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RESEARCH ARTICLE

Nursery Nitrogen Loading Improves Field Performance of Bareroot Oak Seedlings Planted on Abandoned Mine Lands

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Abstract

Although mine reclamation sites are important targets for ecological restoration, they are generally difficult to regenerate successfully. We evaluated the importance of nursery nutrient loading as a new approach to enhance forest restoration on abandoned mine lands. Northern red oak (*Quercus rubra*) and White oak (*Q. alba*) seedlings were nitrogen (N) loaded for 18 weeks at a bareroot nursery in southern Indiana, United States. Fertility treatments followed conventional or modified exponential functions to synchronize N supply with plant demand. Subsequently, nursery-grown seedlings were outplanted the following year onto a mine reclamation site in southwestern Indiana to evaluate effects of nursery N loading on first-year field performance. Nursery N loading promoted total plant dry mass production 25–129% in Red oak and 50–184% in White oak compared to unfertilized plants. Nitrogen loading increased N content 88–145% and potassium (K) content 16–71% for Red oak and N content 124–250% and K content 16–93% for White oak relative to controls. When outplanted, N loading resulted in high seedling survival (>84%) and increased total plant dry mass production 14–30% for Red oak and 23–52% for White oak. Nitrogen loading increased plant N uptake 14–102% in Red oak and 32–105% in White oak under field conditions. Exponential N loading demonstrates potential as a viable technique to improve seedling outplanting performance and reclamation success in Indiana and elsewhere.

Key words: forest restoration, mine lands, nitrogen loading, reclamation, Red oak, White oak.

Introduction

Surface mine reclamation has the potential to develop important forest values on highly disturbed sites. However, performance of forest tree species planted on reclaimed mines has fallen short of those typically associated with native forests sites or other afforestation settings. Low soil fertility (Bussler et al. 1984; Andersen et al. 1989), soil compaction (Unger & Cassel 1991; Bateman & Chanasyk 2001), competition from weeds (Crow 1988; Roberts et al. 1988; Ashby 1997; Casselman et al. 2006), and animal browse (Stange & Shea 1998; Tripler et al. 2002) have been noted as key factors that may limit early establishment success of newly outplanted hardwood seedlings on mine reclamation sites in the Central Hardwood Forest Region of the United States. For example, ground cover plants established concurrently with tree seedlings for erosion control decreased survival and growth of hardwood seedlings (Andersen et al. 1989). Additionally, competition for nutrients has been found to limit seedling survival and growth (Walker 2002; Thompson & Pitt 2003; Valdecantos et al. 2006). Despite these deterrents, studies have shown that forests can be successfully restored on abandoned mine sites with productivity at least equal to that of native forests removed by mining (Torbert & Burger 1990; Torbert et al. 2000; Rodrigue & Burger 2004).

A need exists to identify cost-effective and practical silvicultural approaches both at the nursery stage and at the field levels that will ensure successful forestland restoration on abandoned mine sites. Attempts to improve regeneration success of planted seedlings include herbicide use and field fertilization (Andersen et al. 1989; Walker 2002). Although herbicide application may effectively control competing vegetation and improve seedling establishment success (Andersen et al. 1989; Baer & Groninger 2004), there is increasing public sentiment against herbicide use owing to negative effects on the environment and on biodiversity. Additionally, broadcast field fertilization to stimulate early seedling establishment success may inadvertently increase growth of herbaceous species rather than target trees (Roberts et al. 1988; Casselman et al. 2006).

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Storing nutrients in seedlings through nursery nutrient loading (Salifu & Timmer 2003*b*) is one option that may provide a better rationale to build plant nutrient reserves, which are later exploited to promote seedling field survival and growth. Nutrient-loaded seedlings exhibit superior survival, growth, and competitiveness over nonloaded plants when transplanted on a variety of habitats (Timmer & Munson 1991; Malik & Timmer 1996). Improved performance of loaded seedlings is often associated with depletion of higher preplant nutrient reserves to fuel new growth (Malik & Timmer 1996; Salifu & Timmer 2001).

Nursery hardwood seedlings are commonly grown under only sufficient levels of nutrient inputs, promoting adequate morphological development but limiting internal nutrient storage for later use to support new growth following outplanting. Thus, exponential nutrient loading may provide a new and useful management technique, which has specific significance to improving seedling performance on mine reclamation sites. We have shown that nutrient loading can be applied to facilitate nutrient storage in container Red oak (*Quercus rubra* L.) seedlings (Salifu & Jacobs 2006) and in bareroot Red oak and White oak (*Q. alba* L.) seedlings (Birge et al. 2006), but performance of plants cultured in this manner has yet to be tested under field conditions. Additionally, there is relatively little published information related to nutritional responses of Red and White oak on mine reclamation sites. Therefore, we transplanted seedlings on an abandoned mine land in southwestern Indiana, United States, to examine effects of nursery nutrient loading (Birge et al. 2006) on first-year field performance. Nutrient loading is most important in helping to overcome competitive effects and transplant stress early in the growth stage (Malik & Timmer 1996; Salifu & Timmer 2001). Moreover, the first year following planting represents the critical period for establishment of afforestation plantings; no significant differences were observed in seedling field survival (averaging 65%) between years 1–5 in a survey of operational tree plantations in Indiana (Jacobs et al. 2004). Therefore, the objectives of the current study were to (1) compare growth and nutrient storage in conventionally and exponentially fertilized seedlings prior to outplanting and (2) examine early survival, growth, and nutritional responses of conventionally and exponentially fertilized seedlings established on a mine reclamation site. These species were selected for the study because of their great economic importance to the region, capacity to acclimate to varied site conditions, and increased use in environmental plantings (Jacobs et al. 2004).

