's boreal forest are essentially adapted to even-aged, even-sized forests and their systematic use throughout the boreal forest territory runs the risk of producing a uniform landscape by conferring an even-sized structure on all stands. Uniform stand structure poses a threat to biodiversity (Hunter 1990; Smith et al. 1997), hence the urgency of considering new silvicultural approaches adapted to uneven-sized forests.

In order to be able to prescribe silvicultural treatments appropriate to uneven-sized stands, we must be able to identify them within the forest territory. Stand structure is not currently considered in the forest inventories conducted by the Ministère des Ressources naturelles du Québec (MRNQ), although it was included during the first ten-year program (MTFQ 1971). At the present time, we therefore lack the tools to quickly produce a description of stand structure. In fact, characterizing stand structure would lead to a better understanding of forest dynamics and would therefore provide a basis for the development of new silvicultural strategies. It would also make it possible to more effectively identify appropriate forest management approaches, while maintaining the ecological integrity of ecosystems and facilitate regional forest management planning.

The first objective of this study is therefore to develop a simple tool for quickly and simultaneously evaluating the structure of a large number of stands that can be used by forestry companies for silvicultural management planning. The second objective is to classify the stand structure of two regions using the tool developed, in order to illustrate a possible application of this tool. For these purposes, existing data from the MRNQ's forest inventory of two contrasting (disturbance regime, climate and various physical factors) regions of Quebec, namely the eastern black spruce-moss forest region and the northern portion of the western black spruce-moss forest region (Figure 1), were used.

Methodology

Forest inventory data and regions under study

Inventory data from the second ten-year program gathered by the MRNQ between 1980 and 1988 in the eastern black spruce-moss forest region of Quebec and in the northern portion of the western black spruce forest region (Figure 1) were used for this study. The first region under study (49°00’ – 51°00’N; 65°30’ – 71°00’W), which is part of the eastern black spruce forest region, corresponds to ecological region 6j and the eastern parts of ecological regions 6h and 6i according to the ecological classification system used in Quebec (Saucier et al. 1998). This entire territory is characterized by a maritime climate in which total annual precipitation ranges from 1,000 to 1,400 mm and the average annual temperature is between -2.5 and 0.0°C (Grondin 1996). The regional relief is composed of hills, high hills and mountains, with an elevation exceeding 800 m in places, and till deposits are clearly dominant. The fire cycle in this territory is estimated at more than 300 years (Gauthier et al. 2001). The second region under study (50°05’ – 51°30’N; 70°30’ – 79°30’W), namely the northern sector of the western black spruce forest region (ecological regions 6b, 6d, 6f and 6g; Saucier et al. 1998) is on the other hand characterized by a relatively dry climate in which total annual precipitation ranges from 600 to 1,000 mm and the average annual temperature is between -2.5 and 0.0°C (Grondin 1996). The elevation does not exceed 450 m and the relief is composed of plains, plateaus and hills. The surface deposits consist of fine deposits, sandy glaciolacustrine deposits and tills. The fire cycle is estimated at between 50 and 150 years (MRNQ 2000; Gauthier et al. 2001).

Since the forest inventory is carried out for forest management purposes, it is conducted mainly in accessible stands. Stands located on slopes of more than 40 per cent are therefore not inventoried. The inventories are carried out in 400-m^2 circular plots generally located every

250 m along a 1.5-km transect, yielding five to seven plots per transect. Within each plot, the diameter at breast height (dbh) of each tree with a dbh of more than 9 cm is measured and compiled in classes of 2 cm. Trees 9 cm or less were not included in our study since they are inventoried in a 40-m^2 sub-plot located in the centre of each plot and the distribution of the saplings is quite variable in uneven-sized stands (personal observation).

Only the coniferous plots containing primarily fir (*Abies balsamea* (L.) Mill.) and/or black spruce (*Picea mariana* (Mill.) BSP) were selected for our study, i.e. those whose species group was EE, ES, SE or SS[1] according to the forest inventory system in Quebec. Plots belonging to one of these four species groups have the common characteristic of being occupied by coniferous species over 75 per cent or more of the basal area in a radius of 25 m, according to a field evaluation. The characteristics specific to each of these four species groups are as follows: 1) EE: 75 per cent or more of the basal area of the coniferous portion is occupied by black spruce; 2) ES: black spruce occupies between 50 per cent and 74 per cent of the basal area of the coniferous portion and fir is the second most important coniferous species; 3) SE: fir occupies between 50 and 74 per cent of the basal area of the coniferous portion and black spruce is the second most important species; and 4) SS: fir occupies more than 75 per cent of the basal area of the coniferous portion. The plots selected in the eastern black spruce forest region thus totalled 2,088 plots, or 85 per cent of all the plots inventoried on this territory, while the plots in the western black spruce forest region totalled 1,277 plots and represented nearly 68 per cent of the plots (MERQ 1984). Since very little harvesting was conducted in these two regions at the

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[1] Species group key:
EE = spruce stand
ES = spruce-fir stand
SE = fir-spruce stand
SS = fir stand

time the youngest stands under study (stands in the 30-year age class) were established, it is believed that virtually none of the plots analysed have previously been subject to harvesting.

