Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Forest Ecology and Management xxx (2005) xxx–xxx
Forest Ecology and Management
www.elsevier.com/locate/foreco

Growth and nutritional response of hardwood seedlings to controlled-release fertilization at outplanting

Douglass F. Jacobs [a,*], K. Francis Salifu [a], John R. Seifert [b]

[a] *Department of Forestry and Natural Resources, Hardwood Tree Improvement and Regeneration Center, Purdue University, West Lafayette, IN 47907-2061, USA*
[b] *Southeast Purdue Agricultural Center, Department of Forestry and Natural Resources, Purdue University, Butlerville, IN 47223-0216, USA*

Received 13 October 2004; received in revised form 14 March 2005; accepted 16 March 2005

Abstract

Hardwood bareroot seedlings typically undergo transplant shock immediately following afforestation planting associated with moisture or nutrient stress. Broadcast field fertilization at outplanting with readily available nutrients has shown limited capacity to reduce nutrient stresses. Furthermore, the rapid nutrient release characteristic of broadcast fertilization leads to high levels of nutrient leaching and may stimulate growth of competing vegetation more than target trees. Application of controlled-release fertilizer (CRF) in the outplanting hole could be a useful alternative to help improve fertilizer use efficiency and alleviate competition problems associated with broadcast fertilization, thereby promoting early regeneration success of outplanted seedlings. We tested growth and nutritional response of black walnut (*Juglans nigra* L.), white ash (*Fraxinus americana* L.), and yellow-poplar (*Liriodendron tulipifera* L.) to 6 rates (0, 15, 30, 45, 60, and 75 g plant^{-1}) of polymer-coated CRF applied to the root zone at outplanting in southern Indiana, USA. Fertilizer release was evenly distributed between years 1 and 2. Seedling survival was above 85% for all treatments. Compared to non-fertilized seedlings, the 60 g seedling^{-1} rate accelerated mean height and root-collar diameter (RCD) growth by 52 and 33% in year 1 and 17 and 21% in year 2. Nitrogen (N) and potassium (K) uptake were increased 40 and 30% at the 60 g rate compared with controls. Height and RCD growth were greater by 543 and 200% in white ash and 300 and 233% in yellow-poplar, relative to black walnut. Uptake of N and K was increased by 79 and 22% in yellow-poplar and 93 and 56% in white ash, compared to black walnut. Results suggest CRF has potential to improve early establishment success of hardwood afforestation plantings.

Keywords: Afforestation; Fertilizer release; Nutrient uptake; Plantation establishment; Polymer-coated fertilizer

---

1. Introduction

Hardwood bareroot seedlings typically undergo significant transplant shock immediately following outplanting. Such plant response is generally associated with moisture and (or) nutrient stress (Becker

---

* Corresponding author. Tel.: +1 765 494 3608; fax: +1 765 494 9461.
E-mail address: djacobs@purdue.edu (D.F. Jacobs).

0378-1127/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.foreco.2005.03.053

et al., 1987; Kozlowski, 1987; Struve and Joly, 1992; McMillin and Wagner, 1995). In addition, competition from non-crop vegetation and deer browsing limits afforestation success (Kolb et al., 1990; Gillespie et al., 1996; Martin and Baltzinger, 2002). Consequently, growth of bareroot seedlings is often slow during the first 1 or 2 years after outplanting until root systems can establish to exploit site resources (Rietveld, 1989). In addition to slow growth, transplant shock often leads to high mortality of outplanted hardwood seedlings during the establishment period (Jacobs et al., 2004b).

Susceptibility to nutrient stress can be reduced by traditional approaches such as fertilization at outplanting to supplement nutrients (Burdett et al., 1984) and (or) herbicide application to reduce competition for nutrients (Campbell, 1990; McGill and Brennman, 2002). Fertilization at outplanting has potential to stimulate seedling growth, helping to facilitate free-to-grow status (Brockley, 1988). However, the practice is rarely recommended (Ponder, 1996) and often discouraged (Beineke, 1986) for hardwood seedlings because of inconsistent reports of neutral or negative effects from the practice. For instance, field fertilization reduced survival and growth of outplanted black walnut (*Juglans nigra* L.) seedlings (Williams, 1974). Additionally, height and diameter at breast height growth of black walnut 12 years after fertilization at intervals of 1, 2, and 6 years after outplanting were similar to controls (Braun and Byrnes, 1982).

The above inconsistencies in growth response to nutrient enrichment at plantation establishment could partly be associated with fertilizer type and method of application. Broadcast field fertilization of traditional agronomic fertilizers releases nutrients immediately upon application with generally low rates of fertilizer use efficiency. For example, broadcast field fertilization stimulated growth and nutrient uptake of competing vegetation more than outplanted seedlings (van den Driessche, 1991; Chang et al., 1996; Staples et al., 1999; Chang and Preston, 2000; Imo and Timmer, 2001).

In contrast, controlled-release fertilizer (CRF), designed to release nutrients slowly over longer time frames for plant uptake, offers an alternative to broadcast fertilization. With a single application, CRF may provide plants with enhanced mineral nutrition for extended periods, ranging from about 3 to 18 months. The gradual release pattern of CRF acts to provide a more consistent and sustained nutrient supply that may better match plant demand (Donald, 1991) and helps to minimize nutrient leaching, reduce plant damage, and improve overall fertilizer use efficiency. For instance, application of CRF 5–7 cm from roots improved fertilizer use efficiency compared to comparable reports for broadcast fertilization (Hangs et al., 2003). Incorporation of CRF to root plugs of container seedlings or CRF application using in-hole or adjacent planting-hole placement promoted early growth of outplanted seedlings (Carlson, 1981; Carlson and Preisig, 1981; Brockley, 1988; Arnott and Burdett, 1988; Fan et al., 2004).

