Containerized spruce seedlings: relative importance of measured morphological and physiological variables in characterizing seedlings for reforestation

André L. D'Aoust, Claude Delisle, Ronald Girouard, Antonio Gonzalez and Michèle Bernier-Cardou

Quebec Region • Information Report LAU-X-110E

Natural Resources Canada
Canadian Forest Service

Ressources naturelles Canada
Service canadien des forêts

Canada

THE LAURENTIAN FORESTRY CENTRE is one of six regional establishments of the Canadian Forest Service (Natural Resources Canada). The Centre cooperates with other government agencies, educational institutions and the forest industry to promote through research and development the most efficient and rational management and use of Quebec's forests.

In Quebec, the program consists of forest resource and protection research and forest development. Most research is undertaken in response to the needs of the various forest management agencies. The results of this research are distributed in the form of scientific and technical reports, conferences, and other publications.

LE CENTRE DE FORESTERIE DES LAURENTIDES est un des six établissements régionaux du Service canadien des forêts (Ressources naturelles Canada). Le Centre collabore avec divers organismes gouvernementaux, avec les intervenants de l'industrie forestière et avec les établissements d'enseignement dans le but de promouvoir, par des travaux de recherche et de développement, un aménagement et une utilisation plus rationnels des ressources forestières du Québec.

Au Québec, les activités portent sur la recherche dans les domaines des ressources forestières et de la protection des forêts, et sur le développement forestier. La plupart des travaux sont entrepris pour répondre aux besoins de divers organismes intéressés à l'aménagement forestier. Les résultats de ces travaux sont diffusés sous forme de rapports techniques et scientifiques, de conférences et autres publications.

André L. D'Aoust

André L. D'Aoust has been working for the Canadian Forest Service since 1970. He earned a Ph.D. in biology from Queen's University at Kingston. He especially worked on the physiology of seedlings to be outplanted. He is in charge of the project "Ecophysiology of stresses in forest regeneration".

Claude Delisle

Claude Delisle has been a researcher at the LFC since 1983. He first worked in remote sensing and then oriented his work towards silviculture, particularly artificial regeneration. He obtained an M.Sc. from Université Laval in 1981. Between 1980 and 1983, he worked in the private sector in the field of forest inventories.

Ronald Girouard

Ronald M. Girouard has been a research scientist with the Canadian Forest Service since 1966. He earned a Ph.D. from Purdue University in 1967. He taught as visiting professor at Université Laval from 1969 to 1978. Over the past fifteen years, he studied root development of conifers after outplanting container-grown seedlings. He is a member of the International Society Root Research.

Antonio Gonzalez

Antonio Gonzalez worked for the Canadian Forest Service from 1965 to 1993. He obtained a Ph.D. from Salamanca University in Spain. He is a specialist in soils and in organic matter. In 1980, he joined the project run by André D'Aoust to work on the nutrition and the properties of peat as a growth factor of seedlings.

Michèle Bernier-Cardou

Michèle Bernier-Cardou has been the senior statistician at the Laurentian Forestry Centre since 1989. She earned an M. Sc. from the University of Edinburgh in 1975. From 1975 to 1988, she was the regional statistician at the research branch of Agriculture Canada in Sainte-Foy, Quebec.

Containerized spruce seedlings: relative importance of measured morphological and physiological variables in characterizing seedlings for reforestation

André L. D'Aoust, Claude Delisle, Ronald Girouard,
Antonio Gonzalez and Michèle Bernier-Cardou

Information Report LAU-X-110E
1994

Natural Resources Canada
Canadian Forest Service - Quebec Region

THE NATIONAL LIBRARY OF CANADA HAS CATALOGUED THIS PUBLICATION AS FOLLOWS:

Main entry under title :

Containerized spruce seedlings : relative importance
of measured morphological and physiological variables
in characterizing seedlings for reforestation.

(Information report ; LAU-X-110E)
Issued also in French under title: Semis d'épinettes
en conteneurs.
Includes an abstract in French.
Issued by the Laurentian Forestry Centre.
Includes bibliographical references.
ISBN 0-662-22395-0
Cat. no. Fo46-18/110E

1. Spruce -- Quebec (Province) -- Seedlings, Container.
2. Spruce -- Quebec (Province) -- Growth.
3. Reforestation -- Quebec (Province).
I. D'Aoust, André L. (André Lucien), 1940-
II. Canadian Forest Service. Quebec Region.
III. Laurentian Forestry Centre.
IV. Title: Relative importance of measured morphological
and physiological variables in characterizing seedlings for
reforestation.
V. Series : Information report (Laurentian Forestry Centre) ;
LAU-X-110E.

SD404.3.C86 1994 634.9'75256 C94-980257-3

Catalog No. Fo46-18/110E
ISBN 0-662-22395-0
ISSN 0835-1570

Limited additional copies of this publication are available at no charge from:
Natural Resources Canada
Canadian Forest Service - Quebec Region
Laurentian Forestry Centre
1055 du P.E.P.S.
P.O. Box 3800
Sainte-Foy, Quebec
G1V 4C7

Copies or microfiches of this publication may be purchased from:
Micromedia Ltd.
Place du Portage
165, Hôtel-de-Ville
Hull, Quebec
J8X 3X2

Cette publication est également offerte en français sous le titre «Semis d'épinettes en conteneurs : l'importance relative des variables morphologiques et physiologiques mesurées pour caractériser les semis destinés au reboisement» (Numéro de catalogue Fo46-18/110F).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES
(cont'd)

LIST OF FIGURES

ABSTRACT

The quality of forest tree seedlings produced in nurseries is usually expressed in terms of height and diameter. However, several authors have emphasized the importance of using more dynamic variables that describe the physiological state of seedlings, so as to better characterize the material intended for reforestation. To rate the relative importance of the variables selected in characterizing seedlings, 10 morphological and physiological variables were measured on seedlings from different stocks of spruces. Twenty-three batches of seedlings intended for reforestation were obtained from 7 forest nurseries. These included 11 batches of 2+0 white spruce, 7 batches of 2+0 black spruce and 3 batches of 2+0 Norway spruce, all grown in 45-110 containers. Two additional batches of 1+0 black spruce planting stock raised in smaller containers (67-50) were also studied. Seedlings were dormant upon delivery. Containers were placed in a greenhouse under normal rearing conditions. Each batch of planting stock was sampled at 3-week intervals on 4 different occasions. A first sample was used to measure morpho-physiological variables: stem height, basal diameter, fresh and dry mass of shoots and roots, electrical resistance, water potential, and osmotic potential of the seedling. Root growth capacity of seedlings was assessed from a second sample.

Principal component analysis (PCA) was conducted using the correlation matrix of the observed variables within each unit based on a combination of seedlings from one species of a given age, for the 4 observation periods. For the units of 2+0 white spruce and 2+0 black spruce having a sufficient number of batches, a PCA was performed using means per container. In these analyses, 4 components accounted respectively for 89% and 85% of total variation. Using 9 morpho-physiological variables, excluding root growth capacity and, relying on individual values for the PCA, 80% of total variation is at least accounted for by the first 3 components for the 4 combinations.

The estimation of the variance explained by different subsets of the 10 variables indicated that a specific subset of 4 variables, considered simultaneously, explained on average 75% of total variation. This particular subset is composed of basal diameter, stem height, water potential and root growth capacity.

RÉSUMÉ

Les semis forestiers produits en pépinière sont généralement qualifiés selon leur hauteur et leur diamètre. Cependant, un certain nombre d'auteurs souligne l'importance de recourir à des variables plus dynamiques qui décrivent l'état physiologique du semis afin de mieux caractériser le matériel destiné au reboisement. Pour évaluer l'importance relative des variables à utiliser à cette fin, 10 variables morphologiques et physiologiques ont été mesurées sur les semis de différents lots d'épinettes. Sept pépinières ont fourni 23 lots de semis destinés au reboisement. De ce nombre, on comptait 11 lots d'épinette blanche 2+0, 7 lots d'épinette noire 2+0 et 3 lots d'épinette de Norvège 2+0, tous cultivés dans le conteneur 45-110, ainsi que 2 lots d'épinette noire 1+0, cultivés dans de plus petits conteneurs (67-50). Au moment de leur livraison, les semis étaient en dormance, et les conteneurs ont été placés en serre dans des conditions normales de culture. Chacun des lots a été échantillonné à quatre reprises, à intervalles réguliers de trois semaines. Un premier échantillon a servi à mesurer des variables morpho-physiologiques : la hauteur de la tige et le diamètre à la base, les masses fraîches et sèches de la partie aérienne et des racines, la résistance électrique, le potentiel hydrique et le potentiel osmotique du semis. Un second échantillon a permis d'évaluer la capacité de croissance racinaire des semis.

Une analyse factorielle par composantes principales (ACP) a, pour les quatre périodes d'observation, été effectuée à partir de la matrice de corrélations des variables utilisées pour chaque combinaison formée des semis d'une essence et d'un âge donnés. Pour les combinaisons d'épinettes blanches 2+0 et d'épinettes noires 2+0 qui comptaient un nombre suffisant de lots, une ACP a été effectuée sur les moyennes par conteneur. Dans ces analyses, quatre composantes expliquent respectivement 89 % et 85 % de la variation totale. Lorsque l'on reprend les ACP avec les valeurs individuelles de neuf variables morpho-physiologiques, observées sur les mêmes semis pour les quatre combinaisons, mais en excluant la capacité de croissance racinaire, trois composantes rendent compte d'au moins 80 % de la variance totale.