Development of a statistical tool for characterizing structure

Diameter structure types

Three main diameter structure types are generally recognized: even-sized structure, with a unimodal bell-shaped distribution, "uneven-sized" structure, in which the trees belong to several diameter classes, and inverse "J"-shaped structure (Smith et al. 1997) (Figure 2). The "uneven-sized" structure properly speaking and the inverse "J"-shaped structure are considered two forms of uneven-sized structure (Smith et al. 1997). However, observation of the various forms of diameter distribution within the inventory plots proves to be somewhat limited. First of all, the area of the 400-m^2 plots limits observation of the distributions to a finer scale; bimodal distributions, for example, are difficult to detect. In addition, the absence of stems smaller than 10 cm makes it difficult to observe inverse "J"-shaped distributions. Hence, the stands that we will classify as inverse "J"-shaped are those in which 10- to 14-cm stems are clearly more abundant than the other stems. The inverse "J"-shaped distributions that it is impossible for us to identify, namely those whose most abundant stems are smaller than 10 cm, will instead be classified among the "uneven-sized" stands. Since we consider these two structure types to be two forms of uneven-sized distribution, the results associated with them may be interpreted together. Nonetheless, we opted to distinguish the uneven-sized structures from the inverse "J"-shaped structures since this distinction may be of interest from a silvicultural standpoint. We must, however, be aware, when interpreting the results, that the stands that we classify as having an inverse "J"-shaped structure are not necessarily uneven-aged stands in which mortality is equal to recruitment, as is generally suggested for this type of distribution (Hett and Loucks 1976; Lorimer 1985).

Several indices are commonly used to distinguish the various diameter distribution curves. These indices include the Shannon-Wiener diversity index, which indicates how the elements are distributed among the various dbh classes (Scherrer 1984) and which is equal to:

$$H' = -\Sigma\, p_{cl} * \ln(p_{cl})$$

where p_{cl} is the relative proportion of trees in each of the dbh classes observed; the coefficient of skewness, which is equal to:

$$\alpha_3 = \hat{}\ddagger\Sigma\,(x_i - \text{mean}^3 \ /n - 1 \ / s_x^3$$

where s_x is the standard deviation and the coefficient of variation (standard deviation*100/mean). However, combining several indices makes it possible to more effectively distinguish the various stand structure types. Discriminant analysis was chosen for these purposes since it has the advantage of combining a series of variables while finding the linear combination that best discriminates among the various groups, which is called “classification function” (Legendre and Legendre 1998).

Development of the classification functions

The statistical tool for characterizing stand structure was developed by initially using the plots of the eastern black spruce-moss forest region. Some 50 plots of each stand structure type, totalling 154 plots (48 even-sized, 52 uneven-sized and 54 inverse “J”-shaped plots), were used in calculating the classification function. These plots were first assigned to one of the three stand structure groups on the basis of a visual examination of their diameter distribution. The plots were chosen because they presented distributions whose stand structure type was clear and unambiguous.

A series of variables capable of describing the curves of the three different stand structure types, including the Shannon-Wiener index and the coefficients of skewness and of variation, were calculated based on the inventory data from each of the 154 plots. The list of the variables calculated is presented in Appendix 1. First, a stepwise discriminant analysis, using the STEPDISC procedure (SAS Institute Inc. 1999), was performed in order to identify the variables capable of significantly discriminating the three stand structure types. The five most discriminating variables were then used to calculate the classification functions, using the DISCRIM procedure (SAS Institute Inc. 1999). Variance analysis (PROC GLM; SAS Institute Inc. 1999) was performed to compare the means of the five variables selected among the three stand structure types. The objective was to illustrate the discriminating power of these five variables.

The classification functions calculated on the basis of the 154 typical plots can then be used to classify any other plot among the various stand structure types. The analysis itself estimates an error rate associated with the classification functions. In addition to this error rate, we performed a validation test in order to verify the reliability of the classification. The diameter distribution of 200 other plots chosen at random (100 in each region) was thus observed visually to verify whether the stand structure attributed by the analysis was correct.

Comparison between the eastern black spruce forest region and the western black spruce forest region

The stand structure of all the temporary coniferous plots of the eastern black spruce forest region and of the northern portion of the western black spruce forest region was thus evaluated using the tool described above. The proportion of the various species groups was first calculated for the two regions, since composition probably has an impact on stand structure and is most likely quite different between the two regions. The proportions of each stand structure type within the two regions were compared by means of a frequency analysis using a linear model (PROC CATMOD; SAS Institute Inc. 1999). By calculating the variability of the response of various sources of variation, this analysis makes it possible to compare the proportions of stand structure types between the two regions while taking into account the effect of other independent variables. The following independent variables were included in the model: region (eastern black spruce forest region or western black spruce forest region), density class, height class and age class based on field surveys of the Quebec forest inventory stratification system (see Appendix 2). The frequency analysis makes it possible, in particular, to verify the existence of interactions between the effect of the region and the effect of the other independent variables. Only the plots whose species group was EE were analysed, since the other species groups were not sufficiently represented in the western black spruce forest region. The density, height and age classes which were not sufficiently represented were eliminated. The plots tested thus included density classes B, C and D, height classes 2, 3 and 4, and age classes 50, 70, 90, 120 and VIN [= mature uneven-aged forests].

Results

Statistical tool for characterizing stand structure

Development of the classification functions

The stepwise discriminant analysis identified 12 variables, presented in Appendix 1, capable of significantly discriminating the three stand structure types of the 154 plots chosen. The five most discriminating variables were selected to calculate the classification functions. The Shannon-Wiener diversity index proved to be by far the most discriminating ($R^2 = 0.73$), followed by the density percentage of the 10-cm dbh class ($R^2 = 0.45$), the coefficient of skewness ($R^2 = 0.16$), the density percentage of the 14-cm dbh class ($R^2 = 0.13$) and the coefficient of variation ($R^2 = 0.13$). The seven other significant variables are: the number of classes represented; the number of possible classes; the coefficient of skewness divided by the number of possible classes; the diversity index divided by the number of possible classes; the largest dbh of the plot; the total density of black spruces; and the density percentage of the 16-cm class.