Although CRF has been effective in facilitating seedling growth in some cases, field response has been variable (Brockley, 1988). CRF resulted in slow relative growth rates with western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Arnott and Burdett, 1988). A relatively high CRF rate applied to the outplanting hole increased Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedling water stress relative to non-fertilized plants (Jacobs et al., 2004a), likely due to injury incurred by elongating root tips associated with elevated salt concentrations in the zone of fertilizer placement (Jacobs et al., 2003b). Observed differences in response could be associated with type of CRF product used and application rates, along with site interactions. Many different CRF types are available, primarily differing in terms of nutrient formulations, estimated product longevities, and mechanisms of nutrient release (Goertz, 1993; Jacobs et al., 2003a).

Although CRF has been useful in stimulating field growth of conifer species in the western USA (Carlson, 1981; Carlson and Preisig, 1981; Haase et al., in press), there is little information on its use in hardwood afforestation plantings in the eastern USA. The increased interest in using CRF for tree plantings (Haase and Rose, 1997) suggests the need for a better understanding of how hardwood species respond to CRF at plantation establishment. The primary objective of this study was to evaluate growth and nutritional response of black walnut, white ash (*Fraxinus americana* L.), and yellow-poplar (*Liriodendron tulipifera* L.) to 6 rates of polymer-coated CRF applied to the root zone at time of outplanting on a field site in southern Indiana, USA. Additionally, we examined nutrient release rates over time associated with the CRF product. In this new contribution, we test the hypothesis that CRF addition at plantation establishment will alleviate nutrient stress and promote early growth and nutrition of hardwood seedlings. Because the establishment period (i.e., first 2 years following outplanting) is critical to afforestation success in this region (Jacobs et al., 2004b) and CRF is designed to facilitate early seedling growth and establishment (Carlson and Preisig, 1981), we report seedling response to CRF treatments during this early stage of plantation development.

2. Materials and methods

2.1. Seedling culture and fertility treatments

Bareroot (1 + 0) seedlings of black walnut, white ash, and yellow-poplar were grown under standard nursery cultural practices at the Indiana Department of Natural Resources Vallonia State Tree Nursery in southwestern Indiana (38°48′N, 86°06′W) during 2001. Habitat requirements, growth characteristics and genetic information can be found in Williams (1990) for black walnut, Schlesinger (1990) for white ash, and Beck (1990) for yellow-poplar. Jacobs (2003) presents a comprehensive overview of nursery production of hardwood seedlings in this region. Seedlings were supplied with about 170–225 kg ha^{-1} of urea fertilizer approximately every 2 weeks from May through either July (white ash and yellow-poplar) or mid-June (black walnut). Black walnut seedlings were root wrenched twice during the early part of the growing season, and yellow-poplar seedlings were top clipped twice during the early to middle part of the growing season. Following lifting (mid to late-November 2001 for white ash and yellow-poplar, late-February 2002 for black walnut), plants were stored at 2 °C until delivered to the field planting site in mid-April 2002, located at the Southeastern Purdue Agricultural Center in southeastern Indiana (39°01′N, 85°35′W). The soil, recently reclassified as Mascatatuck (fine-silt, mixed, active, mesic, Fragic Hapludalfs) by the USDA Soil Survey (USDA NRCS Pedon I.D. S02IN-079-001), formed in forest vegetation with a visible plough layer from intermittent cultivation (Soil Survey Staff, 2004). Computation of total N pools within a hectare of soil at this study location was based on the assumption that nutrients within the plough layer (0–20 cm depth), which weighs 2,000,000 kg/ha, are accessible to plants (Brady and Weil, 2002). The soil had a bulk density of 1.31 g cm^{-3} and no coarse fraction (von Kiparski, 2004); hence, computed total N was about 1.4 mg kg^{-1}, which is equivalent to 3668 kg N ha^{-1}. Table 1 summarizes other soil chemical attributes characterizing site conditions.

The CRF examined in this study was Osmocote® Exact Lo-Start 15N-9P-10K plus minors (O.M. Scotts Co., Marysville, OH, USA), in which are nutrients encapsulated within multiple layers of a polymeric resin to slow the dissolution rate into the soil solution. This CRF was designed by the manufacturer to release more than 90% of its nutrients within 16–18 months following application, assuming a soil temperature of 21 °C at position of fertilizer placement. At this longevity rating, we assumed that seedlings would receive enhanced nutrition for two growing seasons because fertilizer release during winter months should be slowed. To estimate rates of nutrient release (Jacobs et al., 2003b), we placed 75 g CRF within PVC rings covered in nylon and buried these at the approximate depth of fertilizer placement (30 cm) in mid-May 2002. Rings were excavated periodically during the experiment (6 sampling intervals × 5 replications) and fertilizer prills were dried at 70 °C for 48 h and reweighed. Changes in weight of polymer-coated CRF over time from field-excavated samples largely reflects laboratory-determined release of nutrient ions (Alzugaray, 2002) and thus, the difference in weight

Table 1
Mean soil chemical properties characterizing outplanting site conditions located at the Southeastern Purdue Agricultural Center, southeastern Indiana, USA

Soil depth (cm)	OM (%)	Available P (mg kg^{-1})	Exchangeable cations (cmol [+] kg^{-1})				BS (%)	Soil pH
			K	Mg	Ca	H		
0–15	2.85	17.61	4.19	19.79	53.17	22.85	77.16	5.96
15–30	2.45	11.13	3.33	20.27	50.81	25.59	74.41	5.93

Note: OM – organic matter; BS – base saturation.

approximated amount of fertilizer released. To measure soil temperature, a HOBO® (Model H08-002-02, Onset Computer Corp., Bourne, MA, USA) data logger was buried on 1 May 2002 at 30 cm in the approximate center of each of the first four blocks. The data loggers recorded soil temperature every 6 h for 2 years.

Seedlings were outplanted in mid-April 2002 using a tractor-hauled coulter with trencher and packing wheels. CRF was applied at 6 rates (0, 15, 30, 45, 60, and 75 g seedling^{-1}) using a modified funnel system installed onto the machine planter. Rates were converted to volume basis from laboratory trials to facilitate application. Thus, for each seedling, the appropriate CRF rate was measured by volume and applied to the planting trench (about 30 cm depth), and the seedling planted with roots extending to just above the fertilizer layer. The applied rate of fertilizer encompassed a length of about 10–15 cm along the trench below each seedling. Effective chemical weed control was accomplished across the entire experiment prior to and following outplanting using glyphosate (Roundup®, 1.68 kg a.i. ha^{-1}), and azafenidin (Milestone®, 0.39 kg a.i. ha^{-1}) to minimize competition for moisture and nutrients from non-crop vegetation. In early May 2002, an electric deer fence was installed around the perimeter of the study and was maintained for the experiment duration.

