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Manual for Exponential Nutrient Loading of Seedlings to Improve Outplanting Performance on Competitive Forest Sites

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ABSTRACT

This manual provides a review of the principles and technology of exponential fertilization and nutrient loading for container stock production, an examination of the growth and nutritional responses of loaded seedlings planted on competitive sites, and information for implementing exponential nutrient loading practices on an operational basis. The loading technique improves the competitiveness of containerized seedlings planted on vegetation rich mixedwood sites by promoting initial growth performance and weed suppression, thus reducing the need for early vegetation control. The approach is based on two new preconditioning practices, exponential fertilization and nutrient loading, which promote steady-state luxury consumption of nutrients in seedlings for outplanting. Exponential nutrient loading regimes integrate exponentially increasing nutrient additions with the high-dose fertilization of seedlings during the greenhouse rotation. Steady-state culture corresponds closer with the competitive outplanting environment, because stable internal nutrient accumulation in the greenhouse phase conforms with steady-state nutrient uptake of natural, exponentially growing vegetation in the field. Exponential nutrient delivery to container-restricted root systems also simulates nutrient flux reached by expanding roots in a field soil with constant nutrient availability. Exposure to high fertilizer additions during loading is gradual and slow, thereby facilitating luxury consumption and tolerance to high nutrient levels. The greater nutrient reserves and improved nutrient balance in seedlings contribute to enhanced growth performance, stress resistance, and weed suppression in the field.

RÉSUMÉ

Ce guide présente une revue des principes et de la technique de fertilisation exponentielle et d'accroissement de la charge en éléments nutritif des plants produits en récipient, examine la croissance et les réactions des semis ainsi traités qui sont transplantés dans des stations soumise à la concurrence végétale et fournit des renseignements pour rendre opérationnelles les méthodes d'accroissement exponentiel de la charge en éléments nutritifs. Cette dernière technique améliore la compétitivité des plants en récipient transplantés dans des stations de forêt mixte où la couverture végétale est abondante; elle favorise ainsi leur croissance initiale et leur compétitivité à l'égard des mauvaises herbes et réduit par le fait même la nécessité d'y appliquer tôt des traitements de désherbage. Cette approche repose sur deux nouvelles méthodes de pré-traitement, soit la fertilisation exponentielle et l'accroissement de la charge en éléments nutritifs, qui favorisent une consommation de luxe stable des éléments nutritifs par les semis destinés à être transplantés sur le terrain. L'accroissement exponentiel de la charge en éléments nutritifs consiste en des apports répétés et croissants d'éléments nutritifs grâce au traitement des semis avec de fortes dose de fertilisants lors de la rotation en serre. Cet état stable est plus étroitement apparenté aux conditions du milieu où les semis seront transplantés, parce que l'accumulation régulière d'éléments nutritifs dans les tissus qui se produit en serre correspond à l'absorption d'éléments nutritifs de la végétation naturelle sur le terrain où la croissance est exponentielle.

L'approvisionnement exponentiel en éléments nutritifs des systèmes radiculaires emprisonnés dans les récipients simule aussi le flux d'éléments nutritifs qu'atteignent les racines en se développant sur le terrain dans un sol où la disponibilité des éléments nutritifs est constante. Les apports de fortes doses d'éléments fertilisants se font graduellement et lentement, facilitant ainsi la consommation de luxe et la tolérance à des niveaux élevés d'éléments nutritifs. Les semis dont les réserves et l'équilibre nutritifs sont améliorés présentent un meilleur taux de croissance et une plus grande résistance au stress et sont mieux en mesure de concurrencer les mauvaises herbes sur le terrain.

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INTRODUCTION

The successful regeneration of forest land in Ontario may be adversely affected by two recent trends in forest management: namely, 1) the increased dependence on containerized seedlings for planting, and 2) the restricted use of chemical herbicides in vegetation control. The high costs of growing and planting bareroot stock have forced the closure of four provincial nurseries that produced bareroot seedlings. Consequently, the demand for less costly planting stock will be met by younger, greenhouse grown containerized seedlings (produced by the private sector), which are considerably cheaper to plant. These developments present a serious challenge to regenerating weed-prone sites, since containerized seedlings are smaller and much more sensitive to competing vegetation than is conventional bareroot stock (Wood and Campbell 1988, MacDonald and Weetman 1993).

In an effort to address this problem, this research has focused on developing cultural techniques that will enhance the growth competitiveness of containerized seedlings in the field, and reduce the need for subsequent vegetation control. To provide a practical orientation to the research, work was carried out cooperatively with North Gro Development, a production facility near Kirkland Lake, Ontario, which is the major supplier of containerized planting stock to Abitibi-Price Inc. in Iroquois Falls. The main approach was to improve seedling quality by introducing new nutritional preconditioning practices, such as exponential fertilization and nutrient loading, during greenhouse culture. Thus far, outplanting results have shown superior field performance of exponentially loaded seedlings over conventionally reared seedlings, especially on vegetation rich competitive sites (Malik and Timmer 1995, Timmer[1]). These new techniques show considerable promise in benefiting regeneration success, but challenge the validity of conventional fertilization practices employed in tree seedling production.

This manual reviews the principles of exponential nutrient loading for containerized planting stock, examines growth and nutritional responses of loaded seedlings planted on weed-prone sites, and describes fertilization practices to produce exponentially nutrient-loaded seedlings on a practical basis. The Forest Soils Group at the University of Toronto, Faculty of Forestry, has been particularly active in evaluating the nutritional aspects of container seedling culture and bareroot planting stock production. Results have been published in a range of graduate students theses, government reports, and journal papers. The intention here is to present in a single document an integrated summary and synthesis of previous work and of new results generated from Northern Ontario Development Agreement (NODA)-sponsored research. The information will provide background and guidance for implementing exponential nutrient loading techniques on an applied scale.

EXPONENTIAL FERTILIZATION

Steady-state Nutrition

The work by the Forest Soils Group on nutrient preconditioning of seedlings is modeled on the concept of "steady-state nutrition", which advocates that plants should be grown with constant internal nutrient concentrations, free from nutrient stress (Ingestad and Lund 1986). This condition is achieved by adding fertilizer nutrients at exponential rather than conventional (constant) rates (Fig. 1), thereby corresponding closer to the desired relative

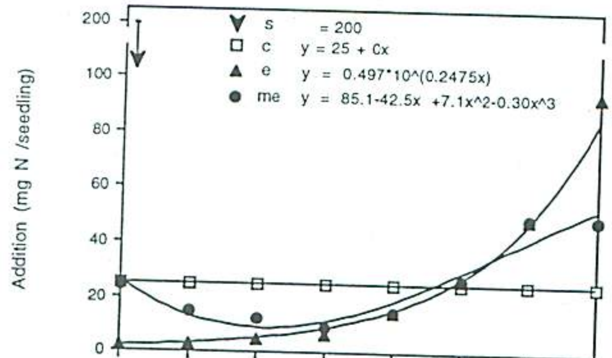

Figure 1. Schedule of fertilizer additions by seedling age applied as singe dose (s), constant top dressing (c), pure exponential (e), and modified exponential (me) fertilization regimes during greenhouse culture. In each regime, a total of 200 mg N per seedling was delivered as a complete nutrient solution starting 2 weeks after germination (from *Imo and Timmer 1992a).*

[1]Timmer, V.R. Exponential nutrient loading: A new fertilization technique to improve seedling outplanting performance on competitive sites. New Forests. (In press.)

growth rate of plants during their exponential phase of growth (Fig. 2). Growth and nutrient accumulation of conventionally fertilized seedlings normally increases as the season progresses, but internal nutrient concentrations usually decline due to growth dilution (Fig. 3). This pattern suggests nutrient stress from excess fertilization at the beginning of the growth period and possible under fertilization at the end. Steady-state nutrition, on the other hand, characterized by stable internal nutrient concentration during exponential growth, is relatively free of nutrient stress. In theory, maintenance of stable or undiluted nutrient concentrations (n/W) in plant tissue over time (t) can be expressed (Ingestad and Lund 1986) by:

$$d(n/W)/dt = 0 \quad (1)$$

where n and W are respective amounts of nutrient and biomass in the seedling. Differentiation of Model 1 yields:

$$[W(dn/dt)-n(dW/dt)]W^2 = 0 \quad (2)$$

which transforms to:

$$(1/w)dW/dt = (1/n)dn/dt \quad (3)$$

By definition, the left and right sides of Model 3 are relative rates of plant growth (R_G) and nutrient uptake (R_U), respectively,

$$R_G = R_U \quad (4)$$

Using solution cultures, the relationship of Model 4 was confirmed, experimentally demonstrating that:

$$R_G = R_U = R_A \quad (5)$$

where R_A is the relative (or exponential) addition rate of nutrients. As a treatment variable, R_A was strongly and linearly related to R_G at suboptimum nutrition, and regressions between R_A and R_G passed close to the origin with a slope of unity. On this basis, Ingestad and Lund (1986) postulated that R_A, which can be readily manipulated in crop management, is the driving variable of plant growth and nutrition, and that steady-state nutrient conditions can be attained by fertilizing with exponentially increasing amounts during the exponential growth period. These fundamental relationships were verified by a series of elegant solution culture experiments (Ingestad and Lund 1986). An important question for containerized seedling growers, however, is whether these relationships hold for commercial soil culture or pot culture.

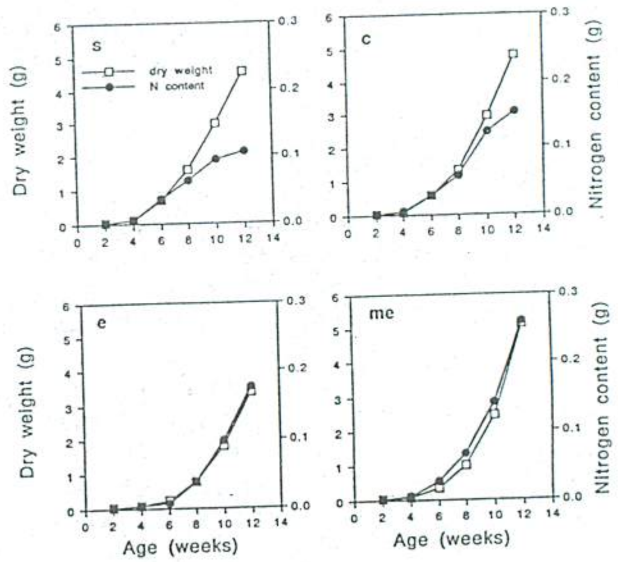

Figure 2. Progression of dry matter production and N uptake of mesquite seedling shoots at singe dose (s), constant top dressing (c), pure exponential (e), and modified exponential (me) fertilization regimes during the growing season (from *Imo and Timmer 1992a).*

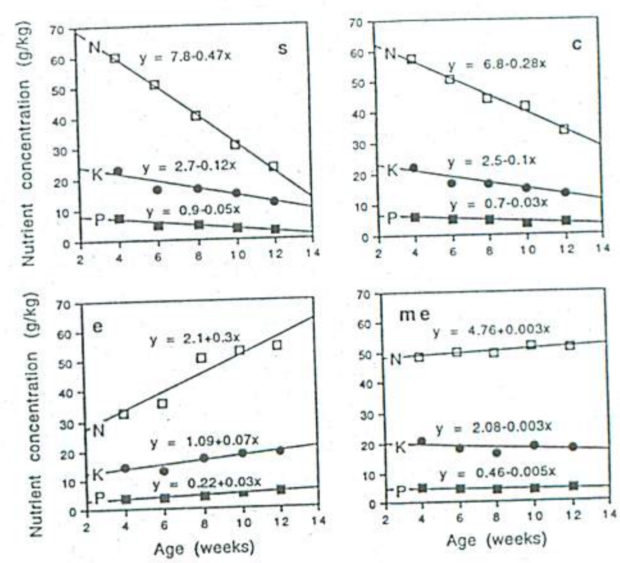

Figure 3. Progression in tissue nutrient concentration of mesquite seedlings cultured under singe dose (s), constant top dressing (c), pure exponential (e), and modified exponential (me) fertilization regimes during the growing season (from *Imo and Timmer 1992a).*

Fertilizer Delivery Models

The goal of the Forest Soils Group has been to adapt steady-state nutrient principles to intensive planting stock production by developing fertilizer delivery models that effectively induce steady-state nutrition. Several types of fertilizer regimes are used by producers. The simplest model, usually employed with slow-release formulations, consists of a single fertilizer dose (N_t) applied at the start of the growing season:

$$N_t = N_T \qquad (6)$$

This nutrient amount (N_t) is assumed sufficient to meet crop requirements for the entire rotation (N_T). The "constant feed" model, used conventionally by most growers, consists of repeated nutrient applications at a constant addition rate as top dressings:

$$N_t = N_T (t^{-1}) \qquad (7)$$

where N_t is the quantity applied on a specific day over t, the number of applications over the growing season. Exponential fertilization delivers nutrients at exponentially increasing additions (Ingestad and Lund 1986) following an exponential function:

$$N_T = N_s (e^{rt}-1) \qquad (8)$$

where r is the relative addition rate required to increase N_s, the initial level of N, to a final level of $N_T + N_s$. N_s is the quantity of N in the seedling at the start of fertilization. Knowing N_T and N_s for a particular crop, r can be determined from Model 8 for the number of fertilizer applications (t) planned. N_t can be calculated from the model:

$$N_t = N_s (e^{rt}-1) - N_{t-1} \qquad (9)$$

where N_{t-1} is the cumulative amount of N added up to and including the previous application (*see* Appendix 1 for sample calculations).