L'estimation de la variabilité expliquée par différents sous-ensembles des 10 variables montre qu'un sous-ensemble particulier de 4 variables, prises simultanément, rend compte

en moyenne de 75 % de la variation totale observée. Les variables retenues sont le diamètre à la base, la hauteur de la tige, le potentiel hydrique et la capacité de croissance racinaire du semis.

INTRODUCTION[1]

The National Forest Regeneration Conference held in Quebec City in October 1977 made those involved in silviculture more aware than ever of the damage caused by deforestation. Information had been circulating in these groups earlier in the decade to the effect that, for large logged (clearcut) areas, only a third of the area regenerated adequately. A compilation by Weetman (1977) showed that of the 0.6 million hectares harvested in Canada each year, barely 50% had regenerated exploitable species 5 years after cutting. If to this cumulative delay, that is annual accumulation of insufficiently regenerated areas, we add those destroyed by fire and other destructive agents, over 28 million hectares still remained unproductive by the end of the 1970s, which represents an area of close to 13% of the commercial forest lands in Canada.

In the early 1980s, plans to correct this situation were announced in each Canadian province, clearly with backing from the federal government, with priority going to artificial regeneration (Reed 1982). For Quebec, the figures proposed were 300 million seedlings to be outplanted annually starting in 1988-1989.

To meet this increased demand for seedlings for reforestation throughout the country, private producers have begun growing seedlings to supplement supplies from government nurseries (Smyth and Brownwright 1984). During the same period, containerized production[2] exceeded the production of bareroot seedlings. A number of factors work in favour of this specialized rearing technique for forest tree seedlings: smaller production space, savings on seed quantities (smaller losses), longer planting period, better return for the tree planter and higher survival rate. This production method also gives nursery managers greater flexibility. For both the nurseryman and the tree planter, however, the quality of seedlings to be produced for reforestation remains a problem.

---

[1] A preliminary report on this project was presented: Proceedings of the 1991 Forest Nursery Association of British Columbia Meeting, Prince George, British Columbia, Sept. 23-26. Compiled by Franck P. Donnelly and Hans W. Lusenburg.

[2] Also known as containerized seedlings, that is seedlings grown in an appropriate medium in a cell with walls that prevent the passage of roots; depending on the size of cavities, the seedlings may remain in the container from one to two years before being outplanted.

Although the use of containerized seedlings in Canada dates back some twenty years (Walters 1968; Matthews 1971), the ideal size of seedlings for reforestation has not yet been determined (Tinus *et al.* 1974; Duryea and Brown 1984; Ontario Ministry of Natural Resources 1987). This problem is linked to the variety of species used, choice of provenances, types of containers, age of stocks and the morphological and physiological characteristics of seedlings produced. Moreover, the ecological aspect of the site to be reforested has not yet been raised. Consequently, the slow progress in this field should come as no surprise.

Despite these difficulties, the initial objective was to reach a certain growth optimum with this specialized rearing technique. During the 1970s, seedlings grown in containers in Canada were generally small, and the maximum opted for was a single growing season before outplanting (Waldron 1972; Carlson 1979). In the late 1970s in Quebec, research projects dealt mainly with infrastructures, types of containers and growing conditions in greenhouses (Barbulescu 1982; D'Aoust 1978 and 1980; Sheedy 1978 and 1980).

Initial reforestation tests in western Canada showed a higher survival rate for containerized seedlings compared with bareroot seedlings, despite their relatively small size (Arnott 1974; Walker and Johnson 1980). Later on, interest turned to larger seedlings (Dobbs 1976). At the present time in Quebec, apart from large-sized seedlings, priority is given to the use of hardier seedlings, that is those with a height/diameter ratio (cm/mm) of ≤ 8 for dormant seedlings and ≤ 10 for growing seedlings. This does, however, leave us with a question: what should be the optimum characteristics of seedlings intended for reforestation?

According to Sutton (1990), the main work in this area was that directed by Wakeley (1935-1971) of the USDA Forest Service. The results of his research on southern pines (*Pinus echinata* Mill., *P. elliotti* Engelm., *P. palustris* Mill. and *P. taeda* L.) showed that morphology described only the silhouette of the seedling and that the addition of another dimension, known as the physiological, should provide us with information on the full capacity of a seedling to be outplanted (Wakeley 1949). These 2 aspects of seedling quality have also been the topic of 2 specialized workshops (Gadgil and Harris 1980; Duryea 1985); however, although some other results have been published, their uses have been limited (Blake 1987; Aussenac *et al.* 1988; Grossnickle *et al.* 1991). For example, root growth capacity was seen as a physiological variable representing root viability at the time seedlings are outplanted; however, this variable did not always yield a positive relation to field performance (Sutton 1990).

The objective of the work presented in this report is to determine the relationships between morphological and physiological variables and to define a subset of variables that could be used to characterize seedlings in the batches produced.

MATERIALS AND METHODS

In early May 1988, the ministère de l'Énergie et des Ressources du Québec supplied the Laurentian Forestry Centre (LFC) with seedlings from 23 batches grown in containers (Table 1). These batches were selected so as to obtain provenances grown in more than one nursery. The seedlings had been produced for reforestation in the Quebec City administrative region (03) and adjacent management units. On arrival at the LFC, the batches were divided into 4 combinations (Figure 1), each one being made up of seedlings from one species and a given age (species-age combination). Three combinations included two-year-old seedlings grown in 45-110 containers[1]: white spruce (*Picea glauca* [Moench] Voss) (WS, 11 batches), black spruce (*Picea mariana* [Mill.] B.S.P.) (BS, 7 batches) and Norway spruce (*Picea abies* [L.] Karst) (NS, 3 batches). A fourth combination was made up of one-year-old (1+0) black spruce seedlings (BS, 2 batches) grown in smaller containers (67-50).

[1] The containers used were Rigi-Pots (IPL®, Bellechasse, Quebec), either model 45-110 with 45 x 110 cm^3 cavities or model 67-50 with 67 x 50 cm^3 cavities.

Table 1. Identification of batches produced by various forest nurseries

Batch[a]	Nursery	Species-age	Provenance[b]
1[c]	C.P.P.F.Q.[d]	BS 1+0	86-Y-44
2[c]	PAMPEV	" 1+0	86-Y-44
3	GRANDES-PILES	" 2+0	82-N-37
4	GRANDES-PILES	" 2+0	84-A-93
5	SAINT-MODESTE	" 2+0	84-N-67
6	SAINT-MODESTE	" 2+0	84-F-62
7	SAINT-MODESTE	" 2+0	84-I-02
8	SAINTE-LUCE	" 2+0	84-F-62
9	SAINTE-LUCE	" 2+0	84-N-48
10	BECHEDOR	WS 2+0	82-I-46
11	C.P.P.F.Q.	" 2+0	84-Y-03
12	C.P.P.F.Q.	" 2+0	84-M-35
13	DUCHESNAY	" 2+0	74-N-13
14	PAMPEV	" 2+0	84-M-35
15	SAINT-MODESTE	" 2+0	87-X-10
16	SAINT-MODESTE	" 2+0	84-X-01
17	SAINTE-LUCE	" 2+0	74-Y-24
18	SAINTE-LUCE	" 2+0	84-C-74
19[c]	C.P.P.F.Q.	" 2+0	84-M-35
20[c]	PAMPEV	" 2+0	84-X-01
21	BECHEDOR	NS 2+0	84-P-64
22	C.P.P.F.Q.	" 2+0	84-P-64
23	SAINT-MODESTE	" 2+0	84-X-16

[a] Batches were supplied courtesy of the Division de la recherche et du développement sur les semences, boutures et plants (ministère des Ressources naturelles du Québec (MRNQ)).
[b] Provenance code is that of MRNQ in which the first 2 numbers indicate the year seeds were harvested; the letter, the township of origin; and the last 2 numbers, the seigneuries involved.
[c] In these specific cases, the container used was the 67-50 and, for the other batches, the container was model 45-110.
[d] C.P.P.F.Q.: Centre de production de plants forestiers de Québec inc.

On arrival at the LFC, the batches were placed in a glass greenhouse until measurements were taken. Greenhouse conditions were a day-night temperature of 20°/18°C and a 16-h photoperiod, obtained using high-pressure sodium vapour lamps (Sylvania 400 W) lit between 6 a.m. and 10 p.m. and having extreme illuminance values of between 4,000 and 6,500 lux (Weston sunlight illumination meter, model 756). The seedlings were watered using a mobile spray boom with sprinklers so as to maintain the moisture content of the peat substrate at between 50% and 60% of effective saturation. The containers were moved from time to time to ensure uniform water content. After budbreak, in early June, nutrients (equivalent to 8.6 mg of 20-20-20 per cavity) were added to the sprinkling water each week.