Methods

Nursery Phase

Bareroot Northern red oak and White oak seedlings were grown from seed germinated in spring 2004 at Vallonia State Nursery (lat 38°85′N, long 86°10′W), Indiana, U.S.A. All standard nursery practices for seedling production were followed except for fertilizer treatments. Seedlings received six fertility treatments (Table 1). Two nonloading treatments were supplied the same fertilizer rate (0.84 g N plant^{-1} season^{-1}) applied either conventionally (C) (i.e., 0.84C) using a constant addition rate or exponentially (E) (i.e., 0.84E). The other treatments followed exponential functions to match nutrient supply with plant demand (Salifu & Timmer 2003*b*). The higher fertility treatments represented N-loading treatments (Table 1). Nitrogen was applied biweekly as ammonium nitrate in crystal form (34-0-0) as described in Birge et al. (2006). Further details on the nursery study can be found in Birge et al. (2006). Seedlings were mechanically lifted in December 2004 and processed for overwinter storage in coolers (3°C) at Purdue University (lat 40°25′N, long 86°55′W) in West Lafayette, Indiana. Plants were removed from storage in April 2005 and sorted for the field experiment. The six selected treatments (Table 1) from Birge et al. (2006) for this field trial exhibited responses that ranged from deficiency to toxicity.

Table 1. Treatment for field experiment and fertilizer delivery schedule adopted during bareroot nursery culture of Red oak and White oak seedlings.

Fertility Treatment Number	*Nursery Fertilization Rate (N g/plant)*	*Fertilizer Delivery Schedule*
1	0.00	C
2	0.84	C
3	0.84	E
4	1.26	E
5	1.68	E
6	3.36	E

C, conventional; E, exponential.

Field Study

Nursery-reared seedlings from the two species and the six fertility treatments (Table 1) were outplanted on 2 April 2005 on an abandoned mine reclamation site (lat 39°4′N, long 87°15′W) in southwestern Indiana to examine effects of prior nursery treatments on seedling field performance. The site was graded to the original contour of the land after mining. The topsoil was replaced to a depth of about 45 cm and compacted. The field design was a split-plot design with a 2 × 6 factorial treatment structure, which was replicated in five blocks. The main plot treatments were the species at two levels, and the subplot treatments were the six nursery fertility treatments (Table 1). Each block measured 21 × 24 m (comprising two 21 × 12–m main plots) and was separated from adjacent blocks by 2-m buffers. Species were randomly allocated to main plots within each block, and the fertility treatments were randomly allocated to subplots within species. The six fertility treatments were represented by six rows within each species. Each fertility treatment consisted of 20 trees planted in one row. A total of 1,200 trees (2 species × 6 treatments × 20 trees per treatment × 5 replications) were planted

1 m apart within rows and 2 m between rows. Planting was conducted using a machine planter (i.e., tractor-hauled coulter with trencher and packing wheels) with a crew of two to three people.

Herbicide was applied 2 weeks (15 April 2004) after planting. A combination of a preemergent (AquaCap [Pendulum]) at the rate of 5 L/ha and a postemergent (GlyproPlus [Glyphosate]) at the rate of 2.5 L/ha at 45% solution concentration was applied. Herbicide use has been shown to stimulate seedling growth because essential resources (light, nutrients, and water) are directed to growth of target trees (Baer & Groninger 2004; Jacobs et al. 2005; Andrews & Broome 2006). Vegetation control minimized damage by rabbits and rodents. Dominant vegetation that persisted on the site included Goldenrod (*Solidago virgaurea* L.), Sericea lespedeza (*Lespedeza cuneata* [Dum.–Cours.] G. Don), Red clover (*Trifolium pretense* L.), Ragweed (*Ambrosia artemisiifolia* L.), and Foxtail barley (*Hordeum jubatum* L.). The experiment was fenced to provide deer browse protection, which was deemed necessary to help facilitate detection of true treatment effects.

Fencing is important because studies have generally shown that deer prefer well-conditioned nursery seedlings whether fertilized or not. However, the intensity of deer browsing varies greatly from place to place (Healy & Lyons 1987). For example, high deer populations of 88–153/km^2 in a game preserve in Massachusetts, United States, created savanna-like conditions, but limited browsing occurred in an adjacent region with 8–21 deer/km^2 (Healy & Lyons 1987) indicating that damage is highly correlated with animal populations. The use of competitive nutrient-loaded seedlings may provide an opportunity to promote rapid growth to reach free-to-grow status above the height of competing vegetation and the level of deer browsing (Jacobs et al. 2004).

Plant and Soil Sampling, Chemical and Statistical Analyses

Seedling morphological and nutritional attributes were evaluated based on standard protocols (Salifu & Timmer 2003*a*; Jacobs et al. 2005). For each treatment, two plants were sampled per replicate and five replicates were evaluated (10 seedlings) per treatment for each species to assess initial status at transplanting. These seedlings were partitioned into stem and root. For the field study, 2 plants were destructively harvested per treatment replication (10 plants per treatment) 4 months after planting, placed in coolers and transported to Purdue University for further analysis. Sampling hardwoods during the active growth stage (June to August) helps to more accurately assess foliar N status (Ponder 2004) prior to N translocation to other storage tissues in preparation for senescence (Dickson 1989; Wilson & Jacobs 2006). Seedlings were partitioned into roots, old stem, new stem, and leaves. For both the initial and the field-excavated seedlings, samples were dried for 72 hours at 70°C for dry mass determination and then milled for chemical analysis. Data on seedling shoot height, basal diameter, and survival were estimated for all the 20 trees per treatment replication 4 months after planting and before excavating.