2.2. Experimental design and sampling

The study was established as a randomized complete block design with a 3 (species) × 6 (CRF rates) factorial treatment structure replicated in six blocks. Environmental conditions differed among blocks but conditions were relatively homogenous within blocks. Each of the 18 treatment combinations was planted as a 20-seedling row and randomly assigned within a block. The sampling unit was each individual seedling and the experimental unit used for data analysis was the mean response from the sampling units for each treatment replication. Seedlings were measured for initial height and root-collar diameter (RCD) in April 2002, and were re-measured in November 2002 and 2003. For nutritional analysis, five seedlings were harvested aboveground within each treatment replication in mid-July 2003 and partitioned into leaves and stems. Each tissue component, composited by replication, was dried at 70 °C for 72 h and re-weighed for dry mass determination and subsequently milled for chemical analysis. Initial soil samples were obtained at plantation establishment and analyzed to characterize native site fertility (Table 1).

2.3. Chemical and statistical data analysis

Plant and soil samples were shipped to A & L Great Lakes Laboratories (Fort Wayne, IN, USA) for chemical analysis, which followed standard analytical protocols. Plant N was determined according to Association of Official Analytical Chemist (AOAC) methods. Total N was determined by combustion (''Dumas'') procedure (AOAC 968.06) using a LECO nitrogen analyzer (LECO Corp., St. Joseph, MI, USA). Additionally, plant samples were digested in nitric + perchloric acids (AOAC 935.13), and the other elements determined using inductively coupled argon plasma (ICAP) analysis (AOAC 985.01). Soil test procedures followed those detailed in Brown (1997). Elemental P, K, Ca, and Mg were determined by ICAP using extracted aliquots from soils.

Analysis of variance (ANOVA) was conducted on growth and nutritional data based on Anderson and McLean's linear model for factorial designs (Anderson and McLean, 1974) using SAS software (SAS Institute, Inc., Cary, NC, USA). ANOVA treatment effects for height and RCD growth data were considered statistically significant at $P \leq 0.05$ and when treatment effects were significant, means were ranked according to Fisher's protected least significant difference test ($\alpha = 0.05$). To minimize the possibility of making a Type II error associated with the reduced number of sampling units (i.e., 5 versus 20 seedlings per treatment replication) for dry mass and nutritional data, ANOVA treatment effects were considered significant for these variables at $P \leq 0.10$ and where significant, treatment means were ranked according to Fisher's protected least significant difference test at $\alpha = 0.10$.

3. Results

3.1. Seedling growth

Initial mean seedling height and RCD (computed from treatment replicates) of the three hardwood

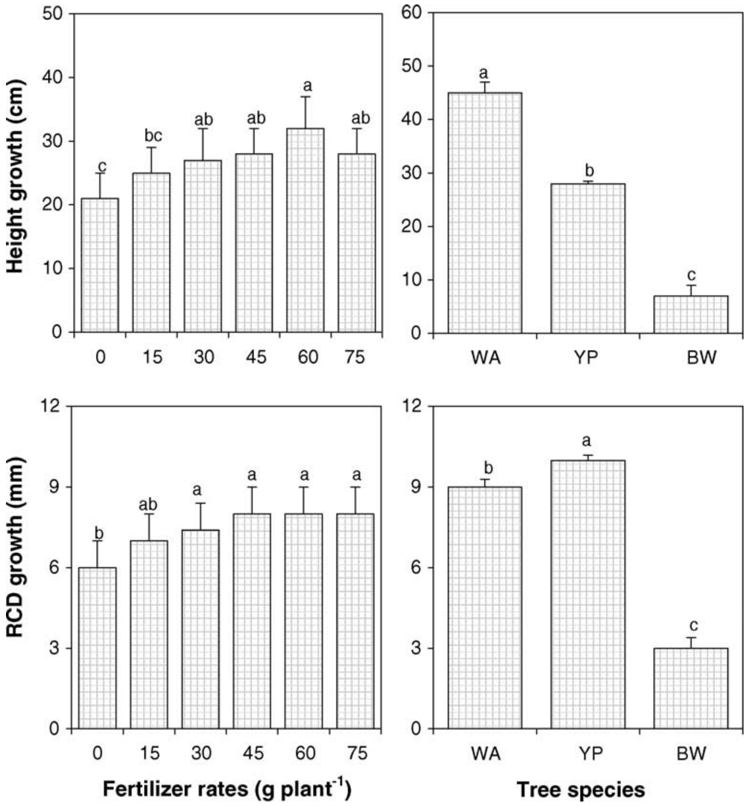

Fig. 1. Mean first-year height and root-collar diameter (RCD) growth of white ash (WA), yellow-poplar (YP), and black walnut (BW) [right] as influenced by different rates of CRF applied at outplanting [left]. Bars marked with similar letters among species or fertilizer rates are not statistically different according to Fisher's protected least significant difference test at $\alpha = 0.05$. Error bars represent the standard error of the mean.

species studied were similar and ranged from 67–77 cm and 8–9 mm, respectively. Fertilization apparently had no negative effect on seedling survival because survival was $\geq$ 90% in all treatments. Survival differed among species ($P < 0.0001$) with yellow-poplar having significantly lower survival (85%) than either white ash (100%) or black walnut (97%). Similar trends were observed in year 2 (data not presented).

Fertilization at outplanting significantly affected seedling growth during the first (height and RCD) (Fig. 1) and second (RCD only) (Fig. 2) growing seasons (Table 2). Species × fertilizer interaction effects were non-significant for both first and second-year height and RCD growth (Table 2). Treatment means for absolute height and RCD followed similar trends as observed for growth increments in both years; hence, data not presented. Generally, seedling height and RCD growth increased along the nutrient supply gradient to the 60 g seedling^{-1} rate and then declined (Fig. 1). For example, mean height growth increased 52% in the 60 g seedling^{-1} rate compared to the control at year 1, but decreased by 14% relative to the 60 g rate at 75 g (Fig. 1). Root-collar diameter growth was stimulated 33% by the 60 g rate compared to the control. Similarly, second-year height and RCD growth increased 17 and 21%, respectively, in the 60 g rate compared with controls (Fig. 2).