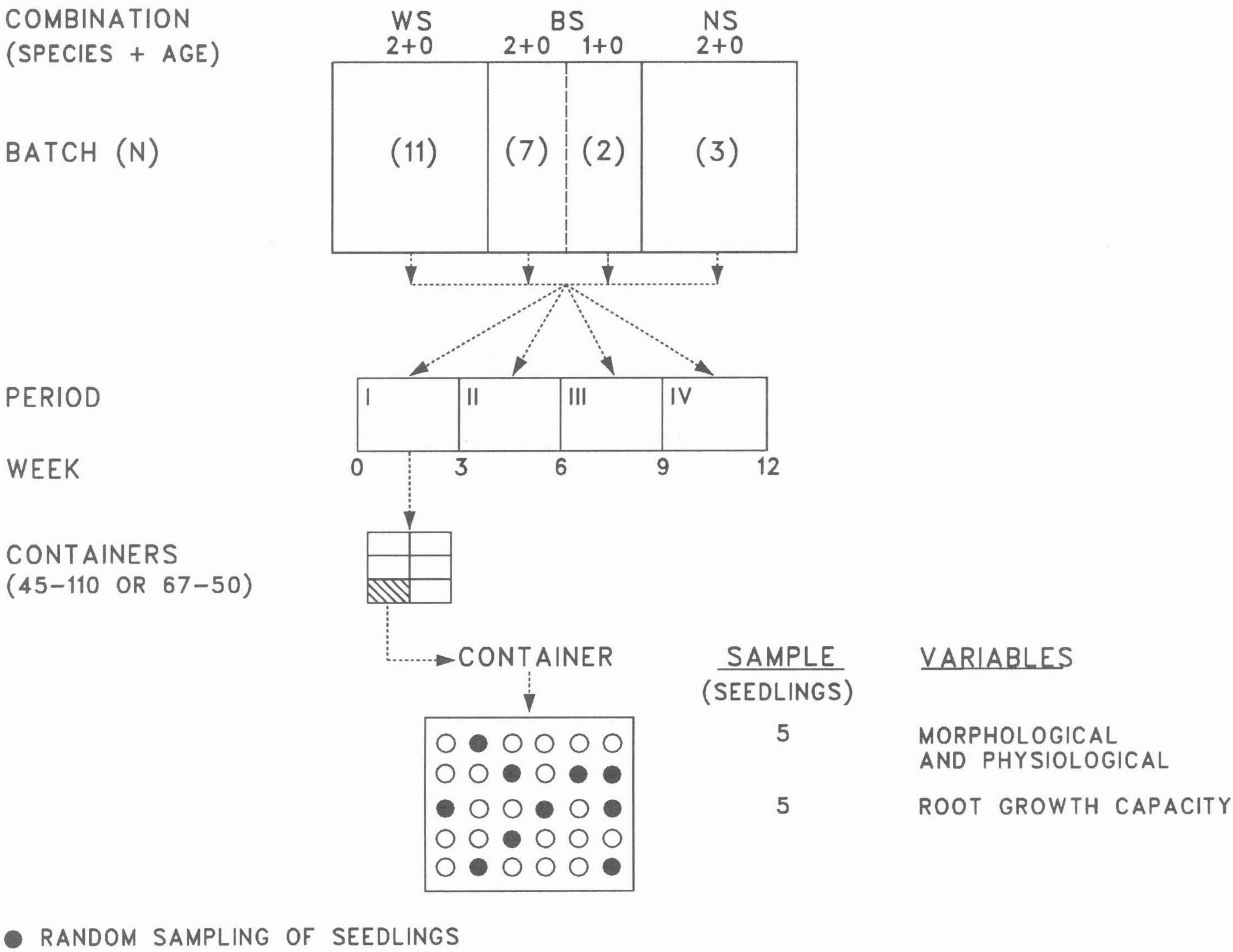

Figure 1. Diagram of batches and seedling sampling procedure.

Since it was impossible to work with all the materials in a short period of time, measurements were spread over 4 three-week periods. All batches were measured during the same period, at the rate of 8 batches per week. The order of batches measured was maintained throughout the 4 periods, to keep a constant time interval between observations of a given batch. Six containers per batch were used for each measurement period.

An initial sample of 5 seedlings per container was selected at random for morpho-physiological observations. Similarly, a second sample was taken from individual containers to assess the root growth capacity of seedlings.

Morphological and physiological measurements

Nine variables were measured on each of 5 seedlings from the first sample (Table 2). The electrical resistance (RES) of the stem was obtained using a probe connected to a «Shigometer» (model 7950, Northeast Electronic, Concord, N.H.). This probe, equipped with 2 fine electrodes 1 cm apart, was inserted into the stem between the first leaves and the base of the seedling. Next, the seedling was cut off at the substrate and the water potential (WP) of the shoots was measured using a pressure chamber (PMS Instruments Co., Corvallis, Oreg.). Also noted were stem height (H), basal diameter (d), shoot fresh mass (SFM) and root fresh mass (RFM). After 24 h in an oven (105°C), the root dry mass (RDM) was determined. The shoot was sealed in a polyethylene bag to be frozen (-20°C). Later on, it was thawed and small quantities of foliar tissue were cut off to determine the osmotic potential (OSP) using the dew point method (model C-52, HR-33T Dew point microvoltmeter, Wescor Inc., Logan, Utah). After this measurement, the sample was recovered and dried with the original shoot to obtain its dry mass (SDM).

Root growth capacity was evaluated on seedlings from the second sample of 5 seedlings (Table 2), which were extracted from their containers and repotted individually in larger containers with peat moss (adaptation by Girouard of the method of Burdett 1979) and kept in a greenhouse (22°/20°C day-night) for one week with periodic watering. The peat moss medium was then broken up, keeping only the original ball, and new white roots over 1 cm long were counted (RGC).

Table 2. Observed morpho-physiological variables and abbreviations[a]

1	RES	Electrical resistance of stem
2	d	Basal diameter
3	H	Stem height
4	WP	Water potential
5	SFM	Shoot fresh mass
6	SDM	Shoot dry mass
7	RFM	Root fresh mass
8	RDM	Root dry mass
9	OSP	Osmotic potential
10	RGC	Root growth capacity

[a] Variables 1 to 9 were observed on the same seedlings, but RGC (No. 10) was calculated on different seedlings.

Principal component analysis (PCA)[1]

With a view to identifying several variables that were good reflections of the information contained in overall observations, a principal component analysis (PCA) was carried out for each species-age combination; first for each period, then for all data collected during the 12 weeks of sampling, as we were able to determine that the results were the same from one period to another and for the whole period. Only the overall results for the 4 periods are presented here. All these PCAs were performed on transformed variables, so as to standardize their marginal distribution and stabilize their variances, then centered and reduced. The procedure used was "FACTORS" (SAS 1990).

Variables were selected using the method described by Jolliffe (1986), which involves the use, in the first stage, of only those components with an eigenvalue higher than 0.7. Then, a variable was selected to represent each component. The variable selection procedure began with the component with the highest eigenvalue and continued to the lowest eigenvalue greater than 0.7. For each of these components, the variable with the highest loading in

[1] More details on principal component analysis can be found in Duntenam (1989), Lebart *et al.* (1982), Kleinbaum and Kupper (1978).

absolute terms was then selected. If a variable had already been selected, the second variable with the highest loading was used.

To calculate the importance of the variables selected, we used the following criterion, based on the total variance explained by the selected variables (Jolliffe 1986). This total variance is calculated using the following formula:

$$S^2_{total} = n_r + \sum_{i=1}^{d} R^2_{i,r}$$

where n_r is the number of retained variables; $R^2_{i,r}$, the multiple correlation coefficient obtained by regression of the ith excluded variable over the r retained variables, and d, the number of excluded variables.

Nine morpho-physiological variables were observed on 5 seedlings from the same container, using 6 containers per batch and period. The tenth variable, root growth capacity, was however calculated on 5 separate seedlings from the same containers. Since these variables were measured on different seedlings, we ran the PCA using means of variables per container. Ideally, PCA requires 10 times more observations than variables (Nunnally 1967). This requirement was satisfied only with 2+0 WS and 2+0 BS, with means per container that provided 190 and 123 observations respectively on each of the 10 variables.

In addition, for the 4 combinations, PCAs were rerun with the 9 morpho-physiological variables, leaving aside RGC.

PCA was based on the Pearson correlation matrix, the significance of which had been assessed beforehand using a Bonferoni test.

RESULTS

Selection of variables to characterize combinations studied

For combinations with a sufficient number of batches (2+0 WS and 2+0 BS), Tables 3a and 3b show the correlation matrices based on the means per tray used for PCAs. There are a number of significant correlations between observed variables, which justifies a more detailed analysis of these relations. The initial results of PCA are eigenvalue, percentage of total variance explained, cumulative percentage for each component with an eigenvalue greater than 0.7 and loadings of observed variables (Tables 4a and 4b). For these 2 combinations, the first 4 components were selected. These explain 89% and 85% of total variance of batches of white spruce (2+0) and black spruce (2+0) respectively. The variables used to characterize the first 4 components were respectively d, WP, RGC and OSP in the case of 2+0 WS and d, WP, H and RGC for 2+0 BS (Tables 4a and 4b).

Table 3a. Pearson correlation matrix between observed variables for batches of 2+0 white spruce

Variable[a]	RES	d	H	WP	SFM	SDM	RFM	RDM	OSP	RGC
RES		- 0.61[b]	- 0.12	0.55[b]	- 0.26[c]	- 0.28[b]	- 0.58[b]	- 0.45[b]	0.14	- 0.32[b]
d			0.50[b]	-0.21	0.74[b]	0.77[b]	0.80[b]	0.78[b]	- 0.32[b]	0.23
H				0.09	0.78[b]	0.77[b]	0.26[c]	0.22	- 0.51[b]	0.26[c]
WP					0.14	0.12	- 0.22	- 0.08	0.16	- 0.25[c]
SFM						0.97[b]	0.62[b]	0.65[b]	- 0.44[b]	0.09
SDM							0.63[b]	0.69[b]	- 0.38[b]	0.11
RFM								0.94[b]	- 0.23	0.06
RDM									- 0.12	- 0.02
OSP										- 0.29[b]
RGC										

[a] Variables identified in Table 2.
[b] Significant at ∝ level = 0.01 (189 d.l.).
[c] Significant at ∝ level = 0.05 (189 d.l.).

