Arboriculture & Urban Forestry 2009. 35(2): 53–62

Identification of Significant Street Tree Inventory Parameters Using Multivariate Statistical Analyses

Pierre Jutras, Shiv O. Prasher, and Pierre Dutilleul

Abstract. Street tree inventories are costly procedures that must be designed to optimally meet management and operational requirements. To assess the importance of several low-technology inventory parameters, a three-step multivariate statistical analysis was designed and tested on growth models of Norway maple (*Acer platanoides*), silver maple (*Acer saccharinum*), common hackberry (*Celtis occidentalis*), green ash (*Fraxinus pennsylvanica*), honeylocust (*Gleditsia triacanthos*), littleleaf linden (*Tilia cordata*), and Siberian elm (*Ulmus pumila*). The first step appraised and compared the significance of qualitative and quantitative parameters. Results revealed that using qualitative indices decreased the explanatory power of models. Accordingly, it was proposed that quantitative parameters be preferred for urban tree inventory. The second step aimed at reducing the volume of necessary information needed for urban tree growth estimation. Various simple and complex combinations of quantitative parameters were tested. Results were conclusive and species independent: the simplified models were statistically non-significant. The best model was composed of multiple parameters. The third step looked for the identification of an inventory parameter that could be used to assess any urban tree physiological stage. It was found that no single parameter can adequately delineate the complexity of all tree physiological stages. The optimal model is rather multidimensional.

Key Words. Correspondence Analysis; Principal Coordinate Analysis; Qualitative Inventory Parameters; Quantitative Inventory Parameters; Street Trees; Urban Tree Inventory.

City trees provide environmental services that directly improve human health and the quality of life (Dwyer et al. 2003). In retail districts, visitors perceive the streetscape canopy to be an integral amenity of the city's shopping environment and well-planned canopy-covered streets are highly appreciated (Wolf 2004). Trees provide relief from high temperatures by reducing the effects of warming of urban environments caused by absorption, advection, and reradiation of heat from streets and buildings (Shashua-Bar and Hoffman 2000). Additionally, trees are vital due to their ability to remove contaminants from the air (Beckett et al. 2000). Trees absorb gaseous pollutants, such as ozone, nitrogen oxides, and sulphur dioxide, release oxygen through photosynthesis, store carbon dioxide, reduce evaporative hydrocarbon emissions from parked vehicles, and intercept dust, ash, pollen and smoke, removing significant amounts of particulate pollution from urban atmospheres (Nowak et al. 2006).

The impact of trees on increased property values and social functional benefits is largely acknowledged (Behe et al. 2005). Despite that, municipal administrations face serious challenges when allotting budget to the different essential activities needed to preserve street trees. For example, maintaining an inventory is a lengthy and costly process. When defining inventory procedures, one must keep in mind that trees are highly complex organisms, and that a complete description of all physiological processes is unrealistic (Constable and Friend 2000). Rather, the physiological complexity must be simplified without excessive loss of the fundamental responses to environmental variables. Therefore, analysis and prediction of growth response must take place at an appropriate level of physiological resolution (Constable and Friend 2000). Additionally, inventory methodology and tools must be adapted to the day-to-day work and must correspond to an optimal balance between cost, effort, and accuracy.

Over the years, many researchers have attempted to fulfill these objectives. Some have measured shoot growth (Close et al. 1996), while others opted for diameter at breast height, height, and crown spread as relevant growth parameters (Larsen and Kristoffersen 2002; Yang et al. 2005). Cumming et al. (2001) assessed tree health using qualitative scales. Iakovoglou et al. (2002) and Quigley (2004) estimated growth by increment core measurements and tree diameter. Kent et al. (2004) and Percival et al. (2006) determined tree stress with leaf chlorophyll concentration, chlorophyll luminescence, leaf temperature, and water potential. Kopinga and van den Berg (1995) favored foliar analysis. In recent years, high-resolution spatial and aerial data acquisition equipment has been developed, and much effort has been devoted to obtain dendrometric and tree-health data sets by using these high technology products. Most of this research has been conducted in the forestry context (Wulder et al. 2003), but it is now expanding to the study of urban forests and trees (Jensen et al. 2005). However, these techniques are still experimental and most cities use traditional inventory procedures.

Historically, data sets collected to ascertain tree growth models were analyzed with standard statistical tools: trends in tree growth and stature were examined with regression techniques and analysis of variance. Per se, these one-dimensional models are usually characteristic of simple conditions. However, because of the numerous variables influencing urban tree survival, relationships between tree growth and environmental factors can be said to be, for the most part, complex and multidimensional. Hence, assessing these relationships with one-dimensional statistics may only extract minimum information from data. The use of multivariate statistical analyses might be an elegant solution to circumvent this difficulty.

Multivariate algorithms are predominantly supported by matrix algebra and statistical theory around the concept of multidimensional space: each of *n* trees is considered a vector in a *p*-dimensional space, where *p* is the number of recorded variables. The axes can be rotated so as to maximize the percentage of variance explained (Legendre and Legendre 1998). This reduces the data set dimensions into a small number of readily interpretable independent axes, and significant variables can thus be identified. Applied research problems were successfully studied with these methods. Plant growth models elaborated by Jutras (1989) made use of cluster analysis, parametric and nonparametric discriminant analysis, and contingency analysis. Savva et al. (2002) compared tree-ring characteristics using cluster analysis. Matyas (1994) developed a growth-response model to predict the effects of climate change on tree growth and survival with principal component analysis. Leclerc et al. (2001) also used principal component analysis for a study on grouping soils of the Montreal lowlands. Hammitt (2002) used factor analysis involving principal components to determine common functions of urban forest and park refuges. Hence, it can be inferred that multivariate methods might be powerful analytical tools to unveil ecological structures related to complex street tree growth patterns.

The main objective of this paper is to assess the relevance of several low-technology parameters and to identify key variables that might be used within a reliable street tree inventory procedure. In view of that, a multivariate statistical analysis scheme was designed and tested on growth models of seven urban tree species. Three primordial and successive steps composed this scheme. The first one aimed at comparing the significance of diverse qualitative and quantitative parameters (section: evaluation of the explanatory potential of qualitative and quantitative variables); the second one explored the likelihood of reducing the volume of information needed for urban tree growth estimation (section: selection of the most important quantitative variables and assessment of model integrity); and the last one looked for the identification of an inventory parameter that could be used to assess any urban tree physiological stage (section: appraisal of the relationships between morphological descriptors and their contribution to growth models).