The variance analysis comparing the means of the three groups of typical stands for the five variables selected helps us to understand how these variables discriminate the stand types (Table 1). Hence, we can see that the coefficient of skewness allows us to distinguish the inverse "J"-shaped distributions from the other types, that the density percentage in the 10-cm class allows us to distinguish the uneven-sized stand structures from the other two types, and that the density percentage in the 14-cm class allows us to distinguish the even-sized stand structures from the other stand structures. The diversity index and the coefficient of variation, on the other hand, appear to be able to distinguish the three stand structure types. Figure 3 represents the 154 typical plots located on the canonical axes and shows that the three groups are clearly distinguished, both on axis 1 and on axis 2.

It should be noted that stand structure in fact constitutes a gradient and that certain plots exhibit a distribution whose stand structure is not very well defined. For these plots, our tool attributes the stand structure closest to their diameter distribution. The discriminant analysis showed that the functions calculated on the basis of the 154 typical stands allow them to be classified with an estimated error rate of 6 per cent, while the validation test performed with the 200 plots chosen at random in the two regions showed that the tool classified the inventory plots with an estimated error rate of 7 per cent. It should be noted that the error rates were not significantly different between the two regions. Using these classification functions, we then calculated, for all the other plots, the probability that they are associated with each type of stand structure. For certain stands, the probabilities tended to be divided between two or three stand structure types and their diameter distribution was examined more closely to verify to which type of stand structure it corresponded. Thus, the stands divided between an even-sized stand structure and an inverse “J”-shaped stand structure were all classified as inverse “J”-shaped stand structures, since their distribution was more similar to this type. The stands whose probabilities were divided between an inverse “J”-shaped stand structure and an uneven-sized stand structure were classified as uneven-sized stands, while those whose probabilities were divided between an even-sized stand structure and an uneven-sized stand structure were characterized by a flatter bell-shaped distribution than for the even-sized stands, as represented in Figure 4. Since these stands probably correspond to relatively mature even-aged stands whose curve is beginning to flatten, a fourth structure class was created, namely stands with a “flattened bell-shaped stand structure." Finally, certain stands presented probabilities divided among the three types and were classified as uneven-sized stands since visually they were more similar to this type.

The coefficients of the three classification functions are presented in Table 2. To attribute a stand structure to a new plot, we only have to multiply these coefficients by the corresponding variables in order to obtain the score for each stand structure type; the stand structure attributed to the plot is the one with the highest score (Legendre and Legendre 1998).

Comparison between the eastern black spruce forest region and the western black spruce forest region

Species composition and stand structure

As might be expected, a significant difference is observed between the two regions in terms of the species composition of the stands. First of all, EE stands constitute the overwhelming majority of the stands in the western black spruce forest region, i.e. nearly 90 per cent of the coniferous stands, unlike the eastern black spruce forest region, where they represent only 54 per cent of the coniferous stands (Table 3). More fir stands and mixed stands containing fir are found in the eastern black spruce forest region, compared to the western black spruce forest region. In the eastern black spruce forest region, the uneven-sized and inverse "J"-shaped stands, taken together, are the most numerous stand structure types among the coniferous stands, representing 66 per cent of the stands (Table 4). Conversely, in the western black spruce forest region, even-sized stands are in the majority with 62 per cent of the stands. Since the differences in stand structure between the regions may be due to differences in composition, we shall examine the proportions by species group.

The inverse “J”-shaped stand structure seems to be associated with fir: in the eastern black spruce forest region, the proportion of this stand structure type increases with the proportion of firs within the stand, ranging from 9 per cent for spruce stands to 41 per cent for fir stands. The same trend is observed in the western black spruce forest region, although it is less obvious. Conversely, even-sized stands seem instead to be associated with black spruce: in the eastern black spruce forest region, 47 per cent of spruce stands have an even-sized structure, while only 13 per cent of fir stands have this structure. In the western black spruce forest region, the proportion of even-sized stand structures in the EE groups rises to 67 per cent, while this same proportion does not exceed 15 per cent for the SS plots. Finally, for each species group, there are always more even-sized stands in the western territory compared to the eastern territory, while the opposite trend is observed for uneven-sized or inverse “J”-shaped stands.

The frequency analyses, performed solely for the EE stands, indicate significant differences between the two regions in terms of the proportions of the various stand structure types (Table 5), but also between height classes and age classes. No significant interaction was found. These results mean that, among stands of the same height or age class, significantly more uneven-sized stands are observed in the eastern black spruce forest region than in the western black forest region. Significant differences are also observed between height and age classes, regardless of region.

The greatest differences in proportions of stand structure types are found among the various height classes ($\chi^2 = 348{,}2$; df = 6) (Table 5; Figure 5a). For both regions, the proportion of even-sized stands is higher among stands of low height: only 8 per cent to 10 per cent of the height class 2 stands are even-sized, while this proportion is 92 per cent in height class 4 stands. Conversely, the uneven-sized stand structure is more frequent when the height of the trees is high. Only 2 to 6 per cent of the plots in height class 4 are uneven-sized, while 81 to 83 per cent of the plots in height class 2 have this stand structure. The proportion of inverse “J”-shaped stand structures, on the other hand, is much more constant from one height class to another.