Table 3b. Pearson correlation matrix between observed variables for batches of 2+0 black spruce

Variable[a]	RES	d	H	WP	SFM	SDM	RFM	RDM	OSP	RGC
RES		- 0.48[b]	- 0.29	0.57[b]	- 0.12	- 0.11	- 0.41[b]	- 0.26	0.46	- 0.28
d			0.45[b]	- 0.07	0.56[b]	0.58[b]	0.72[b]	0.64[b]	- 0.13	0.18
H				0.07	0.71[b]	0.71[b]	0.29[c]	0.22	- 0.30[c]	0.19
WP					0.19	0.24	- 0.06	- 0.11	0.51[b]	- 0.22
SFM						0.94[b]	0.52[b]	0.47[b]	- 0.09	- 0.07
SDM							0.50[b]	0.48[b]	- 0.02	- 0.01
RFM								0.88[b]	- 0.13	0.11
RDM									- 0.04	0.16
OSP										- 0.22
RGC										

[a] Variables identified in Table 2.
[b] Significant at ∝ level = 0.01 (122 d.l.).
[c] Significant at ∝ level = 0.05 (122 d.l.).

Table 4a. Variable loadings, eigenvalue and percentages of variance associated with each principal component, obtained using means per container, for batches of 2+0 white spruce

Variable[a]	Factor 1	Factor 2	Factor 3	Factor 4
RES	-0.56796	0.68159	0.04901	-0.08814
d	0.91722	-0.15372	0.08390	0.07023
H	0.66783	0.47308	-0.41933	0.00969
WP	-0.15386	0.80445	0.26854	0.33012
SFM	0.89293	0.38737	0.00134	-0.00893
SDM	0.90475	0.35500	0.03890	0.05516
RFM	0.83943	-0.26682	0.35601	-0.04871
RDM	0.81351	-0.13071	0.48478	0.03021
OSP	-0.46951	-0.14444	0.60540	0.49558
RGC	0.24792	-0.27683	-0.69831	0.55222
Eigenvalue	4.8978	1.8210	1.4748	0.6787
Percentage of variance	0.4898	0.1821	0.1475	0.0679
Cumulative percentage	0.4898	0.6719	0.8194	0.8872

[a] Variables identified in Table 2.

Table 4b. Variable loadings, eigenvalue and percentages of variance associated with each principal component, obtained using means per container, for batches of 2+0 black spruce

Variable[a]	Factor 1	Factor 2	Factor 3	Factor 4
RES	-0.48086	0.70612	-0.11501	0.16771
d	0.83896	-0.00725	0.23218	0.00223
H	0.70410	-0.04108	-0.58892	0.15999
WP	-0.01665	0.85441	0.07455	0.22690
SFM	0.82684	0.33253	-0.35646	-0.07077
SDM	0.82661	0.36806	-0.33312	0.02401
RFM	0.81682	-0.02780	0.46410	-0.15835
RDM	0.75156	0.12744	0.54922	0.00250
OSP	-0.24043	0.70488	0.33560	0.14045
RGC	0.20111	-0.46751	0.12298	0.84432
Eigenvalue	4.1284	2.2088	1.3023	0.8685
Percentage of variance	0.4128	0.2209	0.1302	0.0868
Cumulative percentage	0.4128	0.6337	0.7640	0.8508

[a] Variables identified in Table 2.

Table 5 shows the values of multiple correlation coefficients between chosen and excluded variables based on the PCA calculated using means per container in the case of 2+0 WS and 2+0 BS. The total variance explained by the variables chosen was 77% for 2+0 WS and 72% for 2+0 BS.

In the second stage, PCAs were rerun for the 4 species-age combinations, but excluding root growth capacity and proceeding with individual data. For two-year-old species, 3 principal components were used, while for one-year-old black spruce, 4 were selected (Table 6). The fractions of total variance explained by the components chosen, using the 0.7 rule, were 83, 80, 88 and 85% respectively for combinations of 2+0 WS, 2+0 BS, 1+0 BS and 2+0 NS. If we used only 3 components for 1+0 BS, since its fourth component had an extreme eigenvalue of 0.7, the percentage of total variance explained by the first 3 components would decrease from 88% to 81% and would thus be as good as that of 2+0 BS, which stood at 80%.

Table 5. Percentage of variance (S^2) explained and multiple correlation coefficients calculated by regression of excluded variables over retained variables, using means per container, for 2+0 white spruce and 2+0 black spruce

Species-age	Variables[a]										
	RES	H	d	WP	SFM	SDM	RFM	RDM	OSP	RGC	S^2 (%)
WS 2+0	0.58	0.44	1.00[b]	1.00	0.70	0.71	0.66	0.65	1.00	1.00	77.4
BS 2+0	0.59	1.00	1.00	1.00	0.66	0.68	0.53	0.43	0.34	1.00	72.3

[a] Variables identified in Table 2.
[b] The variables chosen have a unit value as their multiple correlation coefficient.

Table 6. Eigenvalue and percentages of variance associated with each principal component, obtained using individual values of observed variables, for 4 species-age combinations

Combination	PCA	Component			
		1	2	3	4
WS 2+0	Eigenvalue	5.06	1.45	0.99	0.60
	Percentage of variance	0.56	0.16	0.11	0.07
	Cumulative percentage	0.56	0.72	0.83	0.90
BS 2+0	Eigenvalue	4.73	1.39	1.05	0.65
	Percentage of variance	0.53	0.15	0.12	0.07
	Cumulative percentage	0.53	0.68	0.80	0.87
BS 1+0	Eigenvalue	4.96	1.50	0.80	0.70
	Percentage of variance	0.55	0.17	0.09	0.07
	Cumulative percentage	0.55	0.72	0.81	0.88
NS 2+0	Eigenvalue	5.63	1.22	0.78	0.50
	Percentage of variance	0.63	0.13	0.09	0.05
	Cumulative percentage	0.63	0.76	0.85	0.90

Representative variables for each of the components selected (Tables 7a, 7b, 7c and 7d) were, by order of components, SFM, WP and OSP for 2+0 WS; SFM, WP and H for 2+0 BS; SFM, OSP, RES and WP for 1+0 BS and SFM, WP and OSP for 2+0 NS. Two variables were found systematically in the 4 sets thus selected: SFM and WP, and a third variable (OSP) was selected in three cases out of four.

Table 7a. Variable loadings in 3 principal components, obtained using individual values of observed variables, for batches of 2+0 white spruce

Variable[a]	Factor 1	Factor 2	Factor 3
RES	-0.64997	0.47200	0.08144
d	0.90702	-0.14478	0.02650
H	0.70228	0.50649	-0.11219
WP	-0.05187	0.72200	0.55034
SFM	0.92497	0.26375	0.00537
SDM	0.92392	0.23694	0.08142
RFM	0.87763	-0.28551	0.10766
RDM	0.86937	-0.24293	0.21704
OSP	-0.29383	-0.40409	0.77302

[a] Variables identified in Table 2.

Table 7b. Variable loadings in 3 principal components, obtained using individual values of observed variables, for batches of 2+0 black spruce

Variable[a]	Factor 1	Factor 2	Factor 3
RES	-0.67518	0.31530	0.33646
d	0.82343	0.19715	-0.12894
H	0.72393	-0.24310	0.48423
WP	-0.14303	0.71441	0.53177
SFM	0.90859	-0.03737	0.27265
SDM	0.90436	0.08305	0.27126
RFM	0.83354	0.26325	-0.32129
RDM	0.78585	0.36038	-0.30481
OSP	-0.31283	0.68751	-0.23384

[a] Variables identified in Table 2.

Table 7c. Variable loadings in 4 principal components, obtained using individual values of observed variables, for batches of 1+0 black spruce

Variable[a]	Factor 1	Factor 2	Factor 3	Factor 4
RES	-0.64888	0.16929	0.39692	0.50320
d	0.80273	0.19564	0.08024	-0.11530
H	0.85498	-0.19405	0.35059	0.07422
WP	-0.15847	0.75276	0.30517	-0.51515
SFM	0.93740	-0.07850	0.25663	0.06465
SDM	0.90733	0.10612	0.29823	0.11926
RFM	0.86210	0.16649	-0.35858	0.12257
RDM	0.76778	0.42203	-0.36241	0.13630
OSP	-0.32313	0.78066	-0.05564	0.32542

[a] Variables identified in Table 2.

Table 7d. Variable loadings in 3 principal components, obtained using individual values of observed variables, for batches of 2+0 Norway spruce

Variable[a]	Factor 1	Factor 2	Factor 3
RES	-0.76200	0.10329	0.12240
d	0.91768	0.08266	0.01385
H	0.82353	-0.13352	0.24477
WP	-0.15049	0.79029	0.56654
SFM	0.95696	0.06824	0.06728
SDM	0.93698	0.19564	0.01691
RFM	0.92290	0.08082	-0.16939
RDM	0.85643	0.17883	-0.18664
OSP	-0.35452	0.69003	-0.56471

[a] Variables identified in Table 2.