MATERIALS AND METHODS

The City of Montreal (Quebec, Canada) is located at 45°30'N and 73°34'W. There are over 220,000 trees transplanted along 4,460 km (2,770 miles) of roads, boulevards, and streets. To define the experimentation strategy and sample size, exploratory field work was carried out in 1999 and 2000 in downtown, institutional, commercial (outside the downtown core), and residential zones. Representative streets were selected according to the following criteria: height of buildings and geographic orientation (variable irradiance conditions), importance of vehicular and pedestrian use, size of tree pits, and width of street since trees beside a wide, heavily traveled city street may be subjected to higher salt level and winds than narrower, less traveled streets (Berrang et al. 1985). Sampled tree species were restricted to the most important ones found on Montreal's streets. The final data collection took place in 2001 and was composed of the following species: Norway maple (*Acer platanoides* – 312 trees), silver maple (*Acer saccharinum* – 224 trees), common hackberry (*Celtis occidentalis* – 187 trees), green ash (*Fraxinus pennsylvanica* – 245 trees), honeylocust (*Gleditsia triacanthos* – 301 trees), littleleaf linden (*Tilia cordata* – 116 trees), and Siberian elm (*Ulmus pumila* – 147 trees). The age class distribution of sampled trees is represented in Figure 1.

The variables recorded were: genus and species; number of years after transplantation; diameter at breast height (1.35 m/4.4 ft); width of crown (Coombes 1994); total height and crown base elevation. Crown volumes were calculated by means of the upper-half spheroid model (Ludwig et al. 1975). Qualitative parameters were also assessed: presence or absence of chlorosis; detection and general identification of parasites to characterize the phytopathological condition of trees; presence and intensity of mechanical damages or sunscald/frost cracks (scale: 1: no damage, 2: presence of a few small healed damages, 3: numerous damages partially healed, 4: numerous damages unhealed, 5: very numerous severe damages); evaluation of crown density, from dense foliage to dying trees (scale: 1: 100%, 2: 75%, 3: 50%, 4: 25%, 5: 0%); crown development on the basis of annual shoot growth (scale: 1: vigorous, 2: moderate, 3: fair, 4: poor, 5: dying or dead); general condition of trees (scale: 1: vigorous tree, no dying branches, no insect infestation, no mechanical damage, 2: moderate growing tree, must not have more than three dying main branches, insect infestation if present must be benign, mechanical damages if present must be healed, 3: fair growing tree, may have up to one-third dying branches, insect infestation important but not detrimental, mechanical damages may be numerous but must be partly or entirely healed, 4: poor growing individuals, with one-third to two-thirds dying branches, insect infestation may cause severe defoliation, mechanical damages are unhealed and there is presence of large sunscald cracks, 5: dying trees, severely damaged or infested, with a very low number of poorly growing branches, or dead trees).

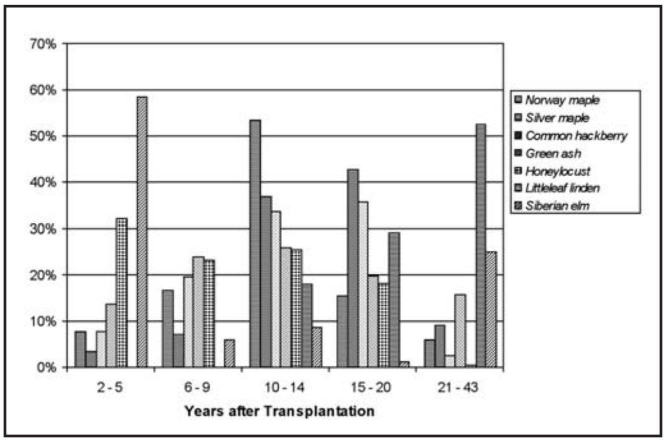

Figure 1. Distribution of age classes per species in experimental design.

In order to possibly improve the growth model precision, combinations of morphological parameters were built up to form composite variables: ratios of crown diameter/diameter at breast height (DBH); crown volume/DBH; total height/DBH; annual DBH increment, crown volume increment, crown diameter increment, and height increment. The last four composite variables are associated with size measurements. An annual crown volume increment was calculated as the difference between measured crown volume and crown volume at transplantation, divided by the number of years since transplantation. To obtain transplantation data, 15 City of Montreal nursery trees of ball and burlap transplanting size were measured for every species and mean values were calculated. Other incremental indices were similarly constructed. Theoretically, such indices should permit differentiation between trees of the same morphological stature but of different ages, thus identifying differential growth.

METHODOLOGICAL ASPECTS OF MULTIVARIATE ANALYSIS

Evaluation of the Explanatory Potential of Qualitative and Quantitative Parameters

Qualitative parameters are rapid appraisals of tree growth and they can be appealing for tree inventory, but they are necessarily biased as their estimation is based on a subjective evaluation that can vary from one observer to another. On the contrary, quantitative measurements are accurate but time-consuming. To assess the respective weight and explanatory potential of both types of variables, the experimental data set was used as input for a multidimensional statistical procedure that allows the simultaneous comparison of data that are of different mathematical formats. First, the records of each sampled tree were transformed into similarities, by using the Gower's similarity coefficient. For instance, when binary variables such as presence or absence of chlorosis were used to compare the physiological status of individual trees, the similarity value (s) between two trees was computed as follows: if both trees were chlorotic, then $s = 1$, otherwise $s = 0$. Semi-quantitative and qualitative variables such as intensity of mechanical damages, crown development and crown density were treated following the simple matching rule: $s = 1$ when the variable took the same value for both trees. Quantitative variables such as DBH, height, crown diameter, and crown volume were evaluated by dividing the difference between the states of the two trees by the largest difference found for a given variable across all pairs of trees. Eventually, the overall similarity between two trees was assessed by computing the average value of calculated similarities for all types of variables. These computations were necessary steps prior to the use of principal coordinates analysis (PCO), a nonparametric statistical procedure that can generate reduced-space ordinations and estimate the variance explained when testing different hypothetical models. In this research, in order to identify which inventory parameters adequately expressed urban tree growth patterns, two models were compared. The first one tested the concurrent use of qualitative and quantitative parameters, while the second one restricted computations to quantitative measurements only.

Selection of the Most Important Quantitative Variables and Assessment of Model Integrity

In this study, the morphological and composite parameters that were used are not independent. For example, DBH and annual DBH increment, crown diameter and crown diameter increment, height and height increment, are just different expressions of trunk, crown and height growth. In addition, crown volume values were computed using crown diameter. Such affinities can induce collinearity that may severely bias any urban tree growth model. To test this hypothesis, six different scenarios were elaborated to investigate interrelationships between variables and identify which combination of parameters is best suited for inventory-data analysis (Table 1).

Table 1. Scenarios designed to test for collinearity between quantitative variables.