Figure 5b presents the proportions of the various stand structure types within the various age classes for both regions. Given the insufficient number of plots of age class VIN [mature uneven-aged], this age class was not illustrated in Figure 5b. In general, the proportion of even-sized stands is higher among young stands and decreases with the increase in age class. Conversely, uneven-sized stands are more numerous within the older age classes. Once again, the proportion of inverse “J”-shaped stands remains relatively constant from one age class to another.

Discussion

Statistical tool for characterizing stand structure

The use of discriminant analysis made it possible to develop a tool for evaluating stand structure on the basis of forest inventory data. The coefficient of variation and especially the coefficient of skewness and the Shannon-Wiener diversity index have been widely used in the literature to describe the diameter distribution of stands (Knox et al. 1989; Buongiorno et al. 1994; Groot and Horton 1994; Kubota 1995; Wikström and Eriksson 2000; Staudhammer and LeMay 2001; Takahashi et al. 2001). However, these indices have rarely been used in combination, even though, individually, their ability to describe the various types of distribution has certain deficiencies. The Shannon-Wiener index, for example, which proved to be the most discriminating in our analysis, has the disadvantage of being insensitive to the relative position of the diameter classes with respect to one another. The use of discriminant analysis made it possible to overcome these disadvantages by combining several variables to discriminate the three stand structure types (Legendre and Legendre 1998). Moreover, the classification functions calculated by the analysis seem to be particularly robust if we consider the estimated error rate of only 7 per cent. It should be noted that the error rates of both regions were similar, which demonstrates again the robustness of the model. We believe that the classification functions could be applicable to other regions of the Canadian eastern black spruce forest, provided that the means and standard deviations of the various variables are similar to those obtained in our study. However, in the event that they are not applicable, the same approach could be used to classify new plots.

Stand structure can obviously be evaluated directly in the field, or by using a graphic representation of its diameter distribution. However, the tool we have developed constitutes an objective and relatively accurate means of simultaneously characterizing the structure of a large number of stands. This feature proves very useful when compiling a description of a particular region and planning its forest management. The approach used could therefore supplement the existing forest typology by identifying the structure of the stands to be managed.

Comparison between the eastern black spruce forest region and the western black spruce forest region

As was expected, there is a significant difference in composition between the two regions that may influence the proportions of the various structure types. Pure spruce stands constitute nearly 90 per cent of the stands in the western black spruce forest region, while the eastern black spruce forest region is composed more of fir stands and stands composed of a mix of conifers. The wet climate of the eastern black spruce forest region seems to favour the growth of fir trees

(Burns and Honkala 1990). In addition, the differences in composition between the two regions seem to reflect their respective fire regimes. Indeed, fir generally takes a certain time to become established following a fire, since it is much less adapted to this type of disturbance than black spruce (Payette 1983; Bergeron and Dubuc 1989; Bergeron 2000). Fir therefore appears to be much less abundant in regions subject to very short fire cycles and its scarcity most likely only increases the time it takes to become established after a fire. Moreover, studies show an increase in the proportion of fir over time in certain regions of the boreal forest (Bergeron 2000; Gauthier et al. 2000) and the large fir component within the mature stands on the North Shore has already been reported (Hatcher 1963; De Grandpré et al. 2000).

With respect to stand structure, the eastern and western black spruce forest regions also exhibit two completely different pictures. While even-sized structures dominate in the western black spruce forest region, uneven-sized stands are clearly in the majority in the eastern black spruce forest region. The uneven-sized structure is generally attributed to mature stands (Henry and Swan 1974), more particularly to uneven-aged stands (Groot and Horton 1994; Smith et al. 1997; Linder 1998), unlike the even-sized structure which appears to be more characteristic of young even-aged stands (Baker 1923; Meyer 1930; Hough 1932; Mohler et al. 1978; Smith et al. 1997). It is in fact recognized that diameter structure changes with time elapsed since the last fire (Knowles and Grant 1983; Lorimer and Krug 1983; Groot and Horton 1994; Linder 1998). These changes are generally associated with secondary disturbances and tree senescence, which create gap dynamics in the absence of fire (Heinselman 1981; Fajvan and Seymour 1993; Hofgaard 1993; Kneeshaw and Bergeron 1998; De Grandpré et al. 2000; McCarthy 2001). Windthrow and insect outbreaks are important disturbances on the territory of the North Shore (Blais 1983; Ruel 2000). Hence, the high proportion of uneven-sized stands observed in the eastern black spruce forest region could be partly explained by the importance of gap dynamics. The shorter fire cycle of the western black spruce forest region apparently helps to maintain a majority of young stands in the landscape (Johnson 1992; Oliver and Larson 1996).

Part of the differences in structure between the two regions may also be attributed to factors other than the disturbance regime, since these regions differ in several other regards. Climate, soil types and topography vary considerably between the two regions (Grondin 1996). While some of these factors may affect disturbance regimes, it is possible that they also have a direct effect on stand structure, for example, by increasing the quantity of firs or by accelerating tree maturation and senescence. However, the links between these factors and stand structure are not well documented for the boreal forest.