In PCAs based on means per container, 4 variables were sufficient to explain more than 72% of total variance (Table 5). In PCAs based on observations of each seedling, but excluding RGC, the variables selected enable us to explain between 62% and 81% of total variance (Table 8): 3 variables were selected for the 2+0 seedlings and 4 variables for the one-year-old seedlings. The choice of these various explanatory variables is the result of an essentially mathematical approach, which is aimed only at maximum variance explanation and does not take into account either biological significance or the acquisition cost of observations. To remedy this problem and meet the needs of certain nurserymen who use variables other than those selected, we then evaluated the different subsets of variables to determine their predictive potential.

Table 8. Percentage of variance (S^2) explained and multiple correlation coefficients calculated by regression of excluded variables over retained variables, using individual values of observed variables, for 2+0 white spruce, 2+0 black spruce, 1+0 black spruce and 2+0 Norway spruce

Species-age	Variables[a,b]									
	RES	H	d	WP	SFM	SDM	RFM	RDM	OSP	S^2 (%)
WS 2+0	0.33	0.64	0.64	1	1	0.94	0.54	0.54	1	73.7
BS 2+0	0.32	1	0.39	1	1	0.93	0.43	0.40	0.17	62.7
BS 1+0	1	0.79	0.56	1	1	0.93	0.55	0.47	1	81.1
NS 2+0	0.45	0.72	0.74	1	1	0.95	0.73	0.57	1	79.6

[a] Variables identified in Table 2.
[b] The variables chosen have a unit value as their multiple correlation coefficient.

Choice of other variables to characterize combinations studied

The subsets of variables were chosen using variable loading graphs on the first 3 components, represented on 3 axes (Figures 2a to 2d). These components were obtained using individual values of variables for the 4 combinations. The variable points on the first axis (Factor 1) fall on either side of the origin (shaded area). For the 4 combinations, the 6 morphological variables (d, H, SFM, SDM, RFM and RDM) lie above this area, while the 3 physiological variables selected (RES, WP and OSP) lie below it. This distribution above and below the shaded area indicates that the variables may be positively or negatively correlated. Moreover, the proximity of variable points, compared with components 1 and 2, illustrates the importance of the correlation that exists between the variables, and this is reinforced as the points fall farther from the shaded area. Graphic representation, based on means per container, yields basically the same distribution of variables (Figures 3a and 3b) as in the previous figures, except that the RGC in these analyses lies in the positive part of the first component.

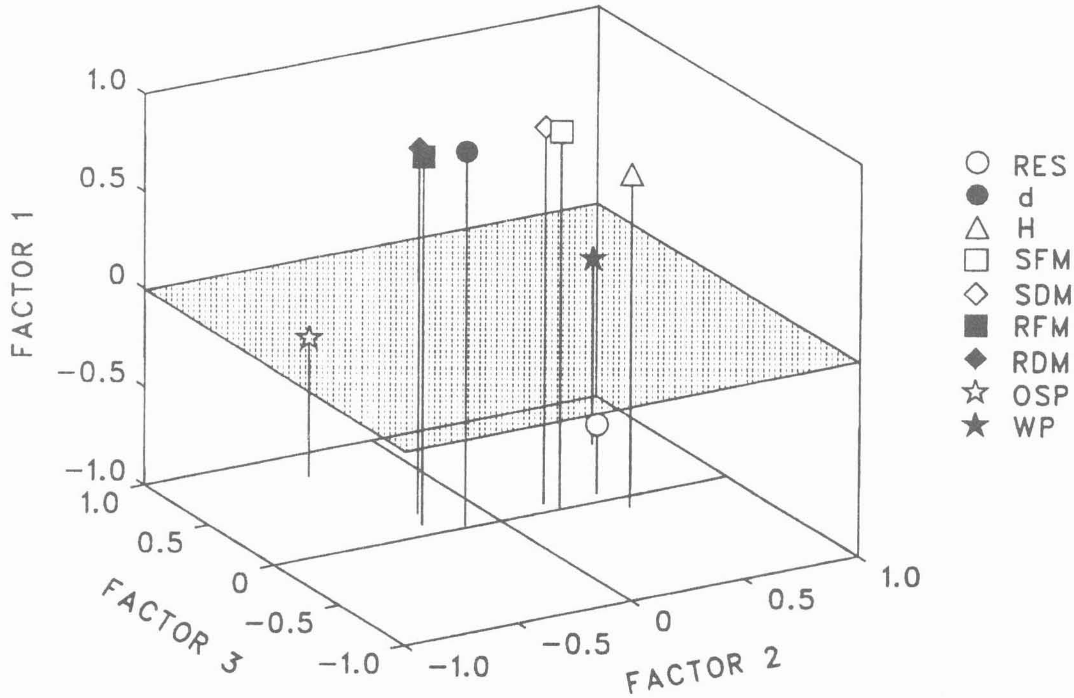

Figure 2a. Projection of loadings of 9 observed variables in the space of 3 principal components; analysis based on individual values for 2+0 white spruce.

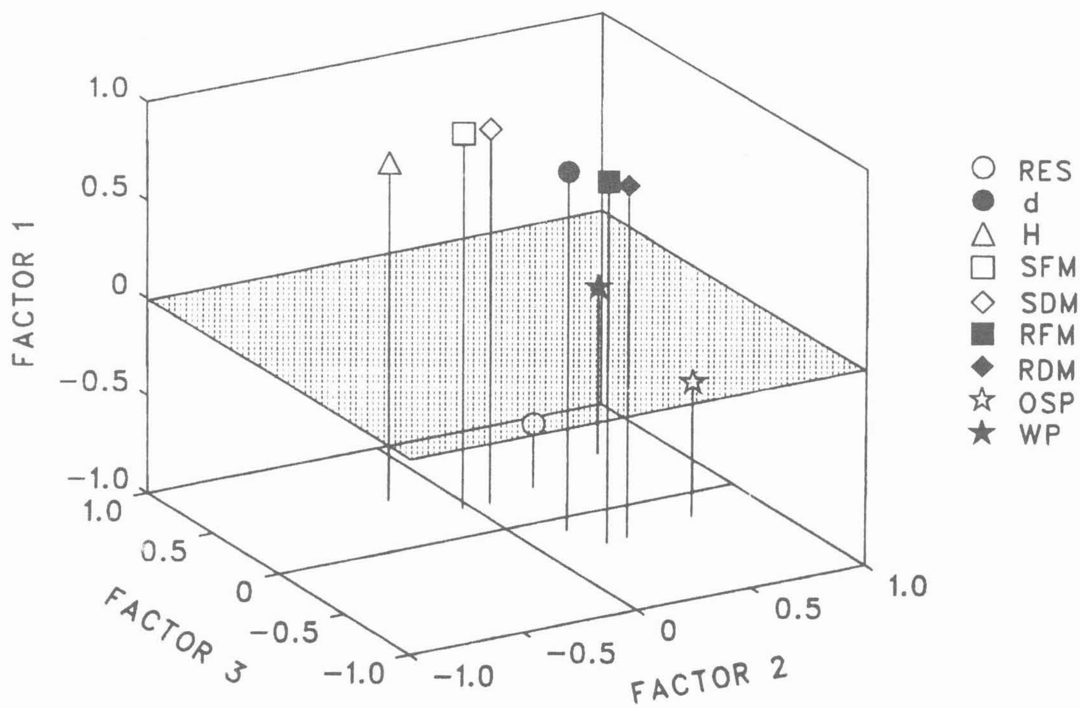

Figure 2b. Projection of loadings of 9 observed variables in the space of 3 principal components; analysis based on individual values for 2+0 black spruce.

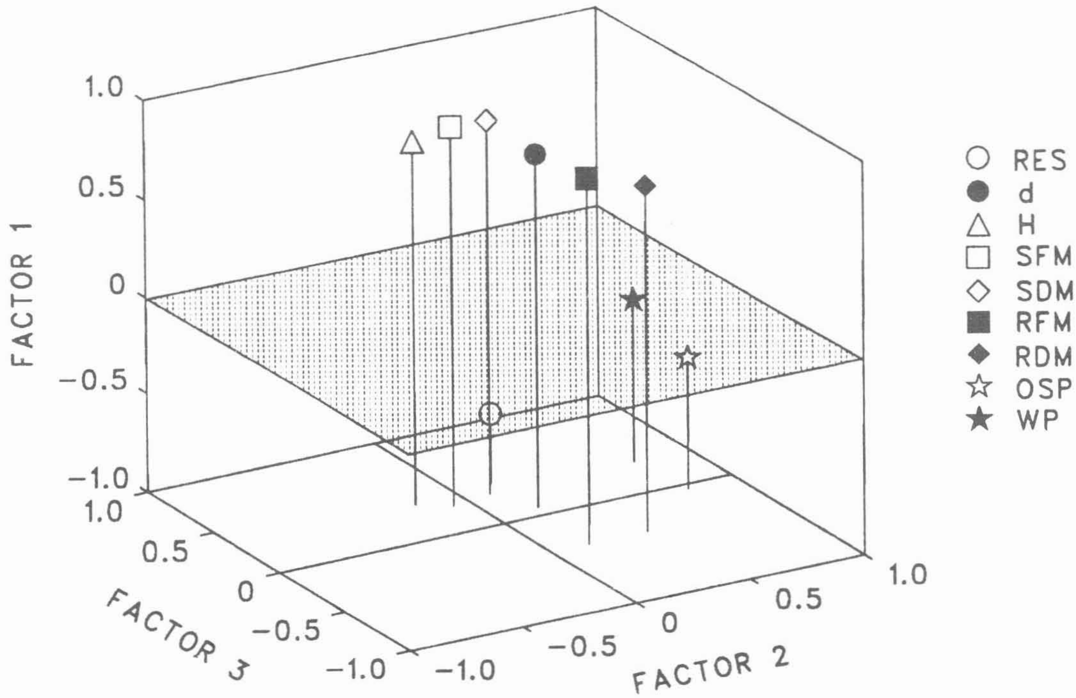

Figure 2c. Projection of loadings of 9 observed variables in the space of 3 principal components; analysis based on individual values for 1+0 black spruce.