	Scenarios					
Quantitative variables	A	B	C	D	E	F
Diameter at breast height (DBH)	•	•	•			•
Annual DBH increment	•	•	•	•	•	
Crown diameter	•	•				•
Annual crown diameter increment	•	•		•	•	
Height	•	•	•			•
Annual height increment	•	•	•	•	•	
Crown diameter / DBH	•			•		
Crown volume / DBH	•		•	•		
Height / DBH	•		•	•		
Crown volume	•	•	•			•
Crown volume increment	•	•	•	•	•	

In scenario A, which is the main hypothesis, all selected parameters were used at once in the multivariate statistical analyses. Scenario B excluded ratio parameters from the analyses to estimate a possible redundancy effect. The results of this test were compared to those of scenario A. The third scenario (C) left out every parameter directly linked to crown diameter, to verify if their use in scenario A inflated the weight of crown inputs and biased the model. Scenario D challenged a key concept in street tree growth: small trees are not necessarily the youngest ones and may be older, poorly growing trees. Accordingly, inclusion of only incremental and ratio parameters in the growth model may have given the best representation of time span and vigor when compared to scenario A. Finally, scenarios E and F were models with the lowest possible collinearity between parameters: only crown volume and diameter could directly be linked. However, we do not believe that crown volumes are systematically related to particular crown diameters. For example, a small cylindrical tree near street curb may have the same mean crown diameter as an asymmetrically pruned old tree transplanted close to a nearby building but the corresponding crown volumes will be significantly different. Scenarios E and F were the simplest models challenging the complexity of scenario A, but they were also designed to estimate the relative explanatory power of incremental parameters over standard morphological variables in any growth model.

Correspondence analysis (CA) was used to test every scenario. Correspondence analysis can be designated as a nonparametric principal component analysis that can reveal the principal axes of a high-dimensional space, enabling projection into a subspace of low dimensionality that accounts for the main portion of variance in the data. This particular property of CA can reveal relationships that would not be detected in a series of pairwise comparisons of variables, and can simplify remarkably complex data (Theodorou et al. 2007). Another procedure, the broken-stick random model, was used concomitantly to enhance the interpretation of CA results. That method compares the computed distribution of variance in CA multidimensional axes to that of a random model. If the CA procedure has distributed the total variance at random among the principal axes, the portions of variance explained by the various axes would be about or less than the broken-stick model on the same data set. If this is the case, it is meaningless to interpret the principal axes (Frisvad 1994). Therefore, to confirm or invalidate the relative superiority of a scenario over the random model, a delta value was computed by subtracting the broken-stick cumulated variance from the model cumulated variance after one, two, and three axes, per species and scenario.

Appraisal of the Relationships Between Morphological Variables and Their Contribution to the Growth Models

Practitioners regularly try to identify a single tree parameter that would a) give an adequate representation of an urban tree population at any physiological stage, and b) allow for temporal or individual comparisons. To many professionals, this objective is a crucial step toward reducing the overall inventory costs. This part of the research was designed to test this intention. To do so, the 11 variables of scenario A (Table 1) were plotted on the first two axes of CA and the degree of association between variables was gauged by the angle formed by pairs or groups of descriptors in the biplot: the more acute the angle, the stronger the association as the cosine of the angles in the biplot approximate correlation between variables (Greenacre 2007). In addition, a Spearman's statistic r_s was computed between each of the descriptors and their positions on the first axes, to estimate their relative contribution to variance. Spearman's r_s is a nonparametric correlation coefficient computed from ranks. All multivariate statistical analyses indicated in the above sections were carried out using Statistica® (StatSoft, 2006) and the R package for multivariate analysis (Legendre and Casgrain 2006).

RESULTS AND DISCUSSION

Evaluation of the Explanatory Potential of Qualitative and Quantitative Descriptors

Two different projections were estimated with principal coordinate multidimensional analysis: quantitative and qualitative descriptors tested concurrently and quantitative inputs only. Table 2 shows the respective cumulative percentage of explained variance for each model for the first three principal axes. The original work investigated more than ten axes for model differentiation but the outcome was identical with the three-dimension projection. In addition, it should be noted that cumulative variances expressed in Table 2 may seem low but this is inherent to Gower's similarity coefficient. To confirm that these results were not erroneous nor an artefact of the analytical methodology and/or experimental protocol, quantitative descriptors were projected using a Euclidian coefficient that preserves the actual distance between objects in the multidimensional space. The results were satisfactory as the explained variance was over 93% for the first three axes.

Clearly, conclusion to be drawn from PCO results is that there was a notable explanatory power decrease when qualitative indices (presence/absence of chlorosis; detection of parasites; presence and intensity of mechanical damages or sunscald/frost cracks; evaluation of crown density, crown development, and of general condition of trees) were included in the model. Rationale behind this conclusion can be explained with different possibilities. First, the classes that were defined for each variable were maybe inappropriate to express the complexity of urban tree condition. On the other hand, these results may have been influenced by the specific nature of qualitative indices. Most likely, despite appropriate calibration between the different observers during data collection, their intrinsic bias induced statistical noise.

The objective of this section was to compare the significance of diverse qualitative and quantitative parameters. Both types have advantages and disadvantages. Since many years, a debate has taken place on the respective superiority of qualitative or quantitative research and typically quantitative parameters were defined as objective, reliable, transferable, and reproducible (Gelo et al. 2008). Based on our results, notwithstanding that qualitative indices are appealing in terms of inventory efficiency; it is proposed that quantitative parameters might take precedence in urban tree inventory.

Table 2. Percentage of explained variance per species for each of the first three principal axes.

Species	Axis	Quantitative and qualitative descriptors	Quantitative descriptors only
Norway maple	1	3.3%	9.8%
	2	1.4%	1.9%
	3	0.8%	1.2%
silver maple	1	4.3%	17.4%
	2	1.8%	3.3%
	3	1.0%	1.2%
common hackberry	1	5.0%	19.0%
	2	2.3%	3.4%
	3	0.7%	1.7%
green ash	1	3.8%	12.8%
	2	1.7%	3.0%
	3	1.1%	1.4%
honeylocust	1	3.4%	9.7%
	2	1.5%	2.8%
	3	1.0%	1.5%
littleleaf linden	1	6.8%	16.8%
	2	4.3%	6.7%
	3	3.1%	2.3%
Siberian elm	1	6.4%	17.0%
	2	3.2%	8.9%
	3	2.6%	1.9%

Selection of the Most Important Quantitative Variables and Assessment of Model Integrity

Results of the delta values that were computed between CA and broken-stick random model cumulated variances for each of the first three axes, per species and scenario are shown in Figure 2. For scenarios E and F, results for the third axis are not visible in the graph because the delta value is zero. Percentages of cumulative variance for the first three axes of CA and the broken-stick model are presented in Table 3.