Stands with an inverse “J”-shaped structure remain relatively scarce in both regions, although they are considerably more abundant in the eastern black spruce forest region. The inverse “J”-shaped diameter structure, like the inverse “J”-shaped age structure, is generally considered the distribution typical of mature uneven-aged stands in which all ages are represented; this distribution appears to be more reflective of a stable state generally associated with the climax concept (Hett and Loucks 1976; Whipple and Dix 1979; Lorimer 1985; Engelmark et al. 1994; Linder et al. 1997; Smith et al. 1997; Kuuluvainen et al. 1998). As noted earlier, we cannot draw any conclusions concerning the uneven-aged or climax status of our inverse “J”-shaped stands. However, their diameter structure continues to be of interest from a forest management standpoint: a stand with a large abundance of 10- to 14-cm stems may lend itself particularly well to harvesting with protection of small merchantable stems.

The proportions of the various structure types also differ by composition. Fir stands are more uneven-sized than spruce stands. Since fir trees are known to be more associated with mature forests (Bergeron 2000; De Grandpré et al. 2000; Gauthier et al. 2000), and to be particularly susceptible to secondary disturbances (MacLean 1984; Blais 1983; Bergeron et al. 1995; Ruel 2000), it is conceivable that fir stands are in fact more uneven-sized.

Moreover, the inverse “J”-shaped distribution, although infrequent, seems to be linked to the proportion of firs in the stand. This structure is in fact more abundant within the SS species group, while its proportion is lowest among the EE stands. This trend may be explained by the fact that fir is very shade-tolerant, even more so than black spruce (Nikolov and Helmisaari 1992). Lorimer (1985) and Lorimer and Krug (1983) claim, moreover, that this distribution is particularly frequent among shade-tolerant species.

However, the difference in composition between the two regions is not sufficient by itself to explain the difference in structure since, if we examine the EE species group, the differences between the two regions remain large and significant, regardless of age or height class.

Interestingly, a high proportion of uneven-sized stands are found in the tall height classes. These results suggest that a substantial proportion of uneven-sized stands have significant productivity and that it may be worthwhile to maintain this type of stand in the landscape, not only from the standpoint of biodiversity, but also from a silvicultural standpoint.

Conclusion

The combined use of various variables with discriminant analysis made it possible to increase the effectiveness of discrimination of the three diameter structure types. The resulting tool can be used to simultaneously characterize the stand structure of a large number of plots, in a satisfactory manner (low classification error rate). The description we have produced of two regions aptly illustrates the usefulness of this tool for forest planning. It makes it possible to assess the relative importance of the various stand structure types in a territory and thus to better target forest management efforts. Additional data could, however, be gathered during forest inventories in order to provide a more detailed characterization of the structure. For example, it would be particularly useful to obtain a more complete distribution of all trees present in the inventory plots. Also, for purposes of conservation of biological diversity, the inventory should be modified to take into consideration the presence and significance of attributes of biodiversity (presence of snags and woody debris, for example).

Nearly 70 per cent of the coniferous plots in the eastern black spruce forest region have an uneven-sized stand structure (inverse "J"-shaped and uneven-sized). This high proportion demonstrates that the uneven-sized forest is far from representing a marginal phenomenon in the boreal forest. In addition to being of particular importance from the standpoint of biodiversity, the presence of uneven-sized stands offers attractive silvicultural alternatives from the standpoint of wood production. Indeed, when the forest exhibits a diversity of stand structure, it is reasonable to assume that these various stands call for (or offer the opportunity for) varied silvicultural treatments. Under these conditions, it is preferable to consider the development of "multi-cohort" silviculture involving various degrees of partial cutting. Several projects have been under way for the past few years on the territory of the North Shore to test various silvicultural alternatives to cutting with regeneration protection. Tools for characterizing stand structure are essential to the diversification of silvicultural practices.

Acknowledgments

We would like to thank the Ministère des Ressources naturelles du Québec (MRNQ) for allowing us to use the forest inventory data. This project was funded in part by the Fonds forestiers and the Sustainable Forest Management Network. We would also like to thank Claude Allain, Jean-Pierre Jetté and Pierre Beaupré for the numerous exchanges of ideas on the typology of stand structure, Michèle Bernier-Cardou for her statistical advice, Jacques Morissette for cartographic support, Isabelle Lamarre for linguistic revision, Diane Paquet for word processing, Thuy Nguyen-Xan and Marc Leblanc as well as two anonymous revisors for their constructive comments on the manuscript.

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Table 1. Mean ± standard deviation of the five variables used to calculate the classification functions, for the three groups of typical stands.

Structure	*N*	**Diversity index**	**Coefficient of skewness**	**Coefficient of variation**	**Density (%) of the 10-cm class**	**Density (%) of the 14-cm class**
Even-sized	*48*	1.48 ± 0.20 **c**	0.71 ± 0.46 **b**	19.49 ± 2.79 **c**	29.32 ± 13.14 **a**	20.90 ± 6.83 **a**
Uneven-sized	*52*	2.22 ± 0.16 **a**	0.64 ± 0.82 **b**	34.43 ± 6.51 **b**	11.46 ± 5.47 **b**	11.15 ± 5.21 **b**
Inverse "J"-shaped	*54*	2.01 ± 0.17 **b**	1.41 ± 0.52 **a**	39.44 ± 7.75 **a**	28.13 ± 6.27 **a**	13.53 ± 5.39 **b**
Total	*154*	1.92 ± 0.35	0.93 ± 0.71	31.53 ± 10.38	22.88 ± 11.99	15.02 ± 7.08

The means of the structure types followed by the same letter are not significantly different (Tukey's test (HSD); $P < 0.05$).