Five soil samples (0–15 cm depth) were collected within each block (total of 25 for the five blocks) and composited by block to obtain five representative replicate samples for further processing and chemical analysis. Soil bulk density (BD) was determined based on standard procedures (Rowell 1994; Salifu et al. 2002). Nutritional analysis of plant and soil samples involved standard procedures used

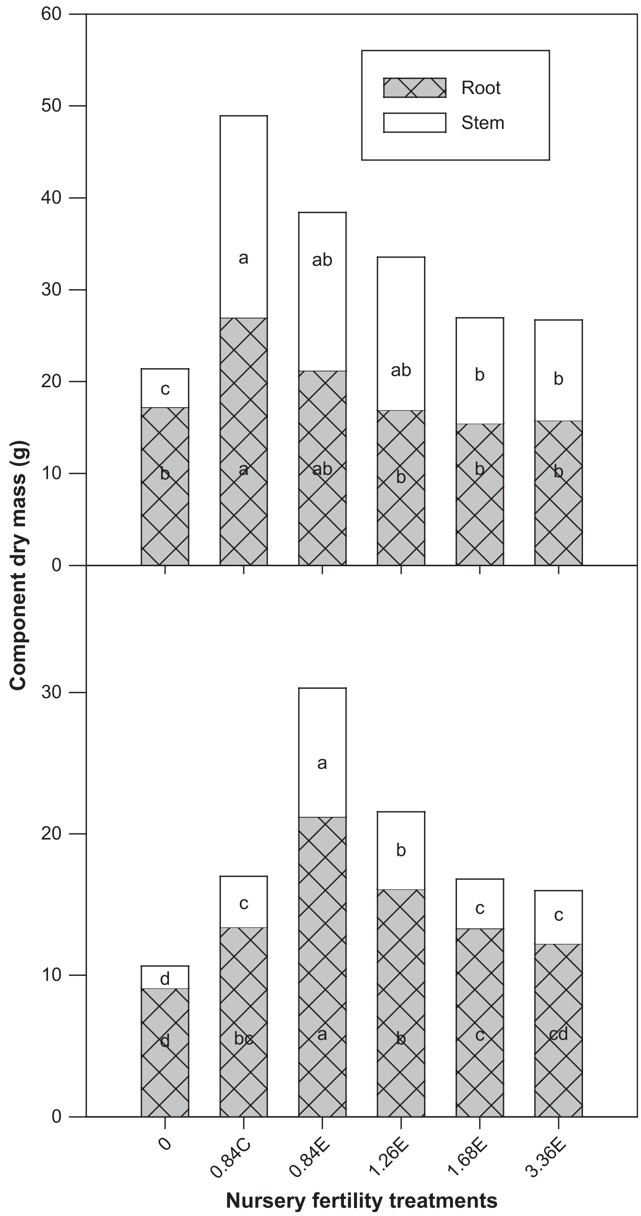

Figure 1. Preplant component dry mass of Red oak (top) and White oak (bottom) seedlings exposed to increasing fertility treatments for one growing season (8 months) during bareroot nursery culture. Treatments marked with different letters differ statistically for each component according to Waller–Duncan's multiple range test at $\alpha = 0.05$.

by A & L Great Lakes Laboratories (Fort Wayne, IN, U.S.A.), following Association of Official Analytical Chemist methods as detailed in Jacobs et al. (2005).

Growth and nutritional parameters were evaluated by analysis of variance (ANOVA) for each species using SAS software (SAS Institute, Inc., Cary, NC, U.S.A.). Prior to ANOVA, the data were tested and found to meet the ANOVA assumptions for normality and constant variance. Significant treatment means ($p < 0.05$) were ranked according to Waller–Duncan's multiple range test at $\alpha = 0.05$.

Results

Nursery Phase

Nursery N loading significantly affected component dry mass production for Red oak (Fig. 1, top) and White oak (Fig. 1, bottom). For example, fertilization increased total plant dry mass production 25–129% in Red oak and 50–184% in White oak compared to unfertilized plants. The same fertilizer rate applied exponentially promoted greater dry mass production than when supplied conventionally for White oak (Fig. 1, bottom). There was greater proportional allocation of dry mass to roots than stems within each treatment (Fig. 1).

Component tissue N concentration significantly increased with fertility for Red oak (Fig. 2, left) and White oak (Fig. 2, right). Increased tissue N concentration was associated with decreased P levels (Fig. 2). Although K concentration remained relatively stable with increased fertility for Red oak (Fig. 2, left), it decreased for White oak (Fig. 2, right). Fertilization increased total N content 88–145% and K content 16–71% for Red oak (Fig. 3, left)