Modified Exponential Regimes

Tests of equivalent amounts of fertilizers applied conventionally (Model 7) or exponentially (Model 8) to containerized red pine (*Pinus resinosa* Ait.) confirmed that superior plant growth and nutrient responses were obtained under exponential regimes at much higher fertilizer-use efficiencies (Timmer and Armstrong 1987). Compared to conventional applications, equivalent exponential additions significantly increased yield (21 percent height, 19 percent dry matter) and nutrient uptake (10 percent N content) of the seedlings (Table 1). Yields were similar with reduced exponential additions (at one-quarter of the rate) resulting in much higher fertilizer-use efficiencies. Enhanced growth and nutrient uptake capacity were reflected in the higher absorption area of roots. The lower dose rates associated with exponential fertilizer delivery also minimized potential leaching of soluble nutrients. Results illustrated the potential yield advantage, fertilization efficiency, and leaching reduction possible with exponential fertilization practices.

Although steady-state achievement was not assessed, Troeng and Ackzell (1988) and Burgess (1990) noted the difficulty in achieving this condition when container conifer seedlings were fertilized according to Model 8 alone. Consequently, this model was modified to raise addition rates slightly at the start of the fertilization period so as to compensate for incomplete root exploitation and reduced nutrient interception in juvenile growth (Timmer et al. 1991). Since root systems expand exponentially, nutrient compensation (N_c) was delivered exponentially, following an inverse function:

$$N_c = N_o (e^{-rt} - 1) \qquad (10)$$

where N_o is the final amount (approaching 0) of N added over the compensation period. N_c, the compensating amount of N, corresponded to the difference between the last and the penultimate fertilizer applications calculated from Model 9. This amount was intentionally subtracted from the final application to avoid possible bud damage before dormancy onset due to excess fertilization. The modified exponential regime ensured steady-state nutrient culture reflected by stable internal nutrient concentrations during the fertilization period (Timmer et al. 1991, Imo and Timmer 1992a, Miller and Timmer 1994).

Model Evaluation

The four types of fertilization schedules (representing Models 6, 7, 8, and 10 or s, c, e, and me in Fig. 1), each delivering 200 mg N per seedling over a 9-week period, were assessed on fast growing *Prosopis* seedlings raised

Table 1. Growth performance and nitrogen content of red pine seedlings raised at conventional and exponential fertilization regimes (*from* Timmer and Armstrong 1987).

Fertilizer regime	N applied (mg/tree)	Seedling height (cm)	Dry mass (mg)	Root surface area (cm^2)	Fertilizer-use efficiency* (mg/mg N)	N content (mg/tree)	N uptake efficiency (%)
High conventional	39	6.8	227	2.8	5.8	6.1	15.6
High exponential	39	8.2	270	4.0	6.9	6.7	17.2
Low exponential	10	8.2	260	5.9	26.0	5.8	58.0

* Yield per unit of fertilizer N applied.

in peat-filled containers (Imo and Timmer 1992a). Of all treatments tested, the modified exponential (me) treatment consistently induced higher N accumulation in the plants that matched dry matter accumulation (Fig. 2) while maintaining steady-state nutrient status (Fig. 3). Nutrient uptake under conventional regimes (s and c) did not match growth, thereby indicating a nutrient stress at various stages of seedling development. Steady-state nutrient conditions induced by the modified technique also favored subsequent outplanting performance, as shown with conifer planting stock (Timmer et al. 1991).

The improved response was demonstrated in pot bioassays with black spruce (*Picea mariana* [Mill.] B.S.P.) seedlings that had received similar seasonal amounts of nutrients, either conventionally or exponentially during the nursery rotation. The exponentially fertilized seedlings exhibited considerably more stable internal nutrient levels (steady-state nutrition) during the active growing period than did those of conventionally fertilized trees, which exhibited declining nutrient concentrations with time because of growth dilution (Fig. 4). Despite somewhat lower biomass and P and K content in shoots before planting, first-year growth and nutrition of the exponentially fertilized trees after outplanting were greater compared to the conventionally fertilized seedlings (Fig. 5). The response was consistent on a variety of site types, suggesting that exponentially fertilized seedlings were better conditioned for field planting than were conventionally fertilized seedlings.

Steady-state growing conditions may correspond better with the natural outplanting environment for several reasons. First, the pattern of stable internal nutrient accumulation in the greenhouse phase conforms closer with steady-state nutrient uptake of natural exponentially growing plants in the field. This was shown by Munson and Bernier (1993), who compared dry matter production and N uptake of similarly sized natural and planted black spruce seedlings established on a clear-cut area in Quebec (Fig. 6). Second, lower nutrient concentrations used with exponential fertilization schedules match field soil-solution concentrations more closely (Linder and Rook 1984, Timmer and Armstrong 1987). Third, especially with small containers, exponential nutrient delivery to container-restricted root systems simulates nutrient flux reached by expanding roots in a field soil with constant nutrient availability (Pettersson 1986). These cultural conditions differ markedly from those of conventional fertilization regimes, and promote initial outplanting growth by reducing planting shock, increasing nutrient uptake, and enhancing the stress resistance of exponentially treated trees (Timmer and Miller 1991, Timmer et al. 1991).

NUTRIENT LOADING

Principles and Approach

Another approach to conditioning planting stock for the field is to build nutrient reserves for low fertility outplanting environments. Early studies with bareroot seedlings have shown that fertilization practices in the nursery significantly improved subsequent field performance (Mullin and Bowdery 1977). In these cases, it was difficult to distinguish whether the response was attributable to differences in preplant seedling size or to the build-up of plant nutrient reserves, although van den Driessche (1980) suggested the former. Late-season fertilization, however, was shown to "load" or increase plant nutrient content with little effect

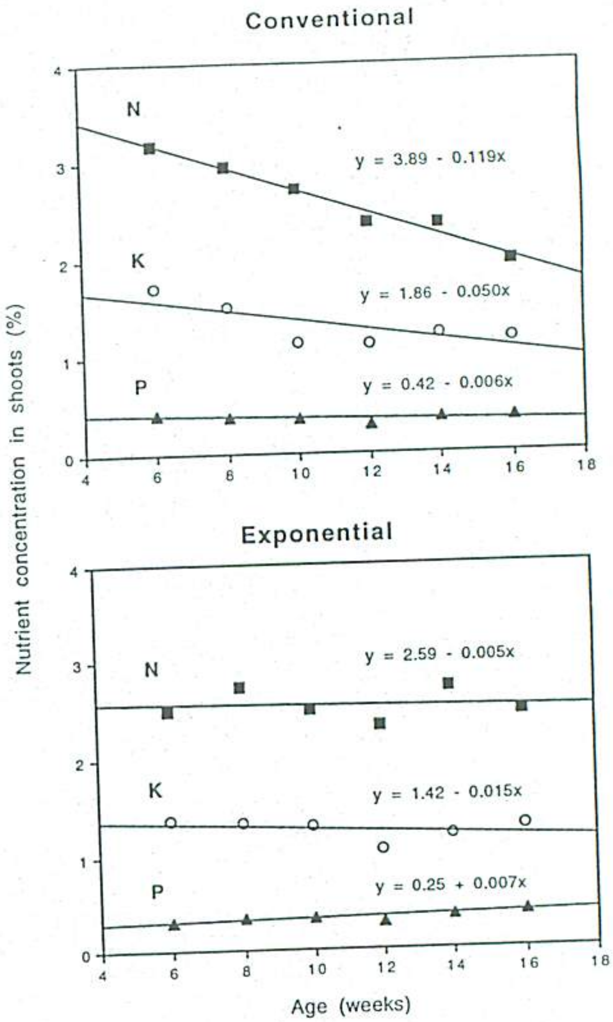

Figure 4. Nutrient status of container black spruce seedlings raised on conventional constant and exponentially based fertilization regimes delivering 10 mg N per seedling during an 18-week growing period in the greenhouse (from Timmer et al. 1991). Note steady-state nutrient status associated with exponential preconditioning regime.

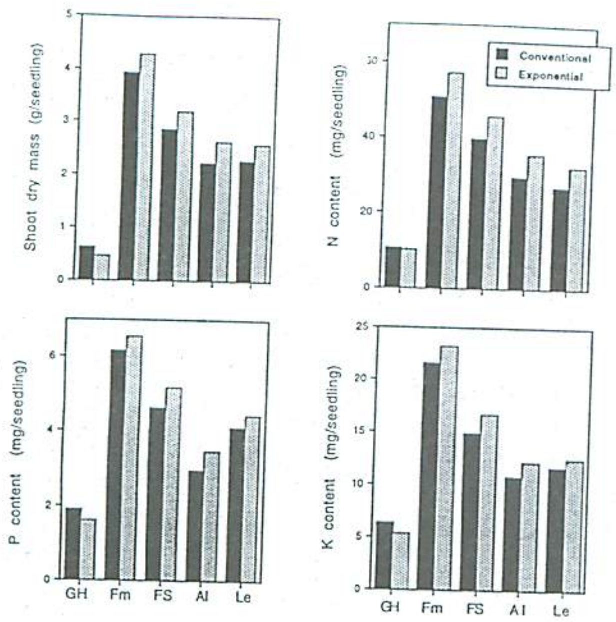

Figure 5. Growth and nutrient content in shoots of black spruce seedlings before (GH) and one season after outplanting on different boreal substrates. Seedlings received equivalent amounts of complete fertilizer (10 mg N per seedling) at conventional or exponential schedules during the greenhouse rotation (from *Timmer et al. 1991). Fm, FS, Al, and Le refer to feathermoss, feathermoss–*Sphagnum, Alnus, *and* Ledum *site types.*

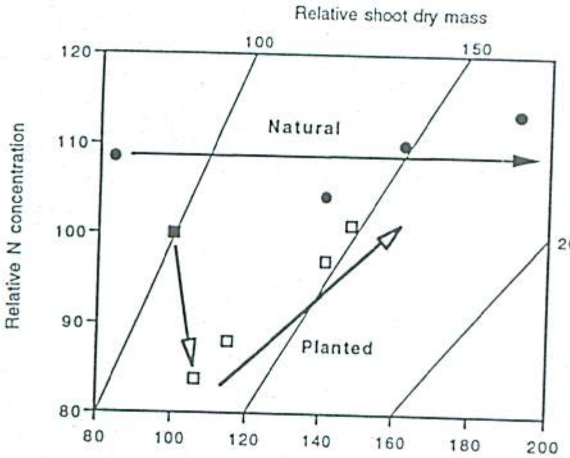

Figure 6. Relative shoot growth and nitrogen composition of similarly sized natural and planted black spruce seedlings on a clear-cut area in Quebec (adapted from *Munson and Bernier 1993). Initial (planting time) biomass and N status of seedlings were normalized to 100, subsequent points reflect progressive samplings at 3–4 week intervals. Container seedlings were sized and paired with natural trees at planting. Comparative stability of natural seedlings indicates steady-state nutrient conditions during the season.*

on seedling size (Benzian et al. 1974; van den Driessche 1985, 1988), and also to accelerate plantation growth rates (Margolis and Waring 1986, Simpson 1988, Gleason et al. 1990). The improved field performance of loaded seedlings was attributed to greater nutrient reserves, increased new root production, and earlier bud break.