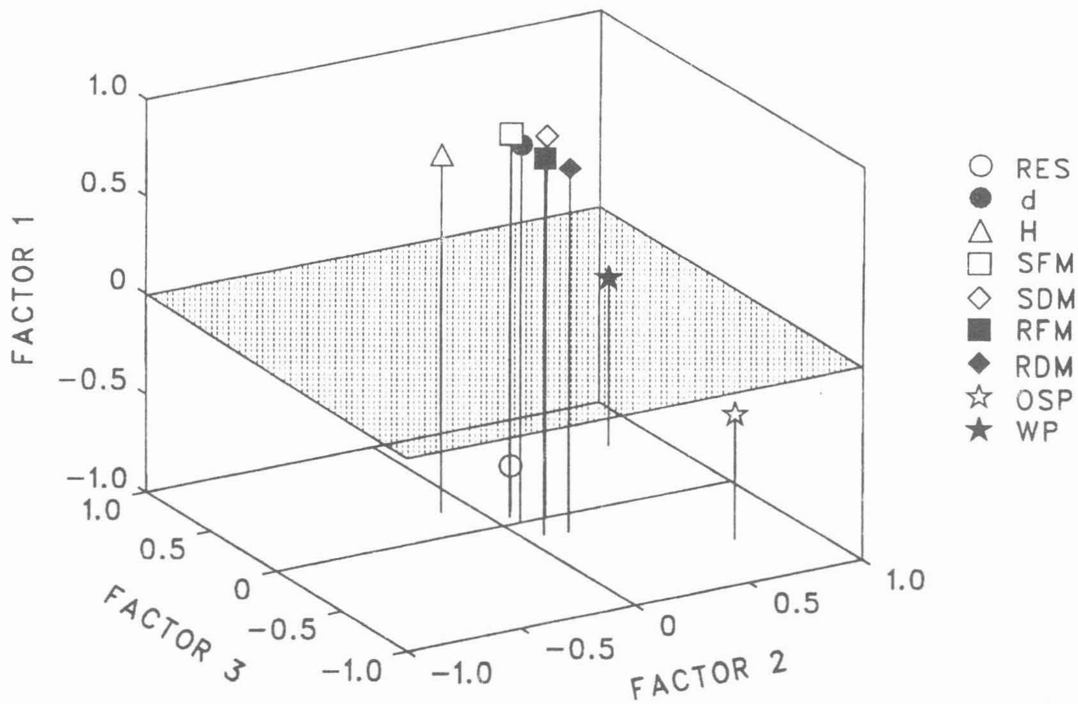

Figure 2d. Projection of loadings of 9 observed variables in the space of 3 principal components; analysis based on individual values for 2+0 Norway spruce.

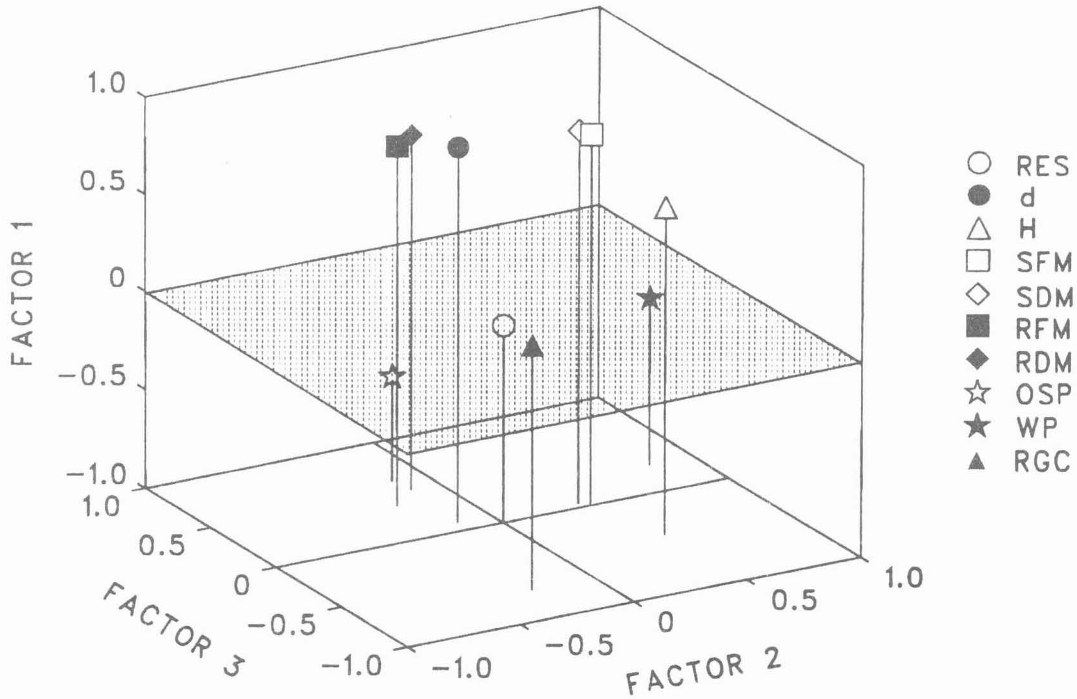

Figure 3a. Projection of loadings of 10 observed variables in the space of 3 principal components; analysis based on means for 2+0 white spruce.

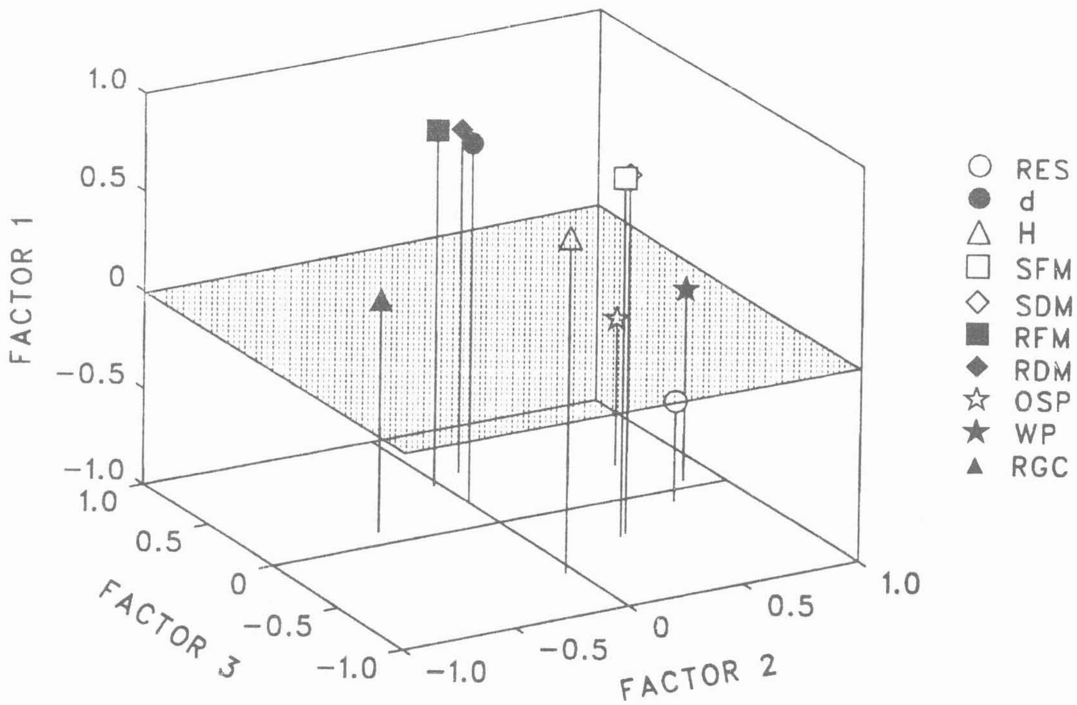

Figure 3b. Projection of loadings of 10 observed variables in the space of 3 principal components; analysis based on means for 2+0 black spruce.

Figures 2 and 3 illustrate the combination of 2 sets of variables, the first being made up of variables H, SFM and SDM, and the second comprising variables d, RFM and RDM. In three cases out of four, biomass of the roots is separate from that of the shoots. For Norway spruce, however, these morphological variables are together. Stem height (H) thus provides a fairly good estimate of shoot biomass, while diameter (d) reflects that of roots.

A weaker association was observed between water and osmotic potentials in the case of 2+0 and 1+0 BS, as well as for 2+0 NS (Figures 2b, 2c and 2d). However, this association does not seem to be confirmed for 2+0 WS (Figure 2a), and the importance of these two potentials in characterizing the seedlings produced remains to be assessed.