Table 2. Coefficients of the classification functions calculated by discriminant analysis.

	Structure		
Variable	**Even-sized**	**Uneven-sized**	**Inverse "J"-shaped**
Constant	-199.910	-2.006	-1.156
Diversity index	-6.081	3.921	1.629
Coefficient of skewness	-0.461	0.309	0.112
Coefficient of variation	0.055	-1.598	1.490
Density (%) of the 10-cm class	-1.176	-0.591	1.614
Density (%) of the 14-cm class	1.070	-1.259	0.261

Table 3. Distribution (%) of the inventory plots among the four main coniferous species groups of the eastern black spruce forest region and of the western black spruce forest region.

		Species group			
Region	***N***	**EE**	**ES**	**SE**	**SS**
Eastern black spruce forest region	2,088	54.3	17.9	13.2	14.7
Western black spruce forest region	1,290	89.5	5.2	3.2	2.1

Table 4. Proportion (%) of the various structure types within the four main coniferous species groups of the eastern black spruce forest region and of the western black spruce forest region. The total numbers of plots are in brackets.

Stand structure	Species group: EE	ES	SE	SS	Total
Eastern black spruce forest region					
Even-sized	46.9	18.5	14.2	13.4	32.6
Flattened bell-shaped	3.1	0.8	0.0	0.0	1.8
Uneven-sized	41.0	52.0	50.5	45.6	44.9
Inverse “J”-shaped	9.1	28.7	35.3	41.0	20.7
Total	100.0 (1,133)	100.0 (373)	100.0 (275)	100.0 (307)	100.0 (2,088)
Western black spruce forest region					
Even-sized	67.2	23.9	20.0	14.8	62.3
Flattened bell-shaped	4.1	1.5	5.0	0.0	3.9
Uneven-sized	20.7	47.8	50.0	55.6	23.8
Inverse “J”-shaped	8.0	26.9	25.0	29.6	9.9
Total	100.0 (1,143)	100.0 (67)	100.0 (40)	100.0 (27)	100.0 (1,277)

Table 5. Frequency analysis of the proportions of the various structure types between the two regions and among the various height, density and age classes. Only the inventory plots of the EE species group were analysed.

Source	**df**	χ^2	$P > \chi^2$
Y-intercept	3	127.6	< 0.0001
Region	3	61.0	< 0.0001
Height class	6	348.2	< 0.0001
Density class	6	11.0	0.0874
Age class	12	24.2	0.0191
Likelihood ratio	240	178.5	0.9989

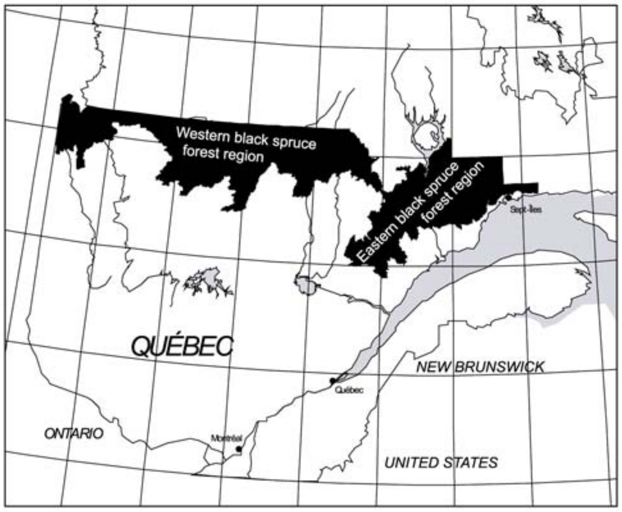

Fig. 1: Location of the two regions under study in the province of Quebec (adapted from the MRNQ's map of ecological regions).

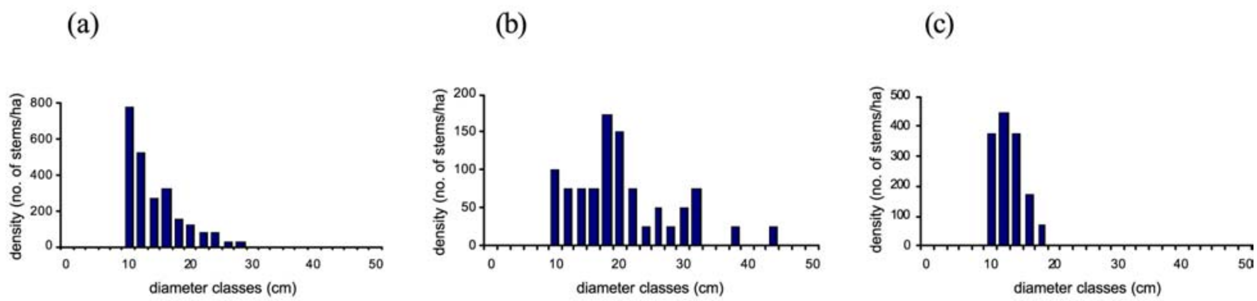

Fig. 2: Diameter distributions corresponding to the three main stand structure types: (a) inverse "J"-shaped structure, (b) uneven-sized structure and (c) even-sized structure.