The approach taken by the Forest Soils Group to nutrient-loading practices was to increase the level of fertilization over the entire growing season rather than the late season alone so as to insure full uptake capacity. The additions are controlled to induce luxury consumption (Fig. 7), which builds up the nutrient reserves of the seedling for subsequent outplanting. Customarily, fertilizers are applied to the sufficiency level, where crop production is maximized. Plant growth below this level, known as the deficiency range, is limited by inadequate nutrients. Fertilization beyond the sufficiency level is considered inefficient since productivity is not raised, although nutrient uptake may still be increased. Nutrient loading involves higher fertilizer inputs and luxury uptake characterized by

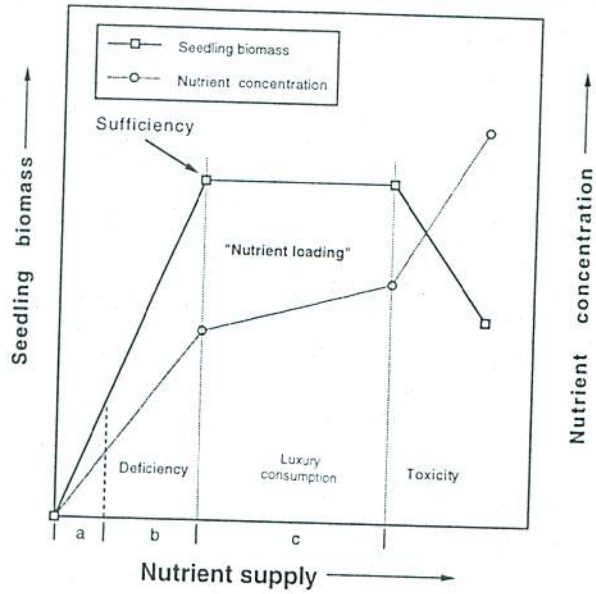

Figure 7. Plant growth to increasing nutrient supply is expected to follow a curvilinear relationship that can be divided into linear phases to define four nutritional states: deficiency, sufficiency, luxury consumption, and toxicity (modified from *Timmer 1991). Conventionally, fertilizer (b) is added to supplement soil nutrient supply (a) to avoid nutrient deficiency and maximize growth development to the sufficiency level. Nutrient loading entails extra fertilization (c) inducing luxury consumption to build up plant nutrient reserves without changing maximum growth production. Excess fertilization reduces growth because of toxicity. Generally, nutrient concentration in the plant will increase with greater nutrient supply, especially in the toxicity range due to accumulation.*

increasing internal nutrient concentrations without significantly changing total dry mass. The higher nutrient reserves in the seedling can be utilized during the critical establishment period to benefit early outplanting performance. The technique necessitates judicious use of fertilizer application to prevent toxicity and disruption of nutrient balance. A familiarity with inherent growing media fertility, sufficiency levels, and loading thresholds (a, b, and c, respectively, in Fig. 7), and frequent nutrient monitoring of plants, soils, and fertilizer solutions is an important part of the procedure, as will be described later.

Outplanting Trials

Test plantings of black spruce seedlings on intact substrates of three ecological site types (upland Feathermoss, lowland *Alnus*, and lowland *Ledum*) varying in fertility have shown that N-loaded seedlings exhibited consistently greater growth and increased nutrient uptake after outplanting, compared to conventionally fertilized seedlings of a similar preplant size (Timmer and Munson 1991). Nitrogen loading significantly increased height growth and dry matter production on all substrates. The relative response was greater on the more N-deficient lowland sites (Fig. 8). Plant nutrients were markedly diluted after establishment, except for N of nonloaded seedlings. The loading response was closely associated with the buildup of preplant N, which served as a critical nutrient source for internal retranslocation to new growth. Nitrogen loading not only stimulated N uptake after outplanting, but also the uptake of other nutrients. Presumably this was due to the expanded root system resulting from the loading treatment. Since the response increased with the inherent nutrient stress of the planting sites, it was thought that loaded seedlings may be better preconditioned for competition on weedy sites, and thus may require less vegetation management or herbicide use.

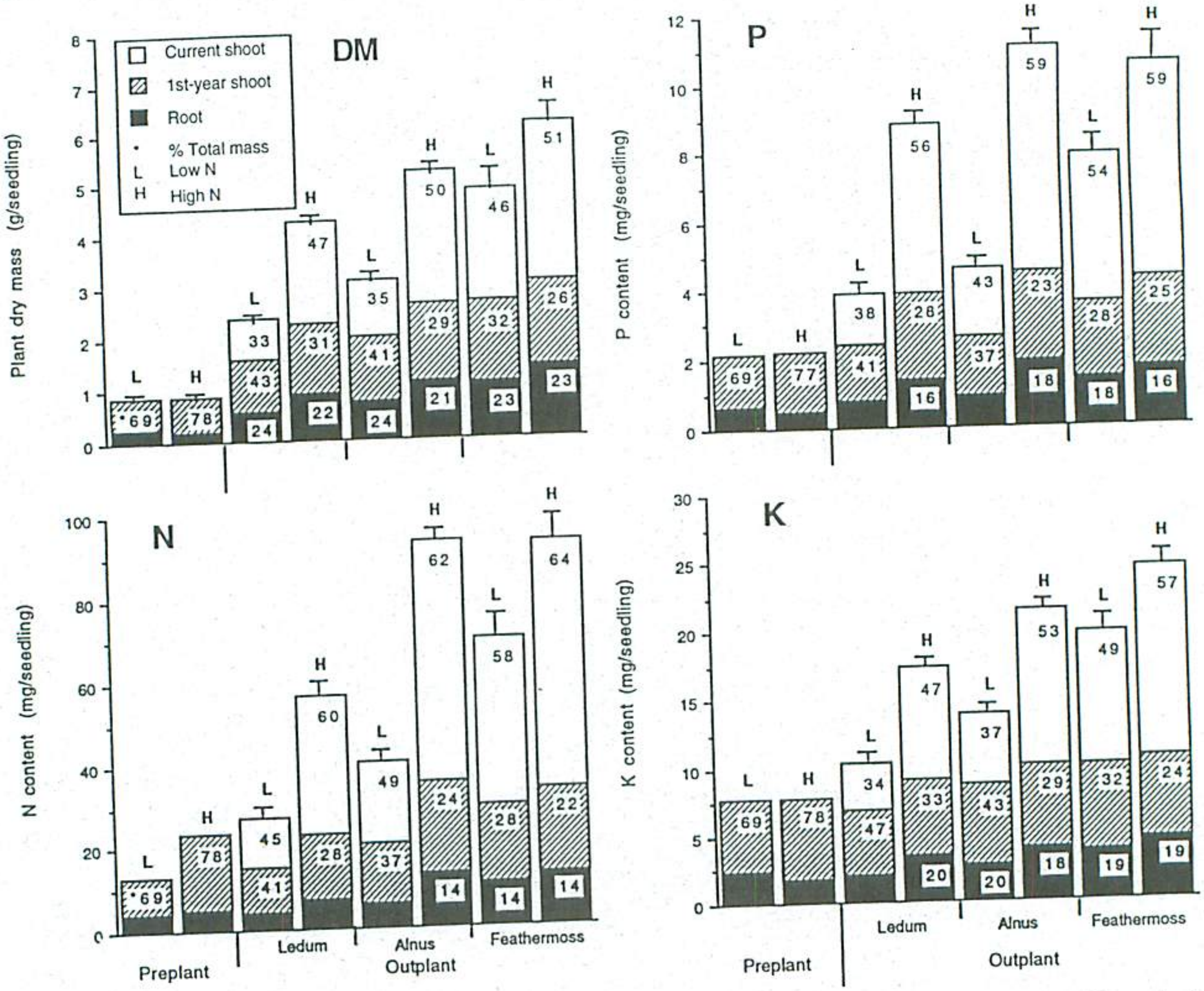

Figure 8. Effect of low (L) and high (H) N-loading treatments on preplant and outplant dry matter (DM) production, and nutrient content in components of black spruce seedlings. Seedlings were planted in potted, intact substrates of three Clay Belt sites (from *Timmer and Munson 1991*).

Interaction with Competing Vegetation

The interaction of newly planted, nutrient loaded black spruce seedlings with naturally occurring vegetation was investigated for one growing season under greenhouse conditions, using pot bioassays retrieved from a boreal mixedwood site (Malik and Timmer 1995). The experimental design was a 2 x 2 factorial, testing trees raised at two fertility levels (conventional, C and loaded, L) in the greenhouse, and outplanted on two weed densities (weedy, W and herbicide, H). The loaded seedlings were similar in size to conventionally fertilized seedlings (Fig. 9, Graph a), but contained 43 percent, 76 percent, and 33 percent more tissue N, P, and K content, respectively, due to higher nursery fertilization, which induced luxury consumption (Fig. 10). Nutrient loaded seedlings were more competitive with weeds, exhibiting 44 percent and 37 percent more height and biomass, respectively, than conventionally fertilized seedlings planted in weedy environments (Fig. 9, Graph a). Biomass of the competing vegetation was suppressed by 27 percent by the end of the season (Fig. 10). The loading treatments also stimulated total nutrient uptake after planting, although the depletion of nutrient reserves was greater for loaded trees (Fig. 11). A significant negative correlation was observed between tree and weed biomass accumulation on the bioassays (Fig. 12). Slope differences indicated that loaded trees were less sensitive to mixedwood competition than were conventionally fertilized trees, inferring greater competitiveness from loading treatments. The enhanced competitive ability of loaded seedlings against naturally occurring vegetation was probably due to the translocation of more nutrients to actively growing parts from reserves built up during the nursery conditioning phase.