Despite the fact that each of the species has its own canopy architecture, they showed remarkable similarity within scenarios. First, scenario E (annual DBH increment, crown volume increment, crown diameter increment, and height increment) and scenario F (DBH, crown volume, crown diameter, and height) rarely provided CA cumulated variances significantly greater than the broken-stick values. This result suggests low explanatory power for these scenarios, close to a random model. Therefore, these variables might not be used as sole measurements to describe the complex reality of tree growth along sidewalks.

Second, when ratio parameters were included in the analysis, tree growth model extraction was improved. For example, scenarios D and E were alike except for the inclusion of these

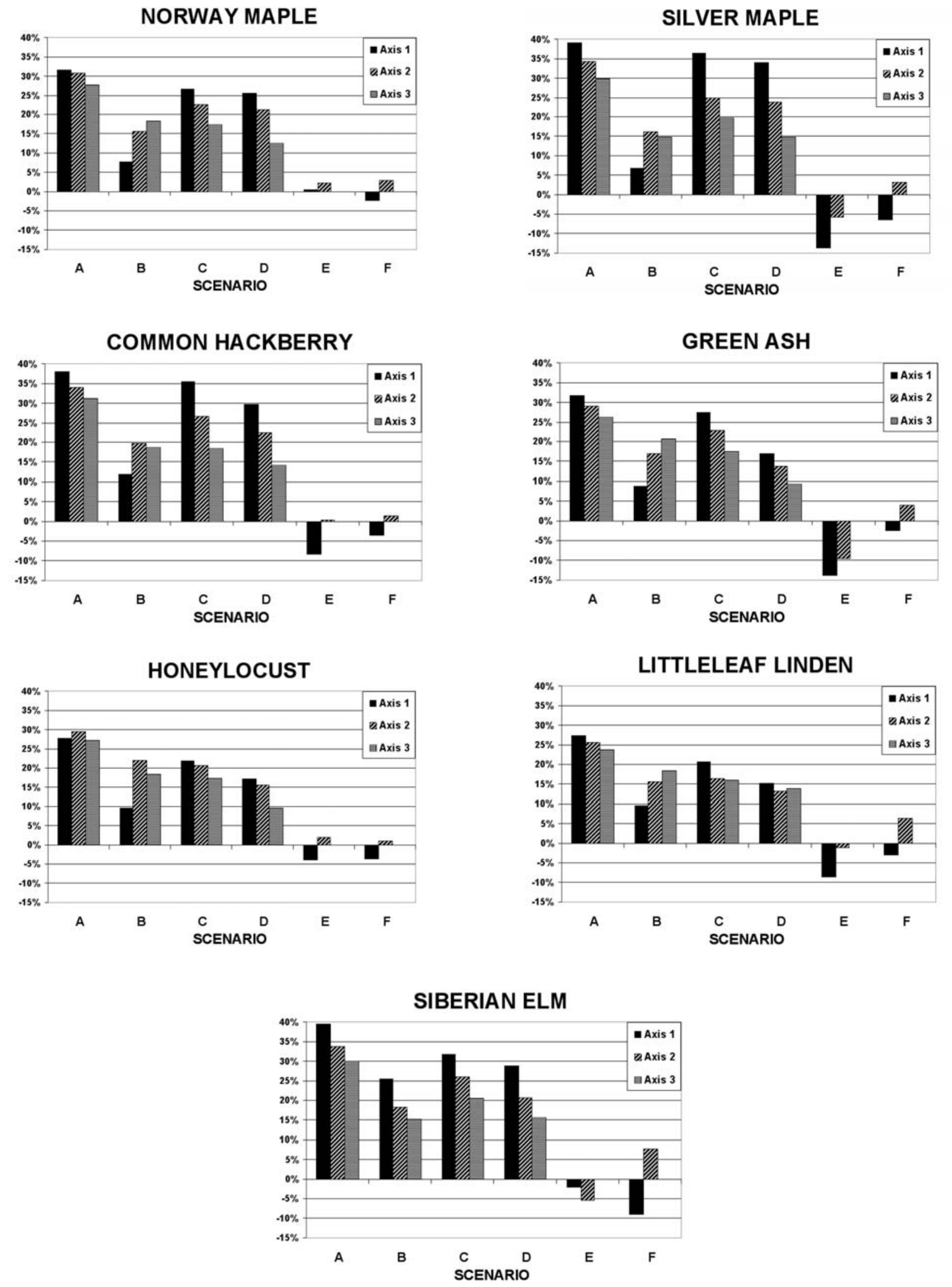

Figure 2. Delta values computed between correspondence analysis and broken-stick model cumulated variances for each species, scenario and the first three axes of correspondence analysis.

Table 3. Percentage of cumulative variance per axis for correspondence analysis and broken-stick model.

		Correspondence analysis - cumulative % of variance per axis								Broken
Scenario	Axis	Norway maple	silver maple	common hackberry	green ash	honeylocust	littleleaf linden	Siberian elm	mean variance	-stick model
	1	61.0	68.5	67.4	61.0	57.1	56.8	68.9	63.0	29.3
A	2	79.4	82.9	82.6	77.7	78.2	74.3	82.6	79.7	48.6
	3	90.8	92.7	94.2	89.3	90.2	86.7	93.0	91.0	62.9
	1	44.9	43.8	48.9	46.0	46.8	46.6	62.7	48.5	37.0
B	2	75.5	76.1	79.6	76.9	81.9	75.5	78.2	77.7	59.8
	3	93.8	90.5	94.2	96.2	94.0	94.0	90.8	93.3	75.4
	1	63.8	73.6	72.7	64.4	59.0	57.8	68.9	65.7	37.0
C	2	82.6	84.7	86.5	82.6	80.6	76.2	85.9	82.8	59.8
	3	92.8	95.3	94.1	93.0	92.8	91.6	96.0	93.6	75.4
	1	66.4	74.8	70.5	57.9	58.0	56.1	69.8	64.8	40.8
D	2	86.4	88.9	87.6	78.8	80.7	78.3	85.9	83.8	65.0
	3	93.4	95.8	95.0	90.4	90.5	94.9	96.5	93.8	80.8
	1	61.6	47.5	52.7	47.4	57.4	52.5	59.3	54.1	61.1
E	2	91.2	83.2	89.3	79.5	91.0	88.0	83.6	86.5	88.9
	3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	1	58.9	54.7	57.7	58.6	57.6	58.3	52.3	56.9	61.1
F	2	92.0	92.1	90.5	93.0	90.1	95.3	96.6	92.8	88.9
	3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

parameters in D. While scenario E's model extraction could be classified as random, scenario D represented a considerable upgrade with significantly positive delta values. Scenarios A and B were also comparable. The former was composed of all 11 biotic parameters, whereas ratio parameters were barred from the latter. Again, improvement was found from scenario B to A. Lastly, the hypothesis that keeping all parameters related to the computation of crown volumes in the model might have incremented the weight of crown inputs and the bias in model extraction proved to be false. Scenario C gave good results but delta values were always lower than those of scenario A. Moreover, close examination of the relationships between crown volume/crown diameter parameters and the first axes of Ca revealed differential Spearman r_s patterns (Table 4).