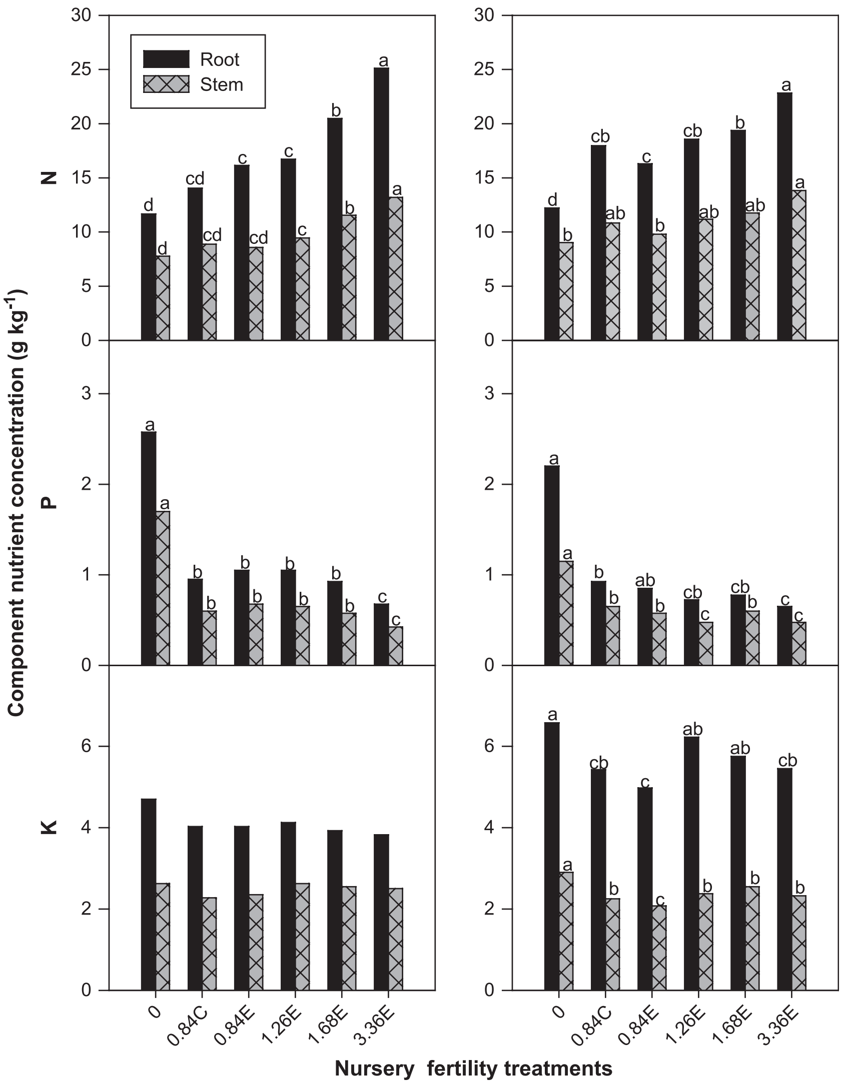

Figure 2. Preplant component tissue nutrient concentration for Red oak (left) and White oak (right) seedlings exposed to increasing fertility treatments for one growing season (8 months) during bareroot nursery culture. Treatments marked with different letters differ statistically for each component according to Waller–Duncan's multiple range test at $\alpha = 0.05$.

and N content 124–250% and K content 16–93% for White oak (Fig. 3, right) relative to the control. However, P content diminished with increased fertility (Fig. 3). Greater nutrient allocation in roots suggests that roots act as primary sinks for nutrient storage and could subsequently serve as critical nutrient sources needed to support new growth following field transplant.

Field Response

Physicochemical properties of the soil characterizing the study site are presented in Table 2. Although the soil textural class is silty clay loam, measured soil BD appears similar to those observed for sandy soils (range from 1.3 to 1.7 g/cm^3) (Foth 1990; Salifu et al. 2002).

Nursery N loading resulted in high seedling field survival (>84%), which was statistically similar across all treatments (Table 3). The highest fertility treatment (3.36 g N plant^{-1} season^{-1}), which induced toxicity in cultured plants during the nursery phase (Birge et al. 2006), resulted in lower mean survival (73–81%) than all other treatments. Initial height and basal diameter increased significantly with fertility to 1.68E but declined at the highest fertility level. Similar trends were observed for seedling shoot height and basal diameter under field conditions (Table 3). Nursery N loading significantly promoted White oak component dry mass production in the field (Fig. 4, bottom). For example, fertilization significantly increased total plant dry mass 14–30% in Red oak and 23–52% in White oak compared with controls. Increased component