The greater depletion of preplant nutrient reserves noted with loaded seedlings (Fig. 10) suggests expression of an exploitative trait on outplanting, which contrasts with a more conservative trait of the nonloaded seedlings where reserves were increased or slightly reduced. If correct, this evidence that manipulation of fertility during the greenhouse rotation may trigger different nutrient utilization strategies in trees after planting has important implications with respect to site-specific seedling production. The ability to precondition seedlings for exploitative (rather than conservative) nutritional traits suggests that planting stock targeted for nutrient competitive, weed-prone sites should be fertilized at high levels (i.e., nutrient loaded) during the nursery stage to promote early dominance at establishment. Although loading also stimulated tree growth on weed-free substrates, conventional nursery fertilization inducing nutrient conservation mechanisms may have long-term benefit for seedlings planted on low competition, infertile sites. Resources such as nutrients may be stored by plants as insurance against future shortages (Bloom et al. 1985). Since immediate productivity is reduced through storage, the loss in competitive advantage from short-term resource accumulation must be balanced by long-term persistence in a stressed environment. Further research is needed to elucidate these nutrient utilization strategies in young trees. Seedling loading responses observed on greenhouse bioassays (Malik and Timmer 1995) were subsequently confirmed by plantation field trials.[2]

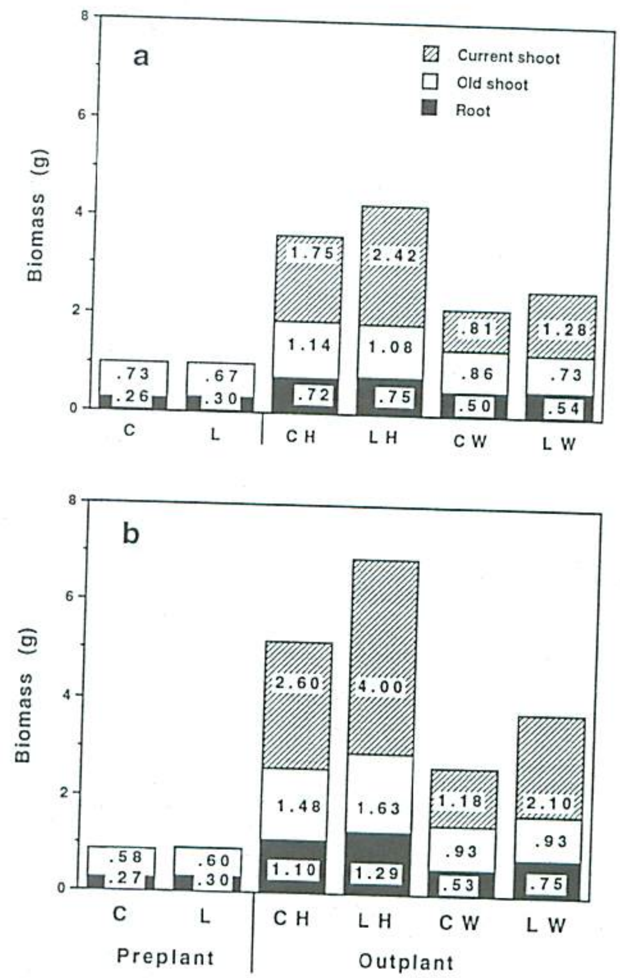

Figure 9. Preplant and postplant component biomass of conventional (C) and nutrient loaded (L) seedlings planted for one season on intact bioassay sprayed with (H) or without herbicide (W) before planting. Nutrient loading (total 32 mg N per seedling) was at constant rates in [a] (from *Malik and Timmer 1995), and at exponential rates in [b] (Malik, V.S. Unpublished data). Note relatively larger growth response with [b].*

[2]Malik, V.S. ; Timmer, V.R. Growth, nutrient dynamics and inter-specific competition of nutrient loaded black spruce seedlings on a boreal mixedwood site. Can. J. For. Res. (In press.)

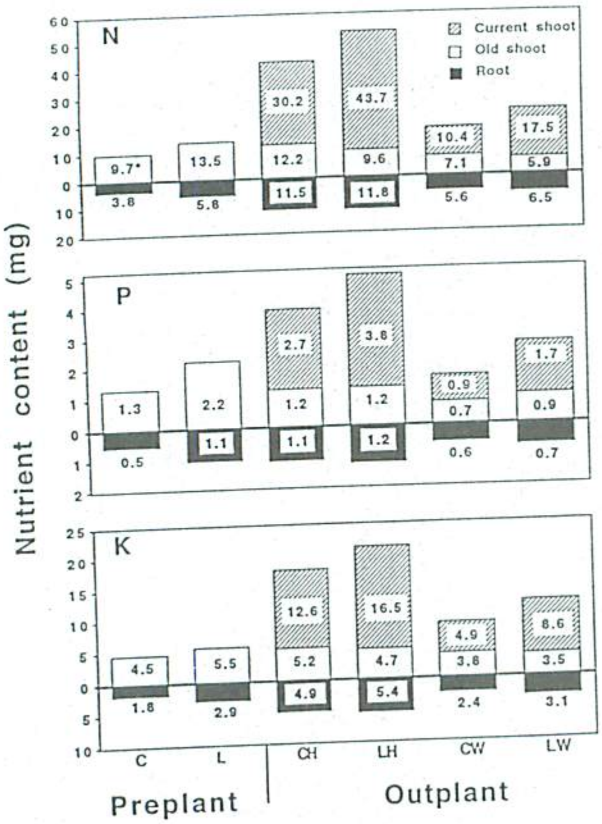

Figure 10. Preplant and postplant nutrient content of components of conventional (C) and nutrient loaded (L) seedlings, planted for one season on intact bioassays sprayed with (H) or without (W) herbicide before planting (from *Malik and Timmer 1995).*

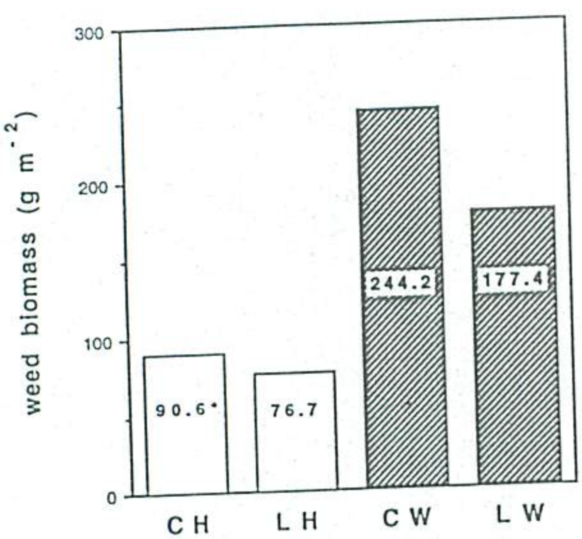

Figure 11. Weed biomass accumulated after one growing season on intact bioassays sprayed with (H) or without (W) herbicide before being planted with conventional (C) and nutrient loaded (L) seedlings (from *Malik and Timmer 1995).*

EXPONENTIAL NUTRIENT LOADING

Rationale

Nutrient loading of the trees of the previous trials was accomplished simply by constant feed schedules (Model 7) using higher concentration levels of the nutrient solution concentrations from the start of the fertilization period. Nutrient loading is more effective when combined with exponential fertilization techniques, since nutrient delivery to the crop increases exponentially, thereby ensuring a progressive building of nutrients in the rooting substrate and minimizing potential toxicity and seedling damage. This is illustrated in progressions of the soluble salt concentration in growing media of black spruce seedlings fertilized at three different regimes (Fig. 13). Two treatments (representing nonloading regimes) delivered 10 mg N per seedling at conventional or exponential addition rates. The third treatment was an exponential loading regime that provided 64 mg N per seedling for the growing season. The conventional low dose regime resulted in relatively constant soluble salt status in the peat growing media. Exposure to high fertilizer dosages under exponential regimes is gradual and slow, thus allowing plants to develop tolerance to high nutrient additions. This contrasts

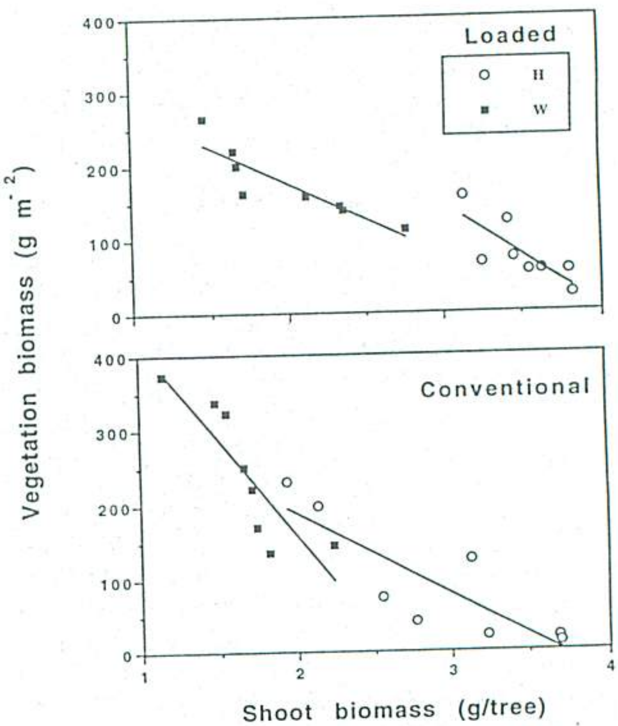

Figure 12. Relationship between biomass of conventional and nutrient loaded seedlings, and weeds growing in bioassay substrates under greenhouse conditions sprayed with (H) or without (W) herbicide before planting (from *Malik and Timmer 1995).*

with constant loading schedules, which expose young germinants to high nutrient levels as soon as fertilization commences (Timmer and Munson 1991), and risks early nutrient toxicity.

Exponentially based loading regimes also result in a steady-state uptake of nutrients at higher levels, as demonstrated with N in red pine (Miller and Timmer 1994), and with black spruce containerized seedlings in Figure 14. The seedlings were fertilized at three different regimes. Two treatments (representing nonloading regimes) delivered 10 mg N per seedling at conventional or exponential addition rates. The third treatment was an exponential loading regime that provided 64 mg N per seedling for the growing season. The conventional (constant addition rate) regime gave rise to declining N concentration in tissues over time. Both exponential regimes maintained relatively stable (steady-state) tissue concentrations, even at appreciably higher levels as in the case of the loading treatment.

Preplant and Postplanting Growth Response

Intraseasonal patterns of growth partitioning between shoots and roots are fundamentally different under the two types of loading regimes (Fig. 15). Although total plant biomass may be similar, conventional constant-rate loading favors early shoot development at the expense of root growth, a trend completely reversed late in the season. In contrast, progressions of shoot:root ratios are much more stable under steady-state nutrient loading, and more closely simulate the pattern of natural trees. Characteristic twisting or spiraling of shoots, often noted with young black spruce seedlings, seems to be absent under exponential loading regimes. Preliminary assessments of constant- or exponentially loaded seedlings after one outplanting season indicate greater growth (see Fig. 9, Graphs a and b) and more effective suppression of competing vegetation by the exponentially loaded seedlings.[3]

STRESS RESISTANCE

Overwintering Stress

There is some concern that high fertilization of seedlings may affect subsequent stress resistance. Margolis and Waring (1986) warn about possible winter carbohydrate depletion and frost damage from early bud flushing with loaded trees, although this must be seen in the light of recent findings that high N fertilization reduced sensitivity to freezing and improved cold hardiness in spruce seedlings (DeHayes et al. 1989, Klein et al. 1989). Freeze tests conducted on conventionally and exponentially nutrient loaded greenhouse transplants reared at the Orono

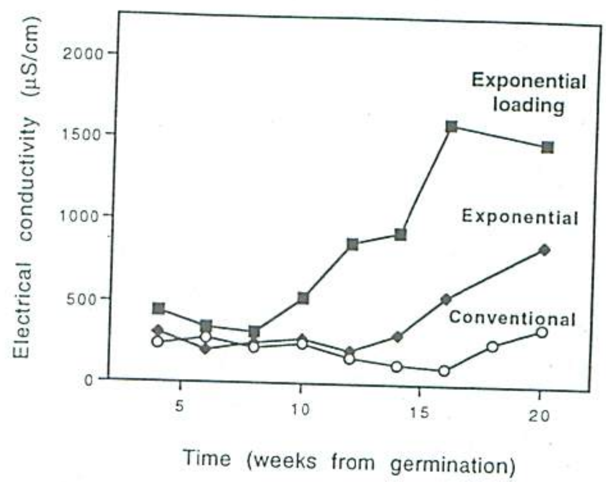

Figure 13. Electrical conductivity of saturated aqueous extracts of peat growing media from black spruce container seedlings raised under three different fertilization regimes during an 18-week greenhouse rotation at North Gro Development. Conventional and exponential regimes represent nonloading nutrient delivery (10 mg N per seedling). Exponential loading regime reflects additions totaling 64 mg N per seedling for the season.