The main goal of this section was to identify which combination of parameters is most proficient in representing the growth of a given urban tree, by using easily-collected field variables and composite parameters. Scenario A, which included 11 morphological and combined descriptors, was the only model that conspicuously met this objective. The cumulated portions of variance for the first three axes of correspondence analysis were the highest of all scenarios. Therefore, it might be concluded that it may be awkward to use a lesser number of variables for urban tree growth estimation.

These results are a key finding for the elaboration of a procedure to identify poorly growing trees. Generally speaking, the management of urban trees calls for appropriate care to young and/or stressed individuals. Although newly transplanted trees can be easily singled out using transplantation date records, stressed ones cannot easily be pinpointed with a single morphological characteristic. By concomitantly using the 11 parameters identified in this research, Jutras (2008) developed a multivariate clustering system that categorizes trees with similar growth patterns. This system further demonstrated that using DBH as the sole tree-inventory measurement for tree care planning may be misleading as scrutiny of class distribution of DBH and years after transplantation showed that clusters with small trees were composed not only of young trees but also of older stressed individuals. In fact, stressed trees were generally as old as 10 to 15 years after transplantation,

Table 4. Spearman r_s correlation[z] between biotic parameters and each of the first two axes of correspondence analysis.

	Norway maple		silver maple		common hackberry		green ash		honeylocust		littleleaf linden		Siberian elm	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
DBH	**-0.99**	0.02	**-0.98**	-0.01	**-0.98**	0.02	**-0.99**	0.02	**-0.98**	0.05	**-0.95**	0.09	**-0.98**	**0.18**
Annual DBH increment	**-0.85**	**-0.17**	**-0.81**	**-0.21**	**-0.90**	0.06	**-0.77**	-0.09	**-0.86**	-0.01	**-0.42**	**-0.20**	**-0.49**	**0.86**
Crown diameter	**-0.84**	**0.20**	**-0.84**	**-0.34**	**-0.85**	**0.31**	**-0.89**	**0.24**	**-0.83**	**0.25**	**-0.52**	**-0.24**	**-0.87**	**0.16**
Crown diameter increment	**-0.57**	0.11	**-0.43**	**-0.70**	**-0.42**	**0.48**	-0.09	**0.30**	**0.22**	**0.28**	0.15	**-0.43**	**0.19**	**0.78**
Height	**-0.79**	**-0.31**	**-0.80**	0.06	**-0.83**	**-0.22**	**-0.85**	**-0.22**	**-0.75**	**-0.41**	**-0.45**	**0.42**	**-0.83**	0.02
Height increment	**-0.44**	**-0.61**	**-0.45**	**-0.16**	**-0.51**	**-0.25**	**-0.23**	**-0.52**	**-0.36**	**-0.63**	-0.02	**0.28**	**0.38**	**0.58**
Crown diameter /DBH	**0.39**	**0.34**	**0.52**	**-0.68**	**0.58**	**0.52**	**0.54**	**0.55**	**0.73**	**0.34**	**0.68**	**-0.41**	**0.61**	**0.34**
Crown volume **/ DBH**	**-0.71**	0.04	**-0.69**	**-0.33**	**-0.73**	**0.17**	**-0.77**	**0.16**	**-0.64**	0.01	**-0.19**	-0.02	**-0.73**	0.13
Height / DBH	**0.87**	**-0.35**	**0.82**	0.10	**0.79**	**-0.35**	**0.90**	**-0.24**	**0.84**	**-0.42**	**0.72**	**0.32**	**0.86**	-0.04
Crown volume	**-0.85**	0.04	**-0.83**	**-0.23**	**-0.87**	0.12	**-0.90**	0.11	**-0.83**	0.04	**-0.49**	0.02	**-0.89**	0.13
Crown volume **increment**	**-0.76**	-0.05	**-0.71**	**-0.36**	**-0.76**	**0.18**	**-0.69**	0.11	**-0.55**	-0.02	-0.18	-0.09	**-0.58**	**0.46**

[z] Correlations in bold type are significant at $\alpha < 0.05$.

but they were still having a DBH close to transplantation size. Moreover, when the growth patterns characterized with the 11 variables were confronted to local abiotic conditions, significant conclusions were derived. For example, trees exhibiting an extremely slow growth rate were found growing over sand-gravel surficial soils that provided an unfavourable root environment.

Appraisal of the Relationships Between Morphological Variables and Their Contribution to the Growth Models

To discuss the relationships between morphological and combined descriptors, the portion of total variance explained by CA axes must be sufficiently high. In this study on seven street-tree species, the smallest variance for Axis 1 was 57%, while the largest cumulative variance for the first two axes was 83% (Table 3). Such percentages of explained variance are satisfactory. Accordingly, CA biplots and Spearman's r_s correlation coefficient were used to ascertain the contribution of morphological variables to the growth model (Figure 3, Table 4).

First, scrutiny over Spearman's r_s values confirmed that the selection of the model with 11 inputs is further justified. Out of 77 possible correlations (11 inputs X 7 species), 95% are significantly related to the first axis, where the most important portion of variance is found (Table 4). In addition, almost 65% of the correlations with Axis 2 are significant, demonstrating its contribution to the growth model. Second, patterns found in projections are very similar from species to species. With the exception of the Siberian elm model, many parameters position themselves within the same quadrant and there is a perceptible right-to-left gradient: the height/DBH ratio is systematically opposed to static growth descriptors such as crown volume, crown diameter and DBH. Had they been represented in the biplots, small trees would have been positioned on the right and the larger trees on the left. Hence, indicators of small tree status (newly transplanted and/or older stressed trees) are linked to ratio variables such as crown diameter/DBH and height/DBH. Midsize trees are more connected to incremental inputs (crown diameter and height increments), while large trees are characterized by nontemporal parameters (DBH, crown volume and height). This sequence of ratio variables, incremental parameters and static inputs is systematically distributed from the right to the left of diagrams. As well, on the far left of projections, relationships can be detected between crown volume, crown volume increment, crown volume/DBH, crown diameter and DBH parameters, as they form a distinct group along Axis 1.