Examination of species effects suggests that significant differences occurred among species during first and second-year growth (Table 2). Height and RCD growth can be ranked as white ash > yellow-poplar > black walnut (Figs. 1 and 2). Height growth increased by 300 and 543% in yellow-polar and white ash, respectively, compared to black walnut (Fig. 1,

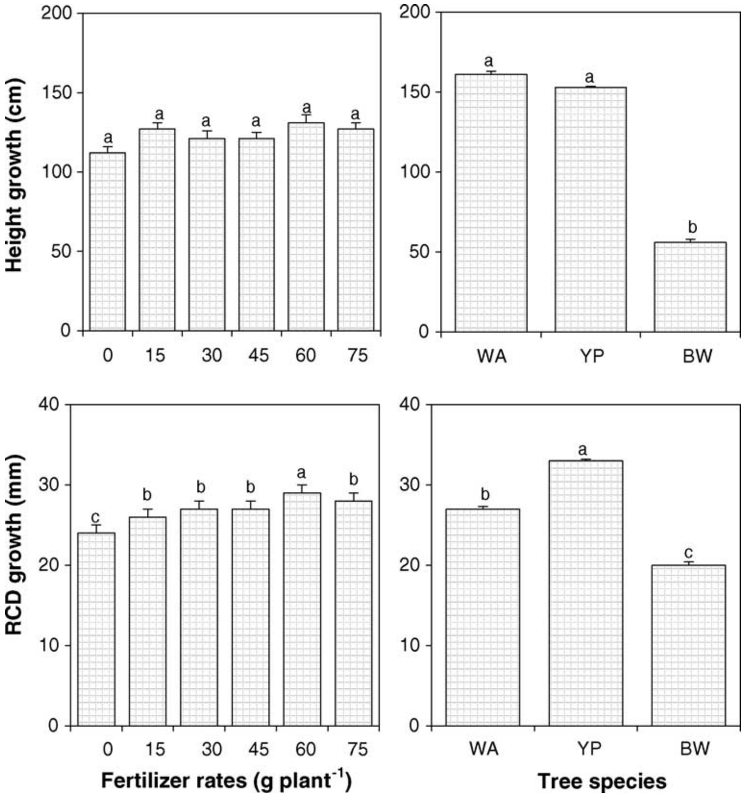

Fig. 2. Mean second-year height and root-collar diameter (RCD) growth of white ash (WA), yellow-poplar (YP), and black walnut (BW) [right] as influenced by different rates of CRF applied at outplanting [left]. Bars marked with similar letters among species or fertilizer rates are not statistically different according to Fisher's protected least significant difference test at $\alpha = 0.05$. Error bars represent the standard error of the mean.

right). Similar comparisons showed a 233 and 200% increase in RCD growth among respective species. Year 2 response was generally similar to that observed for year 1 (Fig. 2). Plant leaf dry mass differed among treatments and species (Fig. 3, Table 2). Dry mass production was 100% greater in white ash and yellow-poplar relative to black walnut, suggesting greater sink strength in the former species (Fig. 3, right). Slower

Table 2
Analysis of variance testing effects of controlled-release fertilizer (CRF) addition at outplanting and tree species (SP) on height and root-collar diameter (RCD) growth, leaf dry mass (DM) production, and seedling nutrient content

Year	Source of variation	$P > F$					
		Height	RCD	DM	N	P	K
	CRF	0.0019	0.0002	–	–	–	–
1	SP	0.0001	0.0001	–	–	–	–
	CRF × SP	0.3358	0.6188	–	–	–	–
	CRF	0.1977	0.0022	0.0816	0.0301	0.3213	0.0625
2	SP	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	CRF × SP	0.9682	0.9761	0.1833	0.1495	0.0549	0.2618

Nutrient and growth data were determined in mid-July and November 2002, respectively. –, not determined.

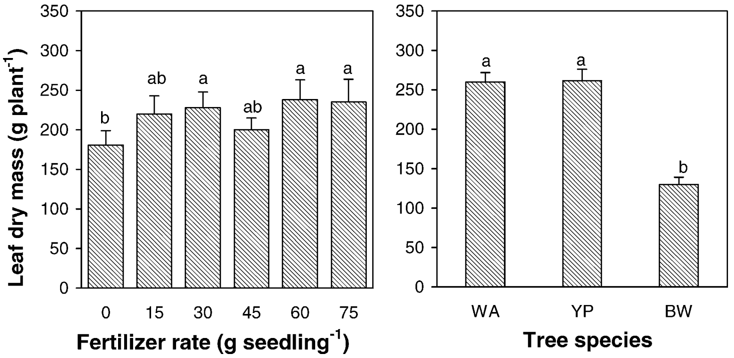

Fig. 3. Mean second-year leaf dry mass production of white ash (WA), yellow-poplar (YP), and black walnut (BW) [right] as influenced by different rates of CRF applied at outplanting [left]. Bars marked with similar letters among species or fertilizer rates are not statistically different according to Fisher's protected least significant difference test at $\alpha = 0.10$. Error bars represent the standard error of the mean.

initial relative growth of black walnut in afforestation plantations of this region has been documented previously (Jacobs et al., 2004b).

3.2. Nutrient accumulation in seedlings

The nutritional data (Fig. 4) suggest that nutrient uptake generally increased with fertilizer rates (Fig. 4, left) and differed significantly except for P (Table 2). Nitrogen and K uptake were stimulated 40 and 35%, respectively, in the 60 g treatment compared to controls. There were no significant fertilizer rate × species interactions (Table 2). However, nutrient accumulation differed among species (Fig. 4, right, Table 2). Nitrogen uptake was 79 and 93% greater in yellow-poplar and white ash, respectively, than in black walnut (Fig. 4, right). Similar comparisons showed increased K by 22 and 56% in yellow-poplar and white ash, respectively.