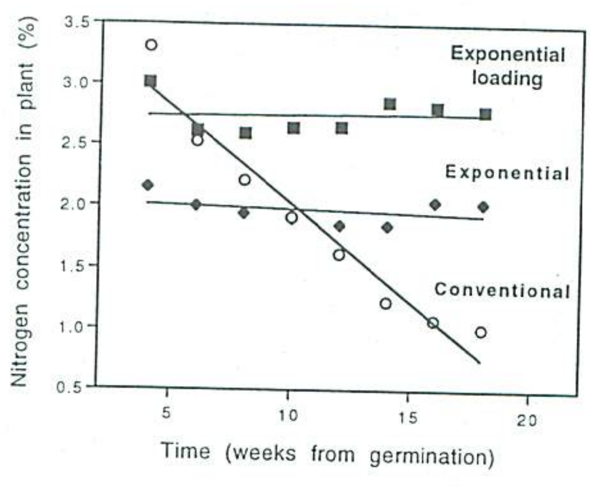

Figure 14. Nitrogen concentration in black spruce seedlings raised under three different fertilization regimes during an 18-week greenhouse rotation at North Gro Development. Conventional and exponential regimes represent nonloading nutrient delivery (10 mg N per seedling). Exponential loading regime reflects additions totaling 64 mg N per seedling for the season.

[3]Malik, V.S. Unpublished data.

Provincial Tree Nursery showed no differences in frost hardiness between treatments (Miller et al. 1995). Surprisingly, survival and damage after one winter in transplant beds was significantly less for the loaded seedlings as compared to the conventionally fertilized trees.[4]

Drought Stress

Lower shoot:root ratio, higher root nutrient reserves, and improved stomatal control over water loss in seedlings produced by exponential fertilization under limited irrigation contributed to better drought and nutritional conditioning for outplanting performance (Timmer and Miller 1991). When exposed to drought, exponentially fertilized red pine seedlings reduced stomatal conductance and transpiration sooner than conventionally fertilized seedlings (Fig. 16), thus reducing water loss. Similarly, exponential fertilization enhanced stomatal control of mesquite seedlings (Imo and Timmer 1992b). Irrigated plants maintained increased stomatal conductance and carbon dioxide assimilation compared to conventionally fertilized plants, while droughted seedlings exhibited earlier control over transpirational water loss by stomatal closure. This allows faster growth with a nonlimiting moisture supply and early conservation of water at the onset of drought. Steady-state nutrient loading of container-grown red pine seedlings improved biomass accumulation and nutrient uptake even after exposure to hardening treatments (water and nutrient withdrawal) imposed to condition planting stock for the field (Fig. 17, Miller and Timmer 1994). These attributes may well promote the competitiveness of exponentially loaded seedlings compared to conventionally fertilized seedlings.

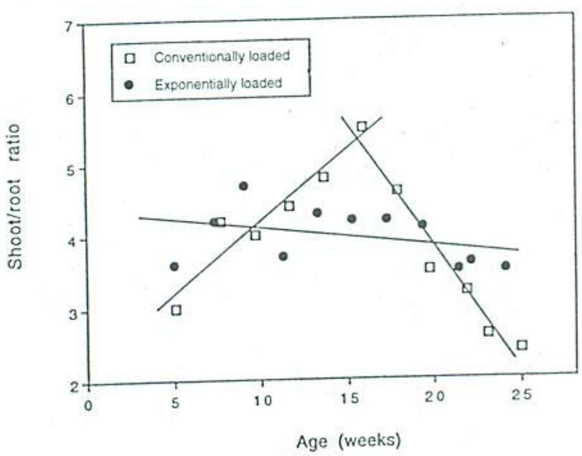

Figure 15. Shoot:root dry mass development of black spruce containerized seedlings reared under conventional and exponential nutrient loading regimes at North Gro Development. Both crops received 64 mg N per seedling as a complete fertilizer solution during an 18-week greenhouse rotation.

FERTILIZER LOADING PROCEDURES

Fertilizer Requirements

The quantitative relationship between increasing nutrient supply, plant growth, and internal nutrient concentration illustrated in the schematic of Figure 7 is useful for conceptualizing fertilizer requirements for seedling crops

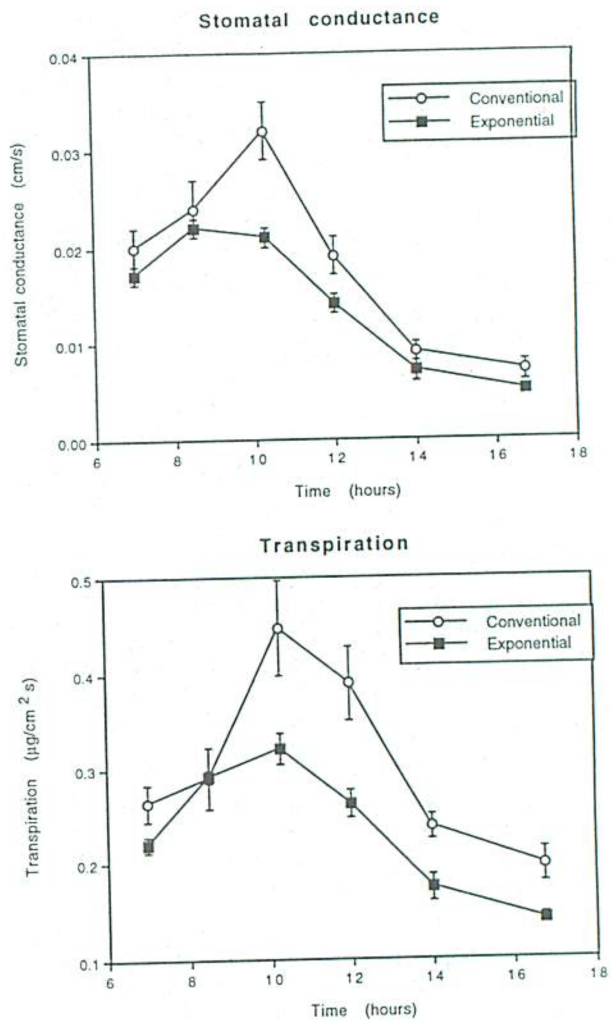

Figure 16. Diurnal changes in stomatal conductance and transpiration rate of 16-week-old red pine seedlings after exposure to drought (from *Timmer and Miller 1991). Seedlings were fertilized either conventionally or exponentially during the nursery stage.*

[4]Farintosh, L. Unpublished data.

(Timmer 1991). Although the relationship is usually curvilinear (see Fig 18), it has been segmented here into three linear phases to characterize four nutritional states of the crop (Fig. 7). The major nutrient sources for plants in container culture are 1) nutrients released from the peat substrate [a], and 2) nutrients added as chemical fertilizers to achieve the sufficiency level [b], or the desired loading threshold [b + c]. The inherent fertility of the growing media is usually not enough to meet the full nutrient requirements of fast growing container crops, hence there is a strong dependence on supplementation by fertilizers. Although nutrient requirements [a + b] for a particular species may be relatively constant for crops reared under similar cultural conditions, the fertilizer requirement [b] depends on the inherent fertility of the growing medium [a], which varies with peat type (Folk et al. 1992, Timmer and Folk 1992). Thus, a prescription of 32 mg N per seedling may be sufficient for a crop produced on a productive peat, but inadequate for a crop reared on a poor peat (see for example peat Sources B and A, respectively, in the Growing Medium Quality section, page 15). Prescriptions for nutrient loading [a + b + c] are similarly affected by peat quality, although under luxury consumption crop yield will be less sensitive than will internal nutrient status.

Although routine fertilizer needs for containerized seedling production are often based on grower experience, accurate prescription for nutrient loading regimes should be guided by quantitative information on the optimum nutrient requirements of the crop, such as the inherent fertility of the peat [a], sufficiency levels [b], and loading thresholds [c] of the cultural systems used. In 1985, cooperative

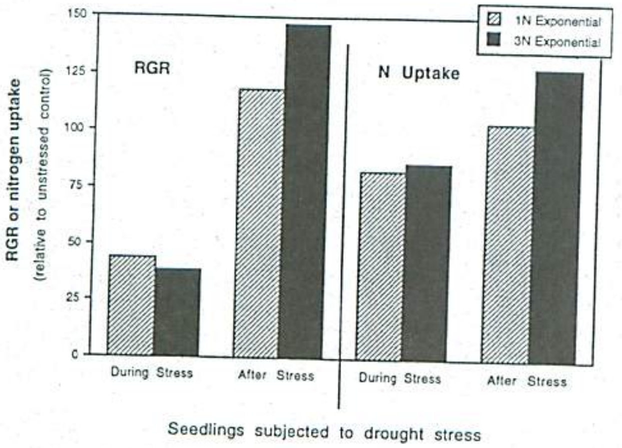

Figure 17. Effect of exponential loading (3N) on the relative growth rate (RGR) and nitrogen uptake of red pine seedlings during and after a hardening (water stress) period. Note improved performance of loaded seedlings after hardening (from *Miller and Timmer 1994*).

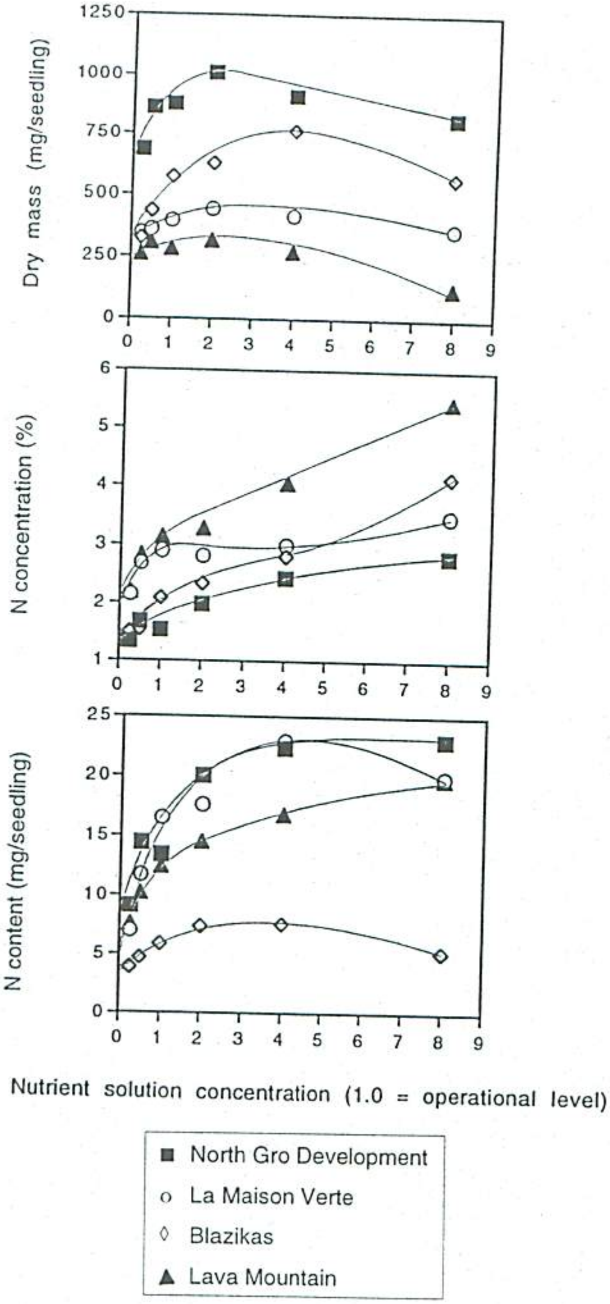

Figure 18. Dry mass, nitrogen concentration, and content of 20-week-old black spruce container seedlings reared at increasing strengths of nutrient solution used at four commercial production facilities. Total addition, delivery frequency and leaching intensity varied among participating growers, but solution concentrations were applied following conventional constant schedules at 0.25, 0.5, 1.0, 2.0, 4.0, and 8.0 times the operational strength.