When comparing the results for Norway maple, silver maple, common hackberry, green ash, honeylocust, and littleleaf linden, striking affinities can be found, even if the age class distribution is not homogeneous (Figure 1). The first five species above have fairly comparable age distribution, except for higher frequency in recently transplanted honeylocust and a larger number of Norway maples in the 10–14 year class. On the contrary, littleleaf linden is not represented in the 2–5 and 6–9 year classes and the 21–43 year class accounts for more than 50% of total sampled trees. This situation illustrates the reality of the City of Montreal reforestation program in 2001 and since then: littleleaf linden is no longer a preferred street tree species because of its high sensitivity to de-icing salts and undesirable dripping of sticky substances exuded by aphids colonizing the trees. Siberian elm shows a CA different pattern: almost all incremental parameters are to the right in the biplot, while static morphological variables are to the left. This can be explained by the age of sampled trees. For many years, this species was not transplanted in Montreal because its brittle wood breaks easily. Yet, it is one of the most tolerant trees to urban environments so, since the mid-1990s, it is transplanted in zones where no other species survives. Distribution of age classes reflects this situation as only very young or very old Siberian elms were sampled (Figure 1).

In this last section, the objective was to identify a single tree parameter that would: a) give an adequate representation of an urban tree population at any physiological stage; b) allow for temporal or individual comparisons. Yet, this goal could not be met as indicators of small tree status (newly transplanted and older stressed trees); midsize and large trees were different. Actually, only the systematic use of the 11 selected inputs brought sufficient robustness to develop a general model for six tree species, notwithstanding their intrinsic variability and differential architectural form. This finding strengthens the conclusion of the preceding section. Therefore, it is proposed that DBH, annual DBH increment, crown diameter, crown diameter increment, height and height increment, crown diameter/DBH, crown volume/DBH, height/DBH, crown volume, and crown volume increment become key elements of efficient street-tree inventories.

SUMMARY AND CONCLUSIONS

Considering that urban tree inventory is a costly but indispensable activity for any municipality, a study was elaborated to assess the explanatory potential of easy-to-collect parameters and to identify key variables that might be used within a reliable street tree inventory procedure. To achieve these objectives, a multivariate statistical analysis scheme was designed and tested on growth models of seven urban tree species. Three primordial and successive steps composed this scheme. The first one aimed at comparing the significance of diverse qualitative and quantitative parameters. Our results showed that there was an explanatory power decrease when qualitative indices were included in models. Therefore, notwithstanding that qualitative indices are appealing in terms of inventory efficiency; it was proposed that quantitative parameters might take precedence in urban tree inventory.

The second part of this research explored the likelihood of reducing the number of variables needed for adequate urban tree growth estimation by identifying the most important ones. Various simple and complex combinations of quantitative parameters were tested. Results were conclusive and species independent: simple models were statistically nonsignificant and the best model was obtained when the following combination of 11 parameters was used: DBH, annual DBH increment, crown diameter, crown diameter increment, height and height increment, crown diameter/DBH, crown volume/DBH, height/DBH, crown volume, and crown volume increment.

This finding was further strengthened by the results obtained in the last step of the multivariate scheme. Despite a different analytical approach, it was impossible to identify a single tree parameter that would give an adequate representation of an urban tree population at any physiological stage and/or allow for temporal or individual comparisons. Indicators of small tree status (newly transplanted and older stressed trees), midsize and large trees were different. Essentially, only the use of the 11 above-described inputs brought sufficient robustness to develop a general model for six

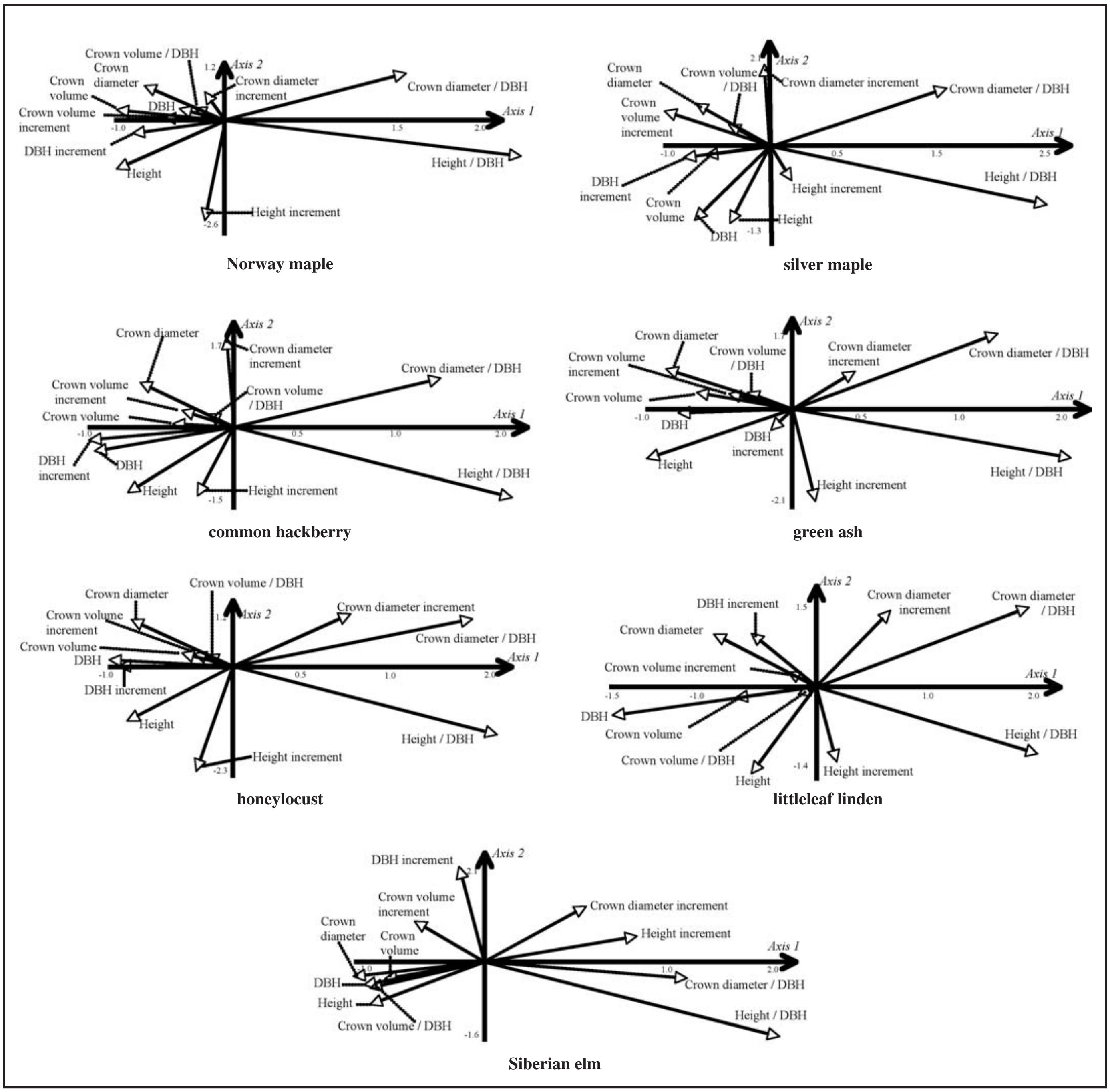

Figure 3. Projections of the morphological variables on the first two axes of correspondence analysis.

tree species, in spite of their intrinsic variability and differential architectural form. Therefore, it is proposed that these 11 selected variables become key elements of efficient street-tree inventories.