Typically, about 33% of residual fertilizer weight (primarily comprised of polymer material) remains at the end of the designated release period with polymer-coated CRF (Jacobs et al., 2003b). Analysis of changes in residual fertilizer weight showed that the initial 75 g of fertilizer decreased to a mean (±S.E.) of 51 (1.0) g in October 2002, indicating that about 50% of the total fertilizer was released during the first growing season. In August 2003, the residual weight was 26.7 (2.0) g signifying that the remaining 50% of fertilizer was released during the second growing season. In August 2004, the residual fertilizer weight of 26.6 (2.2) g (36% of initial weight) verified that fertilizer release had concluded by August 2003, 15 months following application. Mean soil temperature between 1 May and 31 October was 22 °C during 2002 and 20 °C in 2003. For the period 1 November to 31 April, mean soil temperature was 6 °C in 2002 and 2003.

4. Discussion

4.1. Seedling growth

Hardwood plantations have historically been difficult to establish successfully in the eastern USA. A recent survey of 87 afforestation plantations (ages 1–5 years) throughout Indiana reported a mean seedling survival rate of 66%, with only 49% of seedlings considered free-to-grow at year 5 (Jacobs et al., 2004b). This survival rate contrasts markedly with operational conifer tree plantations in the Pacific Northwest and southeastern regions of the USA, where seedling survival is routinely much higher. Most hardwood plantation failures may be associated with competition from non-crop vegetation and (or) damage from animal browse during the early years after outplanting (Cogliastro et al., 1990; Kolb et al., 1990; Gordon et al., 1995; Gillespie et al., 1996; Martin and Baltzinger, 2002). Poor quality seedlings and harsh site conditions may further account for difficulty in establishing hardwood plantations (Dey and Parker, 1997; Ward et al., 2000).

Our study results suggest that application of CRF at outplanting may alleviate poor site conditions and

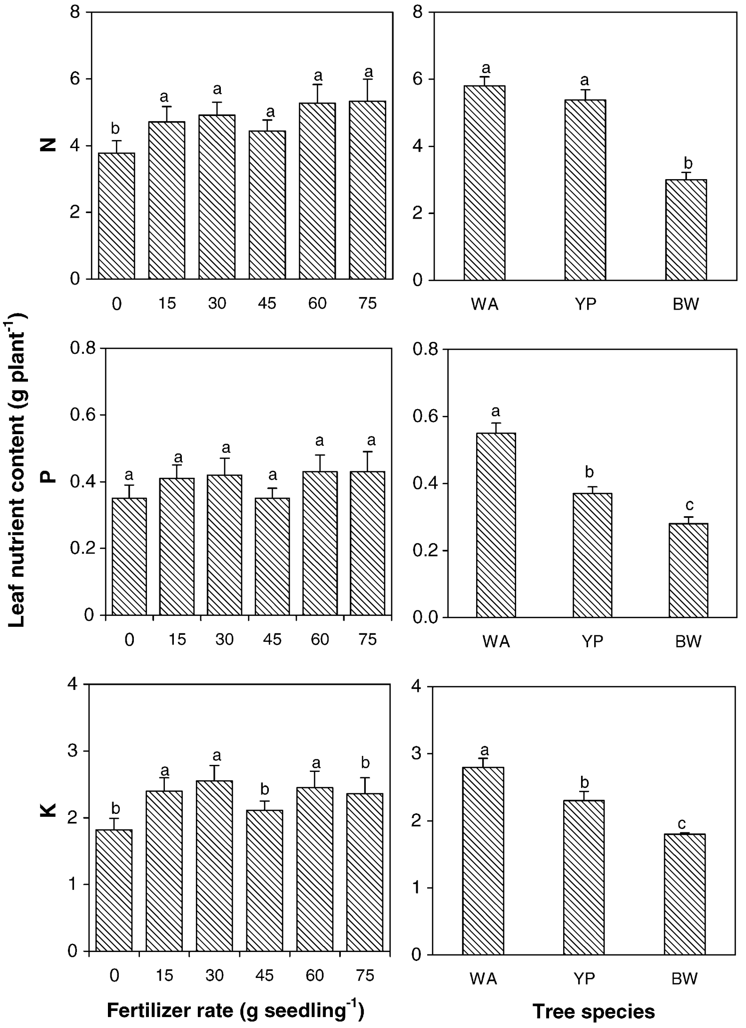

Fig. 4. Mean second-year leaf N, P, and K content of white ash (WA), yellow-poplar (YP), and black walnut (BW) [right] as influenced by different rates of CRF applied at outplanting [left]. Bars marked with similar letters among species or fertilizer rates are not statistically different according to Fisher's protected least significant difference test at $\alpha = 0.10$. Error bars represent the standard error of the mean.

stimulate early growth of hardwood seedlings to help facilitate rapid development to a free-to-grow state above associated levels of browse and competing vegetation. The lack of fertilizer rate × species interaction effects (Table 2) implies that species responded similarly to fertilizer treatments. The significant increase in height and RCD growth from the 60 g seedling^{-1} rate relative to controls (Figs. 1 and 2) clearly demonstrates the potential of CRF application at outplanting in promoting seedling field performance. These results support the contention that CRF application to the outplanting hole or incorporation in container root plugs may provide a more effective means of stimulating seedling growth compared to broadcast application of immediately available fertilizer forms (Carlson and Preisig, 1981; Moore et al., 2002; Fan et al., 2004). Similarly, total height was increased by 42% in Douglas-fir (Carlson and Preisig, 1981) and 27% in western hemlock (Carlson, 1981) seedlings at 2 years following adjacent or in-hole application of 21 g of Osmocote CRF at outplanting. Incorporation of Osmocote

18N-5P-12K into container growing media at 30 kg m^{-3} prior to sowing doubled Douglas-fir stem volume compared to controls after three growing seasons (Haase et al., in press). These results clearly suggest that CRF may offer a means to improve initial establishment success of outplanted seedlings. These findings also contrast markedly with results of other studies suggesting poor seedling performance with application of immediately available fertilizer (Williams, 1974; Braun and Byrnes, 1982) or controlled-release fertilizer (Arnott and Burdett, 1988) at outplanting.