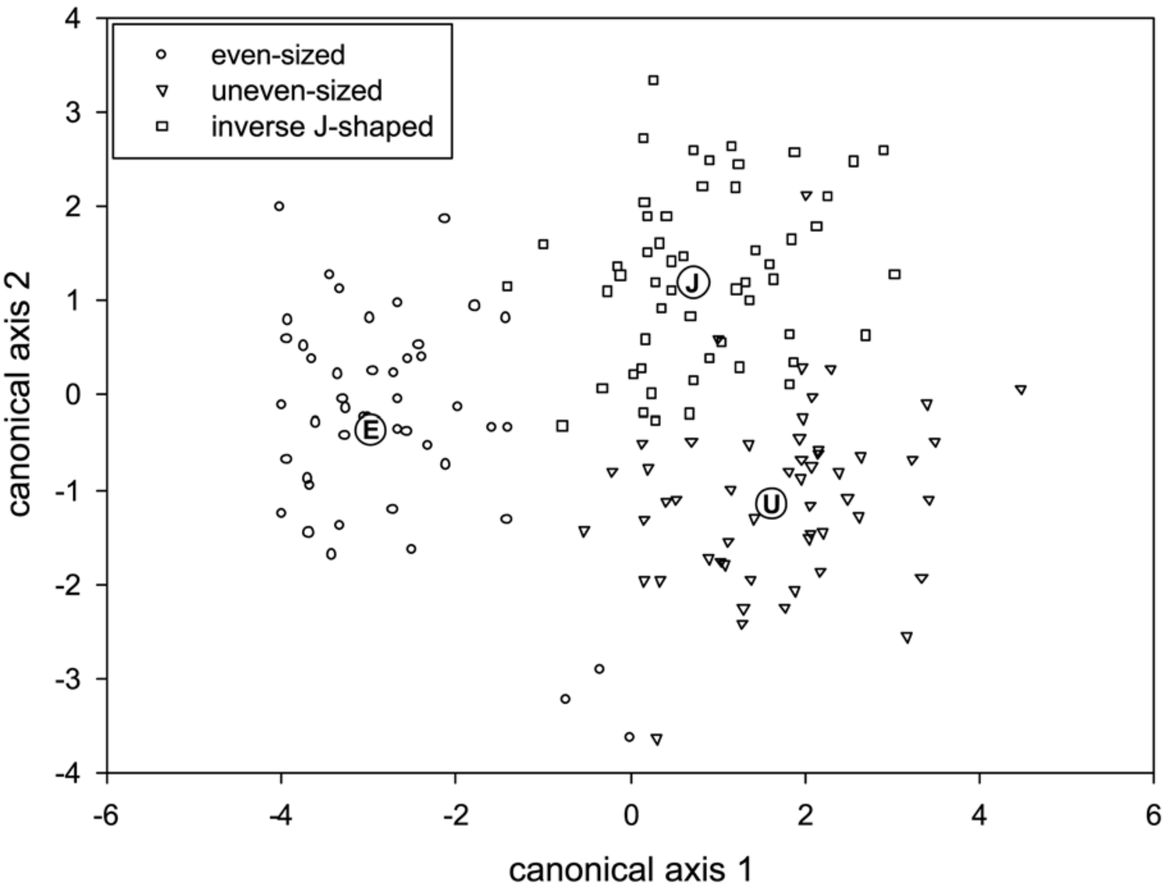

Fig. 3: Position of the 154 typical plots in the canonical space. The centroids of the three structure types are indicated by letters (E = even-sized, U = uneven-sized, J = inverse "J"-shaped).

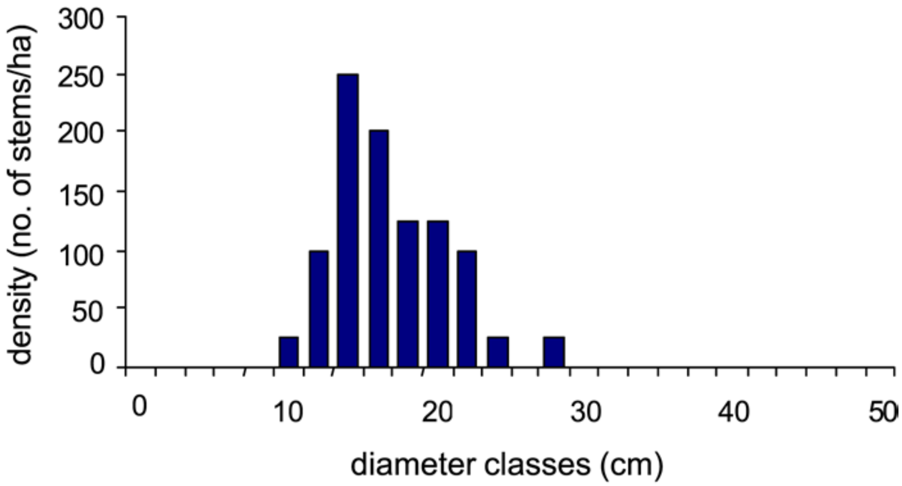

Fig. 4: Diameter distribution of a stand with a flattened bell-shaped structure.