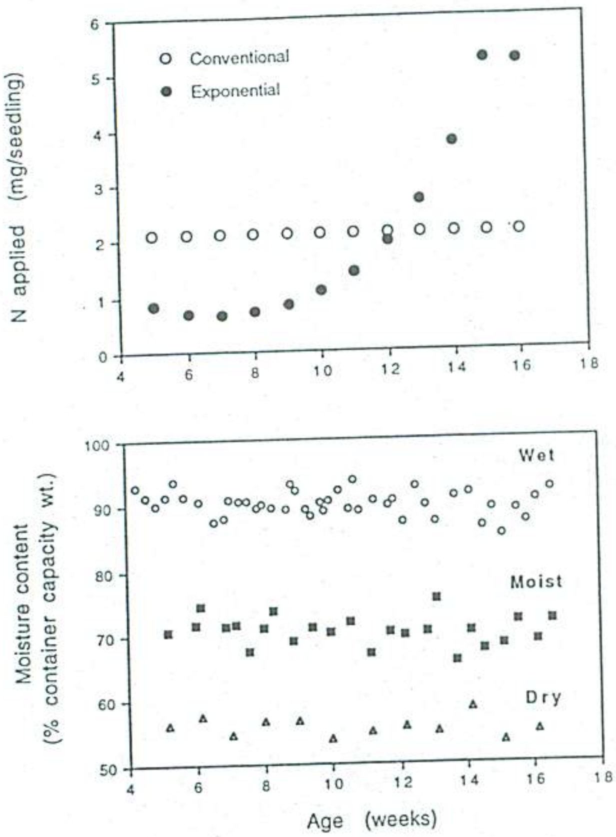

*Figure 19. Example of applying weekly nitrogen additions in solution form following conventional constant and exponentially based fertilization schedules at three contrasting irrigation regimes (*from *Timmer and Miller 1991).*

screening trials with the Ontario Ministry of Natural Resources and several seedling producers were undertaken to quantify some of these parameters under conventional fertilization regimes using a simple dose response approach. Sample crops received increasing concentrations of fertilizer solution (ranging from 0.25 to 8 times the operational strength used at the facility) for a 20-week growing period to generate specific dose response curves for each operator (Fig. 18). The total amounts of nutrients applied varied among growers according to delivery frequency, solution concentration, and leaching intensity, as well as peat quality and cultural environment. No doubt, all these factors contributed to the large variation in responses obtained; maximum biomass production ranged between 250 and 1 000 mg per seedling for the four nurseries participating in the survey.

Nonetheless, each curve depicted common phases of nutrient deficiency, sufficiency, luxury consumption, and toxicity, as illustrated schematically in Figure 7. Dry matter production increased to a maximum and then decreased as fertility was raised (Fig. 18, top). Seedling N concentrations typically increased as nutrient availability increased (Fig. 18, middle). Growth seemed more sensitive to low-dose (< 1x normal or full strength) fertilization than to high-dose fertilization; severe toxicity occurred at about eight times the full strength addition. Interestingly, maximum growth and nutrient (N) uptake (Fig. 18, bottom) was obtained at fertility levels (2 or 4 times) higher than normally applied, exemplifying potential benefits of increased fertilizer use. A rough measure of inherent peat fertility was estimated from curve (back) projections shown in Figure 18 (bottom). The zero intercepts, representing unfertilized peat growing media, suggests that about 3–8 mg N per seedling was supplied by the peat under these particular cultural systems. Maximum N uptake of three of the crops over the 20-week cultural period was about 20 mg N per seedling, which suggests by difference that about 12 mg N was supplied by the fertilizer. Considering the low uptake efficiencies (16–58 percent) usually associated with container fertilization practices (Table 1), about 21–74 mg N would be required per tree. These estimates were certainly much higher than normally used by growers at that time. The results triggered the interest of the Forest Soils Group in the potential of nutrient loading for container seedling production systems.

Although the dose estimates from the screening trials were based on conventional fertilization practices, the experience of this group with exponential fertilization and loading practices indicates that the addition rates and response surfaces shown in Figure 18 are useful guidelines for defining exponentially based loading requirements. Depending on peat quality, it was found that loading levels as high as 65 and 75 mg N per seedling, respectively, were suitable for black spruce[5] and red pine (Miller and Timmer 1994) container production. These loading levels tend to exceed the conventional amounts used operationally (average 13.2 mg N per seedling), but fall short of the estimated dose levels that induced toxicity in the screening trials (Fig. 18).

Characterizing Fertilizer Regimes

Fertilizer requirements for container seedling production are usually expressed in terms of N because, of all nutrients considered essential for growth, this element is most often limiting and required in the largest amounts. It is customary

[5]Timmer, V.R. Exponential nutrient loading: A new fertilization technique to improve seedling outplanting performance on competitive sites. New Forests. (In press.)

to assume that the other nutrients will be supplied in addition to N to ensure a balance; hence, the popularity of mixed fertilizers. Element composition of nutrient solutions is usually in fixed proportion to N (Ingestad and Lund 1986). A variety of fertilizer types, sources, and formulations are available commercially. A "grower" mix usually composed of more N than other nutrients is available for the exponential growth phase of the rotation. So-called "starter" and "finisher" fertilizers containing higher proportions of P and K can be used at the start and the end of the cultural stage to promote root development or hardening, although their effectiveness has not been proven (Scarratt 1986, Troeng and Ackzell 1988).

It is popular to describe fertilizer regimes solely by the concentration of N in the fertilization solution employed, but it can be very misleading because the absolute amount of fertilizer added is a product of both the concentration and the amount and volume of solution delivered. For example, although two producers may use the identical fertilizer formulation at the same solution concentration, their crops may receive different dose levels as a result of different volumes applied over the growing season because of varying irrigation requirements (Table 2). Thus, for comparative purposes it is more precise and informative to describe fertilizer regimes in terms of the quantity of nutrients delivered on a unit basis (per tree, cavity, tray, greenhouse, etc.) calculated by multiplying the concentration of nutrient solution by the volume of liquid applied per unit area. A survey of records of several northern region growers, noting nutrient solution concentrations used and associated water volume delivered per pass by the irrigation boom, found that between 6 and 32 mg N per seedling cavity was applied per season. The average dose amounted to 13.2 mg N per seedling. These values were within the range of fertilizer quantities given to black spruce container stock produced in Quebec (Bigras and D'Aoust 1992, Calmé et al. 1993).

Application Schedules

Effective and efficient scheduling of fertilization should ensure that nutrient supply matches the growth and nutrient demands of the crop. Dry matter production of seedlings after germination usually follows an exponential function for most of the growing season until bud set, stem lignification, and dormancy occur. This model provides the guiding principle for scheduling exponential nutrient loading regimes. Since nutrient addition is synchronized with crop demand, excessive buildup of nutrients in the growing media is minimized. Hence, if applied properly, nutrient loading should be achieved under steady-state conditions.

Once the loading requirement (N_T) has been determined, the application schedules are calculated based on models

Table 2. Example of a conventional fertilization regime utilizing constant strength nutrient solutions during a 16-week fertilization period applied under a conservative or liberal irrigation schedule.

	Conservative irrigation regime			Liberal irrigation regime		
Weekly application	Solution N concentration (mg/l)	Volume applied (ml/sdl)	N applied (mg/sdl)	Solution N concentration (mg/l)	Volume applied (ml/sdl)	N applied (mg/sdl)
1	25	10	0.25	25	20	0.50
2	25	10	0.25	25	25	0.63
3	25	20	0.50	25	15	0.38
4	50	10	0.50	50	10	0.50
5	50	10	0.50	50	20	1.00
6	100	10	1.00	100	15	1.50
7	100	10	1.00	100	10	1.00
8	100	20	2.00	100	20	2.00
9	100	20	2.00	100	25	2.50
10	100	10	1.00	100	10	1.00
11	100	10	1.00	100	20	2.00
12	100	10	1.00	100	15	1.50
13	100	10	1.00	100	25	2.50
14	100	20	2.00	100	20	2.00
15	100	10	1.00	100	25	2.50
16	100	10	1.00	100	25	2.50
Total		200	16.0		300	24.0

Note: similar strength of nutrient solutions, but different quantities delivered to the crop.

(Models 8, 9, and 10) designed to deliver a modified exponential fertilization schedule as weekly nutrient additions extending over the desired fertilization period (i.e., 16 weeks). An example of the calculations involved are shown in Appendix 1. The initial step is to calculate the relative addition rate (r) using N content of the seed as the initial N amount, or starting N level (N_s). A completed schedule, as shown in Table 3, illustrates clearly that the quantity of weekly fertilizer applied following the modified regime is a combination of amounts calculated by an exponential function (Model 8) and by an inverse exponential function (compensating regime, Model 10). The compensation amount (N_c) is the difference between the last and penultimate additions associated with the exponential regime. It is delivered exponentially in reverse order during the first one-half of the growing period, until full root exploitation of the growing medium occurs. The amount and duration of nutrient compensation may vary for different cropping systems, depending on the rooting characteristics of species and the container size or configuration.

Since the concentration range of the nutrient solution applied may be higher than used conventionally, improved control of nutrient delivery in most irrigation systems can be obtained by employing a wider range of stock solutions during the fertilization period, or by installing a variable control fertilizer dilutor and dispensing device, which provides a more precise regulation of the concentration and amount of fertilizer solution applied to the crop. In terms of the fertilization program, the water (or liquid) functions primarily as the carrier for nutrients required by the crop. Depending on the solubility restraints of the fertilizer materials used, prescribed amounts can be dissolved and applied in different volumes of water governed by the irrigation requirements of the crop. Thus, the same quantity of nutrients can be delivered as a concentrated nutrient solution at low watering demands, or as a diluted nutrient solution at high watering demands. This approach is illustrated in Figure 20, which shows a broad range of weekly nutrient additions applied conventionally or exponentially to red pine seedlings reared at three contrasting irrigation regimes. Each week the prescribed quantity of nutrients was delivered in three different volumes of water. Although the seedlings received the same seasonal amount of nutrients (25 mg N/seedling), maximum growth and nutrient uptake was consistently found under the exponential schedule and the "wet" irrigation regime (Fig. 21), illustrating greater fertilizer efficiency with exponentially based nutrient addition and favorable moisture availability (watering at 90 percent of container capacity weight).

Table 3. Example of a modified exponential nutrient loading regime for black spruce seedling crop designed for weekly applications during a 16-week fertilization period. Loading requirement N_T = 64 mg N/seedling, seed N content Ns = 0.2 mg, and relative addition rate r = 0.361 per week. (*See* Appendix 1 for sample calculations.)

Weekly application	Irrigation requirement (ml/seedling)	Exponential regime	Compensation regime	Modified exponential regime	Solution N concentration (mg/l)
		N applied (mg/seedling)			
1	20	0.09	2.12	2.21	110
2	25	0.12	1.38	1.50	60
3	15	0.18	0.90	1.08	72
4	10	0.26	0.59	0.85	85
5	20	0.37	0.38	0.75	37
6	15	0.53	0.25	0.78	52
7	10	0.76	0.16	0.92	92
8	20	1.09	0.11	1.20	60
9	25	1.56	0.00	1.56	62
10	10	2.23	0.00	2.23	223
11	20	3.20	0.00	3.20	160
12	15	4.59	0.00	4.59	306
13	25	6.59	0.00	6.59	264
14	20	9.45	0.00	9.45	472
15	25	13.55	0.00	13.55	542
16	25	13.55*	0.00	13.55	542
Total	300	58.1	5.9	64.0	

* Differential applied to the initial 8-week compensation regime. The amount and duration of nutrient compensation may vary with the cropping system, species characteristics, and container size or configuration.