Another approach to facilitate early seedling development is weed control, which was excellent on this site and is likely a necessary pre-requisite for attaining positive seedling response from any fertilizer application (Nambiar and Sands, 1993). Enhanced hardwood seedling performance following weed control concurs with results of other studies demonstrating that herbicide provides an effective tool for managing competing vegetation (Cogliastro et al., 1990; McGill and Brennman, 2002; Jacobs et al., 2004b). Furthermore, fencing to eliminate browse damage in this study was effective in ensuring high seedling survival and helping promote field response, as noted by others (Gillespie et al., 1996; Ward et al., 2000; Martin and Baltzinger, 2002). Thus, fertilizer addition in the absence of additional silvicultural treatments may not elicit a positive response in hardwood seedling plantations. Rather, it is likely that a multifaceted approach, in which several management strategies work together to produce a desired field response, is needed to enhance plantation establishment success.

4.2. Nutrient accumulation in seedlings

Nutrient enrichment at outplanting may promote early establishment success and growth of seedlings (van den Driessche, 1988; Hunt, 1989; Walker and Huntt, 1992; Cogliastro et al., 1990; Walker and Lane, 1997), which could further enhance exploitation of site resources to meet ongoing growth demand. Improved nutrient acquisition with increasing CRF rates (Fig. 4) is consistent with the preceding contention. The hardwood species used in this study require soils with moderate to high N, P, K, and Ca levels for optimum field performance (Beck, 1990; Schlesinger, 1990; Williams, 1990). Thus, the native soil fertility on this site was likely insufficient to meet growth demand, especially for hardwoods, which generally have greater sink strengths and nutrient requirements than conifers (Davey, 1994). Increased growth in white ash and yellow-poplar (Fig. 3, right) corresponded with greater nutrient acquisition (Fig. 4, right). Higher sink strength in these species also suggested higher CRF rates might be needed to maximize growth at age 2 years.

Estimates of fertilizer release in our study indicated that about 50% of nutrients in CRF prills were released during the first growing season, with the remaining 50% potentially available for plant uptake in the subsequent growing season. The relatively low winter soil temperature (mean of 6 °C from 1 November to 31 April) apparently helped preserve fertilizer for release through the second growing season. Fan et al. (2002) reported a range of 39–86% of total nutrients released from four CRF types, ranging in estimated release duration from 9–15 months, during the first growing season on a site in northern Idaho, USA. Gradual release of fertilizer from polymer-coated CRF into the rhizosphere throughout the first two growing seasons is a clear advantage of planting-hole application of CRF compared to broadcast fertilization of immediately available fertilizer forms. Additionally, growth of outplanted seedlings is largely dependent on retranslocation of nutrients from stored reserves (Malik and Timmer, 1998; Salifu and Timmer, 2001, 2003a). For instance, retranslocation met 100% of N demand for early growth of black spruce (*Picea mariana* (Mill.) BSP) seedlings (Salifu and Timmer, 2003a). The increased growth of fertilized seedlings compared to controls was associated with greater nutrient acquisition (Fig. 4, left), which could increase storage pools for subsequent utilization. Enhanced nutrient status, combined with early growth dominance and rapid attainment of free-to-grow status suggests that improved field performance of fertilized seedlings may continue beyond the first two seasons (Timmer, 1999). We expect to test the importance of nutrient remobilization processes in stimulating hardwood seedling transplanting performance, and to conduct long-term monitoring of this plantation to assess whether the growth responses observed during the first 2 years persist over time.

5. Conclusions

Our study results suggest that CRF may offer a means to improve initial afforestation establishment success of hardwood seedlings and early plantation productivity. Application of CRF at outplanting stimulated initial seedling field growth compared to non-fertilized seedlings, while also maintaining high seedling survival. Species responded similarly to fertilizer treatments. Height growth during the first season was increased by 52% in the 60 g seedling^{-1} rate compared to the control, but decreased 14% relative to the 60 g rate at the 75 g rate. Nutrient acquisition was promoted by CRF enrichment at outplanting consistent with results of previous studies (Hangs et al., 2003). Approximately equal amounts of nutrients were released from this CRF during the first and second growing seasons. Use of planting-hole application of CRF has clear advantages in promoting hardwood seedling plantation establishment over previously tested methods of broadcast application with immediately available fertilizer forms. Continued research should examine the potential to more accurately synchronize nutrient release rates of CRF with crop demand. Additionally, potential for new techniques such as exponential nutrient loading in the nursery (Timmer, 1997; Salifu and Timmer, 2003b) and nutrient spiking prior to outplanting (Timmer and Teng, 2004) should be examined as a means to stimulate hardwood seedling field response while eliminating the cost of field fertilization. The multifaceted approach adopted in this study including browse protection, control of competing vegetation with herbicide, and CRF application at outplanting promoted high rates of early hardwood afforestation plantation establishment success. An integrated combination of management strategies is likely necessary to ensure successful early establishment of outplanted hardwood seedlings.

Acknowledgements

Indiana DNR Vallonia Nursery donated seedlings, and O.M. Scotts Co. donated fertilizer for this experiment. Patricio Alzugaray, Anthony Davis, Bill Maschino, Amy Ross-Davis, Barrett Wilson, and Jewell Yeager assisted with field and (or) laboratory work. Funding support was provided by Purdue University. We are thankful to the Editor and anonymous reviewers for their critical and constructive comments on a previous version of this manuscript.

References

Alzugaray, P.J., 2002. Effects of fertilization at the time of planting on field performance of 1+1 Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] seedlings. M.S. thesis, Oregon State University, Corvallis, OR.

Anderson, V.L., McLean, R.A., 1974. Design of Experiments: A Realistic Approach. Marcel Dekker, New York.

Arnott, J.T., Burdett, A.N., 1988. Early growth of planted western hemlock in relation to stock type and controlled-release fertilizer application. Can. J. For. Res. 18, 710–717.