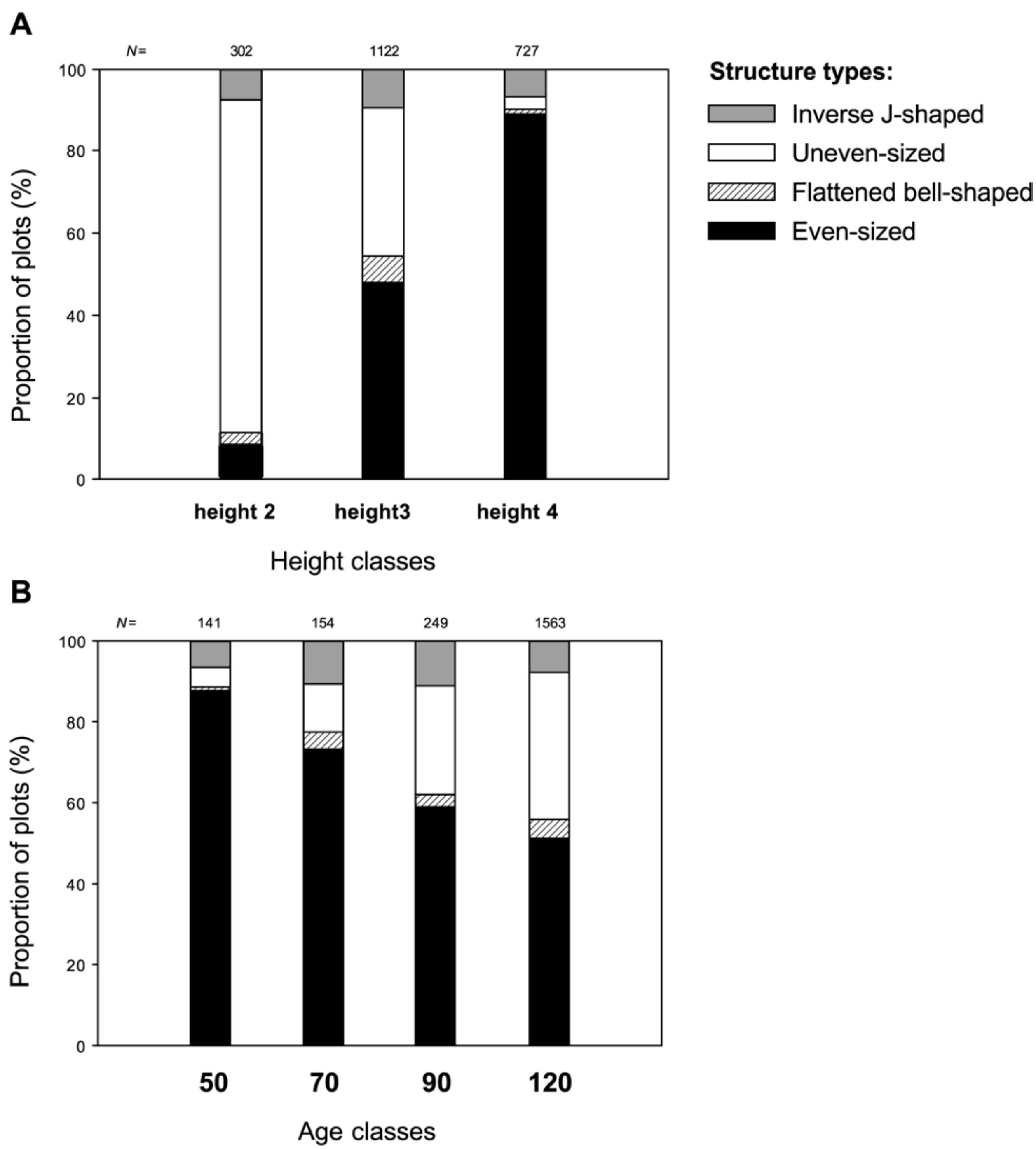

Fig. 5: Proportion (%) of the various structure types within (A) three height classes (2 = 17 to 22 m; 3 = 12 to 17 m; 4 = 7 to 12 m), and (B) four age classes (see Appendix 2). Only the plots of the EE species group are represented. The values include the two regions under study.

Appendix 1: List of the variables calculated on the basis of the inventory data for each plot and included in the stepwise discriminant analysis.

- total stand density (stems/ha);
- density (stems/ha) and percentage respectively for black spruce, fir and white spruce relative to total density;
- largest dbh of the plot;
- maximum age (of three trees surveyed in the plot);
- density of each dbh class (as a percentage);
- number of dbh classes represented;
- number of possible dbh classes (between the largest and the smallest dbh);
- Shannon-Wiener diversity index applied to the diameter classes (classes of 2 cm);
- coefficient of skewness applied to the diameter classes;
- coefficient of variation applied to the diameter classes (cv = standard deviation * 100/ mean);
- Shannon-Wiener diversity index divided by the number of possible classes;
- coefficient of skewness divided by the number of possible classes.

Appendix 2: Description of the density, height and age classes according to Quebec forest inventory standards (MERQ 1984).

Density classes

The density classes of the stands correspond to the percentage of cover comprised of the crown projection of the stems of more than 7 m:

Class	Percentage of cover
A	greater than 80%
B	61% to 80%
C	41% to 60%
D	25% to 40%

Height classes

Height classes are defined on the basis of the mean height of dominant and co-dominant stems. In multi-storied stands, only the story that occupies the greatest percentage of the basal area is considered.

Class	Mean height
1	greater than 22 m
2	17 to 22 m
3	12 to 17 m
4	7 to 12 m

5	4 to 7 m
6	Less than 4 m

Age classes

The age classes selected for this study are defined as follows:

Class	Description
Even-aged stands	
50	the majority of the stems are between 41 and 60 years old
70	the majority of the stems are between 61 and 80 years old
90	the majority of the stems are between 81 and 100 years old
120	the majority of the stems are 101 years old or older
Uneven-aged stands	
VIN [mature uneven-aged]	the majority of the stems belong to several age classes and are more than 60 years old