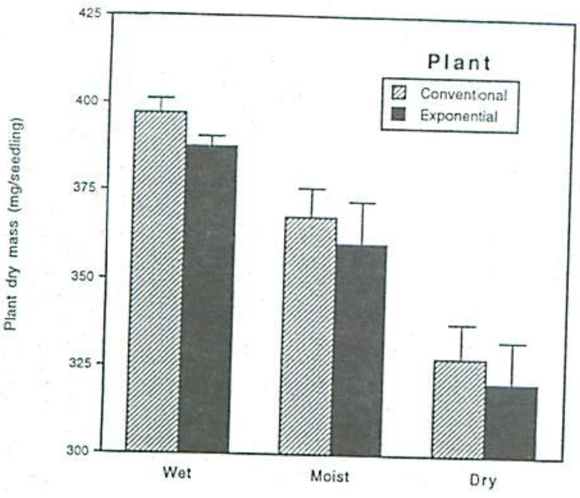

Figure 20. Dry matter production of 16-week-old red pine seedlings receiving 26 mg N per cavity conventionally or exponentially at three contrasting moisture regimes controlled by irrigating at 90, 72, and 55 percent of container capacity (from *Timmer and Miller 1991).*

Monitoring Growing Media Nutrient Status

Use of high fertilization levels for loading combined with high-frequency application increases the risk of a buildup of toxic nutrient concentration in the growing medium, especially during the final applications of exponentially based delivery regimes. Hence, it may be prudent to monitor substrate nutrient status on a regular basis, particularly near the end of the fertilization period when high levels are used. An earlier study with conventional fertilization regimes (Timmer and Parton 1984) noted that soluble salt concentration or electrical conductivity (EC) of a saturated aqueous extract of the growing media is a sensitive indicator of nutrient availability in container substrates of red pine seedlings. Maximum growth was associated with levels of 1.8–2.2 mS/cm, with toxicity occurring at about 2.5 mS/cm. These guidelines may also be applicable to exponential fertilization regimes, since similar end-of-season values (2.0–2.1 mS/cm) were associated with more recent tests of high loading regimes (75 mg N/tree) on red pine seedlings (Miller and Timmer 1994).

Tracking soluble salt levels in the rooting media by periodic monitoring will characterize specific fertilization regimes, especially as the season progresses, as shown for black spruce culture in Figure 13. As expected, the conventional constant regime (10 mg N/seedling) exhibited relatively stable EC status during the growing season. The equivalent exponential regime (10 mg/seedling) exhibited a gradual increase in salt levels at Week 14. The exponential loading (64 mg N/seedling) regime was characterized by a much earlier and sharper increase in soluble salt levels. In this case, the loading treatment peaked at about 1.8 mS/cm, and never approached toxic levels. It is interesting to compare the progressions of nutrient concentration in the growing medium with those in the seedlings receiving the same treatments (Fig. 14). Exponential fertilization induces relatively stable N concentrations in the trees, in contrast to declining N levels under conventional fertilization.

Growing Media Quality

The quality of horticultural peat that is used as the major source of rooting medium for container seedling production can vary markedly between types, and this can seriously affect substrate–fertilizer interactions and nutrient availability to crops (Folk et al. 1992). A previous study, which tested conventional (constant rate addition) fertilizer regimes on conifer seedlings showed that the initial alkali–labile organic–nitrogen (ALON) fraction of peats may be inhibitory to plant growth (Timmer and Folk 1992). The ALON determination proved to be a sensitive and inverse indicator of peat quality, and was effectively used to calculate fertilizer requirements needed to counteract the low fertility of peats. These studies, however, did not evaluate peat quality in relation to steady-state nutrient culture or exponential nutrient loading. Because initial peat quality (reflected as [a] in Figure 7) is a critical variable in calculating loading requirements, the effects of rooting media quality, ALON status, and exponential loading regimes on seedling performance were investigated.[6]

Black spruce seedlings were reared under simulated operational conditions in styroblock containers to test two peat sources (A and B), contrasting in initial ALON levels (101 and 44 mg/L, respectively), and receiving three different exponential fertilization treatments. Two regimes provided 32 mg N per seedling for the season, one as a pure exponential (*e*) schedule (Model 8) and the other adjusted (*ae*) to deliver 22 mg N at exponential rates and 10 mg N at a constant rate (to test fertilizer efficiency and counter the N retention capacity of the peat sources).[7] The third regime represented a loading (*ml*) treatment, and delivered 64 mg N exponentially. The loading increment (amounting to a doubling of the N addition) also served as an adjustment to compensate for the lower fertility of the inferior peat (A), because ALON levels of the peat sources (before potting) differed by an approximate 2:1 ratio (44 versus 101 mg/L).

[6]Bachie, O. Evaluation of chemical indices of peat growing media for exponential fertilization of black spruce seedlings. M. Sc. F. Thesis. University of Toronto, Toronto, ON. (In prep.)

[7]Ibid.

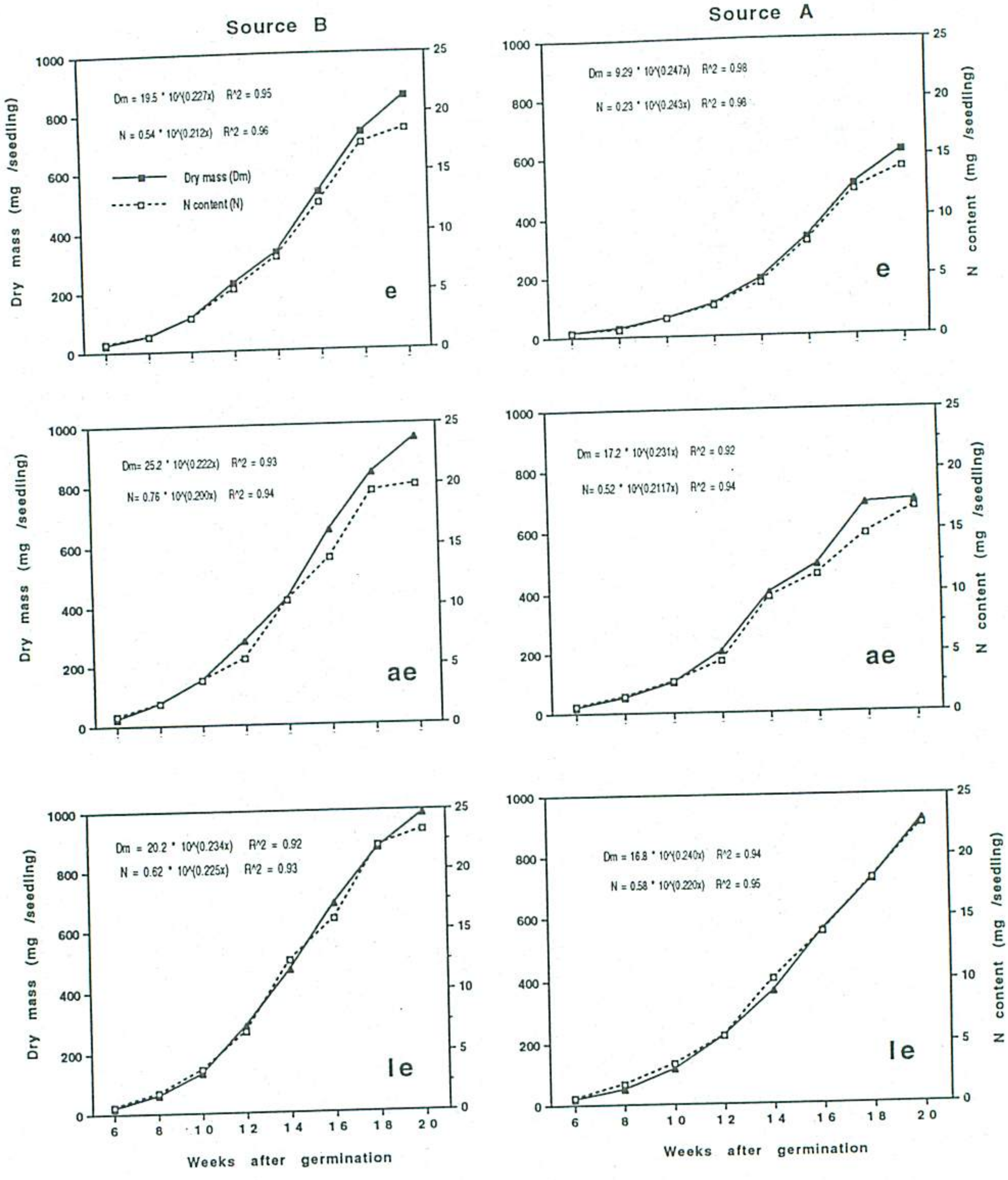

Figure 21. Progression of dry matter production (solid line) and nitrogen uptake (broken line) in shoots of black spruce seedlings reared on contrasting peat sources (A and B). Fertilization was at 32 mg N per seedling following exponential (e) and adjusted exponential (ae) schedules, and at 64 mg N per seedling following an exponential loading (le) schedule.[8]

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[8]Ibid.

Seedling Response to Contrasting Peat Quality

The progressions of shoot dry matter production and N content for the 20-week growing period (Fig. 19) showed that both growth and N uptake of the seedlings occurred exponentially, inferring that steady-state culture was achieved. Synchronization appeared closer for the loading treatment compared to nonloading treatments, indicating an improved steady-state status for the loading regimes. Final harvest parameters (Fig. 22) consistently showed lower shoot biomass (20–30 percent) and N uptake (10–15 percent) for trees on Peat A compared to Peat B at the low fertilization rates, attesting to the poorer quality of Source A. These results tend to confirm the effectiveness (and inverse relationship) of ALON as an index of peat suitability (Timmer and Folk 1992). Increased fertilization (based on a 2:1 ALON ratio difference between peat types) appeared to compensate for inferior growing media quality, because shoot biomass of *ml*-treated seedlings on Peat A matched that of *me*-treated trees on Peat B.

Compared to the pure exponential (*e*) regime, the adjusted (*ae*) regime consistently improved growth and N uptake in the seedlings, but was statistically significant only for dry mass production on Peat B, demonstrating enhanced fertilizer use efficiency. Shoot biomass on this peat type was also greatest and similar under both *le* and *ae* treatments, but N uptake was reduced (by 20 percent) at the lower addition rate. In the context of critical nutritional phases in crop production (*see* Fig. 7), the response patterns suggest that seedlings were fertilized to sufficiency status at the low-dose rate (32 mg N), and to the luxury consumption level at the high-dose rate (64 gm N) because maximum productivity was reached at both supply rates. These response differences exemplify the principle of nutrient loading—fertilization increased internal nutrient reserves of seedlings without changing plant size. A corresponding response pattern was absent for Peat A, which exhibited reduced shoot growth and N uptake for *ae*-treated trees compared to *le*-treated trees (Fig. 22). Evidently, the 32 mg N addition increased performance within the deficiency range, below the sufficiency level, and no doubt reflected the inherently low fertility of the peat source. Hence, similar to the experience with conventional fertilization practices (Timmer and Folk 1992), fertilizer prescriptions to meet sufficiency levels using exponential schedules must also account for the inherent quality of the peat growing media.

Interestingly, this conclusion may not apply strictly to exponential loading regimes, because the loading treatment induced similar responses in shoot growth and N content irrespective of peat source (Fig. 22). Apparently, the higher nutrient additions associated with the loading level also compensated for the inferior quality of Peat A, particularly in regard to enhanced N uptake. Thus, seedlings produced under exponential loading regimes may not be as sensitive to differences in peat quality. The reader is cautioned, however, that this conclusion needs further testing over a wider range of peat types. Overall, the results suggest that it is relatively easy to induce steady-state nutrition in seedlings growing on peat sources of contrasting quality using exponential fertilization regimes.