Beck, D.E., 1990. Yellow-poplar (*Liriodendron tulipifera* L.). In: Burns, R.M., Barbara, H.H. (Tech. Coords.), Silvics of North America: 2. Hardwoods. USDA Forest Service, Washington, DC, Agriculture Handbook 654, pp. 406–416.

Becker, C.A., Mroz, G.D., Fuller, L.G., 1987. The effects of plant moisture stress on red pine (*Pinus resinosa*) seedling growth and establishment. Can. J. For. Res. 17, 813–820.

Beineke, W.F., 1986. Black Walnut Plantation Management. Purdue University Cooperative Extension Service, FNR-119, 11 pp.

Brady, N.C., Weil, R.R., 2002. The Nature and Properties of Soils, 13th ed. Prentice Hall, New Jersey.

Braun, J.M., Byrnes, W.R., 1982. Growth of black walnut in a fertilized plantation. In: Black Walnut for the Future. USDA, Forest Service, North Central Research Station, St. Paul, MN, pp. 97–104, GTR-NC-74.

Brockley, R.P., 1988. The effects of fertilization on the early growth of planted seedlings. a problem analysis. Forestry Canada, Ottawa, Ont. For. Resour. Dev. Agree. Re 0835-0752:011. Victoria, British Columbia, 16 pp.

Brown, J.R. (Ed.), 1997. Recommended chemical soil test procedures for the North Central Region. NCR Publication No. 221 (revised). Missouri Agricultural Experiment Station SB 1001, 75 pp.

Burdett, A.N., Herring, L.J., Thompson, C.F., 1984. Early growth of planted spruce. Can. J. For. Res. 14, 644–651.

Campbell, R.A., 1990. Herbicide use for forest management in Canada. Where we are and where we are going? For. Chron. 66, 355–360.

Carlson, W.C., 1981. Effects of controlled -release fertilizers on the shoot and root development of outplanted western hemlock (*Tsuga heterophylla* Raf. Sarg.) seedlings. Can. J. For. Res. 11, 752–757.

Carlson, W.C., Preisig, C.L., 1981. Effects of controlled-release fertilizers on the shoot and root development of Douglas-fir seedlings. Can. J. For. Res. 11, 230–242.

Chang, S.X., Preston, C.M., 2000. Understorey competition affects tree growth and fate of fertilizer 15N in a coastal British Columbia plantation forest. Can. J. For. Res. 30, 1379–1388.

Chang, S.X., Preston, C.M., McCullough, K., Weetman, G.F., Barker, J., 1996. Effects of understorey competition on distribution and recovery of 15N applied to western red cedar-western hemlock clear-cut site. Can. J. For. Res. 26, 313–321.

Cogliastro, A., Gagnon, D., Coderre, C., Bhereur, P., 1990. Response of seven hardwood tree species to herbicide, rototilling, and legume cover at two southern Quebec plantation sites. Can. J. For. Res. 20, 1172–1182.

Davey, C.B., 1994. Soil fertility and management for culturing hardwood seedlings. In: Landis, T.D., Dumroese, R.K. (Tech. Coords.). National Proceedings: Forest and Conservation Nursery Associations. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 38–49, RM-GTR-257.

Dey, D.C., Parker, W.C., 1997. Morphological indicators of stock quality and field performance of red oak (*Quercus rubra* L.) seedlings underplanted in a central Ontario shelterwood. New For. 14, 145–156.

Donald, D.G.M., 1991. Nursery fertilization of conifer planting stock. In: van den Driessche, R. (Ed.), Mineral Nutrition of Conifer Seedlings. CRC Press, Boca Raton, FL, pp. 135–167.

Fan, Z., Moore, J.A., Shafii, B., Osborne, H.L., 2002. Three-year response of ponderosa pine seedlings to controlled-release fertilizer applied at planting. West. J. Appl. For. 3, 154–164.

Fan, Z., Moore, J.A., Wenny, D.L., 2004. Growth and nutrition of container-grown ponderosa pine seedlings with controlled-release fertilizer incorporated in the root plug. Ann. For. Sci. 61, 117–124.

Gillespie, A.R., Rathfton, R., Myers, R.K., 1996. Rehabilitating a young northern red oak planting with tree shelters. North. J. Appl. For. 13, 24–29.

Goertz, H.M., 1993. Controlled release technology. In: Howe-Grant, M. (Ed.), Encyclopedia of Chemical Technology. 4th ed. Wiley, New York, pp. 254–274.

Gordon, A.M., Simpson, J.A., Williams, P.A., 1995. Six-year response of northern red oak seedlings planted under a shelterwood in central Ontario. Can. J. For. Res. 25, 603–613.

Haase, D.L., Rose, R. (Eds.) 1997. Symposium proceedings: Forest seedling nutrition from the nursery to the field. Nursery Technology Cooperative, Oregon State University, Corvallis, 161 pp.

Haase, D.L., Rose, R., Trobaugh, J., in press. Field performance of three stock sizes of Douglas-fir container seedlings grown with slow-release fertilizer in the nursery growing medium. New For.

Hangs, R.D., Knight, J.D., van Rees, K.C.J., 2003. Nitrogen accumulation by conifer seedlings and competitor species from ^{15}nitrogen-labeled controlled-release fertilizer. Soil Sci. Soc. Am. J. 67, 300–308.

Hunt, G.A., 1989. Effect of controlled-release fertilizers on growth and mycorrhizae in container-grown Engelmann spruce. West. J. Appl. For. 4, 129–131.

Imo, M., Timmer, V.R., 2001. Growth and nitrogen retranslocation of nutrient loaded *Picea mariana* seedlings planted on boreal mixedwood sites. Can. J. For. Res. 31, 1357–1366.

Jacobs, D.F., 2003. Nursery production of hardwood seedlings. Purdue University Cooperative Extension Service, FNR-212, 8 pp.

Jacobs, D.F., Rose, R., Haase, D.L., 2003a. Incorporating controlled-release fertilizer technology into outplanting. In: Riley, L.E., Dumroese, R.K., Landis, T.D. (Tech. Coords.), National Proceedings: Forest and Conservation Nursery Associations. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, RMRS-P-28, pp. 37–42.