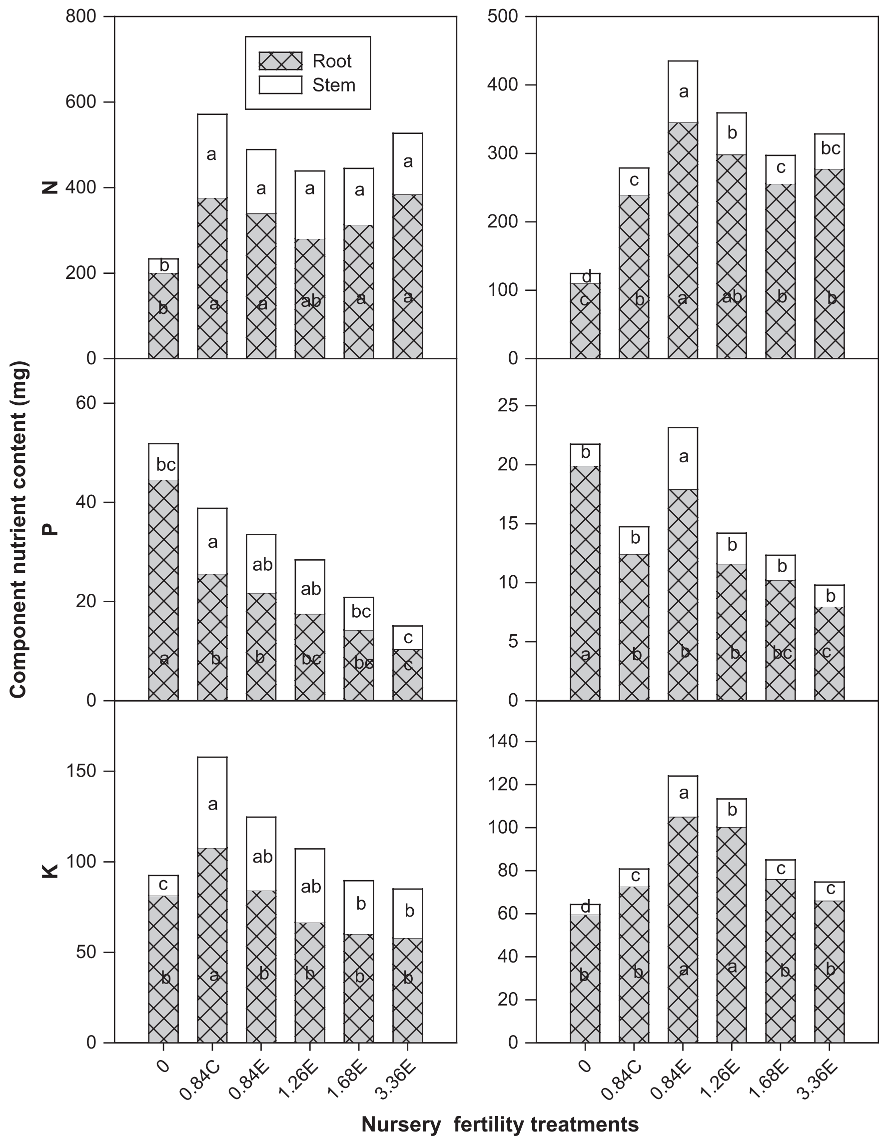

Figure 3. Preplant component nutrient content for Red oak (left) and White oak (right) seedlings exposed to increasing fertility treatments for one growing season (8 months) during bareroot nursery culture. Treatments marked with different letters differ statistically for each component according to Waller–Duncan's multiple range test at $\alpha = 0.05$.

Table 2. Mean (± SE) physical and chemical characteristics of soil on a mine reclamation site in southwestern Indiana, United States, analyzed in 2005.

Soil Depth (cm)	*BD (g/cm³)*	*Sand (%)*	*Silt (%)*	*Clay (%)*	*Soil pH*	*SOM (%)*	*Total N (g/kg)*	*Extractable P (mg/kg)*	*Exchangeable Cations (cmol[+]/kg)*		
									K	*Ca*	*Mg*
0–15	1.75 (0.06)	16.00 (1.92)	56.00 (2.38)	28.00 (0.82)	6.68 (0.16)	1.78 (0.13)	0.24 (0.01)	6.50 (0.29)	3.50 (0.18)	62.50 (2.89)	21.25 (0.56)

tissue N concentration at higher fertility was associated with diminished P levels for Red oak (Table 4, top) and White oak (Table 4, bottom). However, tissue K concentration remained relatively stable. Higher nutrient levels were detected in leaves, demonstrating sensitivity of these tissues to nutrient inputs and the validity of using such tissues to evaluate plant response to fertilization in nutritional studies. Sensitivity is further demonstrated by the relatively narrow variability noted in leaf N levels. For instance, leaf N concentration varied from 17 to 21 g/kg compared with the broad range of 4–14 g/kg in roots of Red oak (Table 4). Plant nutrient content increased with fertility for N 14–102% and K 8–20% in Red oak (Fig. 5, left) and N 32–105% and K 16–44% in White oak (Fig. 5, right). By contrast, P content decreased at higher fertility relative to controls (Fig. 5).

Discussion

Nursery Phase

Increased tissue N concentration at the highest fertilizer rate along with reduced growth and nutrient uptake may be explained by induced toxicity (Birge et al. 2006; Salifu & Jacobs 2006). These nutritional responses highlight problems associated with overfertilization and suggest the need to rationalize and quantify fertility targets to help avert such problems in nutritional studies. Additionally, the lack of P and K in the fertilizer could partly explain such nutritional interactions. Apparently, when the primary limitation for N was met, P and (or) K became the secondary factors that inhibited seedling growth (Birge et al. 2006). This phenomenon has been noted for Black spruce (*Picea mariana* Mill. BSP) seedlings (Imo & Timmer 1992). The use of balanced fertilizers or adequate P and K supplementation with only N-based fertilizers can help avert such nutritional problems. We suggest that the use of balanced fertilizers is critical for successful nutrient loading to help ensure seedling nutritional quality with potential for success on reclamation sites.

The lack of leaves in hardwood species is an important consideration when quantifying fertility targets (Wilson & Jacobs 2006). For example, when sampled with foliage at 18 weeks (2 weeks after last fertilizer application), the 1.68 g N $plant^{-1}$ $season^{-1}$ treatment appeared to be the optimum loading target at that age and under the then-prevailing cultural conditions (Birge et al. 2006).

Table 3. Survival, shoot height, and basal diameter of Red oak and White oak seedlings fertilized conventionally (C) or exponentially (E) during standard bareroot nursery culture for 8 months and then outplanted for 4 months on a mine reclamation site in southwestern Indiana, United States.

Species/Treatment	*Survival (%)*	*Shoot Height (cm)*		*Basal Diameter (mm)*	
		Initial	*Year 1*	*Initial*	*Year 1*
Red oak					
0.00	98a	41.50c	49.82b	5.68d	6.63c
0.84C	85a	87.12a	98.28a	9.00a	9.71ab
0.84E	84a	83.15a	92.01a	8.13b	10.66a
1.26E	89a	76.92a	86.81a	7.78b	8.26abc
1.68E	89a	75.56a	86.13a	8.42ab	9.26abc
3.36E	73a	59.13b	61.67b	7.00c	7.39bc
White oak					
0.00	98a	26.05d	33.79b	4.92b	5.84b
0.84C	98a	31.73cd	42.04ab	6.33ab	7.36a
0.84E	95a	38.91ab	44.10a	6.06ab	6.48ab
1.26E	93a	40.12a	48.85a	6.60ab	6.70ab
1.68E	94a	36.33abc	47.00a	7.15a	6.96ab
3.36E	81a	33.12bc	41.53ab	5.69ab	6.20ab

Initial refers to samples taken before planting and year 1 refers to 4 months after planting. Means in the same column marked with different letters differ statistically according to Waller–Duncan's multiple range test, $\alpha = 0.05$.