Although significant in certain cases, the correlations between RGC and the other variables were generally weak (Table 2a). The distance of this variable from the others would tend to confirm this trend (Figures 3a and 3b). It is likely that this weak association between RGC and the other variables was due to the fact that a different seedling sample was used to assess this physiological root variable. As a result, the role of RGC in characterizing seedlings produced remains unclear.

Electrical resistance (RES) is closely linked to diameter (Tables 3a and 3b). Moreover, as mentioned above, redundancy was noted between diameter and root biomass (Figures 2a and 2b). Because of these many relations between RES and certain morphological variables, it does not seem necessary to use this variable in characterizing batches of spruce. This variable was selected in previous stages only for 1+0 BS, for which it characterized the third principal component.

The foregoing analyses (PCA) indicate 7 variables (WP, OSP, SFM, d, H, RGC, and RES) that best characterized the batches studied. Graphic analysis of the 3 principal factors (Figures 2 and 3) brought out certain associations between variables, and more specifically between morphological variables. Thus, stem height, which is very significantly correlated with the shoot biomass of the seedlings, makes it possible to envisage this type of replacement and, as indicated above, RES does not appear to be indispensable. As a result, 5 variables out of 7 were withheld to characterize batches of seedlings. These variables were WP, OSP, H, d and RGC.

Using the 5 variables chosen, the calculation previously described was carried out for the selected variables to obtain the level of explanation of total variance for various subsets of these variables (Table 9). These calculations clearly show that the 2 morphological variables chosen (H and d) explain between 46.5% and 60.9% of total variation, that the addition of a third variable (WP) brings this percentage up to rates of 63.1% to 73.2%, and that the addition of a fourth (RGC) raises this by about 10%. Conversely, if WP is replaced by OSP in the foregoing subsets, the average level of explanation is reduced by 2.8%. This latter variable (OSP) thus carries a little less information than WP in characterizing seedlings.

In all, selection of a small number of variables in characterizing seedlings intended for reforestation shows that, independent of the species-age combinations used, 4 variables (H, d, WP and RGC) explain approximately 75% of total variance.

Table 9. Percentage of total variance explained by various subsets of retained variables for 2+0 white spruce, 2+0 black spruce, 1+0 black spruce and 2+0 Norway spruce

Subsets of variables[a]	2+0 WS[b]	2+0 BS[b]	1+0 BS[c]	2+0 NS[c]
H+d	54.2	46.5	53.2	60.9
H+d+WP	69.2	63.2	66.9	73.2
H+d+WP+RGC	78.7	72.3	-	-
H+d+OSP	63.4	60.4	66.5	71.1
H+d+OSP+RGC	75.1	70.2	-	-

[a] Variables were stem height (H), diameter (d), water potential (WP), osmotic potential (OSP) and root growth capacity (RGC).
[b] For the variables involved, means per container were used.
[c] For the variables involved, except for root growth capacity, individual values per seedling were used.

DISCUSSION

As indicated previously, the height and diameter variables reflect the biomass of cultivated seedlings: stem height is associated with the shoots, while diameter is generally correlated to the root system. Together, these 2 morphological variables reflect on average 54% of total observed variation with the 10 morpho-physiological variables. These 2 variables are mentioned in the literature as being correlated with long-term field performance (Wakeley 1969; Mexal and Landis 1990). Moreover, these same variables remain the preferred choices of forest nurserymen, since they can easily be measured and these measurements are not destructive to seedlings. When producing seedlings for reforestation, the dimensions of the target seedling may be adjusted to offset problems (dryness, competition) in the reforestation site (Todd 1989). Invariably, however, the larger the seedlings, the better they will perform (Todd 1989; Racey *et al.* 1989; Duddles and Owston 1990). In Quebec, despite a major decline in nursery production of seedlings, that is 145 million seedlings in 1993 compared with 250 million in 1990, the Service de production de plants (MRNQ)[1] set itself the objective of producing 40 million large-sized seedlings in the near future. Although there are certain advantages to these seedlings, we must nevertheless exercise caution and take into account the balance between the shoots and the roots, and more specifically the water relations of seedlings produced and used for reforestation (Thompson 1985; Burdett 1990).

The other important variable, water potential, reflects an average of 14% of total variance in all 10 observed variables for our 4 combinations. This physiological variable characterizes the second principal component of the factorial analysis that contrasts with the first, essentially morphological, component. It is difficult to interpret water potential values in a biological sense (Lopushinsky 1990), but it was observed that the lower the WP (more negative), the less water there is available for the physiological and metabolic reactions of seedlings.

---

[1] Information supplied by Mr. Jean-Guy Brouillette.

In addition to daily variations in WP (McDonald and Running 1979), an increase was also observed during the 4 periods, as well as significant variations between containers of certain batches. These variations indicate that problems might occur when measuring this physiological variable. Thus, to reduce daily variations, biological material should be taken for sampling before sunrise or as soon as supplemental lighting is turned on, then left in darkness until measuring is done. In the case of variance associated with period, this could be controlled by keeping biological material in cold storage to prevent budbreak and predetermined growth. Variation between containers might be due to a lack of uniformity in watering, different evapotranspiration between containers, different substrate grain sizes or compaction of growing medium in individual cells. These latter variations are mainly due to rearing practices and thus require special attention by the producer. All these variations in WP may cause water stress that varies in degree and duration for cultivated seedlings, thus causing a probable change in the ability of seedlings to acclimatize (Levitt 1980; Blake 1987).

Another variation of WP is that associated with various batches. Certain batches in fact maintained low readings throughout the 4 measurement periods, while others showed higher or intermediate values. Unfortunately, our experimental design and the spreading of measurements over time prevented us from determining whether it was the provenance or the nursery that was responsible for this situation. Blake (1987), however, measured the differences associated with genetic material and the type of seedling produced.

Recording water stress using a pressure chamber is now common practice in nurseries (McDonald and Running 1979). Notwithstanding the special attention the measurement of water potential requires, it should enable us to quantify the water status of seedlings under specific conditions before using them for reforestation.

Root growth capacity is the last variable selected as being representative of a major principal component. This variable, when calculated in relation to the 9 other morphological variables, shows a level of explanation close to 10% of total variance for 2+0 WS and 2+0 BS. It was not possible to calculate the importance of this variable for 1+0 BS and NS because of the limited number of batches in these cases.

As indicated previously, the main problem with using RGC is that seedlings different from those that provided morpho-physiological variables were used to calculate RGC. However, this statistical restriction should not diminish the biological importance of RGC in evaluating seedlings for reforestation (Ritchie and Tanaka 1990).

RGC appears to be an important variable in predicting seedling survival potential in the field (Ritchie and Dunlap 1980). However, seedling performance in the field is not always closely linked to the RGC calculated before outplanting (Sutton 1990). For example, it would appear that temperature is a critical factor for rhizogenesis (Ritchie and Tanaka 1990). Calculation of RGC at a high temperature would thus indicate a potential for good environmental conditions. This variable consequently remains of definite interest for characterizing batches of seedlings.

For the nursery operator, measuring this variable requires additional personnel to carry out manipulations and more time to make observations. However, this qualification of the root systems of seedlings intended for reforestation does not make it possible to predict the viability of seedlings for all field conditions (Langerud 1991).

CONCLUSION

1. Morphological variables remain significant variables in characterizing batches of containerized seedlings. Stem height and diameter alone explain over 50% of total variance in seedlings produced.

2. Physiological variables show little relation either to one another or to observed morphological variables. Water potential and root growth capacity nevertheless have a significant impact on the overall characteristics of seedlings.

ACKNOWLEDGEMENTS

This project could not have been carried out without the invaluable assistance of Mr. Charles-Gilles Langlois (MRNQ - Division semences, boutures et plants) in obtaining batches of seedlings. Special thanks also go to Mr. Guy Claveau, who performed the initial analyses and Messrs. Pierre-Yves Bernier and Guy Prégent for their constructive remarks. We would like to express our appreciation to all the members of the project team (summer 1988) for their collaboration and, in particular, Mrs. Diane Trudel and Messrs. Pierre Davignon, Roger Mongrain, René Turcotte and Charles S. Wolff.

LITERATURE CITED

Arnott, J.L. 1974. Performance in British Columbia. Pages 283-290 *in* R.W. Tinus, W.I. Stein and W.E. Balmer, eds. Proc. North Am. Containerized For. Tree Seedling Symp. Denver, Colo., Aug. 26-29, 1974. B.C. For. Serv., Environ. Can., Can. For. Serv., Pacific For. Res. Cent., Victoria, B.C. Great Plains Agric. Counc. Publ. No. 68.

Aussenac, G.; Guehl, J.M.; Kaushal, P.; Granier, A.; Grieu, P. 1988. Critères physiologiques pour l'évaluation de la qualité des plants forestiers avant plantation. Rev. for. fr. 40 (numéro spécial, 1988): 131-139.

Barbulescu, A. 1982. An integrated industrial system for the production of tree seedling containers. Pages 225-229 *in* J.B. Scarratt, C. Glerum, and C.D. Plexman, eds. Proc. Canadian Containerized Tree Seedling Symposium. Toronto, Ont., Sept. 14-16, 1981. Can. Dep. Environ., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont. COJFRC Symp. Proc. O-P-10.

Blake, T.J. 1987. Physiological mechanisms affecting adaptation to site and early plantation performances. Page 47 *in* Ontario Ministry of Natural Resources Fitness for Purpose. Proc. Stock Standards and Early Planting Performance. Timmins, Ont., Dec. 1-4, 1986. Queen's Printer for Ontario, Toronto, Ont.