The geographic location of Montreal entails particular environmental conditions. The climate is continental and humid, with distinct seasonal characteristics that shape the street-tree extreme environment. Moreover, the analytical models developed herein are limited by the specific nature of the studied species. Any extrapolation of the findings of this study to other tree species, urban environment conditions and/or geographic location should be made with caution.

Acknowledgments. The authors are grateful for the financial support of City of Montreal and the Natural Science and Engineering Research Council of Canada (NSERC). We also express gratitude to two anonymous reviewers for their pertinent comments on the original manuscript.

LITERATURE CITED

Beckett, K.P., P.H. Freer-Smith, and G. Taylor. 2000. The capture of particulate pollution by trees at five contrasting urban sites. Arboricultural Journal 24: 209–230.

Behe, B., J. Hardy, S. Barton, J. Brooker, T. Fernandez, C. Hall, J. Hicks, R. Hinson, P. Knight, R. McNeil, T. Page, B. Rowe, C. Safley, and R.

Schutzki. 2005. Landscape plant material, size, and design sophistication increase perceived home value. Journal of Environmental Horticulture 23(3): 127–133.

Berrang, P., D.F. Karnosky, and B.J. Stanton. 1985. Environmental factors affecting health in New York City. Journal of Arboriculture 11: 185–189.

Close, R.E., P.U. Nguyen, and J. Kielbaso. 1996. Urban VS natural sugar maple growth: 1. Stress symptoms and phenology in relation to site characteristics. Journal of Arboriculture 22: 144–150.

Constable, J.V.H., and A.L. Friend. 2000. Suitability of process-based tree growth models for addressing tree response to climate change. Environmental Pollution 110: 47–59.

Coombes, S.A. 1994. Amenity valuation: the Helliwell system revised. Arboricultural Journal 18: 137–148.

Cumming, A.B., M.F. Galvin, R.J. Rabaglia, J.R. Cumming, and D.B. Twardus. 2001. Forest health monitoring protocol applied to roadside trees in Maryland. Journal of Arboriculture 27(3): 126–138.

Dwyer, J.F., D.J. Nowak, and M.H. Noble. 2003. Sustaining urban forests. Journal of Arboriculture 29(1): 49–55.

Frisvad, J.C. 1994. Correspondence, principal coordinate, and redundancy analysis used on mixed chemotaxonomical qualitative and quantitative data. Chemometrics and Intelligent Laboratory Systems 23: 213–229.

Gelo, O., D. Braakmann, and G. Benetka. 2008. Quantitative and qualitative research: beyond the debate. Integrative Psychological and Behavioral Science 42(3): 266–290.

Greenacre, M. 2007. Correspondence Analysis in Practice, 2nd Edition. Chapman and Hall/CRC, Boca Raton, Florida. 280 pp.

Hammitt, W.E. 2002. Urban forests and parks as privacy refuges. Journal of Arboriculture 28(1): 19–26.

Iakovoglou, V., J. Thompson, and L. Burras. 2002. Characteristics of trees according to community population level and by land use in the U.S. Midwest. Journal of Arboriculture 28(2): 59–69.

Jensen, R.R., J.D. Gatrell, and D.D. McLean (Eds). 2005. Geo-Spatial Technologies in Urban Environments. Springer, Berlin; London. 242 pp.

Jutras, P. 1989. Stratégie de Développement de Cinq Espèces dans des Plantations Expérimentales sur les Rives Perturbées de la Région de Montréal, Québec. M.Sc. Thesis. Department of Biological Sciences, University of Montréal, Canada. 109 pp.

Jutras, P. 2008. Modeling of Urban Tree Growth with Artificial Intelligence and Multivariate Statistics. Ph.D. Thesis. Department of Bioresource Engineering, McGill University, Canada. 395 pp.

Kent, D., D. Halcrow, T. Wyatt, and S. Shultz. 2004. Detecting stresses in southern live oak (*Quercus virginiana*) and sand live oak *(Q. virginiana* var. Geminata). Journal of Arboriculture 30(3): 146–153.

Kopinga, J., and J. van den Burg. 1995. Using soil and foliar analysis to diagnose the nutritional status of urban trees. Journal of Arboriculture 21: 17–24.

Larsen, F.K., and P. Kristoffersen. 2002. *Tilia*'s physical dimensions over time. Journal of Arboriculture 28(5): 209–214.

Leclerc, M.L., M.C. Nolin, D. Cluis, and R.R. Simard. 2001. Grouping soils of the Montréal Lowlands (Quebec) according to fertility and P sorption and desorption characteristics. Canadian Journal of Soil Science 81: 71–83.

Legendre, P., and P. Casgrain. 2006. The R package for multivariate and spatial analysis – Version (4.0). University of Montréal, Quebec, Canada. <http://www.bio.umontreal.ca/Casgrain/en/labo/R/v4/>.

Legendre, P., and L. Legendre. 1998. Numerical Ecology, 2nd English edition. Developments in environmental modelling. Elsevier, New York. 853 pp.

Ludwig, J.A., J.F. Reynolds, and P.D. Whitson. 1975. Size-biomass relationships of several Chihuahuan desert shrubs. American Midland Naturalist 94(2): 451–461.

Matyas, C. 1994. Modeling climate change effects with provenance test data. Tree Physiology 14(7): 797–805.

Nowak, D.J., D.E. Crane, and J.C. Stevens. 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry & Urban Greening 4: 115–123.

Percival, G.C., I.P. Keary, and S. AL-Habsi. 2006. An assessment of the drought tolerance of *Fraxinus* genotypes for urban landscape plantings. Urban Forestry & Urban Greening 5: 17-27.

Quigley, M.F. 2004. Street trees and rural conspecifics: Will long-lived trees reach full size in urban conditions? Urban Ecosystems 7: 29–39.

Savva, Y., F. Schweingruber, L. Milyutin, and E. Vaganov. 2002. Genetic and environmental signals in tree rings from different provenances of *Pinus sylvestris* L. planted in the southern taiga, central Siberia. Trees – Structure and Function 16(4): 313–325.

Shashua-Bar, L., and M.E. Hoffman. 2000. Vegetation as a climatic component in the design of an urban street: an empirical model for predicting the cooling effect of urban green areas with trees. Energy and Buildings 31: 221–235.