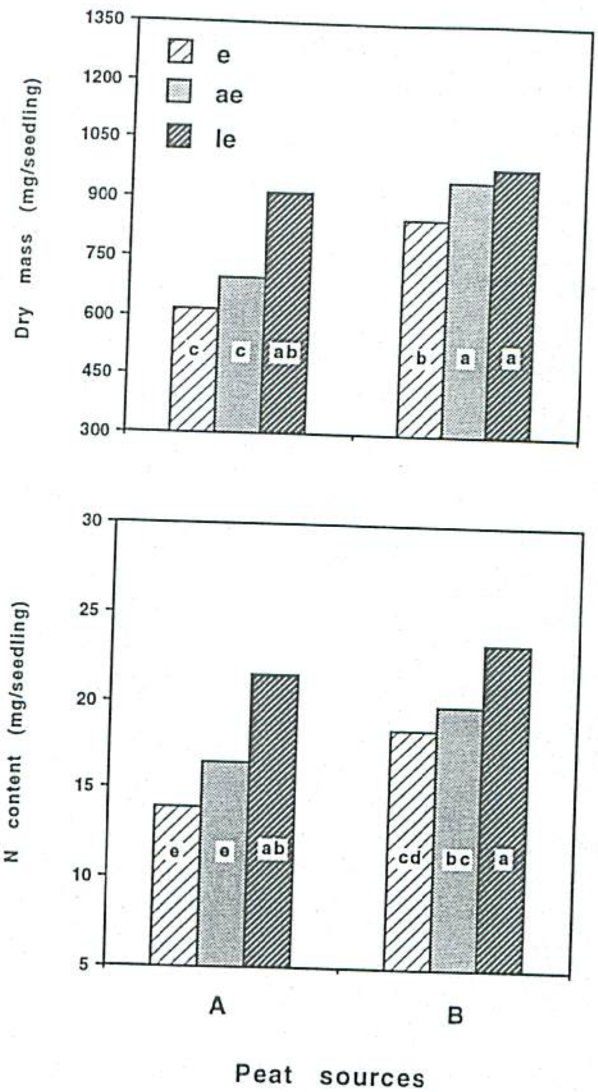

*Figure 22. End-of-season shoot growth and nutrient uptake of black spruce seedlings reared on contrasting peat sources (A and B). Fertilization was at 32 mg N per seedling following exponential (*e*) and adjusted exponential (*ae*) schedules, and at 64 mg N per seedling following an exponential loading (*le*) schedule.*[9]

[9]Ibid.

Seedling performance at low nutrient addition rates is likely to be reduced with inferior peat quality, but seems unaffected at high loading levels (at least within the range of peat types that were tested). Initial ALON tests may serve as a useful predictor of the suitability of peat sources as growing media for seedling culture.

QUALITY ASSESSMENT CRITERIA OF SEEDLINGS

Morphological-based Attributes

Considering the benefits of nutritionally preconditioning seedlings for outplanting, it is inevitable that such practices be recognized in grading schemes purporting to assess the quality of planting stock. The present system in Ontario is essentially based on morphological criteria, such as plant size and dry mass. It should be noted that the superior outplanting responses of exponentially fertilized (Fig. 4) or nutrient-loaded (Figs. 8 and 9) seedlings in the current studies were not associated with preplant size, since the initial size of test plants was similar. These preconditioning regimes were intentionally developed to meet provincial size standards, as reflected by the conventionally reared seedlings used as controls. The results, however, illustrate the weakness of morphologically based attributes for testing stock quality, because field performance was clearly more related to preplant nutrient status and culture than to seedling size. To improve reliability, the authors submit that nutritional, as well as morphological, criteria be included in a system of quality standards for containerized seedlings.[10]

Combined Morphological and Nutritional Standards

For simplicity and convenience it would be logical to link nutritional standards to current sampling protocols for quality testing of conifer seedlings. Effective assessment of steady-state nutrient culture, however, requires criteria that reflect dynamic or seasonal nutrient composition of seedling crops, which may not be compatible with traditional end-of-season measures. The authors propose that a simple two-sample plant analysis program be adopted to improve the present quality assessment procedures.[11] The concept is illustrated in Figure 23, which shows that relative comparisons of seasonal growth and nutrition of differently fertilized seedlings are distinguishable by the magnitude and direction of individual linear responses (vectors). Since seasonal progressions of these parameters can be characterized by vectors based essentially on two sampling points, occurrence of steady-state nutrient achievement (vector *me*), dilution effects (vector *s* and *c*), or accumulation responses (vector *e*) due to specific cultural regimes can be identified quantitatively by growth measurements and nutrient analysis at the beginning and end of the growing season.[12] Thus vector slope depicts the degree of steady-state attainment, and absolute nutrient concentration indicates the level of nutrient loading.

Assuming that standards of dry mass (500 mg, *see* Galloway and Squires [1988]) and nutrient levels (2.8 percent N) for exponentially nutrient loaded black spruce seedlings are accurate, the procedure can be demonstrated with early and late season sample data from Figure 14. In this case, the three crops have been labeled A, B, and C in Table 4 to mask their fertility treatment. As can be seen, only Crop C meets the condition of steady-state nutrient loading, since growth exceeded the dry mass criteria, and internal

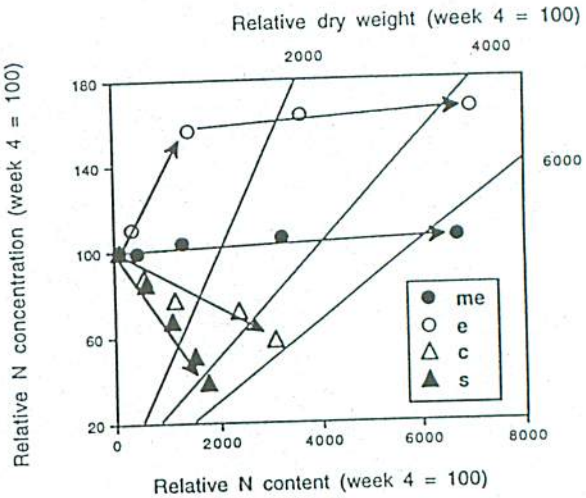

Figure 23. Nomogram of relative changes occurring at 2-week intervals in dry mass and N composition of mesquite seedlings cultured at singe dose (s), constant top dressing (c), pure exponential (e), and modified exponential fertilization regimes (where seedling status at Week 4 was normalized to 100). Vectors reflect progressions in time from Weeks 4 to 12 (from *Imo and Timmer 1992a).*

[10] Timmer, V.R. Exponential nutrient loading: A new fertilization technique to improve seedling outplanting performance on competitive sites. New Forests. (In press.)

[11] Ibid.

[12] Imo, M.; Timmer, V.R. Vector diagnosis of nutrient dynamics in nesquite seedlings. For. Sci. (In press.)

N concentrations were relatively stable and high during the sampling interval. The other crops met the desired dry mass standard, but failed to meet cultural requirements. Crop A reflected conventional nutrient culture because of declining N levels, and Crop B depicted steady-state culture, but at suboptimal late season loading levels. Similar evaluations should include other macronutrients, analyzed to ensure proper nutrient balance in the plants.[13] Procedures can be incorporated with routine growth progression monitoring conducted by most growers. At the appropriate time period, seedlings sampled for regular growth assessment can be composited for nutrient analysis. Thus, the two-time plant analysis required for each crop is the only extra cost incurred. Since these protocols are relatively simple, the inclusion of nutritional parameters in future quality control programs for planting stock is recommended.

Table. 4. Dry mass (DM) in mg and nitrogen (N) concentration (in percent) of black spruce containerized seedlings reared under different fertilization regimes at North Gro Development. Seedlings were sampled early (Week 6) and late (Week 18) in the growing season.

	Early		Late		Fertilization
Crop	DM	N	DM	N	regime
A	46	2.5	530	1.0	Conventional
B	50	2.0	556	2.5	Exponential
C	44	2.7	591	2.8	Exponential loading

CONCLUSION

Exponential nutrient loading practices for seedlings have significant potential to accelerate outplanting performance and reduce vegetation management in plantations. The fertilization delivery models that have been developed are effective in ensuring steady-state nutrient conditions during the loading process, and are also relatively easy to adapt to operational fertilization practices in commercial greenhouses. The extra cost of fertilizers and monitoring is relatively small compared to the total cost of growing containerized seedlings, and can be recovered many times over by improved field performance and reduced vegetation management costs on weedy sites. Outplanting results to date are short term, but loading responses should persist because of the advantage of early dominance in long-term plantation development (Greaves et al. 1978, Fisher and Mexal 1984, MacDonald and Weetman 1993). This will be confirmed by monitoring the field trials as long as possible.

Nutritional conditioning practices for planting stock, such as exponential nutrient loading, will play a more important role in formulating modern reforestation strategies, particularly for boreal mixedwood sites where management is constrained by the limited use of herbicides. Early growth acceleration of trees, combined with increased weed suppression, provides realistic alternatives to herbicide application. The benefits of exponential nutrient loading practices, however, must be recognized by their adoption in effective grading systems for containerized planting stock, and by providing greater financial incentives for producers. Nutritional criteria need to be incorporated in seedling quality tests to improve the precision of field forecasting performance. It is hoped that the information in this manual will contribute to the further development and better understanding of exponential loading practices used for containerized seedling culture.

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APPENDIX 1. EXAMPLES OF CALCULATING FERTILIZER ADDITIONS FOR MODIFIED EXPONENTIAL LOADING REGIMES.

1. Examples of fertilizer addition calculations for exponential regime

A. Known variables:

Fertilizer requirement	$N_T = 64.0$ mg N	(N per seedling)
Initial N in seed	$N_s = 0.2$ mg N	(N per seed)
Fertilization period	$T = 16$ weeks	(applications during the season)

Determine r (relative addition rate) defined as:

$$r = [\ln (N_T/N_s + 1)] / T$$

therefore,

$$r = [\ln (64.0/0.2 + 1)] / 16$$

$$r = 0.361 \text{ per week}$$

B. Consecutive applications are calculated according to Model 9.

Thus for Week 1 (t = 1): $N_{t=1} = N_s (e^{rt} - 1) - (N_{t-1})$

This simplifies to $N_{t=1} = 0.2(e^{0.361*1} - 1) - N_{t=0}$ where the previous addition $N_{t=0} = 0$,

therefore, $N_{t=1} = 0.2(e^{0.361*1} - 1) - 0$

$N_{t=1} = 0.087$ mg N per seedling (*see* Table 3)

For Week 2: $N_{t=2} = N_s (e^{rt} - 1) - (N_{t-1})$

$N_{t=2} = 0.2(e^{0.361*2} - 1) - N_{t=1}$

Note $N_{t=1} = 0.087$ mg N per seedling, from previous calculation

$N_{t=2} = 0.212 - 0.087$

$N_{t=2} = 0.125$ mg N per seedling (*see* Table 3)

2. Examples of fertilizer addition calculations for compensation regime

Calculations for the compensation regime are based on model (10).

$$N_C = N_o (e^{-rt} - 1)$$

C. Known variables:

Compensating amount	$N_C = 5.9$ mg N per seedling	(Note $N_{t=16} - N_{t=15}$)
Initial N in seed	$N_s = 0.2$ mg N per seed	(at time 0)
Compensation period	$T = 8$ weeks	(to full root exploitation)

Thus, the relative addition rate

$$r = [\ln (N_C/N_s + 1)] / T$$

$$r = [\ln (5.9/0.2 + 1)] / 8$$

$$r = 0.427 \text{ per week}$$

D. Week 1 of compensation (t = 8 because of reversed order):

$N_{C=1} = N_s (e^{rt} - 1) - (N_{t-1})$

$N_{C=1} = N_{t=1} = 0.2(e^{0.427*8} - 1) - 0.2(e^{0.427*7} - 1)$

$N_{C=1} = 5.889 - 3.773$

$N_{C=1} = 2.116$ mg of N per seedling (*see* Table 3)

Week 2 of compensation (t = 7 because of reversed order):

$$N_{C=2} = N_s\,(e^{rt} - 1) - (N_{t-1})$$
$$N_{C=2} = 0.2(\,e^{\,0.427*7} - 1) - 0.2(\,e^{\,0.427*6} - 1)$$
$$N_{C=2} = 3.773 - 2.392$$
$$N_{C=2} = 1.381 \text{ mg N per seedling}$$ (*see* Table 3)

3. Examples of fertilizer addition calculations for modified exponential regime

Weekly application of the modified exponential regime combines calculations of 1 (exponential regime) and 2 (compensation regime).

E. Therefore, the first application is:

$$N = N_{t=1} + N_{C=1}$$
$$N = 0.087 + 2.116$$
$$N = 2.203 \text{ mg N per seedling}$$ (*see* Table 3)

Similarly, the second application is:

$$N = N_{t=2} + N_{C=2}$$
$$N = 0.125 + 1.381$$
$$N = 1.506 \text{ mg N per seedling}$$ (*see* Table 3)