Burdett, A.N. 1979. New methods for measuring root growth capacity: their value in assessing lodgepole pine stock quality. Can. J. For. Res. 9: 63-67.

Burdett, A.N. 1990. Physiological processes in plantation establishment and the development of specifications for forest planting stock. Can. J. For. Res. 20: 415-427.

Carlson, L.W. 1979. Guidelines for rearing containerized conifer seedlings in the Prairie Provinces. Environ. Can., Can. For. Serv., Northern For. Res. Cent., Edmonton, Alta. Inf. Rep. NOR-X-214E.

D'Aoust, A.L. 1978. La physiologie des semis d'épinette noire (*Picea mariana* [Mill.] B.S.P.) en contenants. Environ. Can., Serv. can. for., Cent. rech. for. Laurentides, Sainte-Foy, Qc. Rapp. inf. LAU-X-35.

D'Aoust, A.L. 1980. Influence de la concentration d'un engrais chimique sur la croissance et les échanges gazeux de semis d'épinette noire en conteneurs. Nat. Can. 107: 125-133.

Dobbs, R.C. 1976. Effect of initial mass of white spruce and lodgepole pine planting stock on field performance in the British Columbia interior. Environ. Can., Can. For. Serv., Pacific For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-149.

Duddles, R.E.; Owston, P.W. 1990. Performances of Conifer Stocktypes on National Forests in the Oregon and Washington Coast Ranges. Pages 263-268 *in* R. Rose, S.J. Campbell, and T.D. Landis, eds. Target Seedling Symposium: Proc., Combined Meeting of the Western Forest Nursery Associations. Roseburg, Oreg., Aug. 13-17, 1990. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Ft. Collins, Colo., Gen. Tech. Rep. RM-200.

Dunteman, G.H. 1989. Principal Components Analysis. *In* M.S. Lewis-Beck, ed. Quantitative Applications in the Social Sciences Series, No. 69. Sage Univ. Pap., Newbury Park, Calif.

Duryea, M.L., ed. 1985. Evaluating seedling quality: principles, procedures and predictive abilities of major tests. Proc. Workshop. Corvallis, Oreg., Oct. 16-18, 1984. For. Res. Lab., Oreg. State Univ., Corvallis, Oreg.

Duryea, M.L.; Brown, G.N., eds. 1984. Seedling physiology and reforestation success. Proc. Physiol. Working Group, technical session. Soc. Am. For., National Convention, Oct. 16-20, 1983, Portland, Oreg., Martinus Nijhoff/Dr. W. Junk Publ. Dordrecht, The Netherlands.

Gadgil, P.D.; Harris, J.M., eds. 1980. Planting stock quality. N. Z. J. For. Sci. (special issue) 10(1), 303 p.

Grossnickle, S.C.; Arnott, J.T.; Major, J.E.; Tschaplinski, T.J. 1991. Influence of dormancy induction treatments on western hemlock seedlings. I. Seedling development and stock quality assessment. Can. J. For. Res. 21: 164-174.

Jolliffe, I.T. 1986. Principal Component Analysis. Springer-Verlag, New York, N.Y.

Kleinbaum, D.G.; Kupper, L.L. 1978. Applied regression analysis and other multivariable methods. Duxbury Press, North Scituate, Mass.

Langerud, B.R. 1991. Planting stock quality: a proposal for better terminology. Scand. J. For. Res. 6: 49-51.

Lebart, L.; Morineau, A.; Fénélon, J.-P. 1982. Traitement des données statistiques: méthodes et programmes. Dunod, Paris.

Levitt, J. 1980. Responses of Plants to Environmental Stresses. 2nd ed., Vol. 1. Chilling, freezing and high temperature stresses. Academic Press, New York, N.Y.

Lopushinsky, W. 1990. Seedling moisture status. Pages 123-138 *in* R. Rose, S.J. Campbell, and T.D. Landis, eds. Target Seedling Symposium: Proc., Combined Meeting of the Western Forest Nursery Associations. Roseburg, Oreg., Aug. 13-17, 1990. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Ft. Collins, Colo., Gen. Tech. Rep. RM-200.

Matthews, R.G. 1971. Container seedling production: a provisional manual. Environ. Can., Can. For. Serv., Pacific For. Res. Cent., Victoria, B.C. Inf. Rep. BC-X-58.

McDonald, S.E.; Running, S.W. 1979. Monitoring irrigation in western forest nurseries. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exper. Stn., Ft. Collins, Colo., Gen. Tech. Rep. RM-61.

Mexal, J.G.; Landis, J.D. 1990. Target seedling concept: height and diameter. Pages 17-36 *in* R. Rose, S.J. Campbell, and T.D. Landis, eds. Target Seedling Symposium: Proc., Combined Meeting of the Western Forest Nursery Associations. Roseburg, Oreg., Aug. 13-17, 1990. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Ft. Collins, Colo., Gen. Tech. Rep. RM-200.

Nunnally, J.C. 1967. Psychometric Theory. McGraw-Hill, New York, N.Y.

Ontario Ministry of Natural Resources. 1987. Proc. Fitness for purpose: stock production development activity. Meeting Dec. 1-4, 1986, Timmins, Ont. (separate pagination). Queen's Printer for Ontario, Toronto, Ont.

Racey, G.D.; Glerum, C.; Hutchison, R.E. 1989. Interaction of stock type and site with three coniferous species. Ont. Minist. Nat. Resour., Ont. For. Res. Inst., Maple, Ont. For. Res. Rep. No. 124.

Reed, F.L.C. 1982. You can choose your future in forestry. Pulp and Paper Canada 83(8): 33-36.

Ritchie, G.A.; Dunlap, J.R. 1980. Root growth potential: its development and expression in forest tree seedlings. N. Z. J. For. Sci. 10(1): 218-248.

Ritchie, G.A.; Tanaka, Y. 1990. Root growth potential and the target seedling. Pages 37-51 *in* R. Rose, S.J. Campbell, and T.D. Landis, eds. Target Seedling Symposium: Proc., Combined Meeting of the Western Forest Nursery Associations. Roseburg, Oreg., Aug. 13-17, 1990. U.S. Dep. Agric., For. Serv., Rocky Mt. For. Range Exp. Stn., Ft. Collins, Colo., Gen. Tech. Rep. RM-200.

SAS. 1990. SAS/STAT User's Guide, version 6, fourth edition, Volumes 1 and 2. SAS Institute Inc., Cary, N.C.

Sheedy, G. 1978. Production en serre de semis d'épinette blanche en récipient, essais de divers milieux de culture, de trois calendriers de fertilisation et de deux types de contenants. Minist. Terres For., Serv. rech., Sainte-Foy, Qc. Rapp. int. n° 186.

Sheedy, G. 1980. Production en serre de semis de pin gris et d'épinette noire dans deux types de contenants et huit mélanges de sols. Minist. Énerg. Ressour. (For.), Serv. rech., Sainte-Foy, Qc. Note n° 10.

Smyth, J.H.; Brownwright, A.J. 1984. Forest tree production centres in Canada. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont. Inf. Rep. O-X-357.

Sutton, R.F. 1990. Root growth capacity in coniferous forest trees. Proc. Colloquium: Woody Plant Root Physiology, Growth, and Development. HortScience 25(3): 259-266.

Thompson, B.E. 1985. Seedling morphological evaluation: what you can tell by looking. Pages 59-71 *in* M.L. Duryea, ed. Proc. Evaluating Seedling Quality: principles, procedures and predictive abilities of major tests. Corvallis, Oreg., Oct. 16-18, 1984, For. Res. Lab., Oreg. State Univ., Corvallis, Oreg.

Tinus, R.W.; Stein, W.I.; Balmer, W.E., eds. 1974. Proc. North Am. Containerized For. Tree Seedling Symp. Denver, Colo., Aug. 26-29, 1974. Great Plains Agric. Counc. Publ. No. 68.

Todd, A.M.D. 1989. Stock types for planting: what's available, what's required. Pages 24-32 *in* B.A. Schriver, and J. A. MacKinnon, eds. Learning from the past, looking to the future. Proc. Northern Silviculture Committee's 1988 Winter Workshop. Prince George, B.C., Feb. 2-3, 1988. Economic and Regional Development Agreement, Victoria, B.C., FRDA Report 030.

Wakeley, P.C. 1949. Physiological grades of southern pine nursery stock. Proc. Soc. Am. For. 43: 311-322.

Wakeley, P.C. 1969. Results of southern pine planting experiments established in the middle twenties. J. For. 67: 237-241.

Waldron, R.H., ed. 1972. Proc. Workshop on Container Planting in Canada. Kananaskis, Alta., Sept. 28-30, 1971. Dept. Environ., Can. For. Serv., Ottawa, Ont. Inf. Rep. DPC-X-2.

Walker, N.R.; Johnson, H.J. 1980. Containerized conifer seedling field performance in Alberta and the Northwest Territories. Environ. Can., Can. For. Serv., Northern For. Res. Cent., Edmonton, Alta. Inf. Rep. NOR-X-218.

Walters, J. 1968. Planting gun and bullet. Agric. Eng. 49: 336-339.

Weetman, G.F. 1977. Provincial status reports reveal a growing wasteland. Can. Pulp and Paper Industry 30(19): 17.