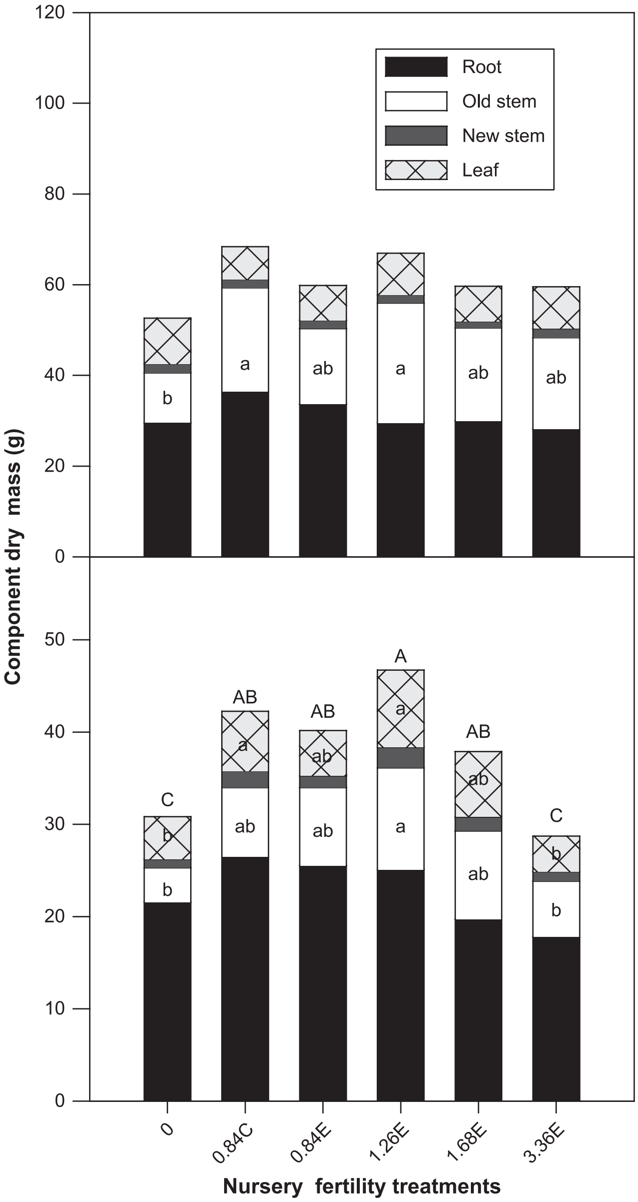

Figure 4. Component dry mass of Red oak (top) and White oak (bottom) seedlings exposed to increasing fertility treatments for one growing season (8 months) during bareroot nursery culture and outplanted in the field for 4 months on abandoned mine lands in southwestern Indiana, United States. Treatments marked with different letters differ statistically for each component according to Waller–Duncan's multiple range test at $\alpha = 0.05$.

However, such a clear trend was not detected when sampled after senescence (at transplanting). Fertilization was terminated 3 months prior to sampling for storage. Withholding of N addition early in the season (Birge et al. 2006) induced growth dilution associated with increased growth and nutrient uptake but diminished tissue N concentration (Imo & Timmer 1992; Salifu & Timmer 2003*a*). Thus, supplemental fertilization or split applications late in the season could be more beneficial to cultured plants. Furthermore, a weekly rather than a biweekly application schedule will make nutrients more readily available to plants to meet continued growth demand, which will improve seedling growth and nutrient uptake efficiency (Dumroese et al. 2005).

Nutrient resorption, an important nutrient conservation mechanism exhibited by deciduous trees, may recover 50–90% of the nutrients from leaves into shoot and root tissues prior to senescence (Duchesne et al. 2001; Cheng & Fuchigami 2002). Resorption may partly explain the increased N and K storage in plant tissues following senescence. There is need to examine the importance and underlying mechanisms of nutrient resorption in nutrient retention and remobilization to support new growth in hardwood species. The greater N and K reserves in loaded plants may be exploited to meet increased sink demand (Crow 1988; Dickson 1989; Tagliavini et al. 1998) with potential to improve seedling field performance and restoration success.

Field Response

Poor site fertility and severe competition may adversely affect seedling survival and growth on mine reclamation sites (Lunt & Hedger 2003; Andrews & Broome 2006). The poor site fertility reflected by low soil organic matter (SOM) and nutrients suggests that the use of high-quality planting stock or appropriate silvicultural techniques (Davidson et al. 1995; Bendfeldt et al. 2001; Groninger et al. 2006) could benefit seedling field performance and restoration success. It has been shown that the nutritional status of a plant can serve as a better indicator of quality and field success than morphological indicators (Quoreshi & Timmer 2000). As expected, N-loaded plants exhibited high survival under field conditions. For instance, mean survival rates of 84% for Red oak and 93% for White oak of exponentially N-loaded seedlings in this study are higher than mean values of 66% noted for operational conservation tree plantings in Indiana (Jacobs et al. 2004) or 30–69% reported from a previous mine reclamation study with Red oak in Indiana (Davis & Jacobs 2004). The nonfertilized control seedlings also exhibited high survival (98%), suggesting that native soil fertility in the nursery was sufficient to encourage early survival on this site.