Jacobs, D.F., Rose, R., Haase, D.L., 2003b. Development of Douglas-fir seedling root architecture in response to localized nutrient supply. Can. J. For. Res. 33, 118–125.

Jacobs, D.F., Rose, R., Haase, D.L., Alzugaray, P.O., 2004a. Fertilization at planting impairs root system development and drought avoidance of Douglas-fir (*Pseudotsuga menziesii*) seedlings. Ann. For. Sci. 61, 643–651.

Jacobs, D.F., Ross-Davis, A., Davis, A.S., 2004b. Establishment success of conservation tree plantations in relation to silvicultural practices in Indiana. USA New For. 28, 23–36.

Kolb, T.E., Bowersox, T.W., McCormick, L.H., 1990. Influence of light intensity on weed-induced stresses of tree seedlings. Can. J. For. Res. 20, 503–507.

Kozlowski, T.T., 1987. Soil moisture and absorption of water by tree roots. J. Arbor. 13, 39–46.

Malik, V., Timmer, V.R., 1998. Biomass partitioning and nitrogen retranslocation in black spruce seedlings on competitive mixedwood sites: a bioassay study. Can. J. For. Res. 28, 206–215.

Martin, J.L., Baltzinger, L.C., 2002. Interaction among deer browsing, hunting, and tree regeneration. Can. J. For. Res. 32, 1254–1264.

McGill, D.W., Brennman, B.B., 2002. Six-year development of regenerating natural hardwood stands with herbaceous weed control. North. J. Appl. For. 19, 14–21.

McMillin, J.D., Wagner, M.R., 1995. Effects of water stress on biomass partitioning of ponderosa pine seedlings during primary root growth and shoot growth periods. For. Sci. 41, 594–610.

Moore, J.A., Fan, Z., Shafii, B., 2002. Effects of root-plug incorporated controlled-release fertilizer on two-year growth and survival of planted ponderosa pine seedlings. West. J. Appl. For. 4, 216–219.

Nambiar, E.K.S., Sands, R., 1993. Competition for water and nutrients in forests. Can. J. For. Res. 23, 1955–1968.

Ponder, F. Jr., 1996. Walnut fertilization and recommendations for wood and nut production. In: Van Sambeek, J.W. (Ed.), Knowledge for the Future of Black Walnut. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN, GTR-NC-191, pp. 128–137.

Rietveld, R., 1989. Transplanting stress in bareroot conifer seedlings: its development and progression to establishment. North. J. Appl. For. 6, 99–107.

Salifu, K.F., Timmer, V.R., 2001. Nutrient retranslocation response of *Picea mariana* seedlings to nitrogen supply. Soil Sci. Soc. Am. J. 65, 905–913.

Salifu, K.F., Timmer, V.R., 2003a. Nitrogen retranslocation response of young *Picea mariana* to nitrogen-15 supply. Soil Sci. Soc. Am. J. 67, 309–317.

Salifu, K.F., Timmer, V.R., 2003b. Optimizing nitrogen loading in *Picea mariana* seedlings during nursery culture. Can. J. For. Res. 33, 1–9.

Schlesinger, R.C., 1990. White ash (*Fraxinus americana* L.). In: Burns, R.M., Barbara, H.H. (Tech. Coords.), Silvics of North America: 2. Hardwoods. USDA Forest Service, Washington, DC, Agriculture Handbook 654, pp. 333–338.

Soil Survey Staff, 2004. National Soil Survey Characterization Data, Soil Survey Laboratory, National Soil Survey Center, USDA-NRCS, Lincoln, NE.

Staples, T.E., Van Rees, K.C.J., Van Kessel, C., 1999. Nitrogen competition using ^{15}N between early successional plants and planted white spruce seedlings. Can. J. For. Res. 29, 1282–1289.

Struve, D.K., Joly, R.J., 1992. Transplanted red oak seedlings mediate transplant shock by reducing leaf surface area and altering carbon allocation. Can. J. For. Res. 22, 1441–1448.

Timmer, V.R., 1997. Exponential nutrient loading: a new fertilization technique to improve seedling performance on competitive sites. New For. 13, 279–299.

Timmer, V.R., 1999. Exponential fertilization and nutrient loading of planting stock for vegetation control. In: Redding, CA, Proceedings of the 20th Annual Forest Vegetation Management Conference, pp. 77–81.

Timmer, V.R., Teng, Y., 2004. Pre-transplant fertilization of containerized *Picea mariana* seedlings: calibration and bioassay growth response. Can. J. For. Res. 34, 2089–2098.

van den Driessche, R., 1988. Nursery growth of conifer seedlings using fertilizers of different solubilities and application time, and their forest growth. Can. J. For. Res. 18, 172–180.

van den Driessche, R., 1991. Effects of nutrients on stock performance in the forest. In: van den Driessche, R. (Ed.), Mineral Nutrition of Conifer Seedlings. CRC Press, Boca Raton, FL, pp. 229–260.

von Kiparski, G.R., 2004. Resource productivity vectors within a temperate alley cropping system. Ph.D. Dissertation, Purdue University, West Lafayette, IN.

Walker, R.F., Huntt, C.D., 1992. Controlled release fertilizer effects on growth and foliar nutrient concentration of container grown Jeffrey pine and singleleaf pinyon. West. J. Appl. For. 7, 113–117.

Walker, R.F., Lane, L.M., 1997. Containerized Jeffrey pine growth and nutrient uptake in response to mycorrhizal inoculation and controlled release fertilization. West. J. Appl. For. 12, 33–40.

Ward, J.S., Gent, M.P.N., Stephens, G.R., 2000. Effects of planting stock quality and browse protection-type on height growth of northern red oak and eastern white pine. For. Ecol. Manage. 127, 205–216.

Williams, R.D., 1974. Planting methods and treatments for black walnut seedlings. Research Paper RP-NC-107. USDA Forest Service, North Central Experiment Station, St. Paul, MN, 5 pp.

Williams, R.D., 1990. Black walnut (*Juglans nigra* L.). In: Burns, R.M., Barbara, H.H. (Tech. Coords.), Silvics of North America: 2. Hardwoods. USDA Forest Service, Washington, DC, Agriculture Handbook 654, pp. 391–399.