StatSoft, Inc. 2006. STATISTICA (data analysis software system) version 7.1. Tulsa, Oklahoma.

Theodorou, Y., C. Drossos, and P. Alevizos. 2007. Correspondence analysis with fuzzy data: The fuzzy eigenvalue problem. Fuzzy Sets and Systems 158: 704–721.

Wolf, K.L. 2004. Trees and business district preferences: a case study of Athens, Georgia, U.S. Journal of Arboriculture 30(6): 336–346.

Wulder, M.A., and D. Seemann. 2003. Forest inventory height update through the integration of lidar data with segmented Landsat imagery. Canadian Journal of Remote Sensing 29(5): 536–543.

Yang, J., J. McBride, J. Zhou, and Z. Sun. 2005. The urban forest in Beijing and its role in air pollution reduction. Urban Forestry & Urban Greening 3: 65–78.

Pierre Jutras (corresponding author)
Research scientist, Arboriculture and artificial intelligence
City of Montreal, Parks Department
801, Brennan Street, 4th floor
Montreal, Quebec, H3C 0G4 Canada
pjutras@ville.montreal.qc.ca

and

Department of Bioresource Engineering,
McGill University
pierre.jutras@mail.mcgill.ca

Shiv O. Prasher
James McGill Professor and Chair
Department of Bioresource Engineering, McGill University,
21,111 Lakeshore Road
Ste-Anne-de-Bellevue, Quebec, H9X 3V9 Canada

Pierre Dutilleul
Professor
Department of Plant Science, McGill University
21,111 Lakeshore Road
Ste-Anne-de-Bellevue, Quebec, H9X 3V9 Canada

Résumé. L'inventaire d'arbres de rues est une activité coûteuse qui doit être conçue de manière optimale pour rencontrer les objectifs de gestion et d'opération. Afin d'évaluer l'importance de certains paramètres d'inventaire à faible technologie, une analyse statistique en trois étapes a été élaborée et testée sur des modèles de croissance pour l'érable de Norvège (*Acer platanoides*), l'érable argenté (*Acer saccharinum*), le micocoulier occidental (*Celtis occidentalis*), le frêne de Pennsylvanie (*Fraxinus pennsylvanica*), le févier épineux (*Gleditsia triacanthos*), le tilleul à petites feuilles (*Tilia cordata*) et l'orme de Sibérie (*Ulmus pumila*). La première étape était d'évaluer et de comparer la signification des paramètres qualitatifs et quantitatifs. Les résultats ont révélé que l'utilisation d'indices qualitatifs diminuait le pouvoir explicatif des modèles. En conséquence, il a été proposé que les paramètres quantitatifs devaient être préférés pour l'inventaire d'arbres urbains. La seconde étape visait à réduire le volume d'information nécessaire qui était requis pour l'estimation de la croissance des arbres urbains. Des combinaisons variées, simples et complexes, de paramètres quantitatifs ont été testées. Les résultats ont été concluants et les espèces indépendantes entre elles; les modèles simplifiés étaient statistiquement non significatifs. Le meilleur modèle était composé de multiples paramètres. La troisième étape cherchait à identifier un paramètre d'inventaire qui pourrait être employé pour évaluer le stade physiologique de n'importe quel arbre urbain. Il a été découvert qu'aucun paramètre individuel ne pouvait adéquatement décrire la complexité de chacun des stades physiologiques de tous les arbres. Le modèle optimal est plutôt multidimensionnel.

Zusammenfassung. Baumkataster sind kostenträchtige Unternehmungen und müssen entsprechend auf ihre Anforderungen gestaltet werden. Um die Bedeutung von Katasterparametern mit geringem, technischem Aufwand zu untersuchen, wurde eine dreistufige, statistische Analyse entwickelt und an Wachstumsmodellen von Spitzahorn (*Acer platanoides*), Silberahorn (*Acer saccharinum*), Zürgelbaum (*Celtis occidentalis*), Esche (*Fraxinus pennsylvanica*), Gleditschie (*Gleditsia triacanthos*), Winterlinde (*Tilia cordata*), und Ulme (*Ulmus pumila*) getestet. Der erste Schritt bewertete und verglich die Bedeutung von qualitativen und quantitiven Parametern. Die Ergebnisse enthüllten, dass die Anwendung von qualitativen Maßstäben die Aussagekraft der Modelle herabsetzt. Entsprechend wurde vorgeschlagen, dass quantitative Parameter bei Baumkatastern vorzuziehen sind. Der zweite Schritt zielte darauf, das Volumen der erforderlichen Informationen für die Baumbewertung einzugrenzen. Verschiedene einfache und komplexe Kombinationen von quantitiven Parametern wurden getestet. Die Ergebnisse waren konklusiv und unabhängig von der Baumart: die vereinfachten Modelle waren statistisch nicht signifikant. Das beste Modell bestand aus vielfältigen Parametern. Der dritte Schritt schaute auf die Identifizierung eines Katastermerkmals, welches zur Untersuchung des physiologischen Zustands verwendet werden kann. Wir stellten fest, dass kein einziger Parameter die Komplexität aller Baum-physiologischen Zustände beschreiben kann. Das optimale Modell ist daher eher multidimensional.

Resumen. Los inventarios de árboles son procedimientos costosos que deben ser diseñados para encontrar los requerimientos óptimos de manejo y operación. Para evaluar la importancia de varios parámetros en inventarios de tecnología regular se diseñó un análisis estadístico multivariado de tres pasos y se probó en modelos de crecimiento de arces Norway (*Acer platanoides*), arce plateado (*Acer saccharinum*), almez común (*Celtis occidentalis*), fresno verde (*Fraxinus pennsylvanica*), acacia de tres espinas (*Gleditsia triacanthos*), tilo (*Tilia cordata*) y olmo siberiano (*Ulmus pumila*). El primer paso valoró y comparó la significancia de los parámetros cualitativos y cuantitativos. Los resultados revelaron que el uso de índices cualitativos disminuyó el poder explicatorio de los modelos. En concordancia, se propuso que los parámetros cuantitativos sean preferidos en los inventarios de árboles urbanos. El segundo paso ayudó en la reducción del volumen de información necesaria para la estimación del crecimiento de los árboles urbanos. Fueron probados varias combinaciones de parámetros cuantitativos simples y complejos. Los resultados fueron concluyentes y especies independientes: los modelos simplificados fueron estadísticamente no-significativos. El mejor modelo estuvo compuesto de múltiples parámetros. El tercer paso vio por la identificación de un parámetro del inventario que pudiera ser usado para evaluar cualquier estado fisiológico del árbol. Se encontró que un solo parámetro no puede adecuadamente delinear la complejidad de los estados fisiológicos de los árboles. El modelo óptimo es más bien multidimensional.