Relative to controls, nursery N loading promoted growth and nutrition of Red oak and White oak seedlings under field conditions. Although not statistically different, the same rate of fertilizer applied exponentially resulted in greater mean N and K uptake in White oak than when applied conventionally. Although not quantified directly, the depletion of nutrients from roots and old stems compared with levels at outplanting suggests retranslocation to support new growth. This observation is consistent with the contention that retranslocation from roots may contribute significant amounts of nutrients to support growth of newly planted seedlings (Nambiar 1987; Hawkins et al.

Table 4. Nutrient concentration in components of Red oak and White oak seedlings fertilized conventionally (C) or exponentially (E) and then outplanted for 4 months on a mine reclamation site in southwestern Indiana, United States.

	Component Nutrient Concentration (g/kg)														
	N					*P*					*K*				
Species/Treatment	*Leaf*	*NS*	*OS*	*Root*	*Plant*	*Leaf*	*NS*	*OS*	*Root*	*Plant*	*Leaf*	*NS*	*OS*	*Root*	*Plant*
Red oak															
0.00	17.40c	6.12	3.38b	4.16b	6.51b	1.12	1.26a	0.78a	0.94a	0.97a	5.24	3.62	1.86	2.46	2.93
0.84C	19.58bc	6.64	4.12ab	6.78b	7.18b	1.06	0.88ab	0.36b	0.52ab	0.52b	5.66	4.34	2.08	2.38	2.69
0.84E	18.34bc	6.60	4.02ab	6.80b	7.16b	1.02	0.94ab	0.54ab	0.60ab	0.65ab	5.14	4.04	2.16	2.40	2.74
1.26E	18.46bc	5.88	3.96ab	7.12b	7.38b	1.00	0.58b	0.30b	0.44b	0.47b	5.42	4.44	2.06	2.54	2.82
1.68E	20.26ab	5.42	4.04ab	7.04b	7.65b	1.14	0.72b	0.38b	0.34b	0.47b	5.30	4.08	1.90	2.32	2.61
3.36E	21.30a	6.44	5.42a	14.12a	11.99a	0.98	0.48b	0.26b	0.26b	0.38b	5.40	3.94	1.70	2.02	2.50
White oak															
0.00	18.08ab	6.72a	5.00ab	6.82	8.30	1.06	1.04a	0.58a	0.76a	0.79a	4.68	4.20	2.42a	3.02	3.23b
0.84C	20.30a	6.48a	4.76bc	9.52	10.28	0.98	0.54b	0.30b	0.32b	0.43b	4.44	3.48	1.78b	2.56	2.74b
0.84E	20.48a	7.58a	6.12a	11.94	11.83	1.00	0.64b	0.34b	0.38b	0.46b	4.78	3.92	2.10ab	3.12	3.13b
1.26E	16.12b	4.94b	3.70c	7.16	7.84	0.86	0.54b	0.28b	0.30b	0.41b	4.56	3.76	2.38a	2.82	3.99a
1.68E	21.04a	6.90a	5.32ab	10.50	11.04	1.00	0.52b	0.32b	0.30b	0.44b	4.36	4.24	2.28a	2.88	3.07b
3.36E	19.90a	6.34a	5.68ab	10.22	10.50	1.00	0.64b	0.38b	0.42b	0.50b	4.40	4.30	2.36a	3.06	3.14b

Data sampled 4 months after planting. Means in the same column marked with different letters differ statistically according to Waller–Duncan's multiple range test, $\alpha = 0.05$. NS, new stem; OS, old stem.

1998). Future studies are needed to quantify the importance of retranslocation from roots in new growth of planted seedlings. The greater growth and nutrient allocation to roots of loaded seedlings lead to the development of large root:shoot, hence large root mass, which is an adaptive strategy to facilitate rapid shoot growth and development (Crow 1988). Enhanced tree growth early in the restoration process accords planted seedlings the competitive advantage to preempt essential growth resources to further benefit subsequent development. This may accelerate early plantation productivity and improve forest restoration processes on degraded landscapes.

Soil BD has been found to correlate negatively with tree growth (Strong & La Roi 1985; Salifu et al. 2002). The reported BD is similar to those generally noted in managed plantations (Hamilton & Krause 1985; Salifu et al. 2002). Tillage practices such as ripping may help ameliorate the detrimental effects of high BD on mine reclamation sites (Cleveland & Kjelgren 1994; Ashby 1996). Other silvicultural inputs may be required to further improve site conditions and restoration success on degraded landscapes. For example, Lunt and Hedger (2003) noted that nutrient or SOM enrichment at transplanting can benefit seedling field performance. In particular, controlled-release fertilizer (CRF) applied to the planting hole at transplanting offers opportunity to stimulate growth of target trees while minimizing competition from nontarget vegetation (Fan et al. 2002; Jacobs et al. 2005). The use of container planting stock (Dixon et al. 1983; Davis & Jacobs 2004), nursery drought hardening (Villar-Salvador et al. 2004), and mycorrhizal inoculations (Zhou & Sharik 1997; Quoreshi & Timmer 2000) are other options that may improve seedling survival and growth with potential to accelerate forest restoration success on highly degraded landscapes.

Our responses demonstrate the potential of nursery N loading to promote seedling field performance and forest restoration success on abandoned mine lands. We propose that storing nutrients in seedlings to facilitate field response and restoration success offers an effective alternative approach compared to field fertilization, which may inadvertently stimulate growth of competing vegetation. Additionally, potential nutrient leaching losses associated with broadcast applications are avoided when nutrients are stored in seedlings for later use to benefit new growth in the field. The approach has potential to confer rapid growth and minimize the need for herbicide use.

Conclusions

Nursery nutrient loading improved first-year field growth and nutrition of planted seedlings, which demonstrates the potential of this practice to facilitate forest restoration success on abandoned mine sites. Nutrient loading provides a new and useful management tool that has specific significance for improving seedling performance on mine reclamation sites. A need exists to critically examine nutrient loading of hardwoods to quantify target rates for nursery propagation of high-quality seedlings for planting on degraded landscapes. However, the use of balanced fertilizers is key to successful nutrient loading. Additionally, SOM enrichment or use of CRF at transplanting may help further promote seedling establishment success to facilitate restoration efforts. Although rarely

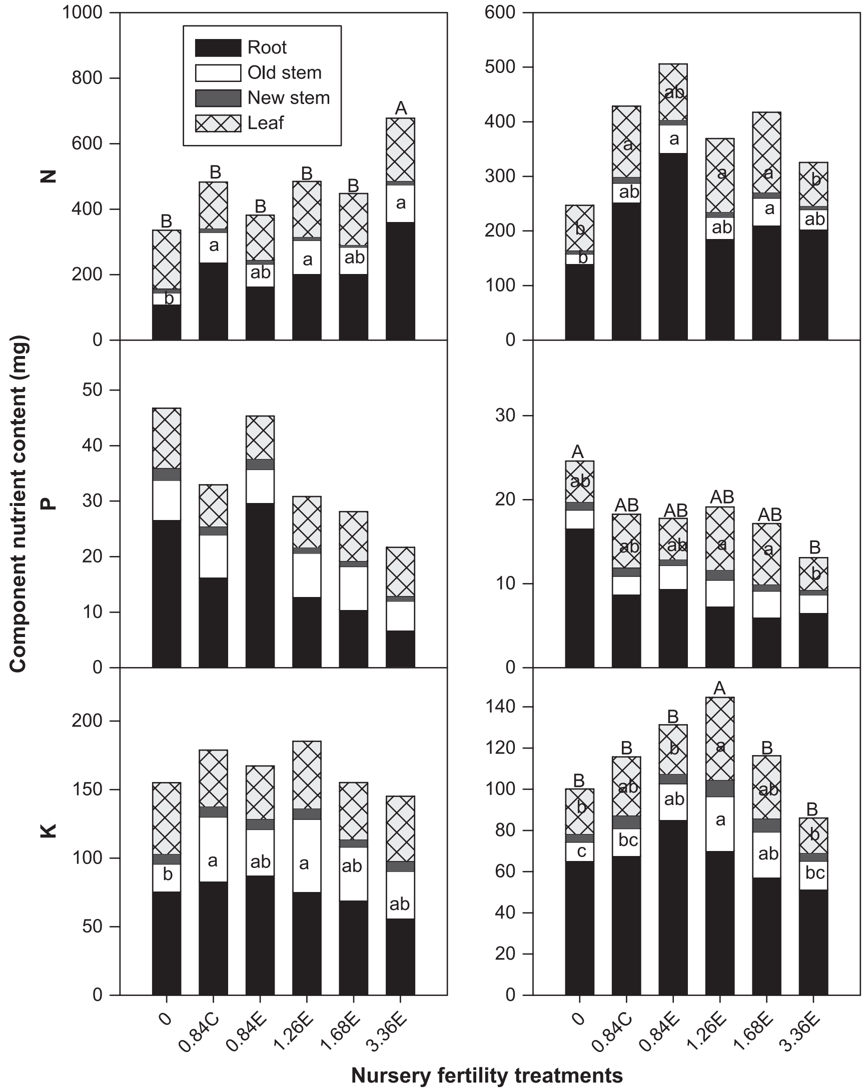

Figure 5. Plant component nutrient content for Red oak (left) and White oak (right) seedlings exposed to increasing fertility treatments for one growing season (8 months) during bareroot nursery culture and outplanted for 4 months on abandoned mine lands in southwestern Indiana, United States. Treatments marked with different letters differ statistically for each component according to Waller–Duncan's multiple range test at $\alpha = 0.05$. Uppercase letters indicate whole-plant responses.

implemented on restoration sites in southwestern Indiana, herbicide use may be essential to enhance early seedling development and restoration success. More research is required to examine the importance of retranslocation from roots in meeting plant growth demand to help further our understanding of the underlying mechanisms of nutrient resorption, as well as subsequent remobilization to support new growth of transplanted hardwood seedlings transplanted into nutrient-limiting conditions. Further studies are needed to elucidate how N loading, resorption, and N remobilization processes can contribute to successful forest restoration on degraded ecosystems. Additionally, future research should examine the long-term effects of exponential nutrient loading on plantation stand development.

Implications for Practice

- Storing nutrients in seedlings at the nursery stage provides a better rationale to promote seedling field performance than broadcast field fertilization that may inadvertently stimulate growth of competing vegetation and cause nutrient leaching.
- Greater plant nutrient reserves have potential to reduce competitive effects and promote internal redistribution to support new growth soon after transplanting.
- High survival and growth of competitive loaded seedlings will accelerate forest restoration success on degraded landscapes, which will help to conserve soil resources as well as provide habitat for wildlife.

- Early rapid growth will allow plants to reach free-to-grow status sooner and minimize potential for animal browse.
- Use of competitive nutrient-loaded seedlings will accelerate early growth and minimize the need to control competing vegetation with herbicides.
- Greater nutrient storage in seedling roots can be used later to benefit future growth.
- Fertilizer addition rates between 1.26 and 1.68 g N/plant appear adequate to culture bareroot White and Red oak under the studied cultural conditions using the same fertilizer product.

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